Facoltà di Ingegneria

Corso di laurea magistrale in Green Industrial Engineering

DIGITAL TWIN SYSTEM

FOR SMART HYDROGEN PRODUCTION

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ABSTRACT

In this thesis I will report the work I have done during the 6 months of internship in TechFem.

During this period I have worked on different things.

First, I have studied all the bibliographic part of the hydrogen (and its production with the electrolyser), of the electric market, and of the digital twin.

Then, I created in Excel different scenarios, to see how the cost of production of the hydrogen can be abated, and also how it is affected by the electric market.

In conclusion, I studied the P&I of the Smart Hydro project and I created a cause-effect matrix, which is the definition of how the digital twin should work, in order to manage every issue.

TechFem

TechFem is a factory situated in Fano (PU), in the center of Italy.

Their target is the green energy, indeed they work on a lot of projects which aim to the sustainability.

This ethic approach contributes to create a corporate philosophy that makes TechFem competitive not only in the business world, but also in the environment, in the social component, and in the governance capacity, with the awareness that the sustainability of these elements is the basement for the factory evolution.

https://www.techfem.com/it/about-us/

Learned skills

The target of this internship was to improve my working skills and to use my previous knowledge to do all the things I have written above.

I can say that during these 6 months I have learned how to interact in a working place, I have improved my skills in communication, in the use of software, and I have done another step of maturity.

Smart Hydro

The Smart Hydro project is a project designed by TechFem.

It aims to the smart production of hydrogen.

All the components (PV, H_2O, electrolyser, compressor, storage tanks, FC) are connected and managed by a digital twin, which, with all the collected data, manages each component in order to abate risks, costs, and to elevate the efficiency of the system.

THE ELECTRIC MARKET

1.1 INTRODUCTION

The electric market arrives in Italy with the D. Lgs. N. 79/99, which aims to:

- Promote the competition of production and sale activity
- Favor transparency and efficiency of the dispatching activity

The electric market is a telematic marketplace for the negotiation of the electric energy, in which the price of energy corresponds to the price of equilibrium obtained between the asks and the bids.

It is, indeed, a real market, where entry and withdrawal programs are defined by the grid, using an economic criteria.

GME

The **GME** (Gestore dei Mercati Energetici S.p.A.) is the company that organizes and manages the electric market, the gas market, and the ambient market, with neutrality, transparency, objectivity and concurrency.

The electric stock market, essential for the development of a concurrent market, provides efficient equilibrium prices that allow producers and wholesalers to buy and sell electric energy in the best economic way.

The electric markets managed by the **GME** are divided in:

- Spot Energy Market (day before, intraday, dispatching)
- Futures Energy Market (physic delivery of the energy)

ACTIVITY

The electric market, in a free market context, is organized in different activities:

- Production
- Transmission
- Distribution

The **production** of electric energy can be done in several ways. It consists in the transformation of primary energy sources into electricity.

The **transmission** consists in the transport of the energy from the production centers to the consumption ones. The grid acts like communicating vessels, where all the input energy will be withdrawn.

The last phase is the **distribution**, which consists in the delivery of the electricity in medium and low voltage, directly to the users.

<u>MEMBERS</u>

The principal members who allow the system to work well are:

- The **parliament** and the **government**
- The **MSE** (Ministero dello Sviluppo Economico), that ensures safety.
- The **AEEG** (Autorità per l'Energia Elettrica e il Gas), that ensures concurrency and efficiency.
- **Terna S.p.A.**, which manages the national transmission grid and the electric energy flows, balancing asks and bids.
- The **GSE** (Gestore dei Servizi Energetici), which supports the development of green sources with incentives.
- The **AU** (Acquirente Unico), which guarantees the correct supply of the energy.
- The **GME** (Gestore dei Mercati Energetici), which organizes and manages the electric market.

CONSTRAINTS

The grid system, in order to be efficient, requires strict constraints:

- Instantaneous ad continuous balancing
- Frequency maintenance (for plants safety)
- Sureness of that energy fluxes don’t overtake each power line limit

DISPATCHER

The complex system needs a central coordinator, that has to have a control power on all the production plants.

This controller is called **dispatcher**, it represents the fulcrum of the electric market system, and has to ensure the correct functioning and the maximum safety.

It, indeed, guarantees that the production equals the consumption and that the frequency and the voltage don’t deviate the optimal values too much.

The dispatcher also balances the system in real-time. This last action (called **balancing**) is guaranteed by the regulation and control systems of the production unities, which increase and decrease the intake of the energy in the grid.

1.2 DIFFERENT MARKETS

The energy market was created in order to promote competition in the production and sale of electricity, and to ensure the economic management of an adequate availability of dispatching services.

The electric market is divided into:

- Day-ahead market;
- Intraday market;
- Balancing market.

DAY-AHEAD MARKET

On the **day-ahead** market, hourly blocks of energy are exchanged for the following day. The operators participate by presenting offers in which they indicate the quantity and the maximum/minimum price at which they are willing to buy/sell.

The session of this market opens at 8.00 on the 9^{th} day before the delivery day and closes at 12.00 on the day before the day of delivery.

Bids are accepted after the close of the market session, on the basis of economic merit and in compliance with the transit limits between zones.

The Italian energy market is divided into 7 zones (North, Center-North, Center-South, South, Calabria, Sicily, Sardinia).

For each hour of the day and for each zone negotiations are carried out, whose results represent the hourly zone prices.

These prices are the meeting point between the energy demand forecast for each hour for each zone (forecast curve) and the energy supply of the other plants.

The purchase offers accepted and referring to the consumption units belonging to the Italian geographical areas are valued at the **PUN** (Prezzo Unico Nazionale), equal to the average of the geographical areas weighted by the quantities purchased in these areas.

GME acts as a central counterparty.

INTRADAY MARKET

The **intraday** market allows operators to make changes to the programs defined in the **MGP** (Mercato del Giorno Prima) through further purchase or sale offers.

It takes place in 7 sessions, and the accepted purchase offers are valued at the zonal price.

GME acts as a central counterparty.

In the **intraday** market, once the results of the **MGP** are known (volumes and prices hour by hour in the individual zones), each energy producer operates trying to optimize the maximum profit from its entire fleet of power plants, managed in a coordinated manner, and therefore optimized before the end of the day.

The accepted purchase offers are valued at the zonal price.

BALANCING MARKET

The **balancing** market is the tool through which **Terna S.p.A.** procures the resources necessary for the management and control of the system (resolution of intra-zonal congestion, creation of the energy reserve, balancing in real time).

Terna acts as a central counterparty and accepted offers are remunerated at the price presented (pay-as-bid).

The **balancing** market takes place in several sessions, according to the provisions of the dispatching regulations.

There is a single session for the presentation of offers, and it opens at 12.55 on the day before the day of delivery and closes at 17.30 on the same day. **Terna** accepts energy purchase and sale offers for the purpose of resolving residual congestion and establishing reserve margins.

1.3 CONSUMPTION TIME SLOTS

Consumption time slots (or electricity time bands) are periods of time during a day when the price of the energy component varies.

Timeslots are established by the **ARERA** (Autorità di Regolazione per Energia Reti e Ambiente), which is the body that carries out regulations and control activities in the electricity, natural gas, water services, waste management and remote heating sectors.

<u>HOW THEY WORK</u>

There are three time slots for electricity market users: **F1**, **F2**, **F3**.

Each time slot is associated with a specific period of the day or an entire day (for example, consumption on Sunday is calculated in the **F3** slot) and the suppliers have the possibility of calibrating their offers according to the needs of the users.

During the day, energy demand is usually higher than in the evening. Let's think, for example, of industries, shops, bars and other activities that open in the morning and close between 18.00 and 20.00. Based on fluctuations in demand, **Enel Energia** (and onther suppliers) modulate their prices and make offers based on time slots, which allow customers to save on electricity.

Understanding the difference between the time slot offers allows you to regulate the use of household appliances, so as to save on your energy costs.

F1-F2-F3

The first slot is called **F1**: active from Monday to Friday, from 8.00 TO 19.00, excluding holidays.

The second slot is called **F2**: active from Monday to Friday, 7.00 to 8.00 and 19.00 to 23.00, and Saturday from 7.00 to 23.00, excluding Saturdays that are national holidays.

Finally, there is the third slot called **F3**: active from Monday to Saturday from midnight to 7.00 and from 23.00 to midnight, and all day on Sundays and holidays.

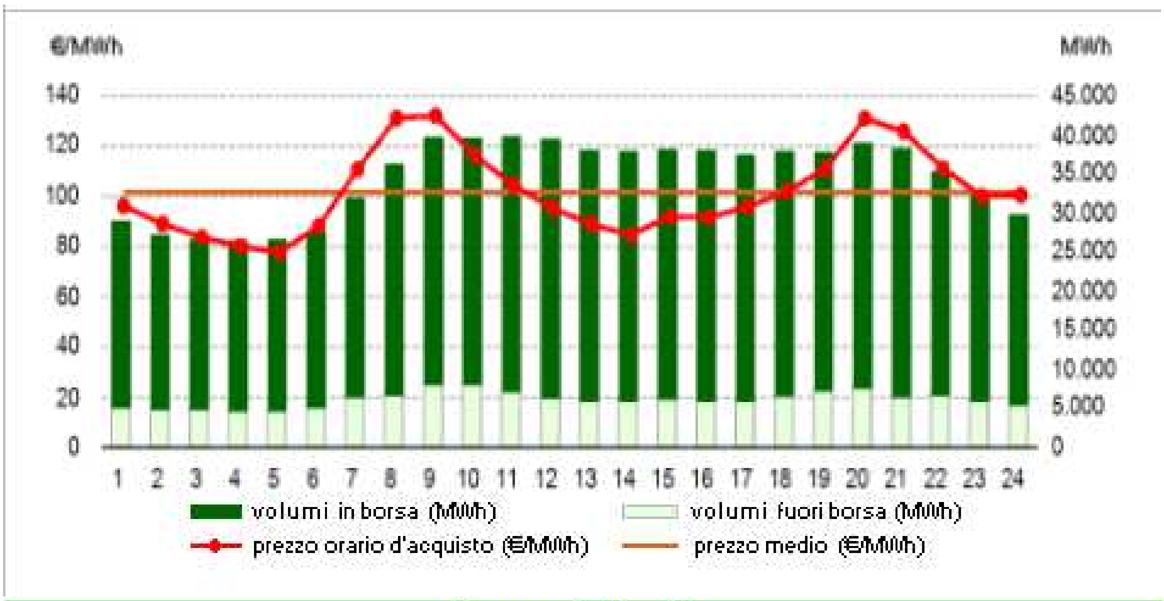
For domestic customers, the price of energy (or the price of energy components) in the **F2** and **F3** slots can coincide and cover the time from 19.00 to 8.00 from Monday to Friday, and all day on Saturdays, Sundays and holidays.

1.4 ELECTRICITY PRICE CURVE

As descripted in the previous paragraphs, the electricity price varies hourly.

Everyday, the **GME** shows the hourly zone prices, in order to calculate the **PUN** and to generate forecasts for the next days.

As you can see, this next image describes the variation of **PUN** in a day.



Prezzo zonale di vendita

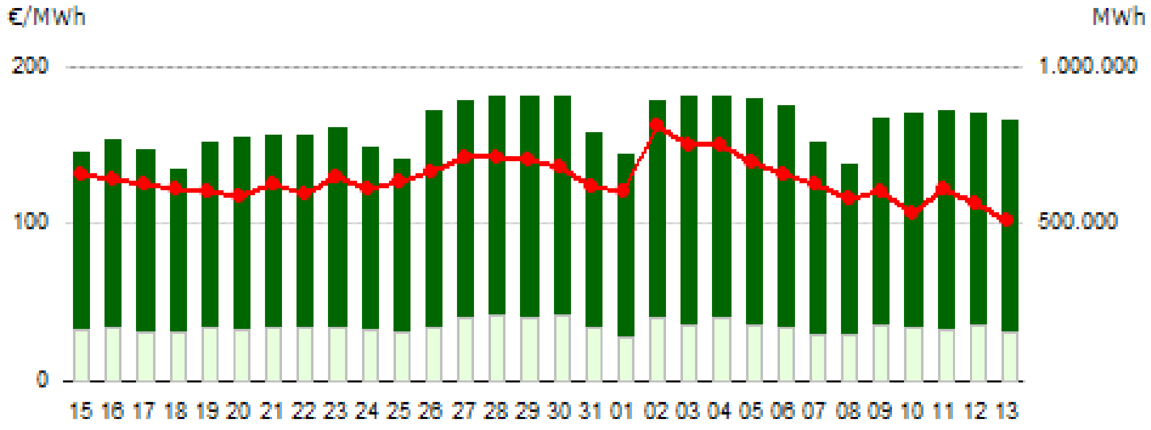
	Nord €/MWh	Centro Nord €/MWh	Centro Sud €/MWh	Sud €/MWh	Calabria €/MWh	Sicilia €/MWh	Sardegna €/MWh
Baseload	**104,04**	**104,04**	**101,24**	**94,87**	**94,87**	**94,87**	**80,01**
Picco	108,51	108,51	102,91	90,17	90,17	90,17	60,45
Fuori picco	99,57	99,57	99,57	99,57	99,57	99,57	99,57
Minimo orario	77,75	77,75	74,20	37,96	37,96	37,96	0,00
Massimo orario	132,04	132,04	132,04	132,04	132,04	132,04	132,04
CCT	**-2,37**	**-2,37**	**0,43**	**6,80**	**6,80**	**6,80**	**21,66**

Volumi zonali

		Nord MWh	Centro Nord MWh	Centro Sud MWh	Sud MWh	Calabria MWh	Sicilia MWh	Sardegna MWh
Offerte	**Totale**	**655.470**	**49.698**	**212.899**	**205.854**	**79.320**	**95.408**	**52.101**
	Media	27.311	2.071	8.871	8.577	3.305	3.975	2.171
Vendite	**Totale**	**339.190**	**35.723**	**69.182**	**114.358**	**38.894**	**52.425**	**40.612**
	Media	14.133	1.488	2.883	4.765	1.621	2.184	1.692
Acquisti	**Totale**	**462.900**	**69.911**	**139.765**	**52.525**	**15.586**	**50.077**	**23.200**
	Media	19.287	2.913	5.824	2.189	649	2.087	967

In the second image you can see all the purchase/sale offers for every zone.

After that, the **GME** exports data for all the previous 30 days, in order to give the opportunity to forecast future prices.



As we can see in this last picture, the **PUN** is a little bit higher than 100 €/MWh with a little decreasing line except for the day number 02.

H2 EFFICIENCY

2.1 H2

<u>Characteristics</u>

Hydrogen is a chemical element. It has symbol H and atomic number 1.

It is the lightest element and, at standard conditions, is a gas of diatomic molecules with the formula **H_2**.

It is colorless, odorless, tasteless, non-toxic, and highly combustible.

Its heating value is the highest between every fuel, meaning that it has the best yield.

<u>Production</u>

Many methods exist for producing **H_2**, but three dominate commercially:

- **Steam reforming**

It consists in the reaction of water and methane. At high temperatures (700-1100 °C), steam reacts with methane to yield carbon monoxide and **H_2**.

