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Sizing of a self-sufficient hydrogen refueling station under Italian subsidy scheme

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Abstract

In order to reduce road transport emissions, the development of xEV(Electrict Power Trains) is essential. To achieve the European Union net-zero goal by 2050, Internal Combustion Engine (ICE) vehicles need to be replaced by vehicles with zero emissions, with a proper mix of Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV).

Thesis aims to satisfy the daily demand of 1035 kg of green hydrogen to refuel HDFCEV (Heavy Duty Fuel Cell Electric Vehicle), the demand is assumed constant for all the days in a year. The H2 green is produced in loco to the station using electrolyzer, it's powered by a dedicated Photovoltaic plant to providing renewable electicity. H2 is stored in the High Pressure hydrogen Vessel storage in the station, it's the dedicated component uncoupling the production and the demand during low irradiance period of time. The three main components: PV plant, electrolyzer and storage will be sized considering different scenarios in order to satisfy the yearly demand with total green hydrogen:

1. The electrolyzer produces hydrogen with only the energy from the dedicated PV plant, in the hours with low irradiance and as a consequence, low H2 production, the Vessel Storage satisfies the demand.

2. When the PV plant provide low energy to the electrolyzer for H_2 production and storage is not able to satisfy the demand, the required amount of green H2 is transported by trucks from a remote facility.

3. As in the previous case, when the electrolyzer does not produce enough hydrogen or the storage is not able to afford the fueling, the remaining H2 to satisfy the demand is produced by the electrolyzer getting the electricity from a dedicated plant with Guarantee of Origin (GO).

The best scenario and sizing are the once that minimize the Levelized Cost of Hydrogen (LCOH). It is emphasized that LCOH does not consider the cost and energy required by the other station components (compressors, coolers, valves, other auxiliary devices).

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Introduction

1.1 Context

Climate change issue

In the last years a lot of attention is focused on the Climate change. It regards the temperature rises with negative impact for the environment, human activity and human health. The issues of Global warming potential and the Climate change rise the attention in the Rio Conference in the 1992. After in 1997, the Kyoto Protocoll was the first international agreement that mentions the commitments of industrialized countries to reduce the emissions of certain greenhouse gases, responsible for global warming. The X- rays coming from the sun are the rays with short wavelenght(100800 nm) and the highest energy content. UV-C rays are absorbed from the diatomic oxygen and create the ozone sphere. The UV-C rays break the O2 molecule and the monoatomic oxygen (O) will recombine with diatomic Oxygen forming the O3(ozone gas). This mechanism is essential for the human health because X-rays with low wavelenght are cancer for epidermic of the skin. There are some gases that in the atmosphere react with the oxygen interfering with these mechanism of screen the UV rays, If the previous reaction do not happen the UV rays will pass through. the Kyoto protocol identified the main responsible gases for the greenhouse effects [27]

- CO_2 carbon dioxide
- CH4 methane
- N_2O nitrousoxide
- HFC Hydrofluorocarbon
- PFC Perfluorocarbon
- SF_6 Sulphur hexafluoride

The gases having the strong impact are the CFC(Chlorofluorocarbons), CLC with the UV rays produce Cl, it will react with oxygen producing chlorine monoxide(ClO) and Oxygen(O_2). ClO react with monoatomic Oxygen(O) producing again Cl, starting the reaction mechanism. The Cl before to recombine with other substances as methane, it could react thousand of time with ozone molecules. In the past CFC are used as refrigerant fluid, especially as fluid for the thermal cycle in the refrigerator, and in spray coils. Now these gases are less used to the global warming problem with the research focused on alternative fluids with the same function. [27].

Global Warming Potential

The impact of theses gases is measured with an index that express its potential as GHG (Green Gas Houses) effect, the GWP (Global Warming potential index) measures the gas damage to spread the hole zone using as base gas the damage atmosphere of the CO_2. As an example the GWP of CF_4 is 6300, it means that the emission in atmosphere of 1 gr of CF4 make the same atmospheric damage of emitting 6300 gr of CO_2. This is the reason why the emissions are not referred to CO_2 but to $CO_{2equivalent}$, equation(1.1), in order to taking into account the environmental damage of the other gases.

$$CO_{2equivalent} = GWP_{gas} \cdot mass_{gas} \qquad [kg_{CO2equ}] \tag{1.1}$$

1.2 EU road to net zero

This an holistic view of the problem, the most developed country consider seriously the climate change impact and the negative implications, after the Rio conference and the Kyoto protocol, the climate change problem coated many attention from government authorities and it has became an important aim for the population linked with the environment respect and emission reduction. the Eu have establish a road map to net zero emission until the 2050,it means that the amount of $CO_{2equivalent}$ emitted must be recovered. This is not an easy goal to reach for many reasons, the most important is that the development of the Nations shows a strong relation with the carbon emissions.In the figures (1.1) and (1.2) there is a clear trend showing that the population rise and the rise of GDP(Gross Domestic Production) is strongly related with the anthropogenic CO2 emission. [22]

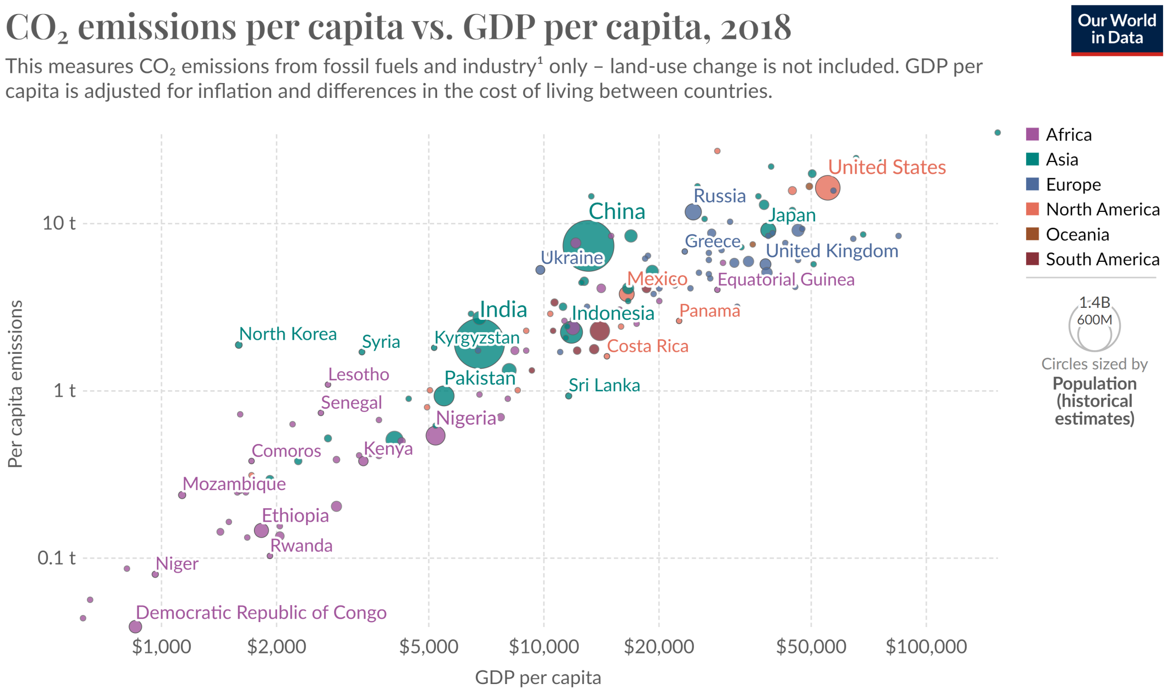

Figure 1.1: CO_2-emissions-vs-gdp [22]

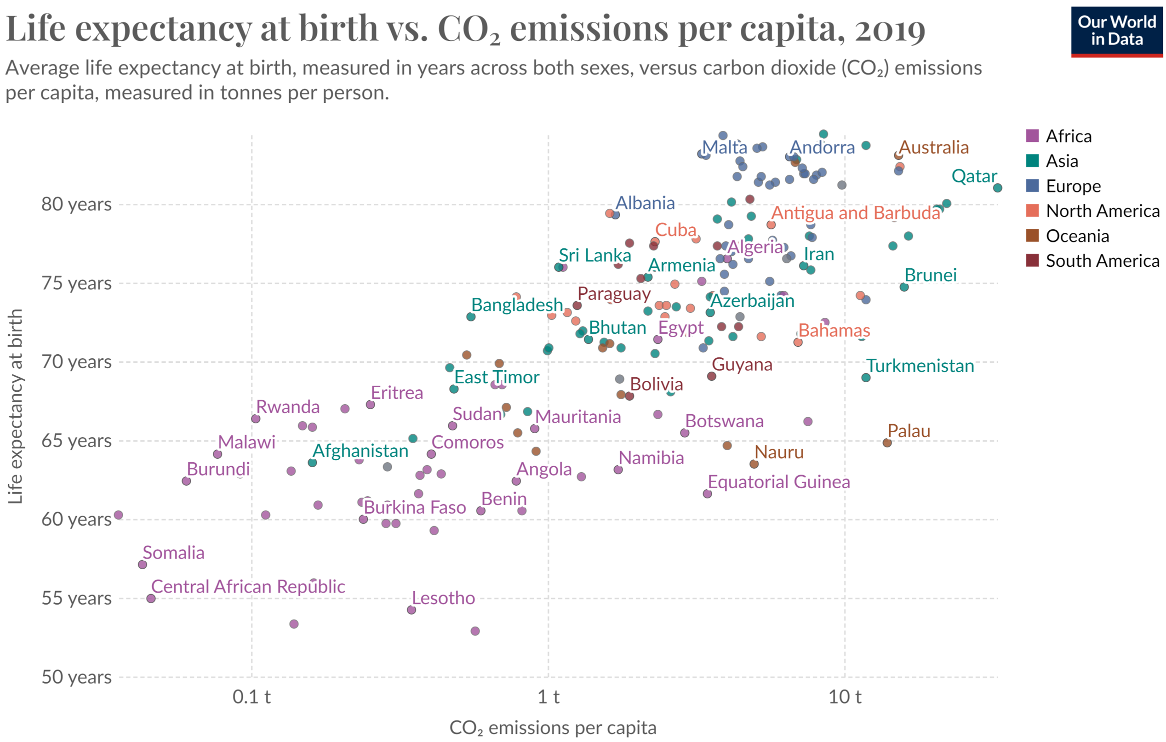

Figure 1.2: Life-expectancy-at-birth-vs-co-emissions-per-capital [22]

The most developed country with the higher GDP are the highest Carbon emitters. This results are due the facts that in the XX century the main technologies worked with fossil fuel input, consider also that there was not attention for the emissions, the resources manage and the sustainability. The challenge of the new century is to achieve a sustainable development that include the carbon emission reduction and a more attention in the resources used. The goal is to not base the economic and the development based on fossil fuel due the carbon emission but also because they time consumption is much more higher than their time formation with the consequence that the fossil fuel could not be available for the future generations. The sustainability concept concern the use of a resource in a clever such that it will be used also by the future generations. As explained, the fossil fuel have a low rate of formation respect the consumption, so the technologies and the development must be based on renewable technologies that use RES (Renewable Energy Sources).

1.3 Literature review

Transport sector decarbonization

One of the most impacting sector from the point of view of the emissions are the Energy and the Transport Sector. The figure (1.3) shows the emission of $CO_{2equivalent}$ for different sectors in Italy at 2021. The main part is related to the energy sector(Industrial energy, manufacturing, transport and residential)covering almost the 80% of the National emissions [19].

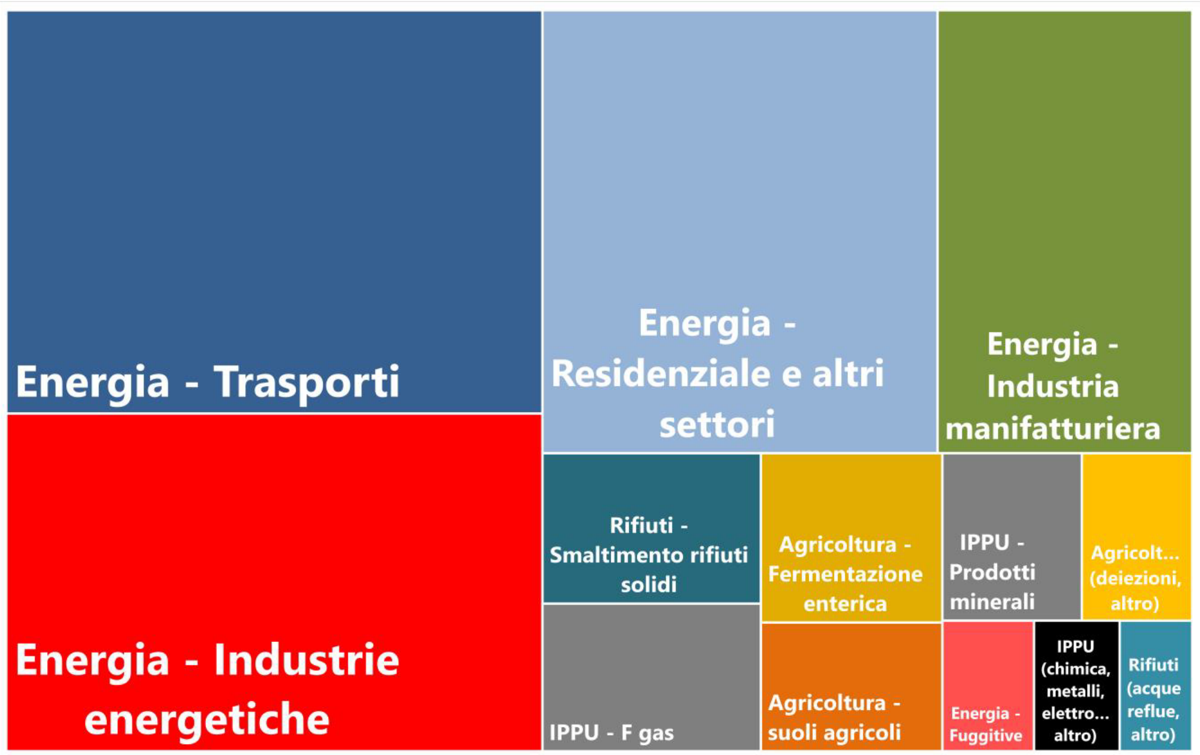

Figure 1.3: Emission from different sectors in Italy at 2021 [19]

The main emissions in the transport sector in Italy is due to road transport, covering over the 92,9%, emissions related top aviation,ship, rails are very low , under the 10%. It's clear that the focus for the decarbonization must begin from the road, figure (1.4).

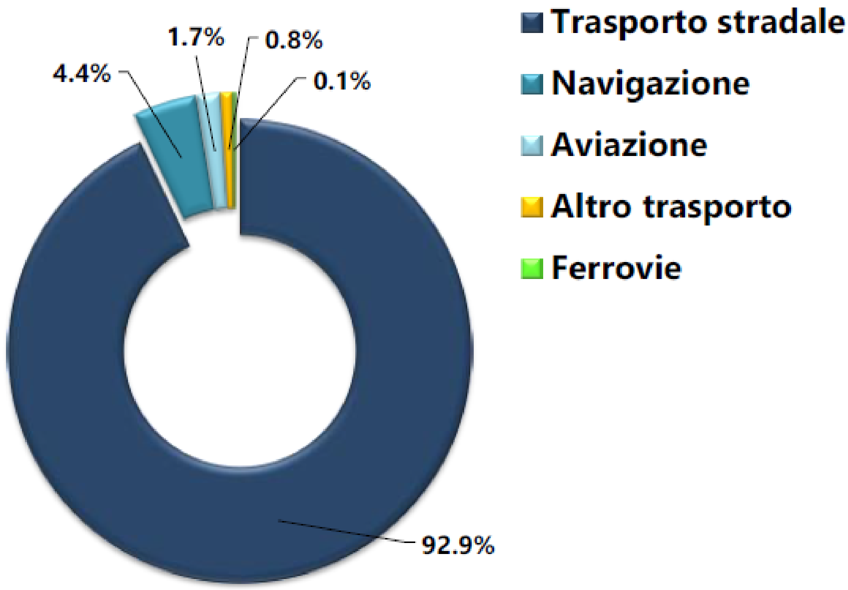

Figure 1.4: Road transport emission share [19]

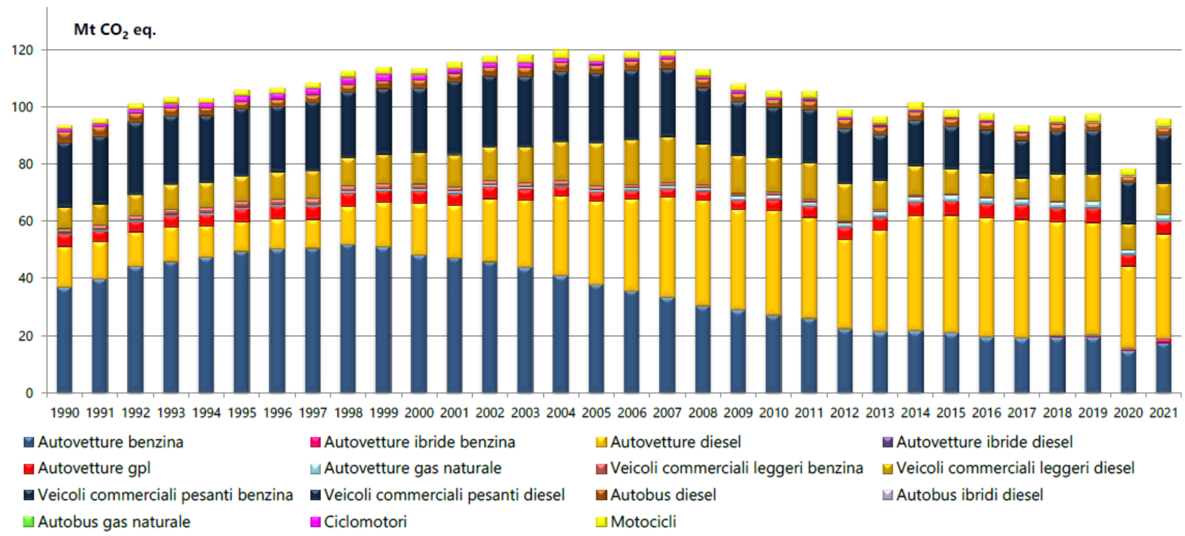

Figure 1.5: Emissions for different type of vehicles and fuel [19]

Figure (1.5) shows In Italy the Mt $CO_{2equivalent}$ emissions on road transport sector from 1990 to 2021 for different vehicle category. from the 1990 to 2021 there is an almost constant emission reduction for gasoline power vehicles, but it is compensated from the increase of the diesel vehicles. In 2020 the reduction is due to the pandemic when the mobility was reduced. In 2021 the category that count for the most emissions it's referred to diesel's vehicles (69,7%). Vehicles using gasoline account for the 21,7%,but it's important to underline that the 18,4%

coming from PCs (Passenger car vehicles), plot (1.5). From the plot is clear that the most road emissions are due to PCs than HDV (Heavy Duty Vehicles) that in 2021 account for almost 20 $MtCO_{2equivalent}$, it suggests that to reduce the road transport emissions the focus have to be on Passenger car, substituting with zero emission vehicles. Vehicles with zero emissions are indicated with xEV(Electric Power Train), it refers to BEV and FCEV.

- in BEVs(Battery Electric Vehicles)the motor is powered only by a battery.

- FCEV(Fuel Cell Electric Vehicles) refers to vehicles using a fuel cell power train. The fuel is the hydrogen that with Oxygen make the reaction producing electric energy.

This two type of vehicles need different station for the recharge/refuel, for BEVs are used a dedicated columns to recharge, the main problem is the time recharge duration, it can last for half and hour, the passenger using ICE make the charge in few minutes so time recharge is a very strong constrain for the development of this type of vehicles. Instead FCEV using as a fuel Hydrogen and time charge is comparable to the ICEs (Internal combustion Engines). Other advantage of this type of vehicles is that the fuel used is a fluid(compressed gaseous H2) , so there are some components, equipment as pumps valves and so on, they are just present in the usual ICE that can be re used in this new type of vehicles. It's an advantage for the companies that do not have too much change their car production cycle.

At the European level,so considering EU27 country +2(United Kingdom and Norway), has been done a projection share of xEV to achieve the zero emission target at 2050. Analysis suggest that one scenario with only one type of xEV(BEV or FCEV) imply too much costs so it's not suggested from a economic point of view and also because depending on the circumstances it's possible to assume one technology or other, with larger choice [3]. In figure (1.6) are indicated the millions of vehicles that need to be adopted in the 27 UE country + 2 country from the 2021 to the 2050.ICEs are not present due the fact that they are not zero emission vehciles and also in Europe, according to the current decision, at 2035 there will be no more ICE vehicles production. From the 2021 to 2030 there are only the BEVs , in 2030 it's also planned the presence of the FCEVs with a constant rise during the year. Depending by the predictable scenario(high or low) the share of the FCEV could change, it's remarked that the major FCEVs share is represented by the Heavy Duty, the reason why it's that they have a fixed path then LDV(Light Duty Vehicles), this explanation will be expanded upon later in the subsequent subsection.

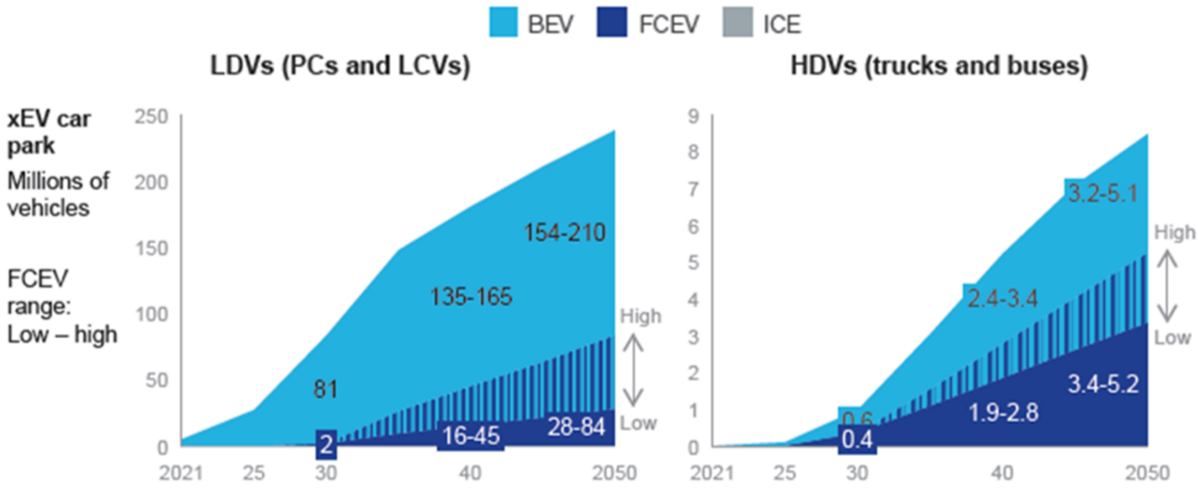

Figure 1.6: BEV and FECV [3]

Chicken and egg problem

The main issue for the the development of alternative vehicles is the so called "chicken and egg problem". The xEVs development is regarded to the station charge development and vice versa. Excluding any economic considerations, focusing only from the driver point of view the achievable places depend on the possibility to rechargerefuel the vehicle in the surrounding area without having the problem to finish the charge, so this concern to have more refueling station spread out in the territory. But on the other side if there are few xEV the station development will be very difficult because time to recover invest are longer and uncertain. So it's clear that the development of one depends on the development of the other, Which should come first, the station or the vehicle?. the question has not a clear answer, for sure with a simultaneously development they push each other.

Italian as main country for transition

Italy is considered one of of the 5 EU country for transition xEV development due to its potentially growth for adoptation of xEVs, due its potentially develop of renewables and its public announcements regarding plans for hydrogen development. This 5 country(Sweden, Germany, Netherlands,Italy and Poland) among which Italy is a part, are selected among EU27 +2 states for the criteria across 5 quantitative categories [3]:

- Economics: the set of data that includes income, urbanization, and average vehicle lifetime.
- Infrastructure readiness: alternative power train, road, and rail infrastructure.
- Renewable energy availability: The level of development and penetration of renewable energy sources.

- xEV adoption: the current level of BEV and FCEV adoption.
- Hydrogen availability: the announced production cost and capacity.
- Regulation: Exploring the range of government subsides, investment, and policies as they relate to EV strategy and policy.

[3]

Italian legislation for hydrogen

Italy legislation for hydrogen promote and invest in the Hydrogen field and in the alternative mobility, the investments amouunt are present in the M2C2 of the PNRR . The investment for the green H2 production, the incentives for HRS the amount of incentives and how to obtain them are explained in the Ministerial decrees.

Incentives for green H2 production

the MASE(Ministero dell'Ambiente e della Sicurezza Energetica) held a public consultation regarding the rules for the incentives for gaseous renewable fuels produced from renewable source. The Italian hydrogen strategy at the end of 2020 have identified a preliminary potential demand equal to 700.000 ton/year at 2030 with the prediction of 5 GW electrolyzer Power and 5-7 Billions € of investment. Updated proposal of the Italian National Integrated Climate and Energy Plan of 2023 remodel the guide lines in 250.000 torn/year at 2030, this estimated demand will be produced for the 80% in the National territory and the remaining will be imported. Assuming a load factor electrolyzer of 40% the Installed electrolyzer capacity will be of 3 GW. At 2030 for the transport sector will be estimated 135.000 ton/yer and almost the 90% for road transport[20] .

The Italian legislation regarding h2 distinguishes between green hydrogen and renewable H2, but at international level this difference is not presence, so it's the case to redefine only renewable/green hydrogen as the same meaning with the following rules:

1. hydrogen must be produced through electrolysis process beginning from renewable energy sources in accordance to the methodologies established for the renewable fuel, liquid and gaseous from not biologic origin for the transport[(UE) 2023/1184]
2. hydrogen must meet the life cycle GHG emission reduction requirement of 73,4 percent compared to a reference fossil fuel of 94 $grCO_{2equivalent}/MJ$ i.e., hydrogen involving less than 3 $tCO_{2equivalent}/t_{H2}$

For the green hydrogen production it's provided the maximum available incentives for the Renewable hydrogen produced:

- 5 $€/kg_{H2}$ if Power electrolyzer < 10 MW

- 4 €/kg$_{H2}$ if Power electrolyzer > 10 MW

These are the maximum incentives, in reality it's not sure that the company obtain this amount of incentive. Incentive it's recognized every week form the GSE (Gestore Sistemi Energetici) [14] for a period of 10 years From the date of commercial operation based on the effective amount of hydrogen sold to the final user. The formula for determining the incentive will also take into account the value of guarantee of origin [20].

Incentives for the HRS

The incentives are announced by the Minister of (Ministero delle Infrastrutture e della mobilità sostenibile) in the content document [21]. The document is finalized to these election of the proposal for the realization of 40 HRS with renewable hydrogen for light an heavy duty vehicles with the aim to develop a experimental hydrogen on road transport. The maximum incentives for HRS s equal to 5.750.000 € up to a maximum of 50% of the total eligible costs. The eligible costs corresponds to a design , construction and installation of the infrastructure that provide only renewable hydrogen for the vehicles, these costs can include.

- infrastructure cost for the fueling
- installation or improvement of electric components, compressors, transformers necessary to link the refueling infrastructure at a local unit of hydrogen production
- technical equipment
- civil engineering works
- adaptation of land and roads.
- installation costs
- permitting costs.

On these costs are excluded the local unit of H2 production, as electrolyzer. The project proposal to obtain the incentive is determined through the score attribution from 0 to 100 based on the followed criteria [21].

- transport scope of the project proposal with score from 0 to 35: they evaluate the volume of vehicles that the station can satisfy, consistency with M2C2 of PNRR part and the presence of link with TEN-T Europe corridors.
- supply chain scope of the project proposal with score form 0 to 15: they evaluate the hydrogen production in the neighbour of the station.
- economic proposal score from 0 to 15
- sharing the project proposal with the territory 0 to 15:

- Environmental impact, score from 0 to 20: the The maturity and sustainability of the proposed project, with specific regard to the aspects of environmental, transportation, energy, technical-operational, safety and economic-management.

The project proposal meet almost the overall request, therefore it's plausible to achieve a great amount of the incentive close to the maximum amount.

1.3.1 Sizing

The sizing components concerns the three main components:

- Dedicated PV plant for renewable electricity production available for the electrolyzer.

- AEK/PEM water electrolyzer for green Hydrogen production.

- Volume of hydrogen high pressure Vessel storage, the only component of the station

Other station components and equipment as: valves, controllers, coolers, compressors and other auxiliary devices are not considered in the sizing and also in the economic calculations. In order to obtain a final LCOH at pump, the prices that user pay to get hydrogen for the vehcile, the costs and the energy required of the other components must be considered. The main energy required device is the compressor and it account for almost half of the station components (1.7).

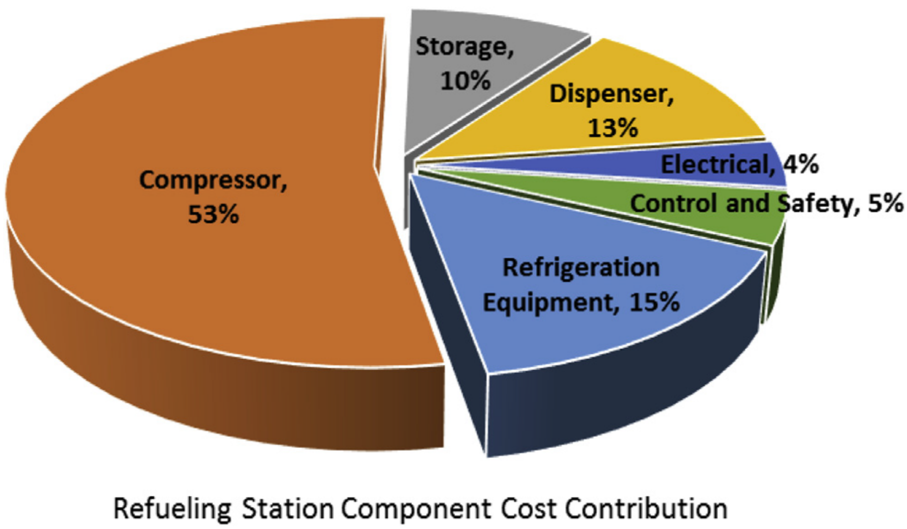

Figure 1.7: Costs share for different HRS devices

The size of the three main components are related, they are tuned in order to find the best design from an economic point of view, also different scenario will be proposed to satisfy the yearly demand.

1.3.2 HRS Design

In this section is explained the main possible HRS configurations. The hydrogen used for the refueling of the FCEVs is provided by a dedicated station, there are different size and configurations. The station size depends by the daily hydrogen provided for the vehicle's fueling. It's used a daily demand of 1035 kg_H2. The total hydrogen produced by the station is green hydrogen.