$CH_4 + H_2O \rightarrow CO + 3\,H_2$

- **Partial oxidation of hydrocarbons**

It consists in a chemical reaction where a substoichiometric fuel-air mixture is partially combusted in a reformer, creating a **H_2**-rich syngas.

$CH_4 + O_2 \rightarrow 2\ CO + \mathbf{4\ H_2}$

$C + H_2O \rightarrow CO + \mathbf{H_2}$

- **Water electrolysis**

It consists in the process whereby water is split into **H_2** and O_2 through the application of electrical energy.

$2\ H_2O + \text{energy} \rightarrow \mathbf{2\ H_2} + O_2$

Applications

Hydrogen can be used for lots of applications, such as petrochemical industry, hydrogenation, as a coolant, and as energy carrier.

Nowadays it is also in growth its use as combustible for transports (cars, ships, trains) and in the gas grid mixed with natural gas.

Transport

The hydrogen can be transported in 2 ways:

- **Pipelines**: transported as a gas or a liquid with high pressures
- **Tanks**: stocked usually in its gaseous form in tanks

Stockage

Also the stockage can be done in several ways.

The most relevant are:

- **Tanks**: stocked in tanks at high pressures (from 700 to 2100 bars)
- **Liquid form**: after it condensation it is put in cryogenic containers at a temperature near to -253 °C
- **"solid state"**: the **H2** is absorbed in a crystal lattice where, reacting with other metals, it forms metallic hydrides

2.2 ELECTROLYSER

An **electrolyser** is a machine that splits water molecules (H2O) in Hydrogen and Oxygen by the process of **electrolysis**.

Electrolysis

The **electrolysis** is a technique that uses direct electric current (DC) to drive a non-spontaneous reaction.

The main components required to achieve it are an electrolyte, electrodes, and an external power source.

The electrolyte is a chemical substance which contains free ions and carries electric current.

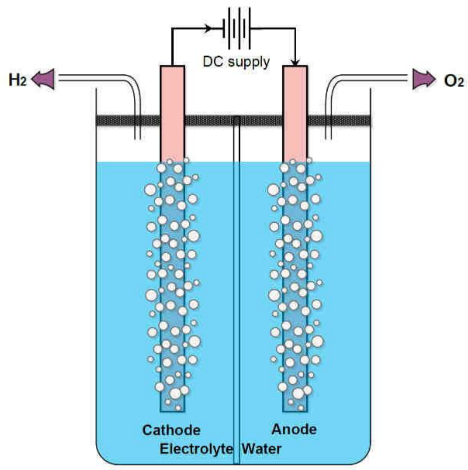
The electrodes are immersed separated by a distance such that a current flows between them through the electrolyte and are connected to the power source which completes the electrical circuit. A direct current supplied by the power source drives the reaction causing ions in the electrolyte to be attracted toward the respective oppositely charged electrode.

The key process of **electrolysis** is the interchange of atoms and ions by the removal or addition of electrons due to the applied current.

Each electron attracts ions that are of the opposite charge. Positively charged ions (cations) move towards the electron-providing (negative) **cathode**. Negatively charged ions (anions) move towards the electron-extracting (positive) **anode**.

Fore example, in the next reaction we can see that 2H+ ions (cations) split from the 2OH- ions (anions).

$$H_2O \rightarrow H_2 + 2\ OH^-$$



There are 4 types of **electrolyzers**.

<u>Alkaline (ALK)</u>

The **alkaline** water electrolysis has a long service life without precious material components, that is why it is widely used in industry.

Its working temperature is 60-80 °C.

In this process, a reduction reaction occurs at the cathode, meanwhile an oxidation reaction occurs at the anode.

Proton Exchange Membrane (PEM)

The **PEM** electrolysis technology differs from the ALK one mainly for the replacement of the asbestos mesh with a proton exchange membrane.

That membrane conducts protons and isolates the gases of the cathode and anode.

PEM electrolysers have high current density and efficiency and their operating temperature is 50-80 °C.

Moreover, they adopt a zero gap structure, reducing the volume of the entire system.

Anion Exchange Membrane (AEM)

AEM electrolytic water technology can only reach kilowatt level, but it solves the problem of high cost of hydrogen production by using non-noble metal catalysts and titanium-free components.

This technology is very similar to the Alkaline one for the use of alkaline solutions as electrolytes. In **AEM** the electrolyte concentration is lower and the asbestos mesh is replaced by an anion exchange membrane.

Solid Oxide Electrolysis Cell (SOEC)

SOEC is a technology for producing hydrogen at high temperatures, leading to good thermodynamics and reaction kinetics.

The high temperature environment reduces the equilibrium voltage of the battery, reducing the power demand.

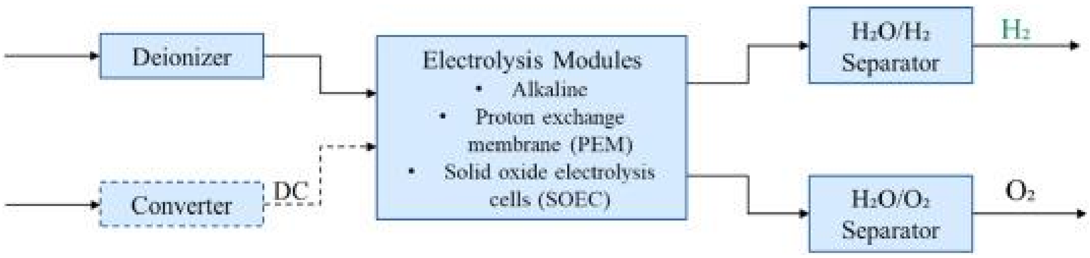
It also uses nickel (non-precious metal with high electrical conductivity) to make electrodes, in order to reduce the cost of hydrogen production.

Main components

Water electrolysis system consists of an electrolyser stack, and the balance of plant (**BOP**).

An electrolyser stack contains multiple cells, consisting of membrane electrode assemblies (**MEAs**), sandwiched between bipolar plates and assembly plates, and stacked in series.

The **BOP** includes water supply and purification units, water-gas separators, pumps, transformers, and rectifiers.



Efficiency

$$\dot{m}_{H_2} = \frac{\eta_I \cdot P_{el}}{HHV_{H_2}}$$

- **μ** is the efficiency of the electrolyser;
- **P** is the power of the electrolyser;
- **HHV** is the high heating value of the hydrogen;
- **m** is the mass flow rate of hydrogen produced;

As we can see in the equation above, the quantity of hydrogen produced is directly proportional to the electrolyser efficiency times its power.

The **HHV** of the hydrogen is a constant value (3,54 kWh/Nm3).

The **power** of the electrolyser is a characteristic of the electrolyser itself, so it is fixed.

The **efficiency** depends on the worn of the electrolyser, and it decreases with time.

2.3 SCENARIOS

In this section I will analyze 3 scenarios (STAND ALONE, grid supplied for 100% capacity an 100% load factor, HYBRID), that varies the H2 cost of production.

The main components of this work are a **PV** (Photo Voltaic plant) and the **electrolyser**.

The **PV** can be chosen between 1 MW or 4 MW of power, with a cost of 1 million € per MW.

The **electrolyser** has a power of 1 MW and a cost of 5 million €. This cost includes also electrical power panels, electrical and mechanical connections, compressor and storage system.

For the electrical energy, I took care of the nowadays average **PUN**. As it was done by my colleagues in TechFem, to obtain good estimations, I consider the price of the electric energy bought equal to the **PUN**, meanwhile the price at which it is sold is equal to the 80% of the **PUN**.

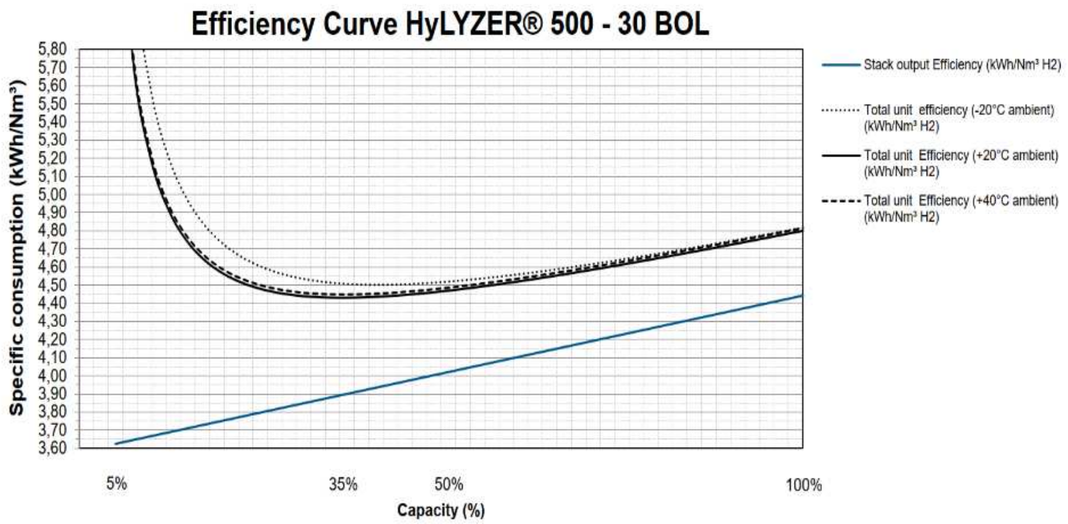
Instead for the price of Hydrogen, in order to make the graph of the **PBP** (Pay Back Period), I considered 13 €/kg, which is the price at which it is sold in the hydrogen pump in Bolzano in the Autostrada del Brennero.

Considering that both the electrolyser and the PV plant have a lifecycle of 20 years, in order to be considered a good investment the project aims to reach a PBP in less than 10 years.

The target production cost is inferior to 7 €/kg in order to be more competitive than diesel. Considering the fact that a diesel car run 100 km with 6 litres and that the nowadays price of diesel is 1,6 €/l, a driver spends 9,6 € every 100 km. On the other hand, due to the high calorific power of the hydrogen, a hydrogen car can run 100 km with only 1 kg of H2. If I produce it at less than 7 €/kg I can sell it to the distributor at a higher price, and the distributor can sell it at a lower price than 9,6 €/kg.

For example, if I produce it at 7 €/kg, I sell it to the distributor at 8 €/kg, which it will sell to the users at 9 €/kg, I earn 1 €/kg, the distributor earns 1 €/kg, and the user saves 0,60 € every 100 km.

Switch ON %



The efficiency curve of our electrolyser varies from its capacity.

As we can see in the figure, it is convenient to switch on the electrolyser only over the **35 %**.

PV production

Production in a typical day of each month in kWh (1MW)

1 MW	Gennaio	Febbraio	Marzo	Aprile	Maggio	Giugno	Luglio	Agosto	Settembre	Ottobre	Novembre	Dicembre
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	3,73256	12,89719	7,516415	0,955164	0	0	0	0
05:00	0	0	0	18,33095	50,64306	69,01238	57,52648	35,21153	10,20843	0,98146	0	0
06:00	0	0,268573	54,68108	147,5188	186,3642	233,0374	209,4347	176,6983	143,0695	80,80842	10,64316	0,33278
07:00	72,28321	123,5491	228,7591	337,257	335,1416	403,2861	409,0004	375,1123	332,5481	253,6623	131,3691	71,2761
08:00	251,8551	287,9193	395,7577	511,0817	489,218	572,4015	564,2368	538,0116	513,9491	427,8162	268,6659	242,9419
09:00	385,5622	418,2729	531,9338	635,6023	598,3187	688,9993	702,0487	667,2327	613,3764	531,3537	353,7795	327,3112
10:00	446,7444	516,7073	605,1278	703,2426	650,8361	749,3793	756,4007	753,0124	697,6951	585,289	409,1721	401,1574
11:00	483,993	552,461	640,1612	719,3456	693,9475	766,0981	774,6972	750,2846	706,7187	587,4923	427,9082	432,9193
12:00	445,3592	513,3932	596,7316	668,4351	664,629	749,5627	759,5824	737,0227	626,147	536,7519	390,1454	393,5503
13:00	369,8655	458,1945	514,9024	590,8326	580,995	657,2521	664,4237	679,4717	552,03	461,9536	323,0665	324,3279
14:00	251,0765	339,9557	401,7117	481,6948	466,3423	534,2196	546,3733	538,8515	452,7564	329,4464	198,4862	199,6011
15:00	89,20608	191,7182	264,0474	325,4698	330,0462	387,9529	400,7262	376,5384	294,0097	167,192	53,70808	18,59541
16:00	0	18,9543	92,53251	141,6243	166,4076	207,3172	223,6433	192,4152	109,8845	21,94518	1,199102	0
17:00	0	0	0,263172	14,28261	37,2554	58,91763	62,50146	41,22178	8,05054	0,328003	0	0
18:00	0	0	0	0	1,053553	11,1218	11,09451	1,896087	0,016275	0	0	0
19:00	0	0	0	0	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0
	31	28	31	30	31	30	31	31	30	31	30	31

Production in a typical day of each month in kWh (4MW)

4 MW	Gennaio	Febbraio	Marzo	Aprile	Maggio	Giugno	Luglio	Agosto	Settembre	Ottobre	Novembre	Dicembre
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	14,93024	51,58877	30,06566	3,820654	0	0	0	0
05:00	0	0	0	73,32382	202,5722	276,0495	230,1059	140,8461	40,83374	3,925841	0	0
06:00	0	1,074293	218,7243	590,0751	745,4567	932,1498	837,739	706,7932	572,2781	323,2337	42,57263	1,331122
07:00	289,1328	494,1965	915,0363	1349,028	1340,567	1613,144	1636,002	1500,449	1330,192	1014,649	525,4764	285,1044
08:00	1007,421	1151,677	1583,031	2044,327	1956,872	2289,606	2256,947	2152,046	2055,797	1711,265	1074,663	971,7676
09:00	1542,249	1673,092	2127,735	2542,409	2393,275	2755,997	2808,195	2668,931	2453,505	2125,415	1415,118	1309,245
10:00	1786,978	2066,829	2420,511	2812,97	2603,344	2997,517	3025,603	3012,05	2790,781	2341,156	1636,688	1604,63
11:00	1935,972	2209,844	2560,645	2877,383	2775,79	3064,393	3098,789	3001,138	2826,875	2349,969	1711,633	1731,677
12:00	1781,437	2053,573	2386,926	2673,741	2658,516	2998,251	3038,33	2948,091	2504,588	2147,008	1560,582	1574,201
13:00	1479,462	1832,778	2059,61	2363,33	2323,98	2629,008	2657,695	2717,887	2208,12	1847,815	1292,266	1297,311
14:00	1004,306	1359,823	1606,847	1926,779	1865,369	2136,878	2185,493	2155,406	1811,026	1317,786	793,9447	798,4043
15:00	356,8243	766,8726	1056,19	1301,879	1320,185	1551,812	1602,905	1506,154	1176,039	668,768	214,8323	74,38166
16:00	0	75,81721	370,13	566,4973	665,6306	829,2688	894,5732	769,6606	439,5379	87,78072	4,796408	0
17:00	0	0	1,05269	57,13045	149,0216	235,6705	250,0058	164,8871	32,20216	1,312011	0	0
18:00	0	0	0	0	4,214211	44,48719	44,37804	7,584346	0,0651	0	0	0
19:00	0	0	0	0	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0
	31	28	31	30	31	30	31	31	30	31	30	31

Parameters

CAPEX electrolyser	5.000.000 €
OPEX electrolyser	50.000 € + energy bought
CAPEX PV	1.000.000 € per MW power
OPEX PV	1% of PV CAPEX
Electric energy bought price	120 €/MWh
Electric energy sold price	96 €/MWh
Power of electrolyser (100%)	960 Kw
Power of electrolyser (35%)	336 Kw
H2 sold price reference	13 €/kg

1) **STAND-ALONE**

The stand alone scenario consists in the 100% production of green hydrogen because the electrolyser is fed only with the energy produced by the PV power plant.