Different HRS design

Liquid HRS

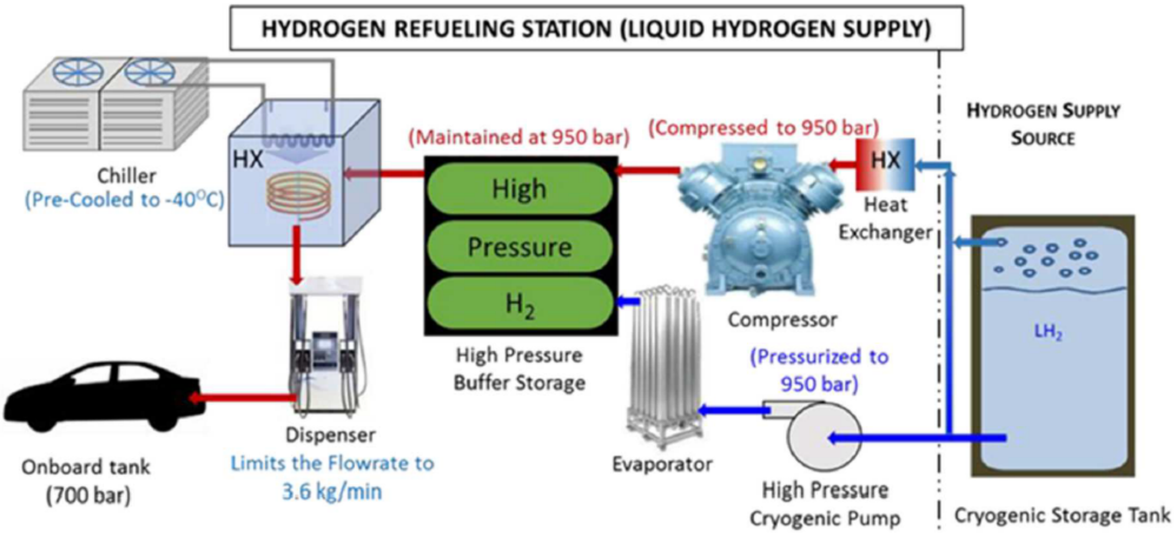

Figure 1.8: HRS liquid H2 supply [13]

In figure (1.8) are showed the main liquid station components, pressures and temperatures. In this case the station is fed with liquid hydrogen coming with trucks from facility. The liquid H2 allows to transport more amount of hydrogen from the facility to the station with less travels for the trucks. It is an advantage but on the other side it's needed much more energy to liquefy H2 than compress and transport in gaseous form to the station. The choice between this two methods depends on transportation costs and also making the consideration that in most of the cases the trucks vehicles that transport hydrogen(liquid or compressed) are not xEVs but they are fueled with gasoline or diesel. If we are focusing on green H2 production to reduce the emission and to get the incentives this aspect have also to be consider. Once liquid hydrogen comes to the station it is placed on Cryogenic Storage Tank, then there are are possible two ways to takes it to high pressure storage:

- liquid hydrogen passes through and Heat Exchange to bring H2 in gaseous form, than it's compressed to 950 bar with multiple compression stages, in figure (1.8) is present one volumetric compressor.

- the liquid hydrogen is compressed to the final pressure buffer(in this case 950 bar) and than at high pressure with an evaporator the hydrogen passes in gaseous form and it's stored in High Pressure Buffer Storage.

The choice of one depend from an energetic and economic evaluation. in the first case the gaseous compressor is the equipment that require the higher amount of energy, due the fact that gas compression, require more compression energy than a liquid. On the other side in the second case the cryogenic pump is more expensive and the evaporator components have to withstand at very high pressure during the heat exchange. The hydrogen stands at very high pressure due the fact that the FCV (Fuel Cell Vehicle) refueling is done by the pressure difference between the High Pressure Storage and the vehicle tank. When the vehicle comes for the fueling, the dispenser makes in communication the High Pressure Storage vessel and the vehicle tank allowing hydrogen flow thanks to the pressure difference. there are other two main equipment: the control valve that regulate the hydrogen flow and in case of problems during the charge it arrest the flowing. When hydrogen flows and expand through the valves passing quickly form high pressure to low pressure in the vehicle's tank there is a suddenly temperature rise effect due to the Joule Thompson effect [17].

When a gas expand through a valve reducing the pressure , there is also the temperature increase effect, H2 show the exactly opposite behaviour respect the other, when H2 expands through the valve the temperature increase. Before H2 enters in the vehicles tank it must be cooled down to -40 °C to assure that in the vehicle tank the hydrogen temperature does not exceed the 85 °C for safety reason. In figure is showed the vehicle charge, the charge depends by the APRR(Average Pressure Ramp Rate) it indicate the pressure rise for each second. Paying attention on temperature it's possible to see that hydrogen is cooled up (-40 °C) during all the fueling time (Temperature at Receptacle[C]), instead the temperature in the vehicle tank is higher, the red curve(Vehicle Tank Temperature [°[C]), at the fueling beginning the temperature in the charge is at ambient temperature (°C) then when hydrogen flows, even it comes to very low temperature it's at high pressure and it mixes with hydrogen just present in the tank, this is the reason why filling vehicle tank vessel , even whit H2 at -40°C, the temperature rise but with a lower slope then the first seconds. it's important that at the end of fueling the temperature limit of 85°C is not reached; If the hydrogen cooling had not been the limit will be exceeded, cooling H2 at so low temperature require higher amount of energy by the cooler but it's necessary [16].

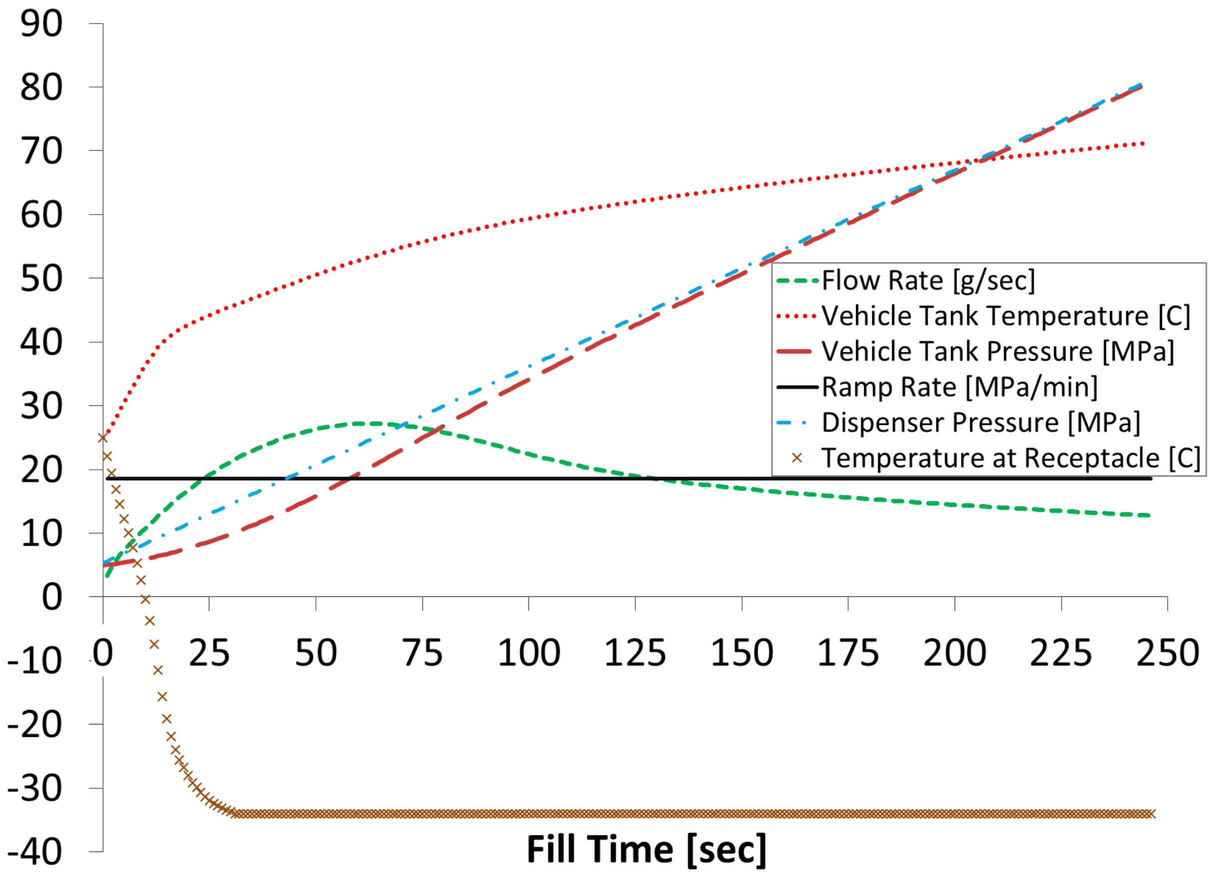

Figure 1.9: Vehicle charge [13]

Gaseous HRS

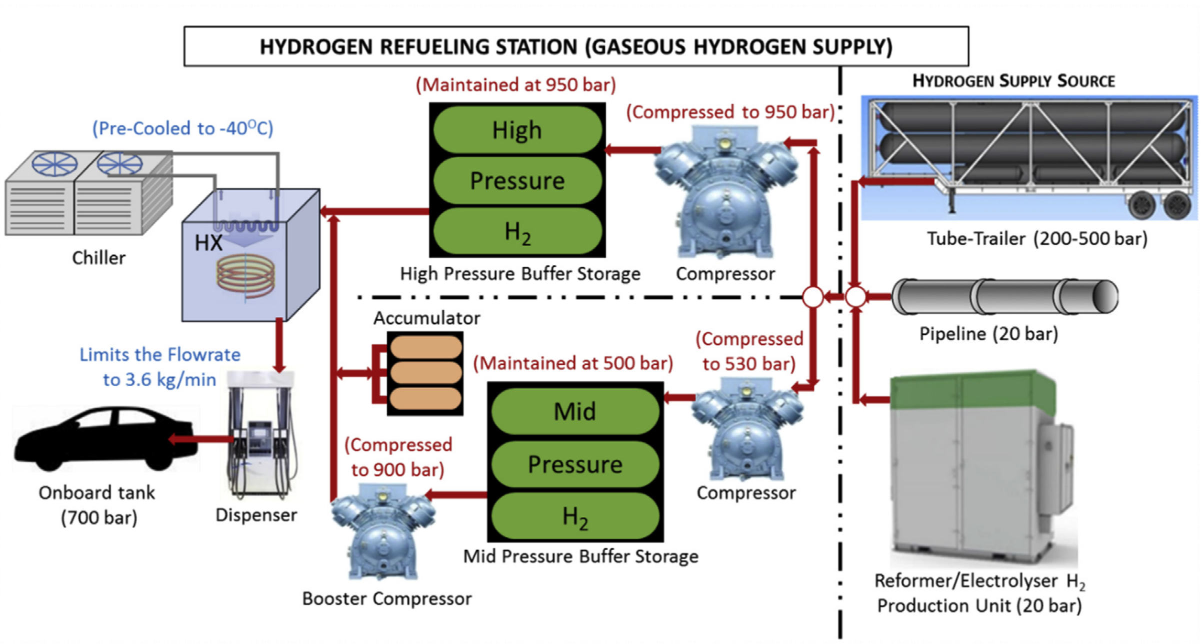

Figure 1.10: HRS gaseous supply [13]

(1.10) The gaseous HRS design is similar to the liquid configuration, the main differences are in hydrogen input to the station. there are three possible way

- Tube-trailer: hydrogen is transported to the station with trucks, similar in the liquid case, and it's compressed up to 200 bar. As said before to send the same amount of hydrogen to station the gaseous truck makes more travels than the H2 liquid. The advantage for the station is that H2 is just at high pressure level 200 bar, so lower compression energy by the station, and the vessel on truck behaves as additional storage.

- gaseous H_2 coming from Pipeline at 20 bar: this scenario is less frequent and it's present in the area where there is just a developed demand for hydrogen due the reason that the pipeline infrastructure must be present and it has to be linked with the facility where H_2 is produced. the main advantage is the supply whenever the HRS need to satisfy the demand. Comparing with the tube-trailer case, the trucks before to return to the facility to recharge the vessel it attend that the overall vessels are empty and it could be possible situation in which the demand cannot be satisfied.

- Local production with ElcetrolyerSteam Methane reforming produced at 20 bar: the local hydrogen production is clever for satisfy on time the demand. the local production can be done with the electrolyzer or Steam methane reforming, in both case these technology need an external source to produce hydrogen, electricity for the electrolyzer and methane for SMR (Steam Methane Reforming). In most of the cases the hydrogen is produced with SMR(95% of the overall world production) but it's not green so it's not considered in this work. the electrolyzer produces with no emission but to assure the green H_2 production the electricity must be renewable, otherwise Hydrogen is not green. One issue is that the electricity coming form national gird is not considered renewable so the electricity have to come from a renewable plant.

Even if the electrolyzer SMR (Steam Methane Reforming) are near the station for the local production they are not considered as HRS equipment. Then there are two possible way , depending by the input H_2 pressure level, if the hydrogen input is at good pressure level(es: 200-500 bar with trucks) only one compressor takes the hydrogen in the High Pressure Buffer storage, in the figure is represented 950 bar but it be can also at lower level. If the H2 input is a lower pressure level it's compressed and stored in a medium Pressure Buffer Storage, (in figure 500 bar but depends by pressure level), in this second way the h2 is stored in a lower pressure level, the advantage to store H_2 at lower pressure level is the lower stress material of the vessel. When there is the demand the Hydrogen is compressed to higher pressure level with Booster Compressor, cooled in the Chiller and provided to the vehicles through the dispenser.

In the two figures are showed the main components that allow the station operation and they are the equipment required more energy. Auxiliary components as valves , controllers, safety devices are not showed and there is not information regarding the equipment disposal and the space occupied.

1.3.3 PEM/AEK

Electrolyzer

Electrolyzer technology uses electricity to make water split reaction

$$H_2O + \text{energy} \longrightarrow H_2 + O_2$$

Hydrogen produced must be purified and separated by the Oxygen molecules present as products of reaction. The electrolyzer is composed by the stack cell stack and other auxiliary components to allow its operation. The stack is composed by many cells in series to increase the current absorbed, more cell are placed in series and higher will be the Power absorbedprovided. The electrolyzer/fuel cell is a reversible machine, it provides power using hydrogen as a fuel and in this case it behaves as Fuel Cell, or when it absorb electric Power to produce H2 it behaves as electrolyzer. in figure (1.11) it's expressed the electrolyzer VI curve corresponding to the power needed to produce hydrogen [18]. The electrolyzer operation curve depends by the temperature of the cell and also the pressure. Lower the curve and lower will be the Power absorbed by the cell stack to produce hydrogen. VI curve shows 3 different behaviour associated to three different phenomena: Activation Potential, Ohmic Potential and Concentration Overpotential:

- Activation Overpotential:this range zone is from the OCV (Open Cell Voltage) to the begin of the straight line. OCV correspond to the condition of zero current and the voltage is equal to the minimum voltage needed to trigger the reaction, for the water split reaction is the OCV 1,23 Volt. In this zone increasing the Voltage there is low current production and so low power, the main problem regards the kinetic reaction and molecules the mass transfer.

- Ohmic Overpotential: in the central zone the relation between the Voltage and the Current is linear in this zone the main phenomena concerns the charge migration.

- Concentration Overpotential: this is a saturation zone when increasing the voltage the current increase is very low due to the mass transport phenomena.

The best operation region for the electrolyer operation is in the Ohimc zone where the current voltage relation is linear, so especially in dynamic situation when the power absorbed change in time depending on the H2 demand it represent the best zone, the other extreme zone are not optimal to work for the inefficiencies previously described. Looking always the figure (1.11) in order to absorb the maximum input power it tends to work in the Ohmic zone closer as a possible to the Concentration Overpotential to maximize the product(Voltage $\cdot$ Current). It's true if we consider only the stack cell but there are the auxiliary equipment that also require electric energy, and the consideration change[18].