The electrolyser is connected to the grid only to sell the energy in excess.

The electrolyser is switched on only if there is enough energy to reach almost 35 % of its capacity. Otherwhise, if the energy produced doesn't permit to reach the 35 % or it permits to reach more than the full capacity, the unused energy is sold to the grid.

<u>1 MW PV</u>

Example

HOURS	January [kWh]	% electrolyser	H2 produced [Nm3]	Unused energy [kWh]	February [kWh]	% electrolyser	H2 produced [Nm3]	Unused energy [kWh]
00:00	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0	0
06:00	0	0	0	0	0,268573154	0	0	0,268573154
07:00	72,28320864	0	0	72,28320864	123,5491198	0	0	123,5491198
08:00	251,8551318	0	0	251,8551318	287,9192916	0	0	287,9192916
09:00	385,5621887	40,16272799	88,06140884	0	418,2728995	43,5700937	95,35567148	0
10:00	446,7444412	46,53587929	101,4392419	0	516,7072579	53,8236727	115,3145749	0
11:00	483,9929848	50,41593591	109,0139121	0	552,4609707	57,54801778	121,8510792	0
12:00	445,3591642	46,39157961	101,1491245	0	513,3931949	53,4784578	114,6907271	0
13:00	369,8655481	38,52766126	84,45256337	0	458,1945479	47,72859874	103,814062	0
14:00	251,0764645	0	0	251,0764645	339,9557283	35,41205503	77,40189568	0
15:00	89,20607605	0	0	89,20607605	191,7181581	0	0	191,7181581
16:00	0	0	0	0	18,95430292	0	0	18,95430292
17:00	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0

As we can see in this example, the only data taken in consideration are the highlighted ones.

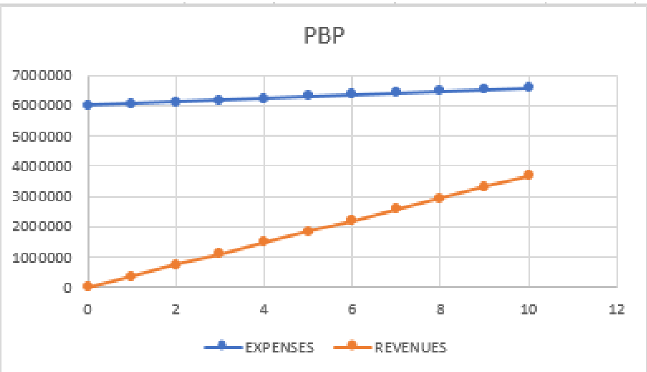
For every hour of the day we have the average quantity of energy produced for each month. When this energy is higher than 336 kWh (the needed quantity for switching on the electrolyser at its 35% of capacity) the electrolyser is switched on. Otherwise, if it is inferior to this value, it is considered unused energy, and it is immediately sold to the grid.

Final Data

% GREEN HYDROGEN	100 %
LOAD FACTOR	30 %
HOURS WORKED	2679 h
CAPEX PV	1.000.000 €
OPEX PV	10.000 €
CAPEX electrolyser	5.000.000 €
OPEX electrolyser	50.000 €
H2 produced per year	26.183 kg
Excess electric energy per year	280 MWh
% CAPEX	90,9 %
% OPEX	9,1 %
PRODUCTION COST	24,18 €/kg

Pay Back Period (PBP)

YEAR	BALANCE PER YEAR	TOTAL BALANCE	€/kg (PBP)
0	-6000000	-6000000	0
1	317348,8239	-5682651,176	231,0611407
2	307348,8239	-5375302,352	115,6465697
3	307348,8239	-5067953,528	77,5182988
4	307348,8239	-4760604,704	58,45416336
5	307348,8239	-4453255,88	47,0156821
6	307348,8239	-4145907,057	39,39002793
7	307348,8239	-3838558,233	33,94313209
8	307348,8239	-3531209,409	29,85796021
9	307348,8239	-3223860,585	26,6806043
10	307348,8239	-2916511,761	24,13871958
	PRICE H2	13 €/kg	



As we can see in the last picture, there is no payback, because the production cost is higher than the sale cost.

In the last column of the las picture there is the ideal sale prices of the hydrogen in order to have a payback period at a desired year.

In order to be economically sustainable the H has to be sold at more than 24 €/kg, that is an unsustainable value.

4 MW PV

The biggest difference between this scenario and the previous one is that there is much more electric energy in excess, and that the electrolyser, when switched on, can work at full capacity.

Example

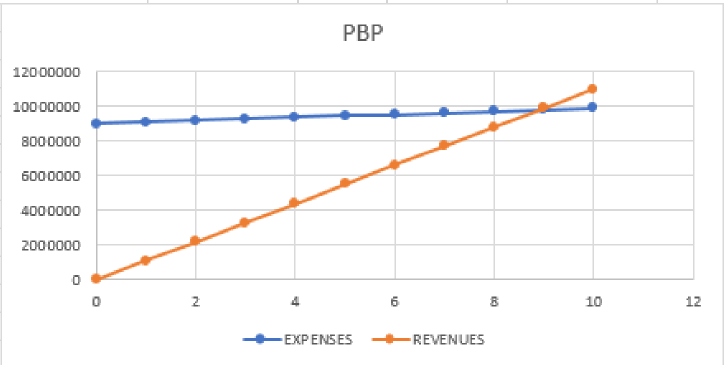
HOURS	January [kWh]	% electrolyser	Unused energy [kWh]	H2 produced [Nm3	February [kWh]	% electrolyser	Unused energy [kWh]	H2 produced [Nm3]
00:00	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0	0
06:00	0	0	0	0	1,074292616	0	1,074292616	0
07:00	289,1328345	0	289,1328345	0	494,1964793	51,47879992	0	111,013571
08:00	1007,420527	100	47,42052708	200	1151,677167	100	191,6771666	200
09:00	1542,248755	100	582,2487548	200	1673,091598	100	713,091598	200
10:00	1786,977765	100	826,9777647	200	2066,829032	100	1106,829032	200
11:00	1935,971939	100	975,971939	200	2209,843883	100	1249,843883	200
12:00	1781,436657	100	821,436657	200	2053,572779	100	1093,572779	200
13:00	1479,462193	100	519,4621925	200	1832,778192	100	872,7781918	200
14:00	1004,305858	100	44,30585789	200	1359,822913	100	399,8229131	200
15:00	356,8243042	37,16919836	0	81,40490193	766,8726322	79,88256586	0	156,7355415
16:00	0	0	0	0	75,8172117	0	75,8172117	0
17:00	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0

Final data

% GREEN HYDROGEN	100 %
LOAD FACTOR	40 %
HOURS WORKED	3559 h
CAPEX PV	4.000.000 €
OPEX PV	40.000 €
CAPEX electrolyser	5.000.000 €
OPEX electrolyser	50.000 €
H2 produced per year	60.648 kg
Excess electric energy per year	3246 MWh
% CAPEX	90,9 %
% OPEX	9,1 %
Total expenses	10.260.000 €
PRODUCTION COST	11,18 €/kg

Pay Back Period (PBP)

YEAR	YEAR BALANCE	TOTAL BALANCE	€/kg (PBP)
0	-9000000	-9000000	0
1	1010075,95	-7989924,05	144,7419164
2	1010075,95	-6979848,099	70,54363614
3	1010075,95	-5969772,149	45,81087606
4	1010075,95	-4959696,198	33,44449602
5	1010075,95	-3949620,248	26,024668
6	1010075,95	-2939544,297	21,07811598
7	1010075,95	-1929468,347	17,54486454
8	1010075,95	-919392,3964	14,89492596
9	1010075,95	90683,55403	12,83386262
10	1010075,95	1100759,504	11,18501195
	PRICE H2	13	€/kg



With this scenario the 10 years investment is concluded with a profit.

Otherwise, there is a payback period on the last year, and the sale price of H2 has to be maintain the fixed 13 €/kg price for the H2, that is not so much competitive in the market.

2) 100% capacity and LF

In this scenario I wanted to use the full potential of the electrolyser, meaning that it works at full capacity 24 hours per day.

The system is connected to the grid, so, if there isn't enough energy to swtich on the electrolyser, electric energy is bought.

The % of green hydrogen is lowered, due to the fact that a lot of energy is bought from the grid. In order to higher the % of green hydrogen green energy should be bought from the grid, but it will be bought at a higher price, so it isn't taken in consideration in these examples.

<u>1 MW PV</u>

Example

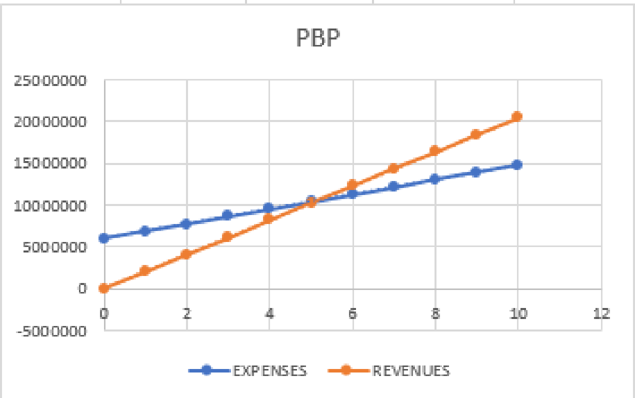
HOURS	January [kWh]	Missing energy [kWh]	February [kWh]	Missing energy [kWh]	March [kWh]	Missing energy [kWh]
00:00	0	960	0	960	0	960
01:00	0	960	0	960	0	960
02:00	0	960	0	960	0	960
03:00	0	960	0	960	0	960
04:00	0	960	0	960	0	960
05:00	0	960	0	960	0	960
06:00	0	960	0,268573154	959,7314268	54,68108463	905,3189154
07:00	72,28320864	887,7167914	123,5491198	836,4508802	228,7590669	731,2409331
08:00	251,8551318	708,1448682	287,9192916	672,0807084	395,7577351	564,2422649
09:00	385,5621887	574,4378113	418,2728995	541,7271005	531,9338355	428,0661645
10:00	446,7444412	513,2555588	516,7072579	443,2927421	605,1277577	354,8722423
11:00	483,9929848	476,0070152	552,4609707	407,5390293	640,161192	319,838808
12:00	445,3591642	514,6408358	513,3931949	446,6068051	596,7316152	363,2683848
13:00	369,8655481	590,1344519	458,1945479	501,8054521	514,9023807	445,0976193
14:00	251,0764645	708,9235355	339,9557283	620,0442717	401,7116861	558,2883139
15:00	89,20607605	870,7939239	191,7181581	768,2818419	264,0473996	695,9526004
16:00	0	960	18,95430292	941,0456971	92,53251039	867,4674896
17:00	0	960	0	960	0,263172408	959,7368276
18:00	0	960	0	960	0	960
19:00	0	960	0	960	0	960
20:00	0	960	0	960	0	960
21:00	0	960	0	960	0	960
22:00	0	960	0	960	0	960
23:00	0	960	0	960	0	960

Final data

% GREEN HYDROGEN	19,28 %
LOAD FACTOR	100 %
HOURS WORKED	8760 h
CAPEX PV	1.000.000 €
OPEX PV	10.000 €
CAPEX electrolyser	5.000.000 €
OPEX electrolyser	864.636 €
H2 produced per year	157.469 kg
Excess electric energy per year	0 MWh
% CAPEX	40,68 %
% OPEX	59,32 %
PRODUCTION COST	9,36 €/kg

Pay Back Period (PBP)

YEAR	YEAR BALANCE	TOTAL BALANCE	€/kg (PBP)
0	-6000000	-6000000	0
1	1172470,06	-4827529,94	43,65686986
2	1172470,06	-3655059,88	24,60559297
3	1172470,06	-2482589,82	18,25516734
4	1172470,06	-1310119,76	15,07995453
5	1172470,06	-137649,6995	13,17482684
6	1172470,06	1034820,361	11,90474171
7	1172470,06	2207290,421	10,99753805
8	1172470,06	3379760,481	10,3171353
9	1172470,06	4552230,541	9,787933166
10	1172470,06	5724700,601	9,364571457
	PRICE H2	13	€/kg



In this case there is a payback period at the 6th year, it means that the investment is good and that the H2 sale price can be lowered, in order to be more competitive in the market.

4 MW PV

In the 4 MW PV scenario less energy has to be bought than the 1 MW one, and there is a lot of it in excess to be sold.

Example

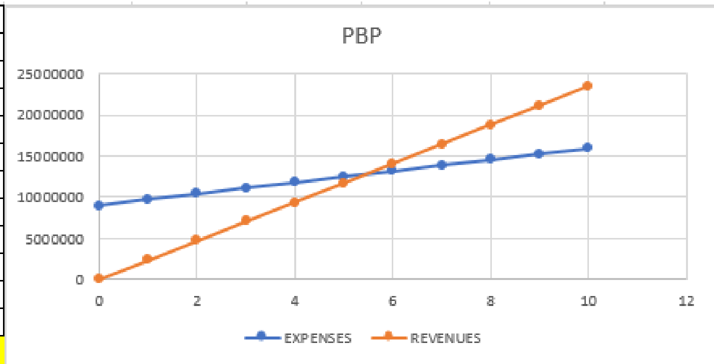
HOURS	January [kWh]	Excessive energy [kWh]	Missing energy [kWh]	February [kWh]	Excessive energy [kWh]	Missing energy [kWh]
00:00	0	0	960	0	0	960
01:00	0	0	960	0	0	960
02:00	0	0	960	0	0	960
03:00	0	0	960	0	0	960
04:00	0	0	960	0	0	960
05:00	0	0	960	0	0	960
06:00	0	0	960	1,074292616	0	958,9257074
07:00	289,1328345	0	670,8671655	494,1964793	0	465,8035207
08:00	1007,420527	47,42052708	0	1151,677167	191,6771666	0
09:00	1542,248755	582,2487548	0	1673,091598	713,091598	0
10:00	1786,977765	826,9777647	0	2066,829032	1106,829032	0
11:00	1935,971939	975,971939	0	2209,843883	1249,843883	0
12:00	1781,436657	821,436657	0	2053,572779	1093,572779	0
13:00	1479,462193	519,4621925	0	1832,778192	872,7781918	0
14:00	1004,305858	44,30585789	0	1359,822913	399,8229131	0
15:00	356,8243042	0	603,1756958	766,8726322	0	193,1273678
16:00	0	0	960	75,8172117	0	884,1827883
17:00	0	0	960	0	0	960
18:00	0	0	960	0	0	960
19:00	0	0	960	0	0	960
20:00	0	0	960	0	0	960
21:00	0	0	960	0	0	960
22:00	0	0	960	0	0	960
23:00	0	0	960	0	0	960

Final data

% GREEN HYDROGEN	39,84 %
LOAD FACTOR	100 %
HOURS WORKED	8760 h
CAPEX PV	4.000.000 €
OPEX PV	40.000 €
CAPEX electrolyser	5.000.000 €
OPEX electrolyser	657.122 €
H2 produced per year	157.469 kg
Excess electric energy per year	3.133 MWh
% CAPEX	56,36 %
% OPEX	43,64 %
PRODUCTION COST	8,23 €/kg

Pay Back Period (PBP)

YEAR	YEAR BALANCE	TOTAL BALANCE	€/kg (PBP)
0	-9000000	-9000000	0
1	1650809,374	-7349190,626	59,67048852
2	1650809,374	-5698381,252	31,09357318
3	1650809,374	-4047571,878	21,56793473
4	1650809,374	-2396762,504	16,80511551
5	1650809,374	-745953,1299	13,94742398
6	1650809,374	904856,2442	12,04229629
7	1650809,374	2555665,618	10,68149079
8	1650809,374	4206474,992	9,660886674
9	1650809,374	5857284,366	8,86708347
10	1650809,374	7508093,74	8,232040907
	PRICE H2	13	€/kg



Also in this case there is a positive investment, with a payback on the 6th year.