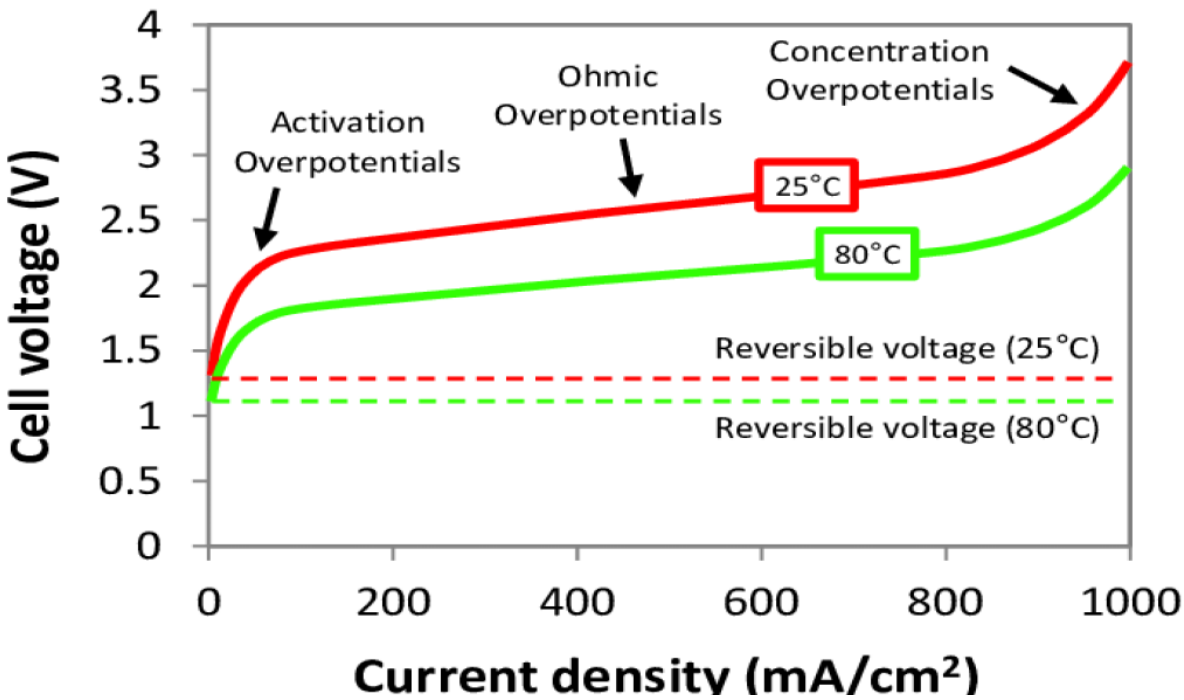

Figure 1.11: VI curve electrolyzer [18]

Increasing the Power absorbed by the cell, so moving upside along the Ohmic straight curve, the cell stack power increase but also the Power absorbed by the auxiliary components increase and the effective electric power coming to the cell stack is lower then the expected, due this it's convenient to work at lower current. In the (1.12) is represented the efficiency curve in function of the Power input needed for the stack and also for the auxiliary components. From a point of view of the cell efficiency (how much hydrogen produce respect the Power input) is convenient at low current, taking into account also the power required by the auxiliary components the efficiency decreases and also in this case the maximum System efficiency is at low current but considering the ohmic zone the system efficiency does not decrease too much but it's in a range efficiency of 0,55 and 0,6.

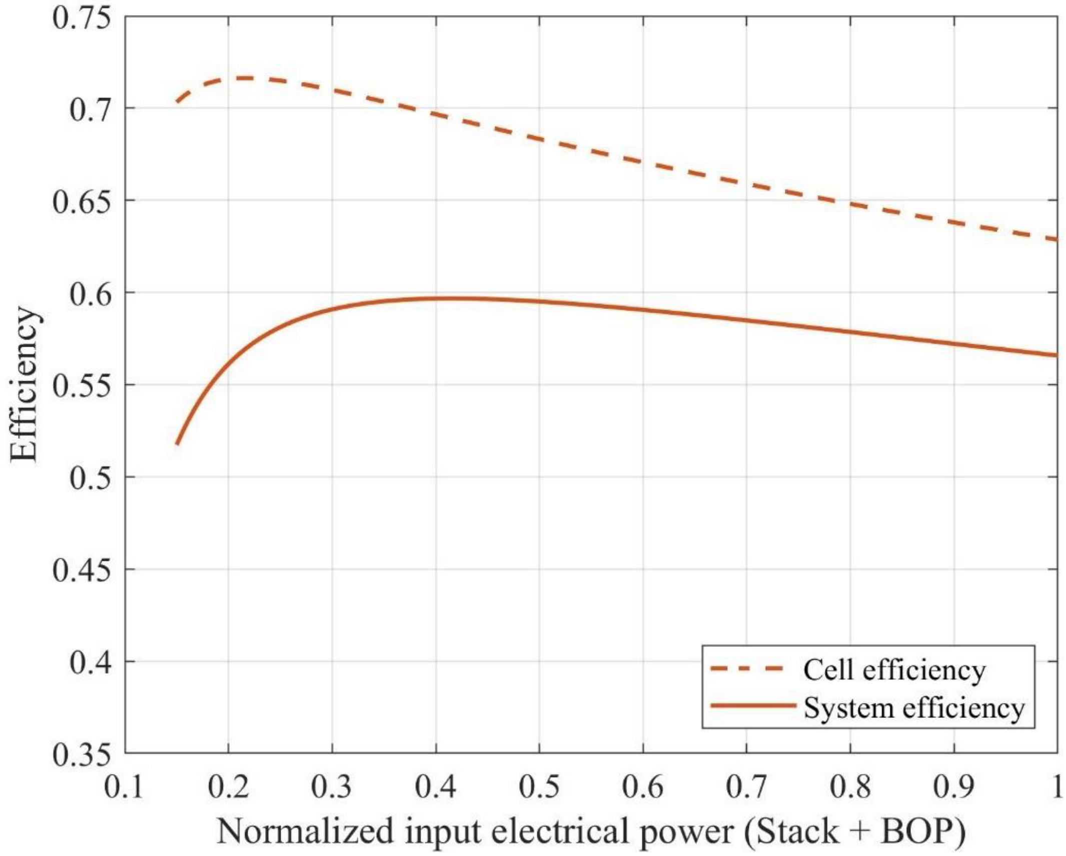

Figure 1.12: Cell and system efficiency [18]

The power required by the elctrolyzer system is not the cell stack power required but the overall system. In this work is not considered a dynamic electrolyzer behaviour but are assumed fixed efficiency values for the stack and auxiliary components, bot for PEM and AEK water electrolyzer (1.1).

Table 1.1: Efficiency Assumption

η_{BoP}	90 %
$\eta_{\text{cell stack}}$	75 %

Overall electrolyzer efficiency equation:

$$\eta_{Electrolyzer} = \eta_{BoP} \cdot \eta_{cellstack} = 0{,}675 \tag{1.2}$$

PEMWE

In the PEMWE (PEM Water Electrolyzer) happen similar reaction as in the AEK, what change is the type of molecule passing through the membrane. (HER) Hydrogen Evolution Reaction at the Cathode:

$$2\,H^+ + 2\,e^- \longrightarrow H_2(g)$$

(OER) Oxygen Evolution reaction at the Anode:

$$H_2O\,(l) \longrightarrow 2\,H^+ + 2\,e^- + \tfrac{1}{2}O_2\,(g)$$

In figure (1.13) is represented the overall water split process, H_2O enter on anode side and it's absorbed on the Anode porous bed where Happen the OER . One water molecule produce 2 cation hydrogen $2H^+$ 1/2 O_2 and 2 electrons $2e^-$ they pass through an external resistance and goes on cathode side where encounter the $2H^+$ passed through the membrane, they make the reaction $2\,H^+ + 2\,e^- \longrightarrow 2\,H_2$ forming h2 that exit form the cathode. the membrane used is called Nafion and it allow the transportation of H^+. Nafion to work properly need the needs the right level of hydration while being careful to not much water avoiding the flooding.

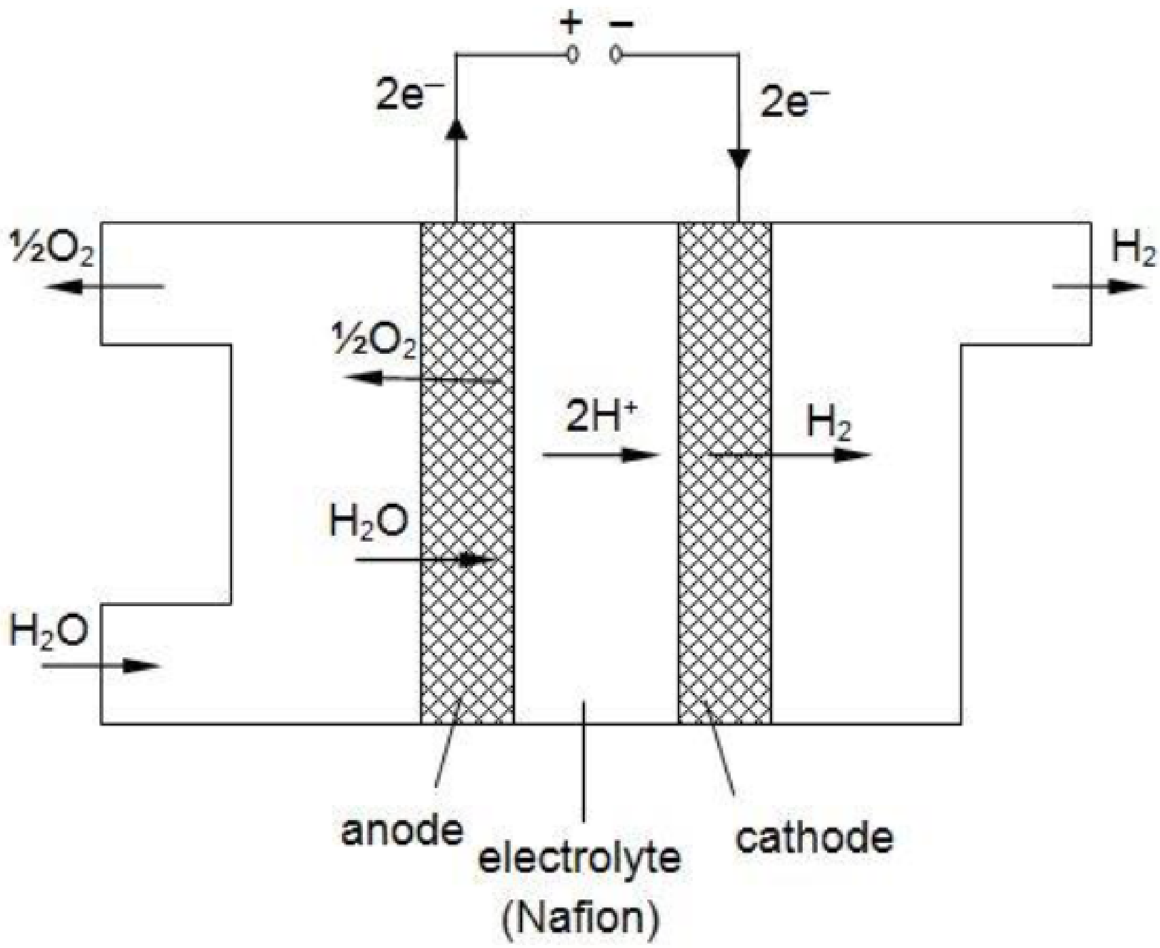

Figure 1.13: PEM electrolyzer [18]

As said before the cells stack is only a single part of the entire electrolyzer system, there are other auxiliary components to assure electrolyzer properly work:

- water purification system: the water coming in the anode side must by demi-water without presence of other ions, they can interfere with the absorption process in the anode
- Pressure and temperature sensor.

- O_2 purified section: the Oxygen in not pure but need to be purified to obtain pure O2.
- H_2 purified section: the H2 flowing from the cathode can contain traces of impurities of Oxygen , so it must be properly removed.

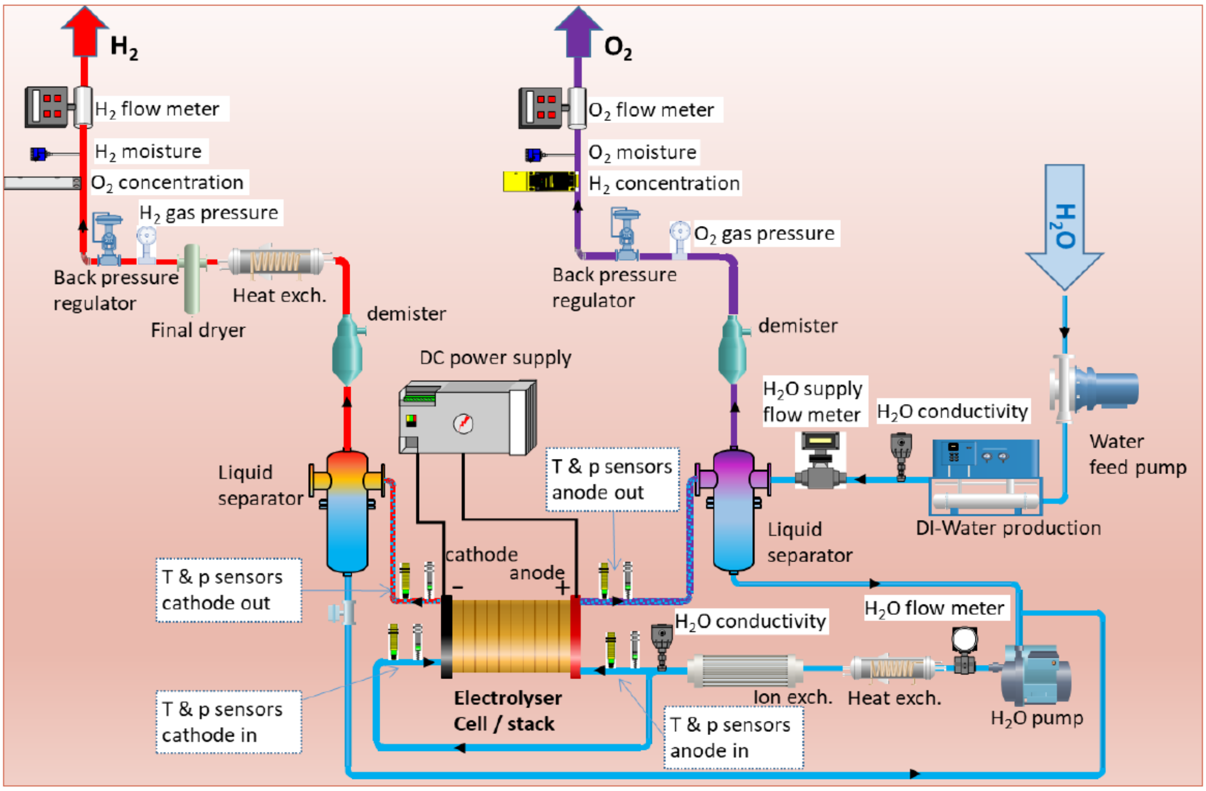

Figure 1.14: PEM BoP ([18])

AEKWE

In the AEKWE (Alkaline Water Electrolyzer) the reactions are different and also is different the ion passing through the membrane(diaphragm). The reactions at the two side are. (HER)Hydrogen Evolution reaction at the Cathode:

$$2\,H_2O\,(l) + 2\,e^- \longrightarrow H_2(g) + 2\,HO^-(l)$$

(OER) Oxygen Evolution Reaction at the Anode:

$$2\,HO^-(aq) \longrightarrow H_2O\,(l) + \tfrac{1}{2}O_2\,(g) + 2\,e^-$$

In figure (1.15) is visible the process, H_20 enter from the cathode downside and with the 2 electrons coming form the external resistance it produce H_2 and $2OH^-$. The OH- passing through the Diaphragm reaching the anode side and make the OER.