Differently from the previous scenario the price at which the H2 will be sold can be reduced, as shown in the last column of the figure.

3) **HYBRID**

In this scenario I wanted to test how the production cost will be affected if the electrolyser has a payload of 100% (maximum hours of work) but at lower capacities.

In other words, if there is enough energy to reach the 35 % of the electrolyser capacity, it is switched on, if not, it is bought from the grid only the needed one to switch it on.

1 MW PV

Example

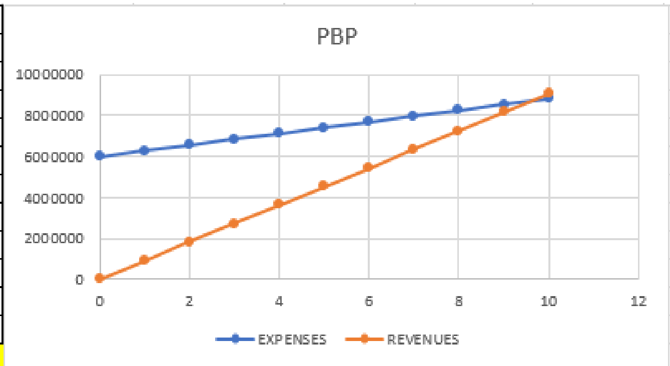
HOURS	January [kWh]	Missing energy [kWh]	% electrolyser	H2 produced [Nm3]	February [kWh]	Missing energy [kWh]	% electrolyser	H2 produced [Nm3]
00:00	0	336	35	76,45399108	0	336	35	76,45399108
01:00	0	336	35	76,45399108	0	336	35	76,45399108
02:00	0	336	35	76,45399108	0	336	35	76,45399108
03:00	0	336	35	76,45399108	0	336	35	76,45399108
04:00	0	336	35	76,45399108	0	336	35	76,45399108
05:00	0	336	35	76,45399108	0	336	35	76,45399108
06:00	0	336	35	76,45399108	0,268573154	335,7314268	35	76,45399108
07:00	72,28320864	263,7167914	35	76,45399108	123,5491198	212,4508802	35	76,45399108
08:00	251,8551318	84,14486823	35	76,45399108	287,9192916	48,08070836	35	76,45399108
09:00	385,5621887	0	40,16272799	88,06140884	418,2728995	0	43,5700937	95,35567148
10:00	446,7444412	0	46,53587929	101,4392419	516,7072579	0	53,8236727	115,3145749
11:00	483,9929848	0	50,41593591	109,0139121	552,4609707	0	57,54801778	121,8510792
12:00	445,3591642	0	46,39157961	101,1491245	513,3931949	0	53,4784578	114,6907271
13:00	369,8655481	0	38,52766126	84,45256337	458,1945479	0	47,72859874	103,814062
14:00	251,0764645	84,92353553	35	76,45399108	339,9557283	0	35,41205503	77,40189568
15:00	89,20607605	246,7939239	35	76,45399108	191,7181581	144,2818419	35	76,45399108
16:00	0	336	35	76,45399108	18,95430292	317,0456971	35	76,45399108
17:00	0	336	35	76,45399108	0	336	35	76,45399108
18:00	0	336	35	76,45399108	0	336	35	76,45399108
19:00	0	336	35	76,45399108	0	336	35	76,45399108
20:00	0	336	35	76,45399108	0	336	35	76,45399108
21:00	0	336	35	76,45399108	0	336	35	76,45399108
22:00	0	336	35	76,45399108	0	336	35	76,45399108
23:00	0	336	35	76,45399108	0	336	35	76,45399108

Final data

% GREEN HYDROGEN	46,83 %
LOAD FACTOR	100 %
HOURS WORKED	8760 h
CAPEX PV	1.000.000 €
OPEX PV	10.000 €
CAPEX electrolyser	5.000.000 €
OPEX electrolyser	271.138 €
H2 produced per year	69.653 kg
Excess electric energy per year	0 MWh
% CAPEX	68,1 %
% OPEX	31,9 %
PRODUCTION COST	12,65 €/kg

Pay Back Period (PBP)

YEAR	YEAR BALANCE	TOTAL BALANC	€/kg (PBP)
0	-6000000	-6000000	0
1	624361,1532	-5375638,847	90,17650772
2	624361,1532	-4751277,694	47,10636671
3	624361,1532	-4126916,541	32,74965304
4	624361,1532	-3502555,387	25,5712962
5	624361,1532	-2878194,234	21,2642821
6	624361,1532	-2253833,081	18,39293937
7	624361,1532	-1629471,928	16,34198027
8	624361,1532	-1005110,775	14,80376095
9	624361,1532	-380749,6216	13,60736814
10	624361,1532	243611,5316	12,6502539
	PRICE H2	13 €/kg	



This scenario is not so much convenient, as we can see in the figure.

The investemtn closes the 10th year with a positive balance, but the payback is on the last year and the sale price of H2 cannot be decreased.

4 MW PV

In this case there is also excess energy to be sold when more power than the maximum capacity of the electrolyser is reached.

Having more energy production means that we also have less energy to buy.

Example

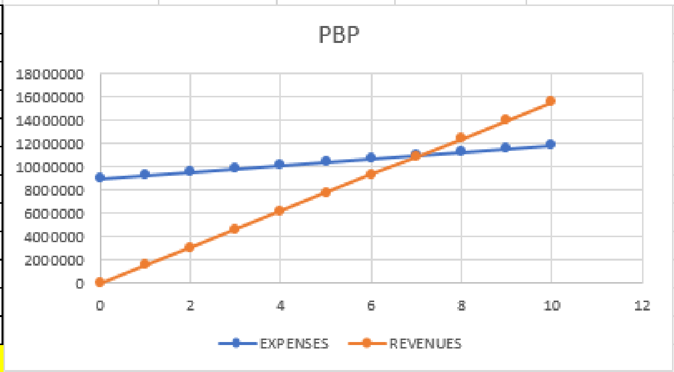
HOURS	January [kWh]	Excessive energy [kWh]	Missing energy [kWh]	% electrolyser	H2 produced [Nm3]	February [kWh]	Excessive energy [kWh]	Missing energy [kWh]	% electrolyser	H2 produced [Nm3]
00:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
01:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
02:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
03:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
04:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
05:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
06:00	0	0	336	35	76,45399108	1,074292616	0	334,9257074	35	76,45399108
07:00	289,1328345	0	46,86716546	35	76,45399108	494,1964793	0	0	51,47879992	111,013571
08:00	1007,420527	47,42052708	0	100	200	1151,677167	191,6771666	0	100	200
09:00	1542,248755	582,2487548	0	100	200	1673,091598	713,091598	0	100	200
10:00	1786,977765	826,9777647	0	100	200	2066,829032	1106,829032	0	100	200
11:00	1935,971939	975,971939	0	100	200	2209,843883	1249,843883	0	100	200
12:00	1781,436657	821,436657	0	100	200	2053,572779	1093,572779	0	100	200
13:00	1479,462193	519,4621925	0	100	200	1832,778192	872,7781918	0	100	200
14:00	1004,305858	44,30585789	0	100	200	1359,822913	399,8229131	0	100	200
15:00	356,8243042	0	0	37,16919836	81,40490193	766,8726322	0	0	79,88256586	156,7355415
16:00	0	0	336	35	76,45399108	75,8172117	0	260,1827883	35	76,45399108
17:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
18:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
19:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
20:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
21:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
22:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108
23:00	0	0	336	35	76,45399108	0	0	336	35	76,45399108

Final data

% GREEN HYDROGEN	67,21 %
LOAD FACTOR	100 %
HOURS WORKED	8760 h
CAPEX PV	4.000.000 €
OPEX PV	40.000 €
CAPEX electrolyser	5.000.000 €
OPEX electrolyser	246.175 €
H2 produced per year	96.387 kg
Excess electric energy per year	3.133 MWh
% CAPEX	75,87 %
% OPEX	24,13 %
PRODUCTION COST	9,18 €/kg

Pay Back Period (PBP)

YEAR	YEAR BALANCE	TOTAL BALANC	€/kg (PBP)
0	-9000000	-9000000	0
1	1267692,616	-7732307,384	93,22069494
2	1267692,616	-6464614,767	46,53435549
3	1267692,616	-5196922,151	30,97224234
4	1267692,616	-3929229,535	23,19118577
5	1267692,616	-2661536,919	18,52255182
6	1267692,616	-1393844,302	15,41012919
7	1267692,616	-126151,6862	13,18697017
8	1267692,616	1141540,93	11,51960091
9	1267692,616	2409233,546	10,22275814
10	1267692,616	3676926,163	9,185283934
	PRICE H2		13 €/kg



Also this scenario is a good one, because there is a payback on the 8th year with the standard price of 13 €/kg.

In conclusion, we can say that the best scenario is the 100% capacity one with a PV of 4 MW, because the cost of production is the lowest, helping us reducing the cost of sale.

We can also say that the best formula for each scenario is to have a dimension of the PV 4 times the dimension of the electrolyser, in order to have 2 revenues (H2 and electric energy).

Unfortunately, until you reach a production cost of 7 €/kg, producing hydrogen is economically unsustainable. So, the only way to have convenience in producing H2 is to abate CAPEX with **incentives**.

Incentive example

Typically, incentives can abate the CAPEX till the 60 %.

In this table I examine how incentives of 20 % - 40 % - 60 % can change the cost of production of our previous scenarios.

	0 %	20 %	40 %	60 %
1 MW SA	24,18 €/kg	20,36 €/kg	16,54 €/kg	12,72 €/kg
4 W SA	11,18 €/kg	9,54 €/kg	7,89 €/kg	6,24 €/kg
1 MW HYB	12,65 €/kg	11,21 €/kg	9,78 €/kg	8,34 €/kg
4 MW HYB	9,18 €/kg	8,15 €/kg	7,11 €/kg	6,07 €/kg
1 MW 100 %	9,36 €/kg	8,73 €/kg	8,09 €/kg	7,46 €/kg
4 MW 100 %	8,23 €/kg	7,60 €/kg	6,96 €/kg	6,33 €/kg

As we can see in the table, we have 4 economically sustainable situations (highlated ones).

The more the CAPEX is abated, the more is convenient to install the 4 MW PV power plant. Moreover, the more the incentive is higher, the more the production cost decreases for the stand alone scenarios, meaning that is better to buy as less energy as needed, with the result of having a higher percentage of green hydrogen.

Only PV

Anyway, nowadays it is more convenient to produce only electric energy and selling it immediately (first because there is a convenient price, second because you can surely sold it buy putting it into the grid, avoiding the risk of finding final users like with the hydrogen).

In this example I analyzed an investment of installing only PV (both of 1 MW and 4 MW of power).

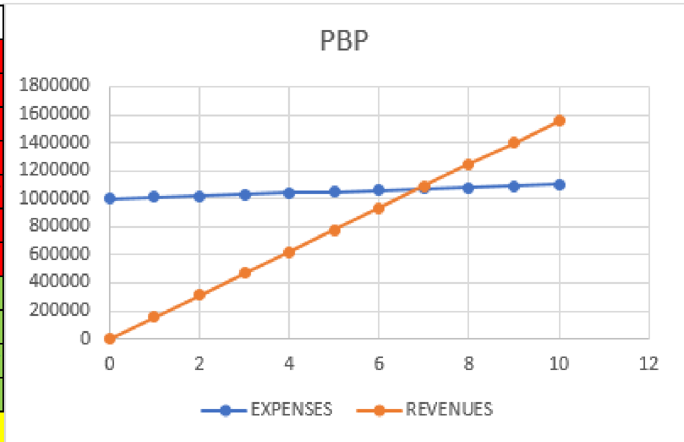
For this example I considered a price of sale of 96 €/MWh (as the 80% of the nowadays **PUN** reference).

Data 1 MW

Energy produced per year	1.620,95 MWh
CAPEX	1.000.000 €
OPEX	10.000 €
Revenue per year	162.095 €

PBP 1 MW

YEAR	YEAR BALANCE	TOTAL BALANCE
0	-1000000	-1000000
1	145612,1441	-854387,8559
2	145612,1441	-708775,7118
3	145612,1441	-563163,5678
4	145612,1441	-417551,4237
5	145612,1441	-271939,2796
6	145612,1441	-126327,1355
7	145612,1441	19285,00853
8	145612,1441	164897,1526
9	145612,1441	310509,2967
10	145612,1441	456121,4408
PRICE ELECTRIC ENERG 96 €/MWh		

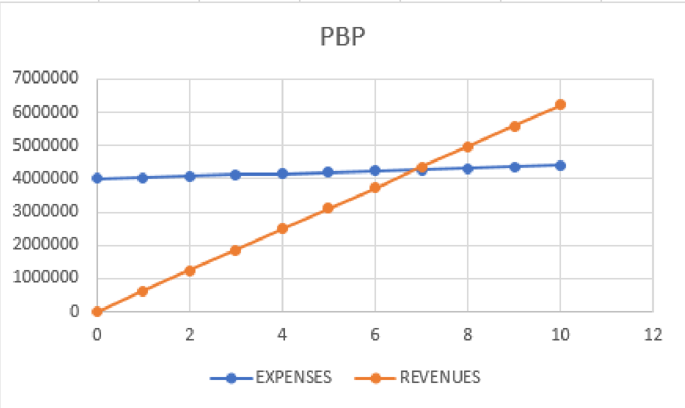


Data 4 MW

Energy produced	6483,84 MWh
CAPEX	4.000.000 €
OPEX	40.000 €
Revenue per year	648.384 €

PBP 4 MW

YEAR	YEAR BALANCE	TOTAL BALANCE
0	-4000000	-4000000
1	582448,5763	-3417551,424
2	582448,5763	-2835102,847
3	582448,5763	-2252654,271
4	582448,5763	-1670205,695
5	582448,5763	-1087757,118
6	582448,5763	-505308,5422
7	582448,5763	77140,03411
8	582448,5763	659588,6104
9	582448,5763	1242037,187
10	582448,5763	1824485,763
PRICE ELECTRIC ENERGY	96 €/MWh	



As we can see from the graphs, the two investments are the same, with a positive final balance and a payback period on the 7th year.

The main difference is that the more you spend, the more you gain.

It has also to be said that the electric market is dynamic and in continuous change, and that during the plant lifetime the price of the energy can have a dizzily change.

In the next chapter, I will analyze a possible and reliable future change of the electric market curve.

2.4 *ELECTRIC MARKET DEPENDENCY*

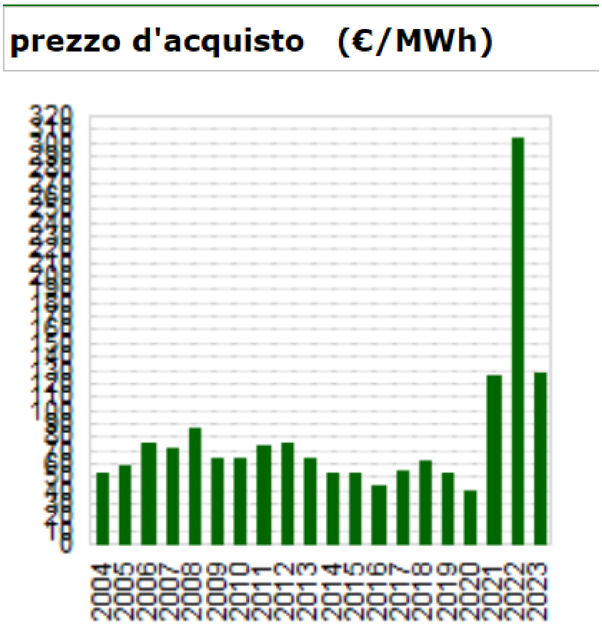
As we have seen in the first chapter, the electric market has a very dynamic trend.

Because of this, the **H2** market has a strong dependency on the price of the electric energy, that can significantly varies its cost of production.

PUN

The **PUN** (Prezzo Unico Nazionale) is the reference price at which the electric energy is bought at the wholesale. Deeper, it is the weighted average of the zonal sale prices for every hour of every day.

sintesi annuale			
periodo	Prezzo d'acquisto. PUN (€/MWh)		
	media	**min**	**max**
2004*	51,60	1,10	189,19
2005	58,59	10,42	170,61
2006	74,75	15,06	378,47
2007	70,99	21,44	242,42
2008	86,99	21,54	211,99
2009	63,72	9,07	172,25
2010	64,12	10,00	174,62
2011	72,23	10,00	164,80
2012	75,48	12,14	324,20
2013	62,99	0,00	151,88
2014	52,08	2,23	149,43
2015	52,31	5,62	144,57
2016	42,78	10,94	150,00
2017	53,95	10,00	170,00
2018	61,31	6,97	159,40
2019	52,32	1,00	108,38
2020	38,92	0,00	162,57
2021	125,46	3,00	533,19
2022	303,95	10,00	870,00
2023	127,24	2,46	295,00



In the previous picture there are all the data relative to the PUN of the last 20 years.

As we can see the **minimum** and the **maximum** values are really unstable.

Meanwhile the **average** price has a slightly decreasing wave trend. Indeed from 2004 to 2020 the price decreased of more than 10 €/MWh.

Unfortunately in the last 3 years there were two accidents that changed its trend. First, COVID-19 and lockdown of 2020 had the effect of rising the PUN price for all the 2021. Then, in February 2022 there was the outbreak of the war in Ukraine, that affected all the energy markets.

Nowadays the price is more or less levelled to 120 €/MWh, but the biggest hypothesis is that it will start to decrease again due to the fact that renewable energies plants are increasing, meaning that the quantity of energy produced is higher day by day.

POSSIBLE TRENDS 2026-2045

Due to the increase of electric production and the global aim of sustainability, the price of electric energy is going down year by year.

In the next figures future forecasted data of the electric price are shown.

2	3	4	5	6	7	8	9	10	11
0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
2026	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
127,20 €	98,98 €	90,50 €	78,45 €	73,23 €	74,41 €	73,82 €	74,21 €	74,13 €	73,05 €
38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €
4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €
170,00 €	**141,78 €**	**133,30 €**	**121,25 €**	**116,03 €**	**117,21 €**	**116,62 €**	**117,01 €**	**116,93 €**	**115,85 €**
anno di inizio									
anno del PEF	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
12	13	14	15	16	17	18	19	20	21
0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
2036	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**
70,79 €	73,71 €	73,57 €	74,98 €	70,20 €	68,92 €	69,79 €	71,24 €	69,43 €	69,74 €
38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €	38,80 €
4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €	4,00 €
113,59 €	**116,51 €**	**116,37 €**	**117,78 €**	**113,00 €**	**111,72 €**	**112,59 €**	**114,04 €**	**112,23 €**	**112,54 €**
									anno di fine
anno del PEF	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*	*anno del PEF*
11	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*

- GREEN = raw material (PUN)
- PINK = network charges
- BLUE = surcharge
- ORANGE = total

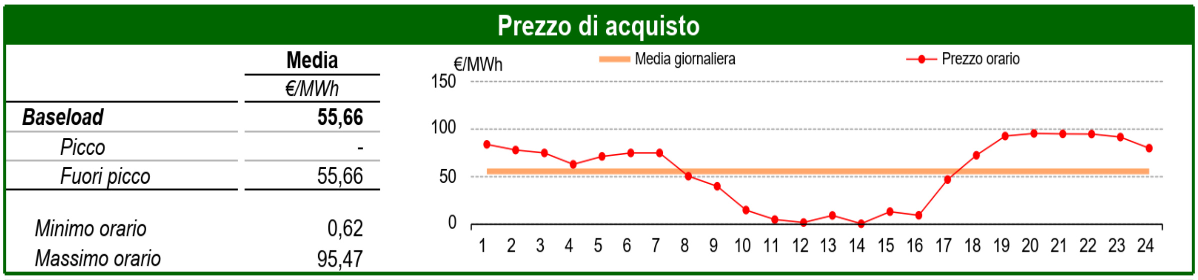
The green prices are related to the price of the **PUN** (which is the variable one), meanwhile the pink and the blue ones are the constant prices for transport. The orange one is the sum of the three above.

Inversion of curve

The more predictable scenario is the so called ***inversion of electric market curve***.

As it literally says, the nowadays electric sale price curve will be put upside down, in order to have a lower price during the day, and a higher price during the night.

Future inverse curve



If this scenario will take place, we would have a much more competitive price for the hydrogen.

As you can see, the maximum price of energy in that day is 95,47 €/MWh, meanwhile the minimum one is a 0,62 €/MWh, meaning that during the central hours of the day the energy is near to being gratis.

In the next table I show how the cost of production of hydrogen will be affected by the lowering of the **PUN** from 120 €/MWh to 55 €/MWh.

Change of scenarios

	120 €/MWh	95 €/MWh	75 €/MWh	55 €/MWh
1 MW SA	24,18 €/kg	24,39 €/kg	24,56 €/kg	24,73 €/kg
4 MW SA	11,18 €/kg	12,25 €/kg	13,11 €/kg	13,97 €/kg
1 MW HYB	12,65 €/kg	11,99 €/kg	11,46 €/kg	10,93 €/kg
4 MW HYB	9,18 €/kg	9,41 €/kg	9,59 €/kg	9,77 €/kg
1 MW 100 %	9,36 €/kg	8,29 €/kg	7,42 €/kg	6,56 €/kg
4 MW 100 %	8,23 €/kg	7,83 €/kg	7,50 €/kg	7,18 €/kg

As shown in the table, the 1 MW PV scenarios have a decrease in the cost of production (except from the stand alone one, because the excess energy is sold at a very low price), meanwhile the 4 MW ones has an increase (except the 100 % one, because in this case we produce a very higher quantity of hydrogen compared to the hybrid and the stand alone).

This is explained by the fact that with the 1 MW scenarios we have to buy energy, that is cheaper with the collapse of the **PUN**, and with the 4 MW one we have also to sell it, and in this case it is sold at a very low price.

Moreover, if the hydrogen will be competitive in the market, there will also be a lot of incentives to produced it, reducing the CAPEX, and so the cost of production.

Incentive + PUN Example

In this example I analyze how much the cost of production would be lowered with an incentive of 20 % - 40 % - 60 % of the CAPEX of the electrolyser combined with the hypothetical decrease of the **PUN** (I put three standard values following the previsions of the previous chapter for the 2026-2045: 95 €/MWh as forecasted for 2020s, 75 €/MWh as forecasted for 2030s, and 55 €/MWh as in the “inversion curve” scenario).

Taking into account only the scenarios that decrease with the lowering of the **PUN** (1 MW HYB, 1 MW 100%, 4 MW 100%), with the strong abatement of the CAPEX, the cost of production of H2 is significantly reduced.

For the next tables, the % on the abscissa is the incentive on the H2 capex, the prices on the ordinate are the average prices of the PUN.

1 MW HYB

	0 %	20 %	40 %	60 %
120 €/MWh	12,65 €/MWh	11,21 €/MWh	9,78 €/MWh	8,34 €/MWh
95 €/MWh	11,99 €/MWh	10,55 €/MWh	9,12 €/MWh	7,69 €/MWh
75 €/MWh	11,46 €/MWh	10,02 €/MWh	8,59 €/MWh	7,15 €/MWh
55 €/MWh	10,93 €/MWh	9,49 €/MWh	8,06 €/MWh	6,62 €/MWh

1 MW 100%

	0 %	20 %	40 %	60 %
120 €/MWh	9,36 €/MWh	8,73 €/MWh	8,09 €/MWh	7,46 €/MWh
95 €/MWh	8,29 €/MWh	7,65 €/MWh	7,02 €/MWh	6,38 €/MWh
75 €/MWh	7,42 €/MWh	6,79 €/MWh	6,15 €/MWh	5,52 €/MWh
55 €/MWh	6,56 €/MWh	5,93 €/MWh	5,29 €/MWh	4,66 €/MWh

4 MW 100%

	0 %	20 %	40 %	60 %
120 €/MWh	8,23 €/MWh	7,60 €/MWh	6,96 €/MWh	6,33 €/MWh
95 €/MWh	7,83 €/MWh	7,19 €/MWh	6,56 €/MWh	5,92 €/MWh
75 €/MWh	7,50 €/MWh	6,87 €/MWh	6,23 €/MWh	5,60 €/MWh
55 €/MWh	7,18 €/MWh	6,54 €/MWh	5,91 €/MWh	5,27 €/MWh

Every highlighted case (considering the fact that under 7 €/kg the hydrogen is economically sustainable) will be very competitive in the market.

As analyzed in the previous chapters, the more the CAPEX is abated, the more power is better to install. On th eother hand, the more the **PUN** decreases, the more is better to produce as much hydrogen as possible.

Summarizing all, the best scenario in order to be more dynamic in the market is the 4 MW 100% one, which have the maximum production of hydrogen with a pretty good percentage of green one (~40%), but also a lot of electric energy in excess to be sold.

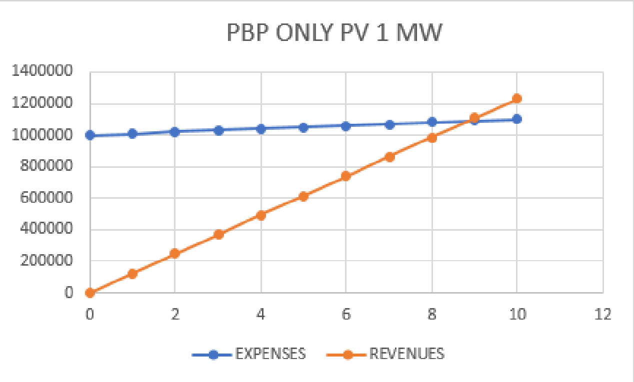
Only PV inconvenience

With this new trend of the electric market we can also see that it is not convenient anymore to produce only electric energy.

In this part I analyze how the decrease of the PUN will affect the scenario of the only PV plant (for convention I show only the 1 MW one because as we have seen in the previous example the 4 MW has the same results multiplied by 4).

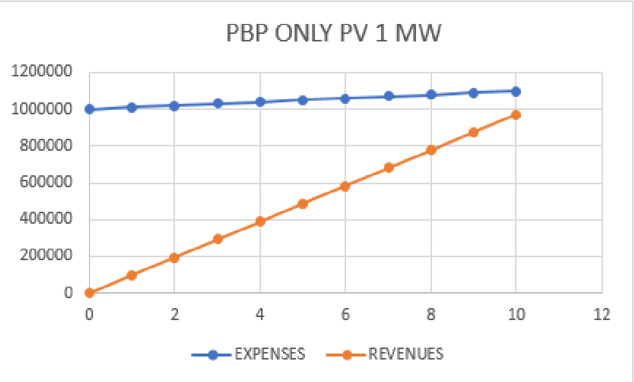
95 €/MWh PUN

YEAR	YEAR BALANCE	TOTALBALANCE
0	-1000000	-1000000
1	113192,9474	-886807,0526
2	113192,9474	-773614,1052
3	113192,9474	-660421,1578
4	113192,9474	-547228,2104
5	113192,9474	-434035,263
6	113192,9474	-320842,3156
7	113192,9474	-207649,3682
8	113192,9474	-94456,42086
9	113192,9474	18736,52654
10	113192,9474	131929,4739
PRICE ELECTRIC ENERGY	76 €/MWh	



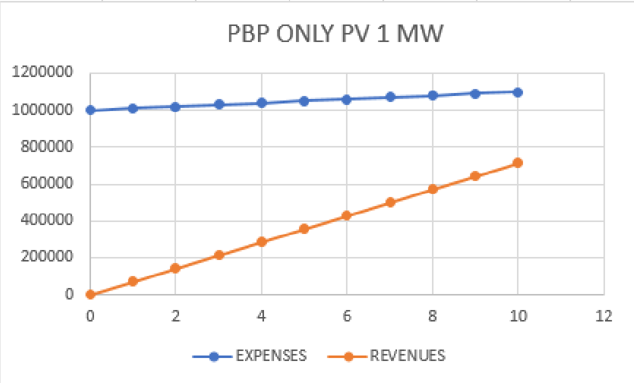
75 €/MWh PUN

YEAR	YEAR BALANCE	TOTALBALANCE
0	-1000000	-1000000
1	87257,59005	-912742,41
2	87257,59005	-825484,8199
3	87257,59005	-738227,2299
4	87257,59005	-650969,6398
5	87257,59005	-563712,0498
6	87257,59005	-476454,4597
7	87257,59005	-389196,8697
8	87257,59005	-301939,2796
9	87257,59005	-214681,6896
10	87257,59005	-127424,0995
PRICE ELECTRIC ENERGY	60 €/MWh	



55 €/MWh PUN

YEAR	YEAR BALANCE	TOTALBALANCE
0	-1000000	-1000000
1	61322,2327	-938677,7673
2	61322,2327	-877355,5346
3	61322,2327	-816033,3019
4	61322,2327	-754711,0692
5	61322,2327	-693388,8365
6	61322,2327	-632066,6038
7	61322,2327	-570744,3711
8	61322,2327	-509422,1384
9	61322,2327	-448099,9057
10	61322,2327	-386777,673
PRICE ELECTRIC ENERGY 44 €/MWh		



As we see in the graphs, the balance is negative for every year, except for the 95 €/MWh scenario.