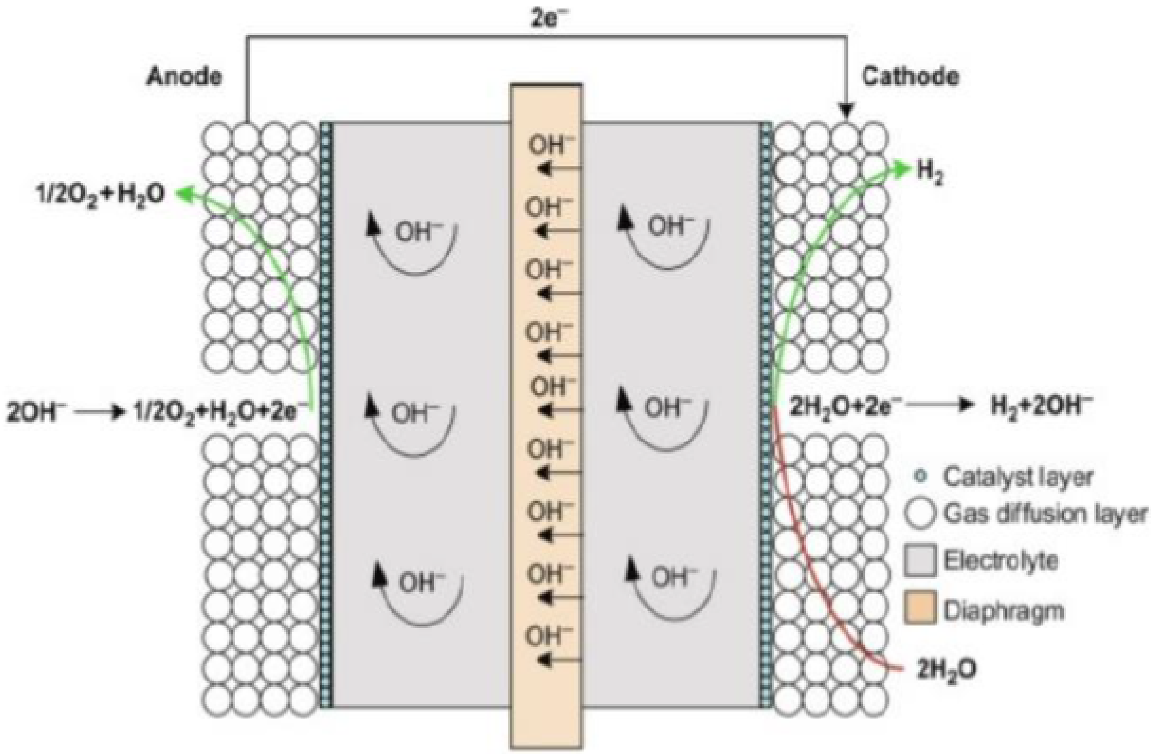

Figure 1.15: AEK electrolyzer [[18]]

As for the PEM electrolyzer also the AEK is formed by many other auxiliary components, figure (1.15), there is another part the electrolyte solution of KOH or NaOH it's provided in the stack and it also need to be purified and recirculated.

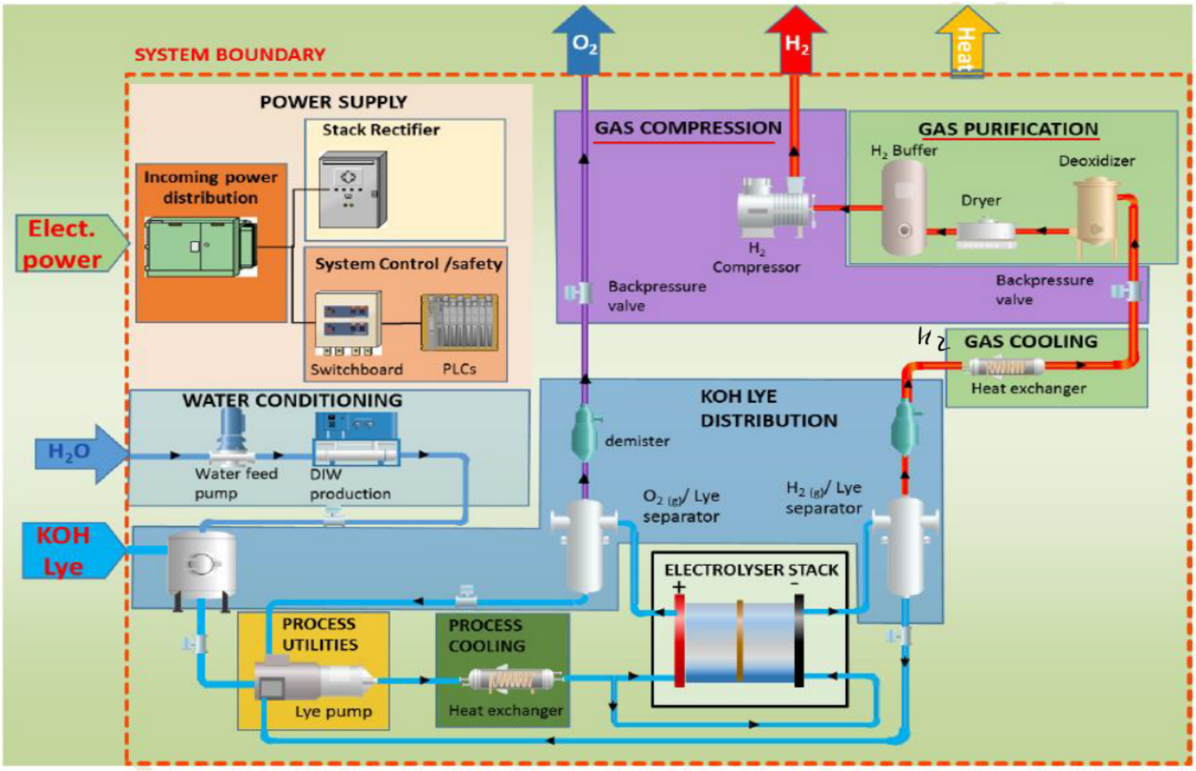

Figure 1.16: AEK BoP ([18])

Comparison PEM and AEk Water electrolyzer

In this table are analyzed the main differences between the two different :

Table 1.2: Electrolyzer Specifications [18]

Electrolyzer type	PEM	AEK
Charger carrier	H+	OH-
Reactant	Liquid water	Liquid water
Electrolyte	Proton exchange membrane	NaOH or KOH
Anode Electrode	IrO_2	CO_3O_4
Cathode Electrode	PtC	Ni, Co, Cu, NiCu
Current Density	$0.2\,A\,cm^{-2}$ to $0.8\,A\,cm^{-2}$	$0.2\,A\,cm^{-2}$ to $2.5\,A\,cm^{-2}$
Temperature	20 °C to 90 °C	40 °C to 90 °C
Cathode Reaction	$2\,H^+ + 2\,e^- \longrightarrow H_2(g)$	$2\,H_2O\,(l) + 2\,e^- \longrightarrow H_2(g) + 2\,HO^-\,(l)$
Anode Reaction	$H_2O\,(l) \longrightarrow 2\,H^+ + 2\,e^- + \frac{1}{2}O_2\,(g)$	$2\,HO^-\,(aq) \longrightarrow H_2O\,(l) + \frac{1}{2}O_2\,(g) + 2\,e^-$

Both of them are coupled with the renewable energy source due their capability to work in dynamic conditions. PEMWE is very versatile with renewable (photovoltaic and wind) and it can work until to the 5% of its nominal power, instead AEKWE can work until the 20% of its nominal power due to structural problem. If AEKWE work at very low current could be a issue related with the cross molecule membrane that damage the diaphragm reducing the performances and the lifetime.

1.3.4 Vessel

The storage vessel is the only equipment analyzed of the HRS. Vessel storage has two function: contain the high pressure hydrogen and to store the H_2 decoupling the time of production respect the time of demand. The green H_2 production is linked to the power coming from PV plant so in period of time with high presence of solar irradiation I have to push as much as a possible the production to afford the demand in the periods of no solar irradiance.

Table 1.3: Tank Specifications

Tank type	Max pressure (bar)	Construction
Type I	< 500	All-metal cylinder
Type II	-	OH-r
Type III	< 450	Load-bearing metal liner, hoop wrapped with resin-impregnated continuous filament
Type IV	< 1000	No-loadbearing, non metal liner, axial and hoop wrapped with resin-impregnated continuous filament

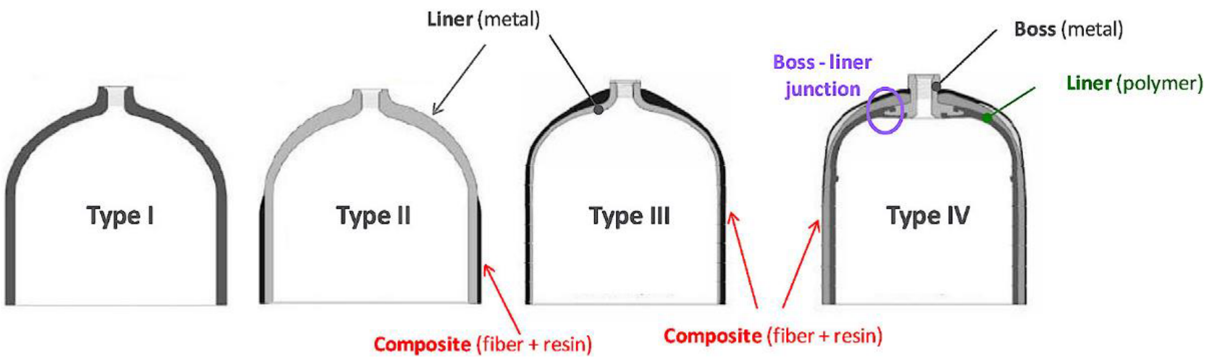

Figure 1.17: different type vessel storage [10]

Different tank types are used for distinct purposes mainly due to their cost and mass storage efficiency. Type I tanks are used for industrial applications due to lower cost and mass storage efficiency. For hydrogen vessel storage in station is used type IV to support the maximal pressure.in own case it's assumed only one tank with hydrogen stored at 950 bar. For a safety reason the maximal available pressure in the tank is 1000 bar, it has been decide to reach to high pressure(950 bar) to store more hydrogen in a lower volume and to make possible more charge of HDFCEV. In the vessel 950 bar are reached when the it's full, when the hydrogen is drained form storage the H_2 content decrease and even if the compressor take H_2 at 950 bar when gaseous H_2 enter in the storage vessel it tends to fill the overall tank volume, if there is low amount of hydrogen the result will be lower pressure than 950 bar.

Chapter 2

Methodology

2.1 Heavy Duty Vehicles

A vehicle is classified ad heavy-duty if it has a gross vehicle weight rating(GVWR) greater than 26000 lbs. GVWR is the maximum loaded weight of vehicle which is the weight of the vehicle in addition to its payload [9]. HDFCEVs(heavy Duty Fuel Cell Electric Vehicles) use the fuel cell power train , it consists of fuel cell that convert the chemical energy of hydrogen into electricity heat and water, there is also a battery for many purpose as:

- fuel cell start-up.
- capture regenerative breaking energy.
- provide extra power during accelerations.
- help in low speed production when fuel cell work in low efficiency region.

there is also the possibility to add the ultracapacitor instead of battery, or ultracapacitor and batteries. In figure (2.1) there a scheme of the HDFCEV with the arrangement of the Power train and the hydrogen tanks. Hydrogen tank are placed in vertical position below the driver's cabins instead the fuel cell and the battery are placed in the bottom section.

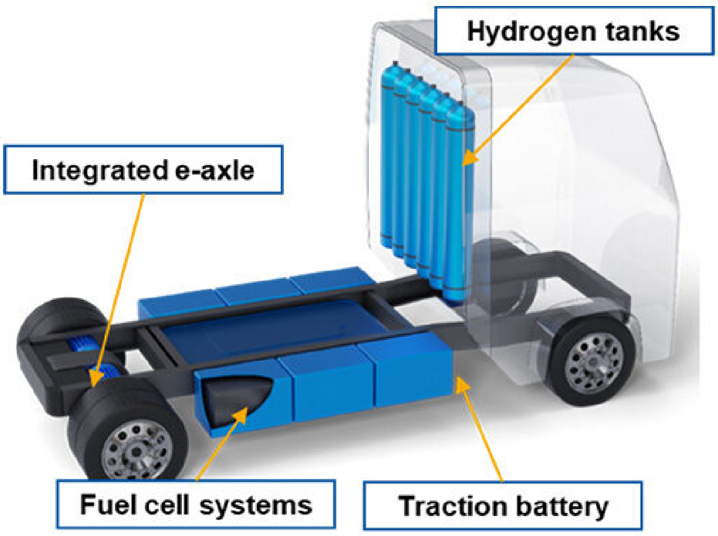

Figure 2.1: HDFCEV scheme [23]

It's assumed that every HDFCEVs coming to the station make a full vessel charge of 45 kg$_{H2}$ at final pressure of 700 bar , allowing a range of 600 km[[15]], there are also some Heavy duty with final pressure of 350 bar. Instead light duty vehicles admit only 700 bar as final pressure. The dispensers allow 350 bar and 700 bar so the station can be versatile for the light and heavy duty vehicles.

considering the previous plot of daily distribution demand, the plot is discretized for the HDFCEV demand.

- 0 kg$_{H2}$ no demand to the station
- 45 kg$_{H2}$ means that in 1 hour arrive at the station 1 HDFCEVs for a full charge
- 90 kg$_{H2}$ means that in 1 hour arrive at the station 2 HDFCEVs for a full charge

In real scenario the HDFCEVs does not arrive to the Station with no more hydrogen in the tank, but there is a minimum residual quantity, also for a safety the protocol for refueling allow the HDFCEV charging with only 5 pressure bar on the vehicle vessel fuel tank([23]). The curve is fitted emulating the heavy duty behaviour, the truck driver stop to the station in the last hours of the days for rest and at the same time make the refuel. This explain the difference respect the demand curve that in the last hours of the day have lower demand.

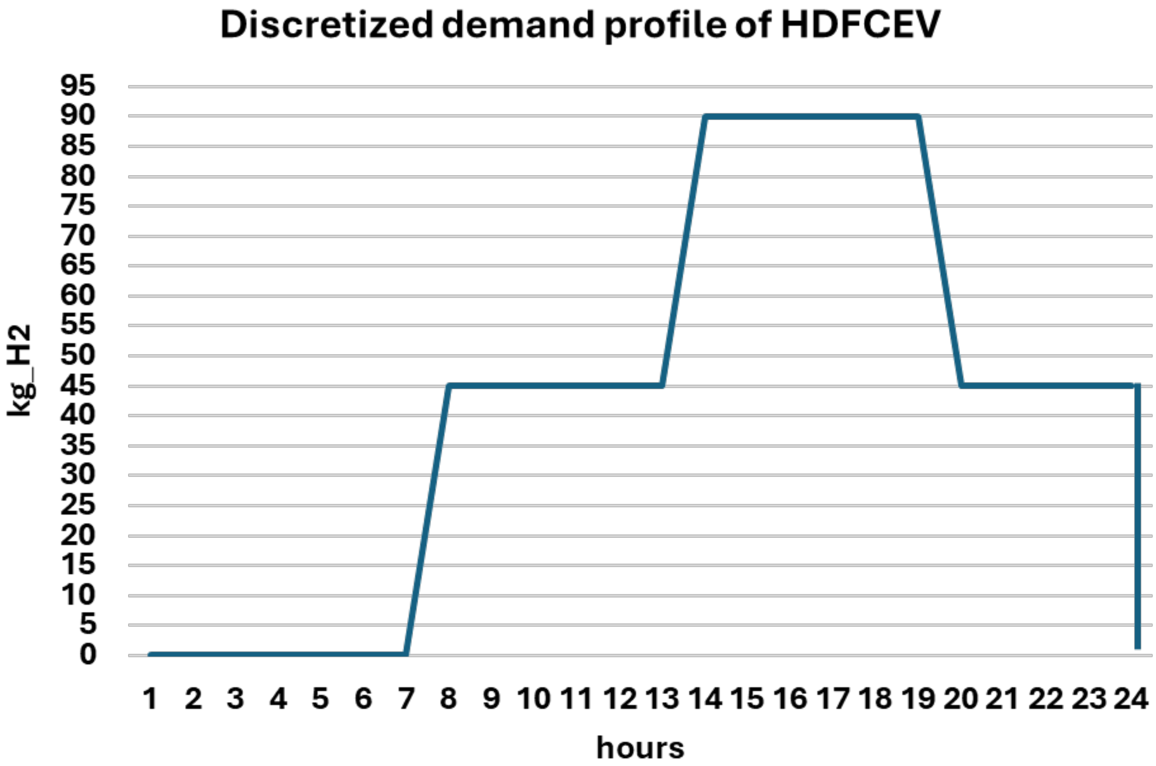

Figure 2.2: Discretized demand

Size of HRS are of many type depending on daily hydrogen amount dispensed(small 200 kg_{H2}, medium 400 kg H2, large 1000kg_{H2}, X-large 4000 kg_{H2}). The small stations have limited economic viability,[3] larger is the station and lower is the time to cover the investment due to economic of scale. The station size is assumed to be large dimension, 1000 kg_{H2} a day, consider the frequency distribution and the number of vehicles 23 HDFCV in a day each one need 45 kg_{H2} so in total the station provide 1035 kg_{H2}day. Last assumption is that the station works for all the 365 days of the year, so in one year the station provide 377.775 kg of green H2.