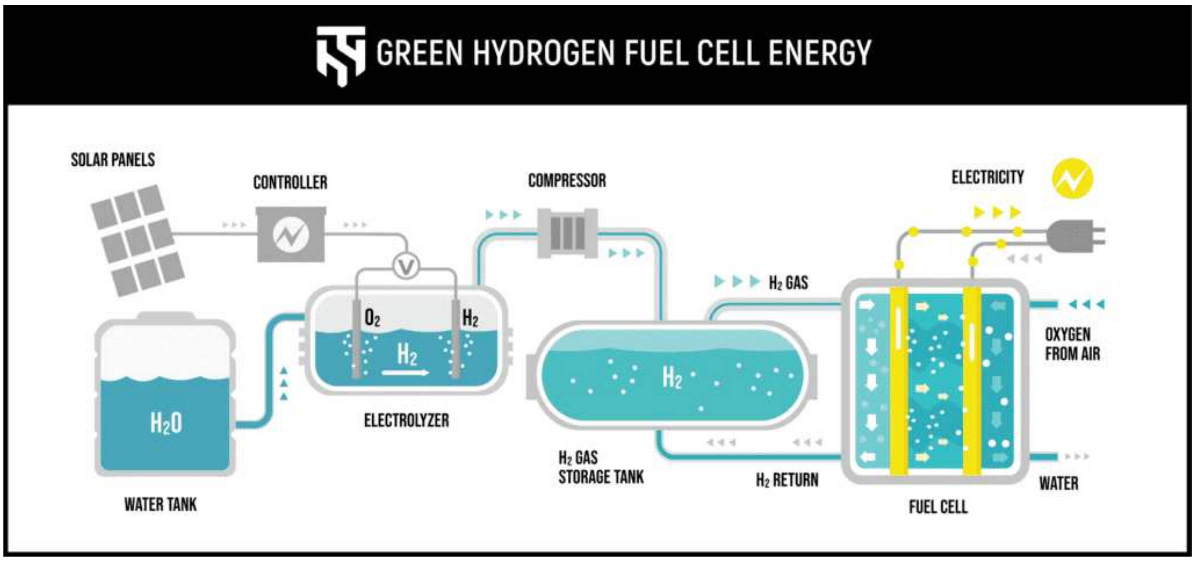
If the previsions of the change of the **PUN** for the next year will be correct, it is convenient to produce only electric energy till 2028, when the **PUN** remains over 90 €/MWh.

SMART HYDRO

The Smart Hydro project is a project realized by TechFem that aims to the smart production of hydrogen.

The aim of the factory is to produce green hydrogen at the lowest possible price, following in real-time the electric market changes.

Moreover, with the digital twin system, it can also be monitored the state of every component, in order to change the asset of the project in real time, having the maximum automation possibilities.



3.1 COMPONENTS

PV

First, in order to be green hydrogen, we need to produce electric energy.

So, as we have seen in the scenarios of chapter 2, the project starts with a **Photovoltaic** plant of a determined power.

The **PV** plant is also connected to the grid, in order to exchange energy in both ways (to sell it if it isn't needed or to buy it if it is missing).

WATER

The main feed to produce **H2** with electrolysis is water (**H2O**).

In the P&I we will see an entire package dedicated to the treatment and transport of **H2O**, because it has to be purified, stocked, and then pumped in the electrolyser in the desired quantity.

ELECTROLYSER

As we have seen in chapter 2, the main component of the project is for sure the **elctrolyser**.

The **elctrolyser** process is composed by more than one component.

As we see in the picture, this boxes are composed by a lot of components.

First, we can see that they are divided into the **process** container and the **power** container.

The **process** container is the part that contains all the process equipment:

- Gas generating system and cell stacks
- Water purification system
- Demineralized water polishing system

- Gas & electrolyte cooling system
- Instrument air compressor
- Hydrogen purification system
- Power and control panels

The **power** container instead, includes all the power management equipment:

- Medium voltage switch gear
- Medium voltage transformer
- Rectifier
- Distribution panel
- Auxiliary power supply

In order to have a good functioning of the **electrolyser**, we have to calculate its main parameter: the efficiency.

$$\dot{m}_{H_2} = \frac{\eta_I \cdot P_{el}}{HHV_{H_2}}$$

The previous formula is the electrolyser characteristic equation, which calculates the mass flow rate of **H2** produced, proportionally to the efficiency of the **electrolyser** and the electric power fed.

COMPRESSOR

After the hydrogen is produced, in order to be stocked, it has to be compressed.

In this project the **compressor** compresses the **H2** from 35 bar to 220 bar.

The stocking pressure is very high, and if we consider its flammable characteristics, the **H2** is so delicate to be treated.

Also for the **compressor** its main parameter is the efficiency, because it determines how much hydrogen can be compressed to the desired pressure without having losses.

$$P_{compressione} = \frac{\dot{m}_{H_2} \cdot c_p \cdot (T_2 - T_1)}{\eta_m}$$

Another important parameter in this case is the temperature.

$$T_2 = T_1 \cdot \beta^{\frac{k-1}{k} \cdot \frac{1}{\eta_{pc}}}$$

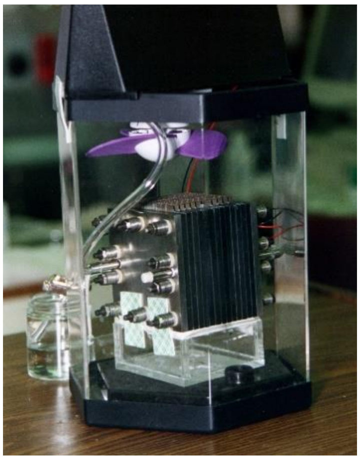
STOCKAGE

After the **H2** is compressed, is than **stocked** in tanks.

As seen in the picture there are stack of tanks, which are put in an isoletad zone, in order to be protected from free flames.

FC

The last part of the project, used only in special cases, is the **Fuel Cell**.



The **FC** consists in the inverse procedure of the electrolysis, recombining hydrogen with oxygen, in order to obtain water and electric energy.

Unfortunately, its efficiency is very low (more or less 35 %), and, as we will see in the last paragraph of this chapter, the use of the **FC** is limited.

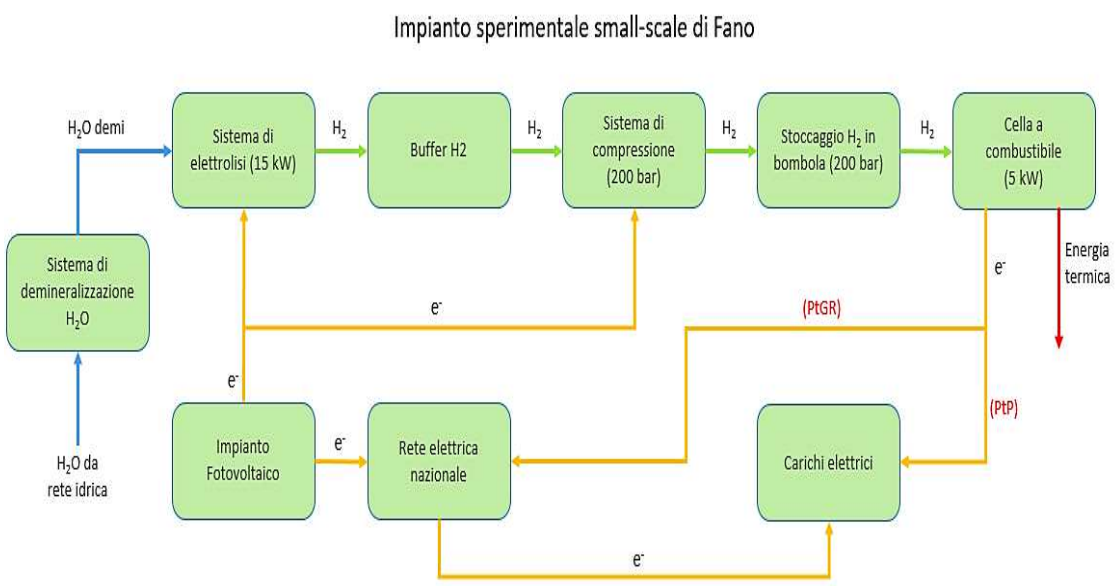
3.2 P&I

In this part we will see the **P&I** (piping and instrumentation diagram) of the project, which describes all the components, how they are linked and which logic regulates every emergency.

The aim of the project is to produce electric energy from the **PV** plant, then use this energy to run the **electrolyser** fed by the water transport package.

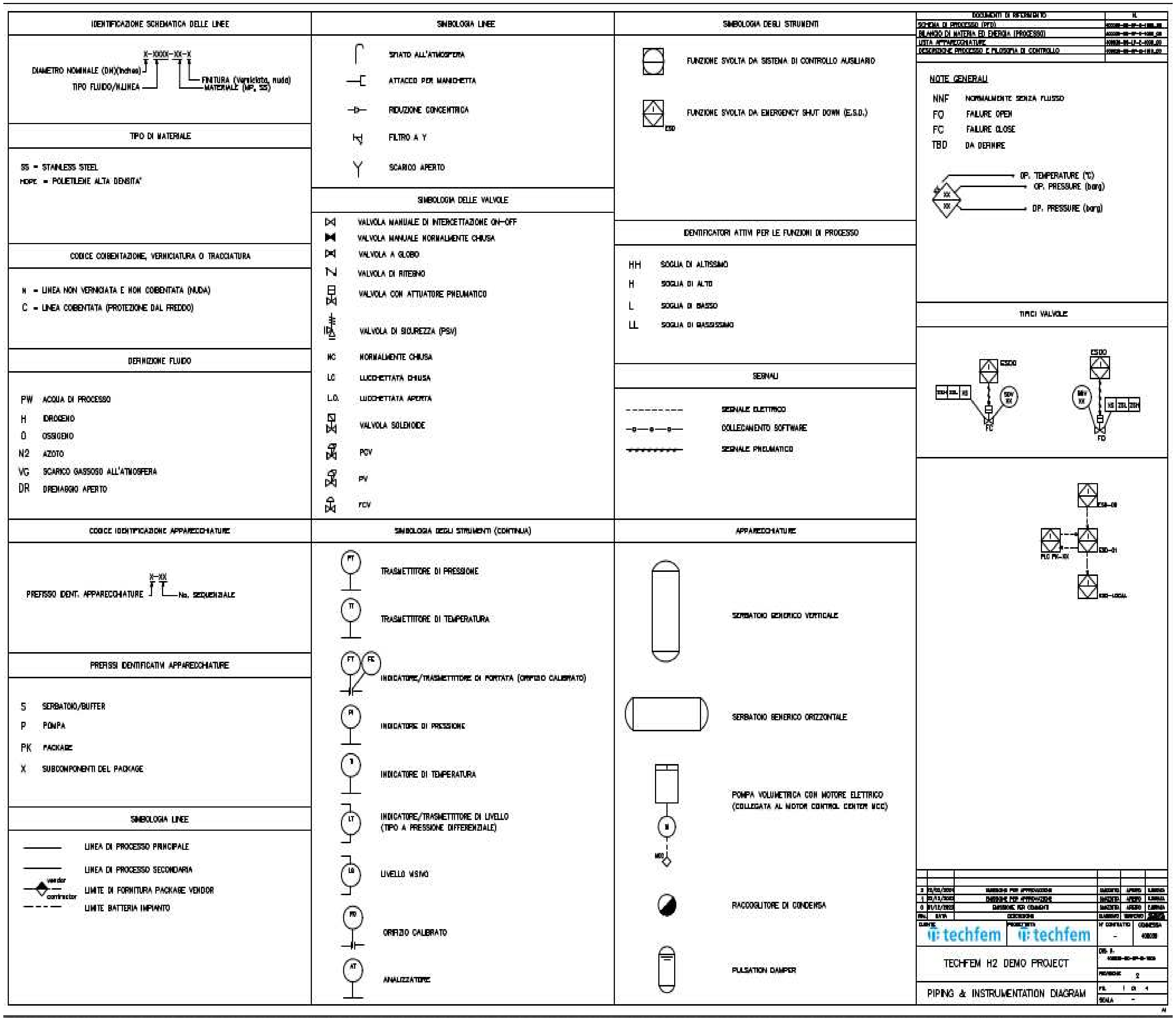
Once the **H2** is produced, it is compressed by the **compressor** and stacked into the tanks.

Finally, it can be sold or it can be reused to produce electric energy in the **FC**.