2.2 Design HRS

2.3 Other components

Photovoltaic Plant

For green h2 production the electrolyser gets the electric power from a dedicated Photovoltaic Plant. In most of the HRS with local production through the electrolyser is linked with the National grid for the production. Unlucky the electricity taken from the national grid is not considered renewable. As mentioned, emission limit to consider the H2 as green or renewable is equivalent to 3 kg of CO_2 equivalent for each kilogram of H2 produced [20].

PVGIS

PVGIS software is used to obtain data, choosing a place in the National territory it provides the data [1]. In figure is showed the place where the data are provided, the locality is near Fidenza (PR), it's a place to build a possible station and PV plant due the fact that:

- near there is the highway A1 with a very huge vehicles number passing in a year
- the surrounding area is flat so it could be possible the PV plant construction

This is are a simplified reason to choose the place, to decide where to build the station and the PV plant there must be careful analysis considering the flows of HDV and their routes, and the availability to build the HRS and the PV plant if the construction permits allow the construction and also the acceptance of local population for this new technology (2.3).

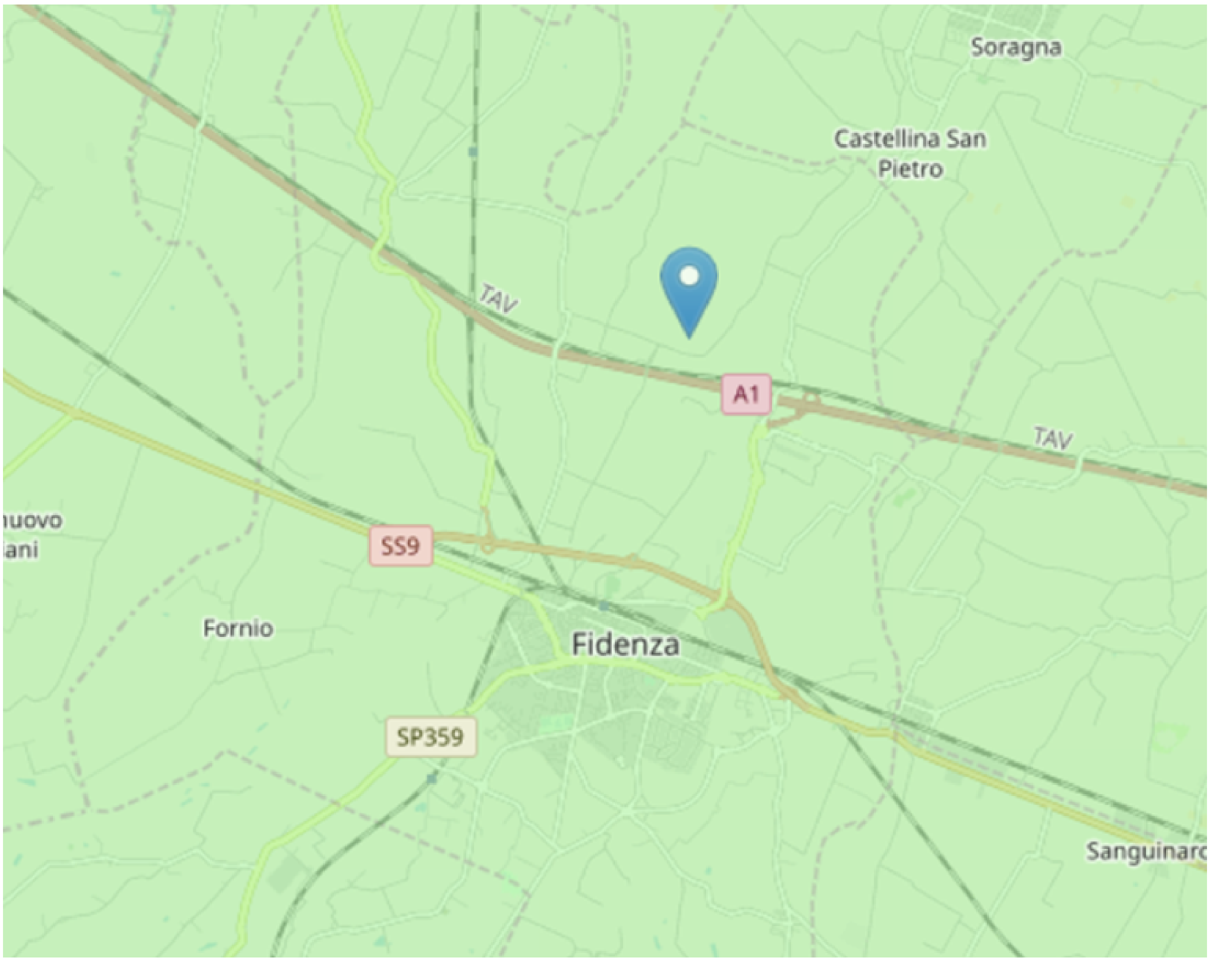

Figure 2.3: PVGIS Fidenza [1]

data provided by PVGIS are based on TMY (Tipical Meteorological Years) it's a data average regarding the last 15 years, this allow to make a very precise analysis respect the data regarding one year. PVGIS provides data for 8760 hours in one year of :

- Solar Irradiance G_H on horizontal plane to the surface. This irradiance is used for module with constant inclination without tracking the sun position, in that case it's better to get the the normal irradiance G_n
- ambient temperature

the two data are essential to obtain the cell temperature of the module and the Power Output provided by the module.

Cell temperature:

$$T_{\text{cell}} = T_{\text{ambient}} + (\text{NOCT} - 20°C) \cdot \left(\frac{G_H}{800\,\text{W/m}^2}\right) \tag{2.1}$$

NOCT(Normal Operation Cell Temperature), it's a data provided by the manufacture, it express the equilibrium cell temperature obtained in the following conditions:

- Solar irradiance = $800\,\text{W/m}^2$
- Ambient temperature = 20°C
- Wind speed = 1 m/s
- Air mass (AM) = 1,5

Power obtained by the Photovoltaic plant:

$$P_{PV} = P_{design} \cdot (\frac{G_H}{G_{Stc}}) \cdot [1 - \lambda \cdot (T_{cell} - 25°C)] \tag{2.2}$$

PV power provided to the electrolyzer considering transmission losses:

$$Power_{output_PV} = P_{PV} \cdot (1 - losses) \tag{2.3}$$

the transmission losses is a data output of PVGIS software equal to 14%. [1]

thermal power coefficient λ(%/°C), lower it's the coefficient and higher will be the Power obtained from the module. (STC)Standard test condition are different respect the NOCT conditions:

- solar irradiance = 100 W/m^2
- ambient temperature = 25 °C
- wind speed= 1,5 ms
- (AM) Air mass= 1,5

the NOCT e λ are provided by the manufacturer depending by the module [5]. 95% of global installed PV module is made by mono cristalline silicon(mc-Si) and poly cristalline silicon (pc-Si). New advanced technologie are based on : Thin films technologies, peroskyte, alla blacks multilayer technologie, bifacial pannel. These new technologies show better performance but they have an higher cst and they are not so common. So the NOCT and λ are chosen with mono and poly cristalline silicon comparing top 5 manufacture

Rank	Solar cell production (GW)	PV module production (GW)	PV module shipment (GW)
1	Tongwei Solar (21.4)	LONGI Green Energy Technology (26.6)	LONGI Green Energy Technology (24.5)
2	LONGI Green Energy Technology (17.6)	Jinko Solar (17.6)	Jinko Solar (18.8)
3	Shanghai Aiko Solar Energy JA (13.3)	Trina Solar (16.4)	Trina Solar (15.9)
4	Solar Technology (11.3)	JA Solar Technology (14)	JA Solar Technology (15.9)
5	Jinko Solar (10)	Canadian Solar (11.4)	Canadian Solar (11.3)

Figure 2.4: Best PV manufacturer [5]

the values used are NOCt=45°C and λ=-0,35%

The costs used for the main components are obtained analysing making comparison between different papers, international agency, it's difficult to obtain the purchase cost of the components due the fact that the manufacturer provide it only in real in real purchase intention. So the costs are analysed and compared from different literature sources. For the conversion money has been used the value 1 \$= 0,948 €[7].

PV costs

Form the PV costs is considered the crystalline silicon technology, account for 95% of global PV module production. Of these, 80% are monocrystalline(mono-C-Si) modules and the remaining are polycrystalline (poly C-si) modules. Module efficiency are 24,4% for monocrystalline and 20,4% for polycrystalline. Other technology as multi-junction, all black technology, bifacil module technology reach higher efficiency but are more expensive and not so common used so they are not considered [5]. for PV panel cost are considered the module price, the inverter and the electrical component expressed in \$/W, they are converted in [€/W].

Table 2.1: PV Panel Price [19]

Components	\$/W	€/W
Module	0.34	0.323
Inverter	0.05	0.0475
Electrical Components	0.14	
Total	0.53	0.5

The final PV module price is rounder at 0,6 €/W. Consider these 3 component price(module, inverter,electrical components) it reflects the PV price in Italy only considered the hardware part,figure (2.5) the installation and the soft cost will be considered after in the CAPEX.

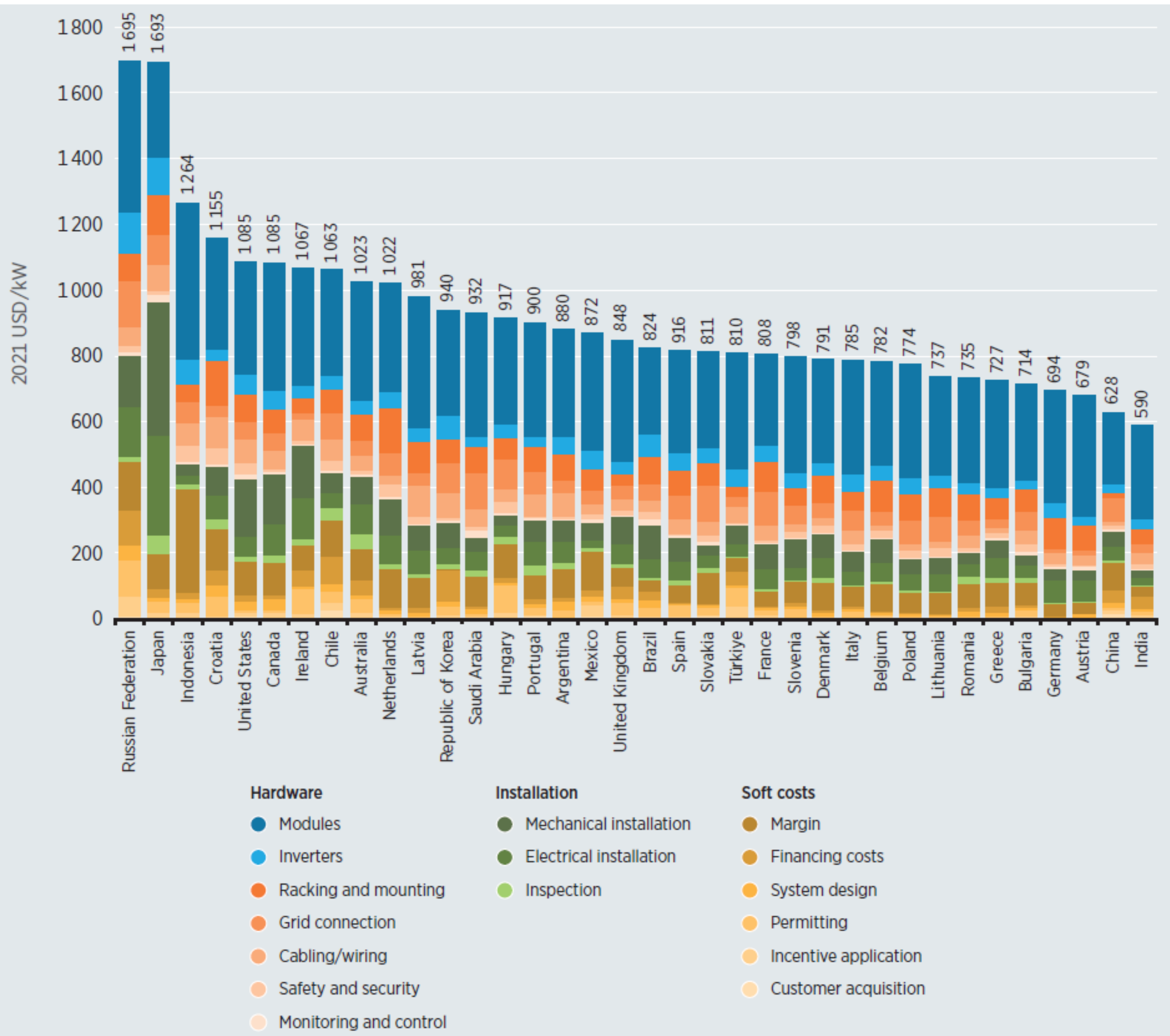

Figure 2.5: PV trend cost [5]

Electrolyzer costs

For the electrolyzer costs is taken the costs[5] expressed in \$ at 2020, AEK=1083 \$ and PEM=1176 , for the PEM the data projection are provided at 2017 and 2025, so it's done an average. For each year is estimated a price reduction for both technologies, λ express the percentage price reduction respect the previous year, λ_{PEM}=4,77% and λ_{AEK}=2,97% form the 2020 it's done a reduction until the 2023.

$$Price_i = Price_{2020} - (Price_{2020} - \lambda_j) \quad j = PEM, AEK \tag{2.4}$$

$$Price_{i+1} = Price_i - (Price_i - \lambda_j) \quad j = PEM, AEK \tag{2.5}$$

at 2023 the price obtained are converted from dollars to euro, 1\$=0,9,48 €, [7], obtaining the prices in table (2.2).

Table 2.2: Electrolyzer cost [6]

electrolyzer	0,6 [€/W]
PEM	963,80
AEK	938,42
Storage vessel	57344 [€/m^3]

Hydrogen vessel costs

Hydrogen storage vessel cost is obtained referred to a a pressure vessel at 950 bar, in figure (2.6) the Depart of energy indicate a cost of around 1000 \$ /kg$_{H2}$ compressed at 860 bar, consider that the vessel have to be a pressure of 950 bar it's considered a cost of 1200 €/kg$_{H2}$ [25]. To express the cost respect to the volume is used the hydrogen density at 950 bar, ρ_{H2}=47,78 m^3 cost volume storage vessel at 950 bar:

$$\text{cost}_{\text{storage}} = \rho_{\text{H2}} \cdot \text{hydrogen mass} \qquad [€/m^3] \tag{2.6}$$

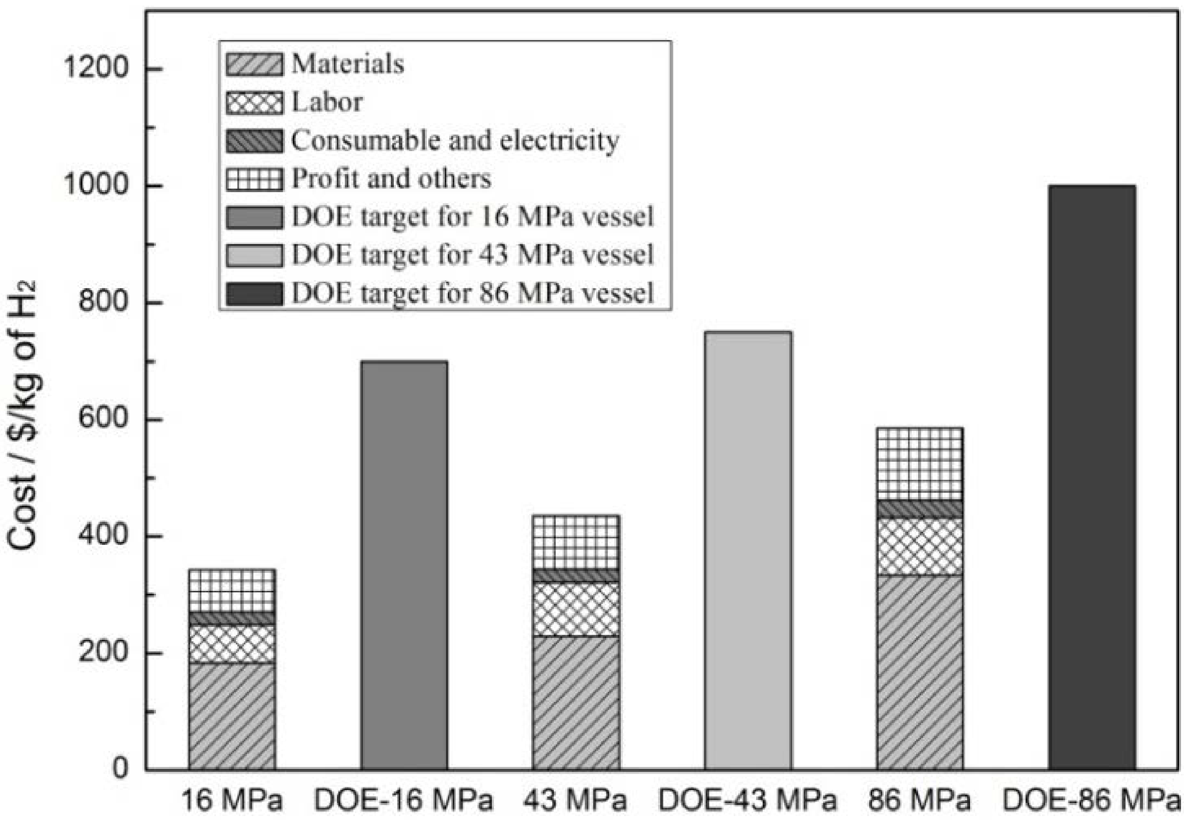

Figure 2.6: Storage Vessel costs ([25])

Summary of costs use for the analysis

Table 2.3: Summary of Base Erected Costs

PV cost	0,6 [€/W]
Electrolyzer [€/kW]	
PEM	963,80
AEK	938,42
Storage vessel	57344 [€/m^3]

2.4 Metrics

In order to evaluate the performances of the analysis there is the needs to measure the how the production of green hydrogen in different way, in this chapter will be introduced the KPI(Key Performance Indicator) to measure the demand satisfied in a year and the economic indicator the LCOH (Levelized Cost of Hydrogen).

KPI, Yearly Demand satisfied

The Key performance indicator used to measure in one year how much the yearly demand is satisfied. It express the number of hours in one year that the Storage is able to satisfy.

$$\text{Yearly demand satisfied} = \frac{\text{number of hours in which mass storage>minimum amount } H_2 \text{ in storage}}{8760h} \cdot 100\,\% \tag{2.7}$$

In any hour when the solar irradiance is too low to produce enough hydrogen for the demand and also the storage is not able to satisfy the demand , that specific hour is not counted in the metric and there will be not the 100% yearly demand satisfied.

Economic indicator, LCOH

Every project in order to be developed it must be economically viable. The economic indicator used is the Levelized cost of Hydrogen, it express the cost of 1 kg of green hydrogen produced.The costs considered are the overall plant cost, the CAPEX (Capital expenditure), and the OPEX(Operational Expenditure) during the all the lifetime project(assumed to be 20 years). the aim is to choose the design that minimize the LCOH, recalling that the LCOH obtained in this work is referred only to the three main components analyzed:

- PV plant
- Electrolyzer
- H2 vessel storage of HRS

The LCOH obtained it's not the LCOH at the pump, so the cost per kg of hydrogen that the costumer have to pay at the fueling because must be added the costs and consumption energy of: compressors, cooler, dispenser and other auxiliary components. These are not consider in this analysis due the fact that the station's equipment need energy also when there is not the solar irradiance but when there is the demand, so in a scenario where the only energy input it's the Electric Power provided by the PV plant it's difficult to consider also the energy for these remaining components. Thesis work is a possible start for possible improvement analysis.

WACC

It's the Weighted Average Capital costs formula it's the following

$$\text{WACC} = k_E(\frac{E}{E+D}) + (1-t_\alpha)k_D(\frac{D}{E+D}) \tag{2.8}$$

E(Equity) and D(Debt) they are complementary and express D the amount of debt that the private investor have to borrow by the bank or some financial institute, the Equity it's the remaining part that the private investor have to afford for the project. The HRS is considered an high risk projects so it's assumed Debt=60% and Equity=40% . t_α (tax shield) and it's available for the company [29] k_E is the cost of equity and it's calculated

$$k_E = R_F + (\beta \cdot EMPR) \tag{2.9}$$

- R_F=3,78% it's the Italy National bond at short term [26].
- β=1 it's the sensitivity and it's assumed equal to 1.
- (EMPR) Equity Market Risk Premium =7% it's the premium to invest in activity in Italy [11].

k_D is the cost of Debt and it's calculated as:

$$k_D = Spread + IRS20 \tag{2.10}$$

- Spread=1,726% it's obtained making the average spread months os the last 5 years [2].
- IRS20=2,623% it's obtained by the average months of IRS20 from 31/01/2023 to 02/01/2024 [28].

Exhibit 4-2 Financial structure for investor owned utility high and low risk projects

Type of Security	% of Total	Current (Nominal) Dollar Cost	Weighted Current (Nominal) Cost	After Tax Weighted Cost of Capital
LOW RISK				
Debt	50	4.5%	2.25%	
Equity	50	12%	6%	
Total			8.25%	7.39%
HIGH RISK				
Debt	45	5.5%	2.475%	
Equity	55	12%	6.6%	
Total			9.075%	8.13%

Exhibit 4-3 Financial structure for independent power producer high and low risk projects

Type of Security	% of Total	Current (Nominal) Dollar Cost	Weighted Current (Nominal) Cost	After Tax Weighted Cost of Capital
LOW RISK				
Debt	70	6.5%	4.55%	
Equity	30	20%	6%	
Total			10.55%	8.82%
HIGH RISK				
Debt	60	8.5%	5.1%	
Equity	40	20%	8.0%	
Total			13.1%	11.16%

Figure 2.7: Financial structure of investment

Tables summarize the COST ASSUMPTION, for the green H2 production form PV it's assumed the same cost for the wind source [8].

Table 2.4: GREEN H2 FORM OUTSIDE

SPECIFIC cost H2 from remote facility	10,21 [€/Kg$_{H2}$]
Green production	7,77 [€/Kg$_{H2}$]
Transportation	2,44 [€/Kg$_{H2}$]

Table 2.5: RENEWABLE ELECTRICITY FROM THE IGO

GREEN PPA	200 €/MWh

Table 2.6: MAXIMUM AVAILABLE INCENTIVES

INCENTIVES HRS	5.750.000 €
INCENTIVES FOR GREEN PRODUCTION, VALID FOR 10 YEARS	
ELECTROLYZER SIZE < 10 MW	5 [€/Kg$_{H2}$]
ELECTROLYZER SIZE > 10 MW	4 [€/Kg$_{H2}$]

Life time plant is assumed = 20 years. The PV module can work also for longer time, reaching also 30 years, electrolyzer also work for 20 years but it's different the lifetime cell stack depending by the working hours, in fact cell stack changed more times during electrolyzer lifetime. HRS on average work for 20 years as showed in figure (2.8). The plot show the investment vulnerability of HRS with a PBT (Pay Back Time) of 15 years, PBT indicate the time when the investment is repaid and it signs the time after that the investment is profitable with positive Net Present Value. At the beginning is necessary the public investment to push this technology, even this support during the years the CCF (Cumulative Cash flow) decrease reaching after around 10 year the so called " Death Valley" when the CCF follow to strong negative values. After this negative peak there is Cumulative cash flow increase that take the investment to cross the zero line and reach positive CCF. The reason why it's called the death valley is that when this period is passe the investment became positive with the yearly revenues higher then yearly cost.

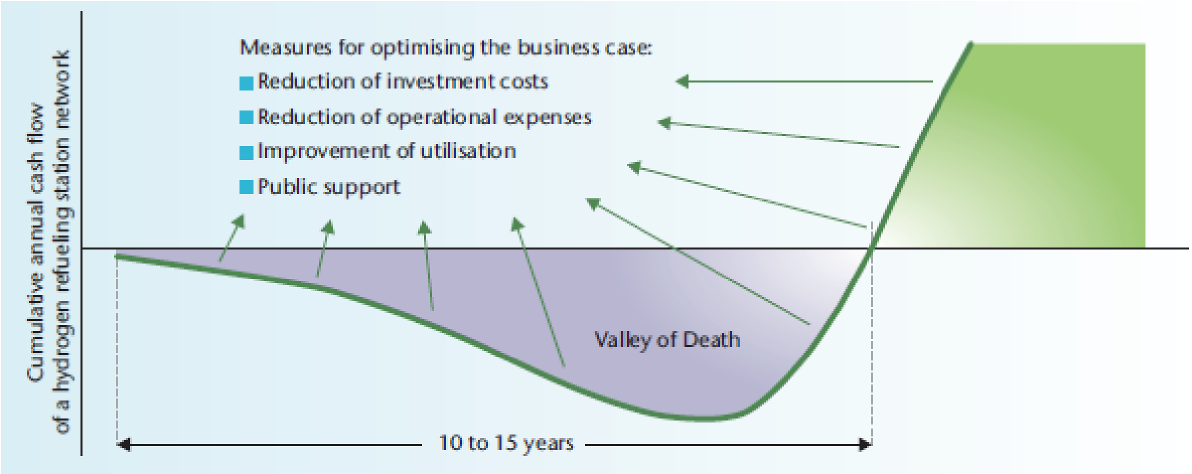

Figure 2.8: Investment time of HRS [12]

LCOH formula used:

$$\mathrm{LCOH} = \frac{\frac{\mathrm{CAPEX}}{\mathrm{capex\ partition}} + \sum_{k=1}^{10}(H_{\mathrm{incentive}_k})(1+\mathrm{wacc})^{-k} + \sum_{k=10}^{20}(H_{\mathrm{not\ incentive}_k})(1+\mathrm{wacc})^{k}}{mass_{\mathrm{H_2\ yearly\ demand}} \cdot \sum_{k=1}^{20}(1+\mathrm{wacc})^{-k}} \tag{2.11}$$

The OPEX are splitted in two parts, one with the incentives and the other without:

$$\mathrm{H}_{incentive_k} = \mathrm{OPEX}_{\mathrm{incentive}} + \mathrm{CAPEX}_{partition} + \mathrm{cost}_{stackreplace_j} \qquad j = 1 \ldots 10 \tag{2.12}$$

$$\mathrm{H}_{notincentive_k} = \mathrm{OPEX}_{\mathrm{incentive}} + \mathrm{CAPEX}_{partition} + \mathrm{cost}_{stackreplace_j} \qquad i = 10 \ldots 20 \tag{2.13}$$

In the OPEX costs it's also taking into account the stack replace cost, it depends by the number of electrolyzer working hours. For both AEKWE and PEMWE is assumed a cell stack lifetime of 50.000 hours [4]. The average stack lifetime is 8-9 years, so during the 20 lifetime plant , the cell stack is replaced twice, once in the first 10 years when the incentives are present and the other in the remaining 20 years without incentives. The index i refers to the years in which the cell stack need to be substituted in the first 10 years, the index j refers to the second substitution in the remaining 10 years.

$$CAPEX_{part} = \frac{number_{partitions} - 1}{number_{partitions} \cdot n_{plantlifetime}} \tag{2.14}$$

CAPEX calculation

The CAPEX is not formed only by the purchase equipment cost or base erected cost but we have to consider other parts, looking the image the CAPEX is formed by many parts.

- BEC(Bse Erected Costs) comprises the costs of process equipment, on-site facilities and infrastructure that support the plant, the direct and indirect labour cost for the installation

- EPPC (Engegneerig Procurement and Construction) consider BEC plus the cost of services provide by engineering, procurement and construction.The contractor include: detailed desing , contractor permitting and project/construction management costs. it's expressed as a percentage of the BEC, around 8% of BEC

- TPC(Total Plant cost) consider EPCC plus project project and process contingencies, it's the 20% of the EPPC

- TOC(Total Plant cost) comprises the TPC plus all other overnight costs, including owner's costs.

These costs are "Overnight Cost", means that is not considered the inflation money during the construction time. The last the TASC consider the money inflation during the construction phase, but it's not considered because we assume that the overall Plant is built at year zero [30].

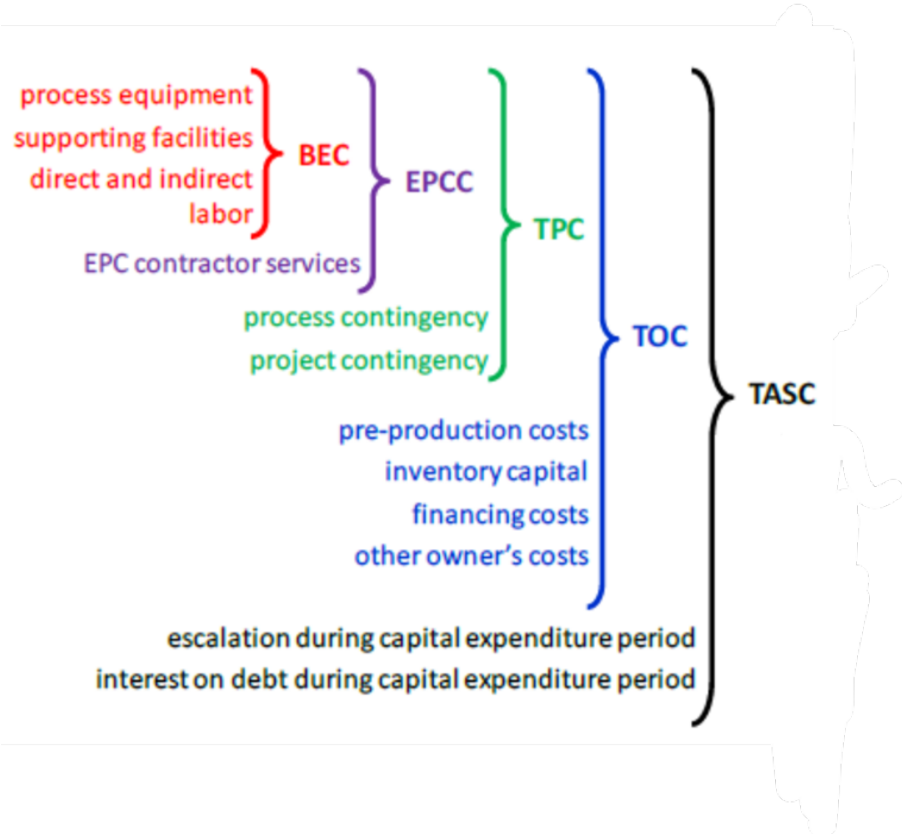

Figure 2.9: EPPC, TPC ,TOC

It's also introduced a CAPEX partition, the CAPEX is huge and it's not payed at year zero, so we have decide to amortize the huge investment , consider this partition we have a reduction in the LCOH, it's showed in the figure (2.10). It has been selected the capex payment in 6 partitions, this allow to reduce the LCOH. So the first part of the Capex(1/6) it's payed at year zero, the remaining parts the 56 is payed during the 20 lifetime plant year, counted with the interests.