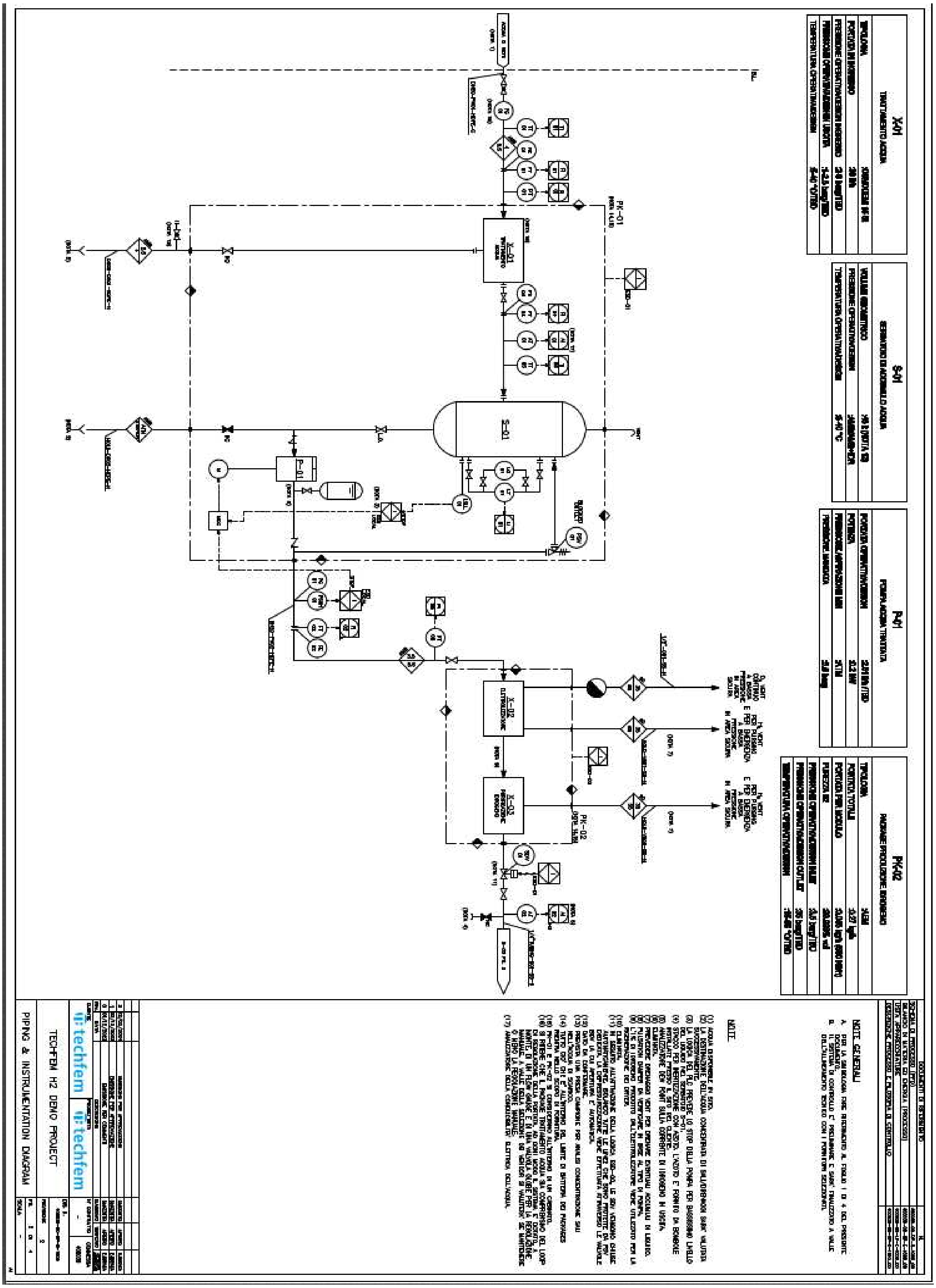


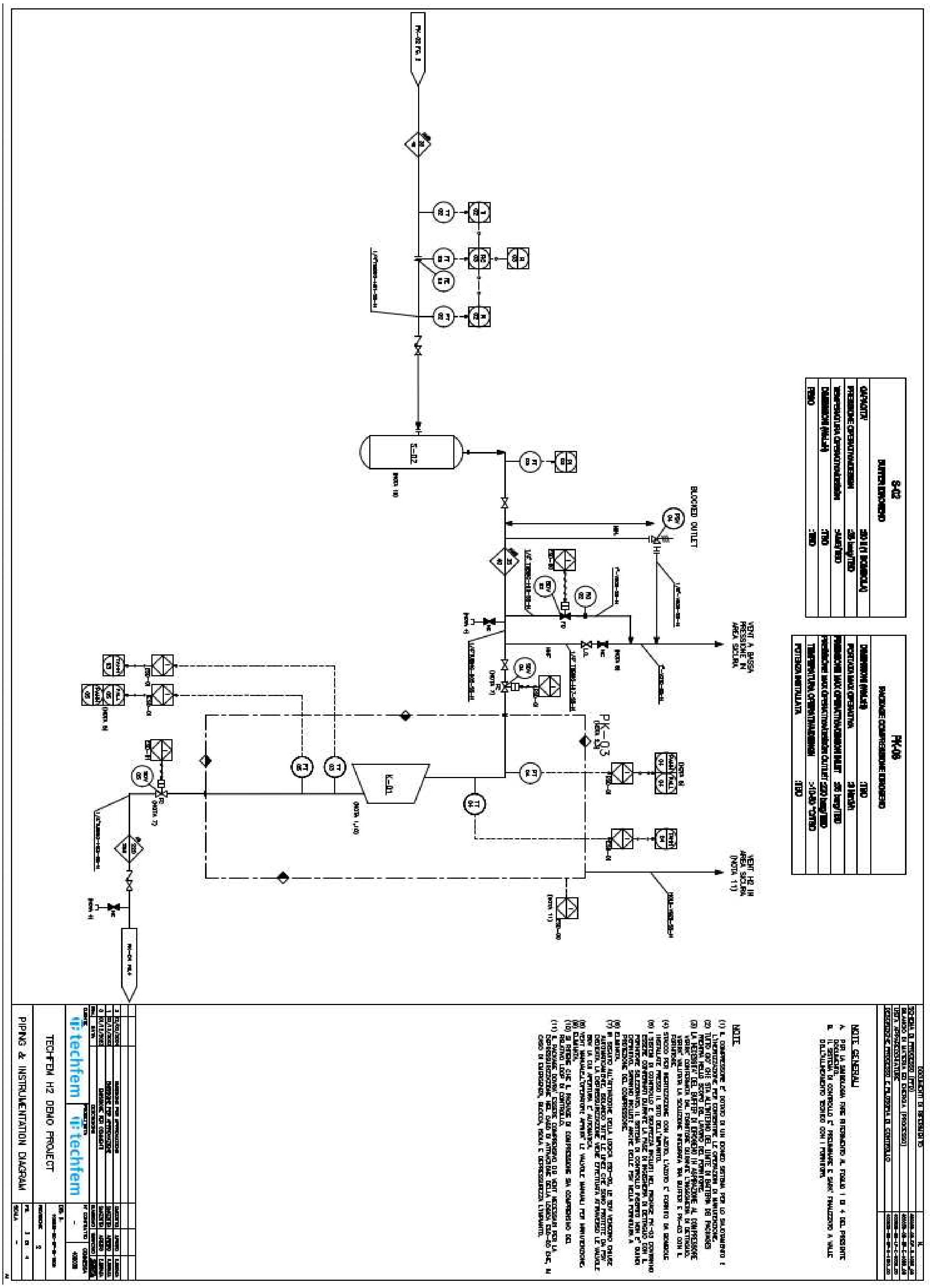
In the first picture we can see the description of all the symbols.

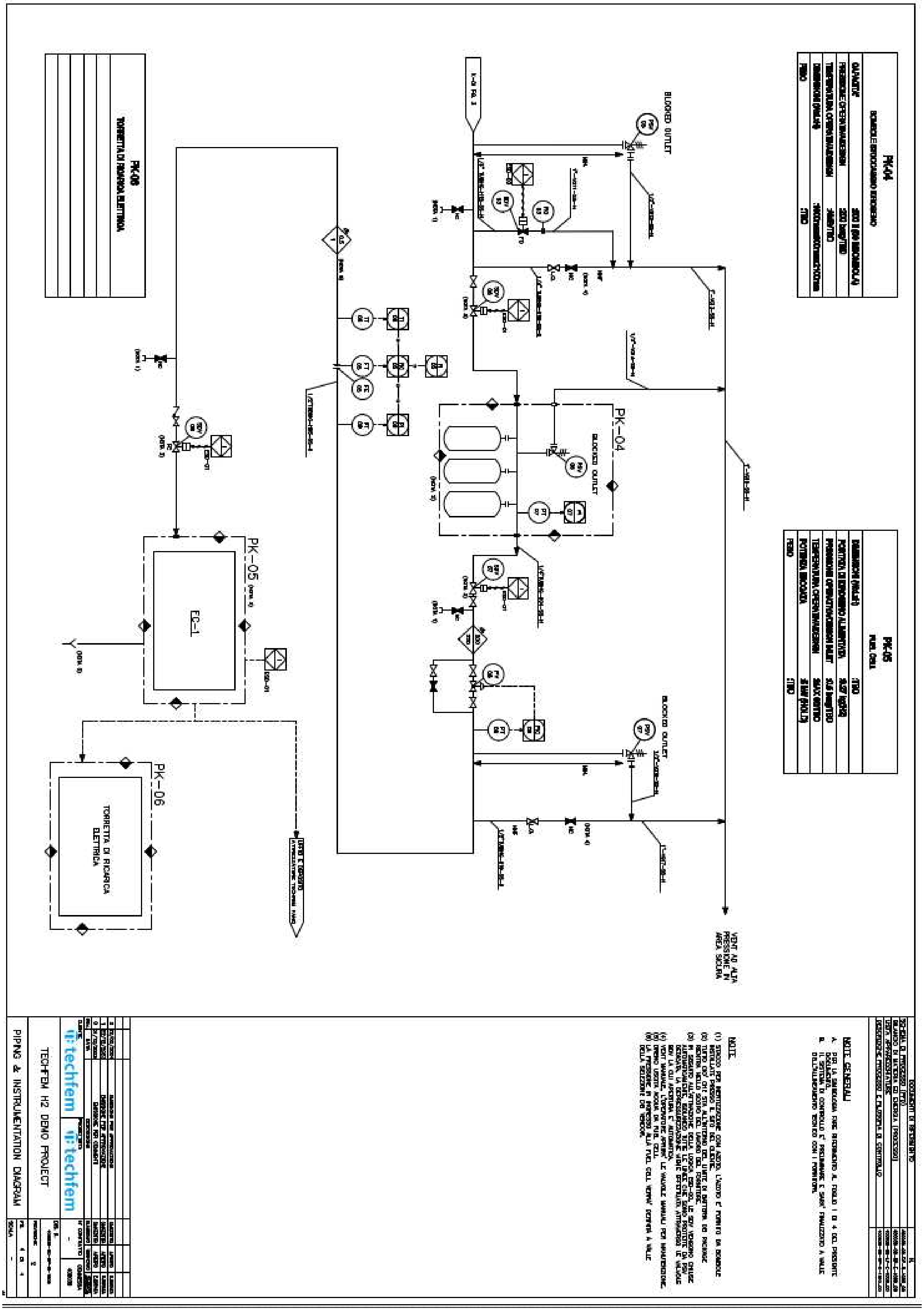
Then, in the next ones, we can see how every component works (at which values, with which valve and in which case).



IDENTIFICAZIONE SCHEMATICA DELLE LINEE
X-XXXX-XX-X
DIAMETRO NOMINALE (DN)(Inches)
TIPO FLUIDO/N.LINEA
FINITURA (Verniciata, nuda)
MATERIALE (MP, SS)
TIPO DI MATERIALE
SS = STAINLESS STEEL
HDPE = POLIETILENE ALTA DENSITA'
CODICE COIBENTAZIONE, VERNICIATURA O TRACCIATURA
N = LINEA NON VERNICIATA E NON COIBENTATA (NUDA)
C = LINEA COIBENTATA (PROTEZIONE DAL FREDDO)
DEFINIZIONE FLUIDO
PW ACQUA DI PROCESSO
H IDROGENO
O OSSIGENO
N2 AZOTO
VG SCARICO GASSOSO ALL'ATMOSFERA
DR DRENAGGIO APERTO
CODICE IDENTIFICAZIONE APPARECCHIATURE
X-XX
PREFISSO IDENT. APPARECCHIATURE
No. SEQUENZIALE
PREFISSI IDENTIFICATIVI APPARECCHIATURE
S SERBATOIO/BUFFER
P POMPA
PK PACKAGE
X SUBCOMPONENTI DEL PACKAGE
SIMBOLOGIA LINEE
LINEA DI PROCESSO PRINCIPALE
LINEA DI PROCESSO SECONDARIA
vendor
contractor
LIMITE DI FORNITURA PACKAGE VENDOR
LIMITE BATTERIA IMPIANTO
SIMBOLOGIA LINEE
SFIATO ALL'ATMOSFERA
ATTACCO PER MANICHETTA
RIDUZIONE CONCENTRICA
FILTRO A Y
SCARICO APERTO
SIMBOLOGIA DELLE VALVOLE
VALVOLA MANUALE DI INTERCETTAZIONE ON-OFF
VALVOLA MANUALE NORMALMENTE CHIUSA
VALVOLA A GLOBO
VALVOLA DI RITEGNO
VALVOLA CON ATTUATORE PNEUMATICO
VALVOLA DI SICUREZZA (PSV)
NC NORMALMENTE CHIUSA
LC LUCCHETTATA CHIUSA
LO LUCCHETTATA APERTA
VALVOLA SOLENOIDE
PCV
PV
FCV
SIMBOLOGIA DEGLI STRUMENTI (CONTINUA)
PT TRASMETTITORE DI PRESSIONE
TT TRASMETTITORE DI TEMPERATURA
FT FE INDICATORE/TRASMETTITORE DI PORTATA (ORIFIZIO CALIBRATO)
PI INDICATORE DI PRESSIONE
TI INDICATORE DI TEMPERATURA
LT INDICATORE/TRASMETTITORE DI LIVELLO (TIPO A PRESSIONE DIFFERENZIALE)
LG LIVELLO VISIVO
FO ORIFIZIO CALIBRATO
AT ANALIZZATORE
SIMBOLOGIA DEGLI STRUMENTI
FUNZIONE SVOLTA DA SISTEMA DI CONTROLLO AUSILIARIO
ESD
FUNZIONE SVOLTA DA EMERGENCY SHUT DOWN (E.S.D.)
IDENTIFICATORI ATTIVI PER LE FUNZIONI DI PROCESSO
HH SOGLIA DI ALTISSIMO
H SOGLIA DI ALTO
L SOGLIA DI BASSO
LL SOGLIA DI BASSISSIMO
SEGNALI
SEGNALE ELETTRICO
COLLEGAMENTO SOFTWARE
SEGNALE PNEUMATICO
APPARECCHIATURE
SERBATOIO GENERICO VERTICALE
SERBATOIO GENERICO ORIZZONTALE
POMPA VOLUMETRICA CON MOTORE ELETTRICO (COLLEGATA AL MOTOR CONTROL CENTER MCC)
RACCOGLITORE DI CONDENSA
PULSATION DAMPER
DOCUMENTI DI RIFERIMENTO
SCHEMA DI PROCESSO (PFD)
BILANCIO DI MATERIA ED ENERGIA (PROCESSO)
LISTA APPARECCHIATURE
DESCRIZIONE PROCESSO E FILOSOFIA DI CONTROLLO
NOTE GENERALI
NNF NORMALMENTE SENZA FLUSSO
FO FAILURE OPEN
FC FAILURE CLOSE
TBD DA DEFINIRE
OP. TEMPERATURE (°C)
OP. PRESSURE (barg)
DP. PRESSURE (barg)
TIPICI VALVOLE
ESDO
FC
FO
ESD-01
ESD-LOCAL
techfem
techfem
TECHFEM H2 DEMO PROJECT
PIPING & INSTRUMENTATION DIAGRAM
FG. 1 DI 4
SCALA -


TECH-FEM H2 DEMO PROJECT
PIPING & INSTRUMENTATION DIAGRAM


PIPING & INSTRUMENTATION DIAGRAM
TECHFEM H2 DEMO PROJECT
techfem
VENT A BASSA PRESSIONE IN AREA SICURA
VENT H2 IN AREA SICURA (NOTA 11)
BLOCKED OUTLET
PK-03
K-01
S-02
NOTE GENERALI
NOTE



PK-04
PK-05
PK-06
EC-1
TORRETTA DI RICARICA ELETTRICA
BLOCKED OUTLET
VENT AD ALTA PRESSIONE IN AREA SICURA
NOTE GENERALI
NOTE
TECHFEM H2 DEMO PROJECT
PIPING & INSTRUMENTATION DIAGRAM

The project functions with an **ESD** (Emergency Shut Down) logic, which is an automatic logic that opens and closes some valves in order to isolate the package that creates the problem.

The ESD logic is divided in three: ESD-00, ESD-01, ESD-LOCAL.

The **ESD-00** is the most powerful, and it is the one that blocks all the process with the help of the other two.

The **ESD-01**, with the help of the LOCAL, is the one that isolates every damaged package without shutting down all the process.

The **ESD-LOCAL** is the less powerful one and functions only for simple operation (such as opening or closing a valve).

The ESD logic is mandatory as set in the decree of 7th July 2023.

Here we are also the main parameters evaluated for every component during the process.

Legenda acronimi	
P	processo
EL	elettrico
MT	meteo
ME	mercato elettrico
IN	ingresso item
OUT	uscita item

Buffer H_2	P	Pressione	-
Sistema di compressione	EL	Tensione di alimentazione	-
		Frequenza di alimentazione	-
		Potenza attiva	-
		Potenza reattiva	-
		Demand	-
	P	Pressione H_2	IN/OUT
		Portata H_2	OUT
		Temperatura H_2	IN/OUT
		Frequenza vibrazionale	-
		Stato di funzionamento	-
Stoccaggio H_2 in bombole	P	Pressione	-
Cella a combustibile	EL	Corrente	-
		Tensione	-
		Demand	-
	P	Pressione H_2	IN
		Portata H_2	IN
		Temperatura H_2	IN
Impianto fotovoltaico	EL	Potenza attiva	-
		Potenza reattiva	-
		Tensione (RMS)	-
		Corrente (RMS)	-
		Frequenza	-
		Demand	-

ITEM	TIPO	PARAMETRO	
Sistema di demineralizzazione H_2O	P	Portata H_2O	IN/OUT
		Pressione H_2O	IN
		Temperatura H_2O	IN/OUT
		Conducibilità elettrica	OUT
Serbatoio di stoccaggio H2O demi	P	Livello	-
Sistema di elettrolisi (produzione + purificazione)	EL	Tensione di alimentazione	-
		Frequenza di alimentazione	-
		Potenza attiva	-
		Potenza reattiva	-
		Demand	-
	P	Portata H_2O	IN
		Pressione H_2O	IN
		Concentrazione O_2 (vent)	-
		Portata H_2	OUT
		Pressione H_2	OUT
		Temperatura H_2	OUT
		Purezza H_2	OUT
		Tensione delle celle di elettrolisi	-
		Stato di funzionamento	-
Rete elettrica nazionale	EL	Potenza attiva	-
		Potenza reattiva	-
		Tensione (RMS)	-
		Corrente (RMS)	-
		Frequenza	-
		Demand	-
Carichi elettrici (modulabili/interrompibili)	EL	Potenza attiva	-
		Potenza reattiva	-
		Tensione (RMS)	-
		Frequenza	-
		Demand	-
Altre grandezze	MT	Radiazione solare	-
		UV	-
		Piovosità	-
		Temperatura	-
		Umidità	-
		Velocità del vento	-
		Direzione del vento	-
	ME	Prezzo Unico Nazionale	-
		Prezzo zonale	-

3.3 DIGITAL TWIN

A **digital twin** system (**DT**) is the virtual representation of a physical entity, which can exchange data and information in both synchronous (real-time) and asynchronous way.

The **DT** can also include all the information related to the entire lifecycle of the element it represents.

Its main components are:

- Data & Info of the twined element
- Connection between the physical and the digital parts
- Big data, machine learning and AI
- Sensors and actuators for Data & Info exchanges

The **DT** creates digital simulation models of real entities, which update themselves whenever the physical entities they represent are updated, and it allows to simulate every possible scenario of what you have to do.

Its biggest potential depends on the integration of **IoT** an **AI**, which gives it unlimited knowledge.

Description

The purpose of a **DT** is to build effective communication between the physical world and the information world, using a large amount of data collected with experience.

The needed characteristics to be considered a **DT** are:

- Network connectivity
- Physical entity
- Virtual entity
- Synchronization
- Twinning rate (frequency of synchronization)
- Processes
- Fidelity (accuracy)
- Replication
- Persistency
- Composability
- Modularity

The concept of **DT** has most recently been recognized as a disruptive technology that can completely alter the operations, security, and manufacturing tendencies of a cyber-physical system.

DT provides an innovative way to gather insights, optimize performance, and make data-driven decisions in real-time by developing virtual representations of physical objects, systems, and processes.

A **DT** is fundamentally dependent on the datasets it generates in order to predict the behavior, enhance intrusion detection, and improve the performance of its physical equivalent. Equally, physical objects generate datasets via network devices, sensors, measurements, and observations, which are crucial for overseeing and managing their operations and further assist in predictive intrusion detection.

This approach saves time, energy, and, most importantly, resources.

Applications

Several studies have proposed a set of expected features to distinguish **DTs** from other technologies. However, the analysis being held in those works establishes a general overview for several application domains.

- **Lifecycle**: The **DT** must be aligned with the lifecycle of the twinned system, from design to disposal. In this way, the **DT** is evolving with the system, capturing and storing information throughout the lifecycle of the PO.

- **Safety:** The model representation in this application domain vary according to the expected functional output of the **DT** and the industrial field. In construction and manufacturing applications, geometric models are combined with remote sensors for generating the virtual replica. Also ML techniques are used to update the parameters or state variables of the physical-based models, evaluating the **risk assessment**.
- **Emergency management:** Geometric models and VR techniques have been exploited in the automative industry to support the implementation of human-machine interfaces (HMIs). All these stuffs are used to manage automatically the **emergency** cases, either changing automatically the asset of the process or giving instructions in order to put it in safety.
- **Forecasting: DTs** are also of fundamental importance while speaking about forecasting. Thanks to the data stored with the experience and ML techniques, the **DT** system can predict future moves, in order to asset the process in the most functional way. For example, in the Smart Hydro project, it can change the way of H2 production due to the weather, the electric market, and the gas market forecasts.

Machine Learning (ML)

The real power of a **DT** system stays on the **ML**.

Machine learning is a branch of the Artificial Intelligence (**AI**) that uses different techniques such as computational statistics, neural links, images elaboration and data mining.

It uses statistic methods to improve algorithms performances, in order to make the algorithm autonomous to learn new skills alone, without the help of the programmer.

ML is now used in a lot of fields, such as medicine, industry and information.

The main method is to create a neural link (equivalent of a physical one) organized and projected to learn only specific skills. It needs supervision and to be reprogrammed, to change its learning routine. After that, with time it can learn specific skills in an autonomous manner and with a high computational power.

ML is also linked to the pattern recognition and to the computational theory of learning, and explores the study and the building of algorithms that can learn from big data and forecasts.

3.4 CAUSE-EFFECT MATRIX

In this last section we will see the cause-effect matrix of the project, that describes how the digital twin will take the decisions.

As we have seen in the chapter of the **P&I**, this project uses the **ESD** logic (00-->01-->LOCAL) to open and close automatically the valves that links each component.

For this target, I have analyzed three scenarios.

The first one consists only in the **STAND-ALONE** scenario, where the only energy used to produce hydrogen derive from our PV plant..

The second one introduces the possibility of being connected to the **grid**.

The third one is the **forecasting** one, that takes into account the possible scenarios of the next day (in term of electric and gas market and also weather conditions).

- PK1: H2O
- PK2: ELECTROLYZER
- PK3: COMPRESSOR
- PK4: STOCK TANKS
- PK5: FUEL CELL
- PK6: ELECTRIC CHARGE

1) H2 STAND-ALONE

ESD-00
BLOCCO IMPIANTO DI EMERGENZA

CAUSE: IMPIANTO E/O APPAREC.	SCHEMA	SIGLA	FUNZIONE	SERVIZIO	DELAY	NOTE	blocco produzione FER	blocco PK-01	apro valvola PSV-01	meolo dal motore pompa P-01	blocco PK-02	chiudo valvola SDV-01	apro valvola PSV-04	apro valvola SDV-02	chiudo valvola SDV-04	blocco PK-03	chiudo valvola SDV-05	apro valvola PSV-05	apro valvola SDV-03	chiudo valvola SDV-06	apro valvola PSV-06	chiudo valvola SDV-07	apro valvola PSV-07	chiudo valvola SDV-08	blocco PK-05	isolamento PK-01	isolamento PK-02	isolamento PK-03	isolamento PK-04	isolamento PK-05	isolamento PK-06	meolo en el in elettrolizzatore
						FUNZIONE							PI-03																			
						NOTE														stock	P stock	stock	P FC	FC	FC	gli isolamenti sono manuali						
		Pot el IN-0		danneggiamento FER			X																									
		<Pot el IN		presenza nuvole						X																						X
		<FT/FE	FI-02	carenza H2O						X																						X
		>FT/FE	ESD-LOCAL	troppa H2O					X	X																						X
		<efficienza	AI-02	malfunzionamento elettrolizzatore																						X	X					X
		>PT-03	PI-03	sovrapressione serbatoio S-02									X																			
		>PT-05	ESD-01	sovrapressione compressore				X		X		X			X		X	X		X		X		X	X							
		<PT-04	ESD-01	sottopressione compressore				X		X		X			X		X			X		X		X	X							
		>PT-07	PI-07	sovrapressione stoccaggio																	X											
		>PT-06	PIC-06	sovrapressione FC																			X									
		<efficienza		malfunzionamento FC																										X		
		F&G	ESD-00	rilevamento fuoco o perdita gas				X		X	X	X		X	X	X	X		X	X		X		X	X							
				impossibilità stoccaggio																						X	X	X	X	X	X	
		H2O-0		rottura impianto H2O																						X	X	X	X	X	X	

In this scenario the hydrogen produced is only sold to the **user**.

As said in the introduction of the paragraph, the **ESD** logic is firstly used for safety, but when everything is safe its main target is maximization of production.

Every valve is linked to a package (as descripted in the P&I) which help speeding up the modification processes of the system.

As you can see in the image, the process follows only one main flow (PV->H2O->ELECTROLYZER->COMPRESSOR->TANKS->USER) and if something is going wrong the production needs to be stopped.

2) H2 connected to the grid

ESD-00
BLOCCO IMPIANTO DI EMERGENZA

CAUSE (SCHEMA / SIGLA / FUNZIONE / SERVIZIO / DELAY / NOTE) — EFFETTI (FUNZIONE ATTIVATA / FUNZIONE / NOTE)

FUNZIONE ATTIVATA	FUNZIONE	NOTE	Pot el IN = 0 — danneggiamento FER	< Pot el IN — presenza nuvole	< FT/FE — FI-02 — carenza H2O	> FT/FE — ESD-LOCAL — troppa H2O	< efficienza — AI-02 — malfunzionamento elettrolizzatore	> PT-03 — PI-03 — sovrappressione serbatorio S-02	> PT-05 — ESD-01 — sovrappressione compressore	< PT-04 — ESD-01 — sottopressione compressore	> PT-07 — PI-07 — sovrappressione stoccaggio	> PT-06 — PIC-06 — sovrappressione FC	< efficienza — malfunzionamento FC	F&G — ESD-00 — rilevamento fuoco o perdita gas	impossibilità stoccaggio	H2O = 0 — rottura impianto H2O
blocco produzione FER		FER	X													
blocco PK-01	ESD-01	trasporto H2O												X		
apro valvola PSV-01		P serbatoio H2O				X										
regolo giri motore pompa P-01	ESD-LOCAL	portata H2O		X	X	X								X		
blocco PK-02	ESD-00	elettrolizzatore												X		
chiudo valvola SDV-01	ESD-01	elettrolizzatore												X		
apro valvola PSV-04	PI-03							X								
apro valvola BDV-02	ESD-00													X		
chiudo valvola SDV-04	ESD-01	compressore							X	X				X		
blocco PK-03	ESD-00	compressore												X		
chiudo valvola SDV-05	ESD-01	compressore							X	X				X		
apro valvola PSV-05									X							
apro valvola BDV-03	ESD-00													X		
chiudo valvola SDV-06	ESD-01	stock							X	X				X		
apro valvola PSV-06		P stock									X					
chiudo valvola SDV-07	ESD-01	stock							X	X				X		
apro valvola PSV-07		P FC										X				
chiudo valvola SDV-08	ESD-01	FC							X	X				X		
blobbo PK-05	ESD-01	FC							X	X				X		
vendita immediata en el alla rete		gli isolamenti sono manuali					X							X		X
isolamento PK-01							X									X
isolamento PK-02							X									X
isolamento PK-03																X
isolamento PK-04															X	X
isolamento PK-05													X		X	X
isolamento PK-06															X	X
regolo % H2 in rete									X	X					X	
regolo en el in elettrolizzatore		elettrolizzatore		X	X	X	X									
prendo en el dalla rete			X	?												

In this scenario the main difference is that the electric energy can also be sold to the **grid**.

In this case, when something goes wrong, the production shouldn't be stopped. For example, if only the compressor is damaged, there is the impossibility to store H2 in tanks and sell it to **users**, but electricity can be sold to the **grid**, changing the process flow.

On the other hand, the percentage of energy inputted in the **grid** and how much hydrogen wanted to sell to **users** can be regulated. This decision is influenced by the prices and contracts of sale.

3) Forecast scenario

ESD-00
BLOCCO IMPIANTO DI EMERGENZA

EFFETTI

FUNZIONE ATTIVATA	FUNZIONE	NOTE
vendita immediata en el alla rete		
isolamento PK-01		H2O
isolamento PK-02		elettrolizzatore
isolamento PK-03		compressore
isolamento PK-04		stock
isolamento PK-05		FC
isolamento PK-06		batterie
regolo % H2 in rete		
impedisco vendita en el		
impedisco vendita H2 user		

CAUSE

SCHEMA	SIGLA	FUNZIONE	SERVIZIO	DELAY	NOTE	vendita immediata en el alla rete	isolamento PK-01	isolamento PK-02	isolamento PK-03	isolamento PK-04	isolamento PK-05	isolamento PK-06	regolo % H2 in rete	impedisco vendita en el	impedisco vendita H2 user
	> € en el		aumento richiesta energia elettrica			X	X	X	X						X
	< € en el		crollo richiesta energia elettrica								X	X	X	X	
	> € H2		aumento richiesta H2 user								X	X	X	X	
	< € H2		crollo richiesta H2 user										X		X
	> € H2 rete		aumento richiesta H2 in rete										X	X	
	< € H2 rete		crollo richiesta H2 in rete										X		
	< Pot IN		brutte previsioni meteo								X	X	X	X	X

This last scenario is an improvement of the first two because you can estimate in advance your tomorrow production, without being unprepared to every anomaly.

In this case the flow is regulated in function of the price **forecasts** of hydrogen and electricity, and also in function of the weather **forecast** of the next day.

For example, if today hydrogen price is low and tomorrow will be higher, the process is modeled in order to have full storage tanks, having the maximum quantity for tomorrow.

Another example could be if tomorrow it will rain, meaning that the PV plant won't produce electricity. In this case the hydrogen storage is managed to be regulated taking into account the fact that tomorrow there isn't the possibility to produce it.

Usually, the **ESD** logic is used only for safety. In these scenarios, indeed, the first possible cases studied are all the possible dangerous situations that can put the life in risk and also damage the plant.

On the other hand, as analyzed before, it is also used for directing the production of **H2** as preferred. In all the three scenarios, in parallel to the safety and the maintenance of the plant, the main aim of the **DT** is the economical one.

The first target of the Smart Hydro project, indeed, is to abate the production cost of the hydrogen, monitoring the system in function of the changes of the markets (electrical and gas ones).

CONCLUSION

4.1 SUMMARY

To summarize all this work, I can conclude that the hydrogen is a very powerful renewable resource.

Nowadays, as we have seen in all the graphs in chapter 2, it is still economically unsustainable. Fortunately, the European Commission is creating a lot of incentives, like the “hydrogen bank”, which incentivizes hydrogen production guaranteeing a fixed tariff for every kg produced.

Moreover, the world of hydrogen is in continuous development. Mainly, it is going to be worldwide used for transports (cars, trains, ships). Then it could be exploited for having high quantities of stocked energy with the new development of safer stocking ways. Last but no least, it would be used directly as a gas due its high calorific power (mixed with the GNL in the gas grid).

Due to all these changings and adding the fact that we are going through a more sustainable and cleaner world, the hydrogen could be one of the most important green energy source for the near future.

4.2 SITOGRAPHY

Electrolysis

https://en.wikipedia.org/wiki/Electrolysis

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Electrolyser

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Partial Oxidation

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