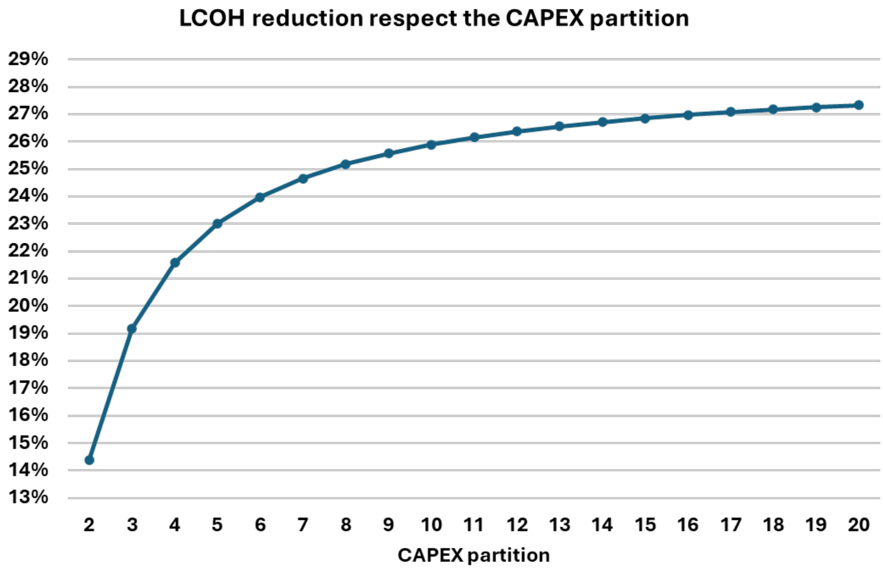

Figure 2.10: CAPEX partition

In the calculation there is also the incentives considered the CAPEX formula:

$$CAPEX = BEC(1 + 8\%)(1 + 20\%)(1 + 20{,}2\%) \tag{2.15}$$

$$BEC = PVcost + Electrolyzercost + StorageVesselcost \tag{2.16}$$

In case it's considered the station incentives they are subtracted by the CAPEX.

$$CAPEX_{incentive} = \text{CAPEX} - \text{HRS incentives} \tag{2.17}$$

OPEX calculation

The OPEX it's the Operational Expenditure, it indicates the operational costs necessary for the working activity. It is formed by the Operational and Maintenance(O&M) the cost for equipments maintenance, it's referred as a percentage of the CAPEX(without incentives). There is also the yearly cost of the hydrogen get from outside or the yearly renewable electricity,it's indicated as H2 from outside (€/kg), if it's considered the case in which I produce hydrogen getting the renewable electricity from IGO(Impianto Garanzia Origine)[14] is measured in €/MWh so to obtain [€/kg$_{H2}$] it has made a conversion factor.

$$\text{conversion factor} = \frac{m_{H2} \cdot HHV_{H2}}{\eta_{BOP}\eta_{electrolyzer}} \tag{2.18}$$

$$OPEX_{\text{not incentive}_k} = O\&M + \text{H2 from outside} \quad [€/\text{kg}] \quad k = 1, \ldots, 10 \tag{2.19}$$

Opex is the first 10 years where the incentives for green H2 production are not present and the remaining where the incentives are present.

$$OPEX_{\text{incentive}_k} = O\&M + \text{H2 from outside} - (\text{incentives green H2 production})[€/\text{kg}] \quad k = 1, \ldots, 10 \tag{2.20}$$

the incentives are available from the first 10 years when the HRS start going into operation, the remaining 10 years the incentives for green H2 production will not be present. The incentives for the green H2 production depends by the Electrolyzer size [20].

$$\text{green incentives} = \begin{cases} 5\,€/\text{kg}\,(\text{yearly percentage green H2} \cdot \text{yearly H2 demand})\,\text{if}\ P_{\text{nominal electrolyzer}} < 10\,\text{MW} \\ 4\,€/\text{kg}\,(\text{yearly percentage green H2} \cdot \text{yearly H2 demand})\,\text{if}\ P_{\text{nominal electrolyzer}} > 10\,\text{MW} \end{cases} \tag{2.21}$$

yearly percentage H2 from outside express the amount of green hydrogen that it's needed to get from outside in order to satisfy the yearly demand.

$$\text{H2 from outside} = \begin{cases} (\text{specific cost green H2 from Facility})(\text{yearly percentage H2 from outside}) \\ (\text{renewable electricity price})(\text{conversion factor})(\text{yearly percentage H2 from outside})) \end{cases} \tag{2.22}$$

2.5 Scenarios

Thesis's aim is the design of dedicated PV plant for the production of the renewable electricity, the size of electrolyzer and the volume of the hydrogen vessel storage, it's the only component analysed of the Hydrogen station. There will be proposed other solution for the design

The sizing of components is started from the demand. the figure (2.11) showed the daily frequency distribution of FCEV(PCs,Light-duty vehicles and Heavy-duty vehicles) at the station to make the fueling. This graph refers to a developed market as California and Florida in USA or in Germany for UE. in the first hours of the day the demand is related to the HDFCEVs in the morning the demand start to increase reaching the peak at he 17 PM , it's the time when the most of people end the work and coming at home, than the demand decrease follow down to the 2% [24]. The graph (2.11) express the average demand,of course depending on the place the curve change but not too much respect this.

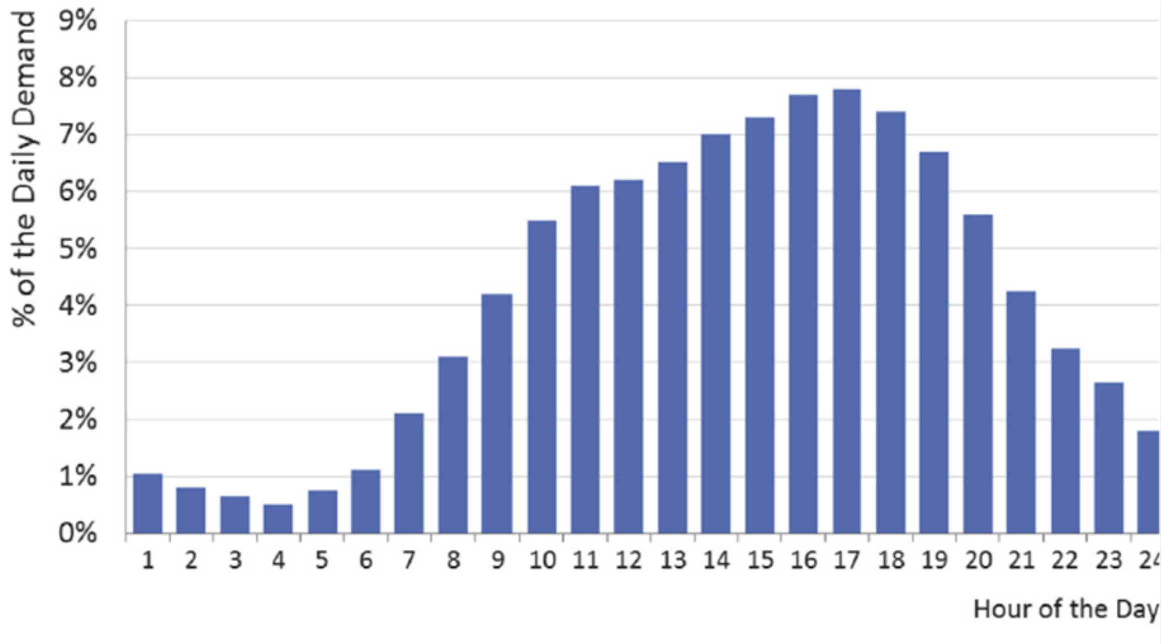

Figure 2.11: Daily demand [24]

In Italy FCV market is quite not present despite the German that is the only Country in Europe that has a developed market for FCEVs and more than 114 HRS in operation([13]). As said in the previous chapter the most relevant emissions are due to the Passenger cars and light duty vehicles but at the market beginning it's better to consider the Heavy Fuel vehicles due the fact that they have a fixed route and this make simple to schedule on time the demand, despite the Light Duty vehicles that have a more random path with less predictability on space and time. So in this work is considered only the Heavy-Duty vehicles coming at the station for the refueling.

Chapter 3

Results and Discussions

From the previous chapter it's clear that satisfy the demand with the electrolyzer powered only by the PV plant is not possible from an economic point of view the LCOH is very huge and it's not the most effective way. To withstand during the period of low irradiance when there is low solar irradiance for production and the storage is not able to satisfy the demand, instead of increase the size components it's introduced an external support. The remaining amount of green H2 to satisfy the demand is get outside from a Facility or it's produced by the electrolyzer getting the renewable electricity not from the PV plant but from another plant. In the following section the configurations are explained.

3.1 Scenario only PV

The configuration adopted is represented in figure (3.1). The PV plant provide the renewable energy, the electrolyzer produce hydrogen when there is the electricity available from the PV and the H_2 produced is stored at 950 bar in the High pressure storage.

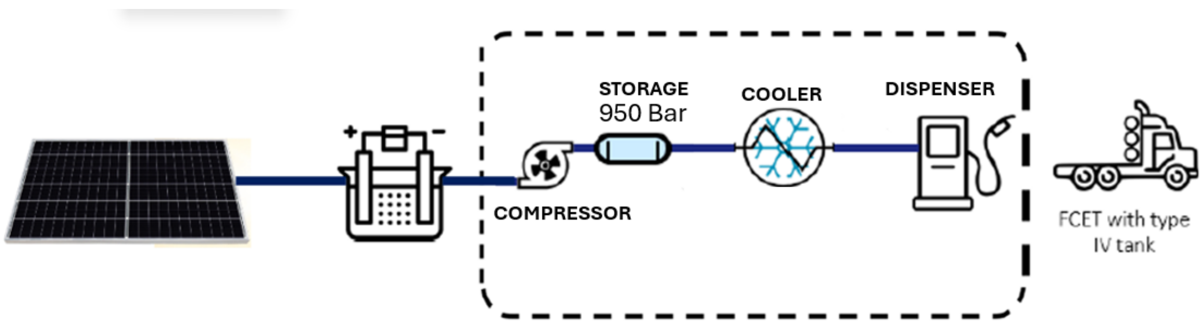

Figure 3.1: PV electrolyzer HRS

The aim is to produce green H2 to satisfy the demand with only the Input energy coming from the PV plant. In this section there are not economic consideration,The size of PV, electrolyzer and storage are tuned in order to see which is the configuration that satisfy the yearly demand. Increasing the size of PV plant there is higher input electricity and higher production by the electrolyzer, the storage is the equipment that satisfy the demand, all the H_2 produced pass through it because it need to be compressed. Larger the storage volume and higher H_2 mass can be stored and for longer period of time the station can satisfy the demand even when there is no local production for low solar irradiance availability. The three components are linked together.

results

The plot (3.2) is obtained for a PV power design of 30 MW. For a lower design the yearly demand is not satisfied there is not enough Solar Power for hydrogen production. The YDS is plotted as a function of electrolyzer size (Nominal Power) and for different total Volume Storage. From 2 to 6 MW power design the curves are superposed due the fact that, the electrolyze size is not big enough for adequate H_2 production, so the storage volume is not discriminant. Focusing in the range of 6 MW to 12 MW PEM power design, the KPI rises depending on the total volume storage, for a fixed PEM power, doubling the total volume storage (55, 110, 209,407), the YDS increment is low, in the best case 10 % increment from 209 to 409 m^3. YDS tend to reach the 100% for very huge total storage volume. The configuration that gives the 100% YDS is for 10 MW and total volume storage of 902 m^3. The YDS=100% is also obtained for V=803 m^3 and PEM=12 MW, the two solutions are similar, one need a lower volume but higher PEM Power, the other concerns higher volume but lower PEM Power. Both of theme consider very huge size component. For PEM design higher than 12 MW the YDS tends to saturate for whatever volumes,there are two reasons for that. Power output of PV plant depends on the available irradiance so increasing the PEM size does not allow more H_2 production. In the hot season even if could be possible to produce more H_2 with great PEM there is the limit of the volume storage. When Storage is full even there is possibility for production the electrolyzer does not work.

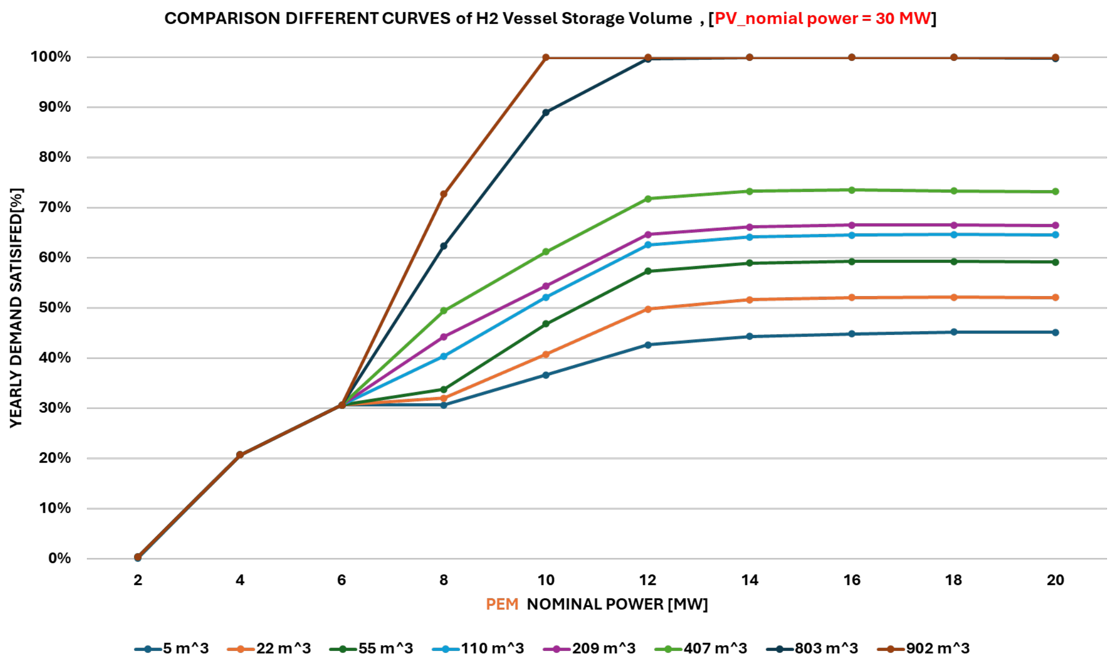

Figure 3.2: YDS, PEM

The figure (3.3) is similar to the previous, same PV plant and volume storage curves. The YDS is obtained for different AEK electrolyzer nominal Power. The difference respect the case with PEM electrolyzer is the YDS decrease with the AEK nominal power increase. This behavior depend by the technology limit said before, AEK does not works under the 20% of Nominal Power design due to structural problem. Increasing the size means increases the limit of unaccepted solar power by the AEK. This is a result with the hypothesis to have only one Electrolyzer, in a real applications is more feasible to have more AEK electrolyzers with lower nominal power, minimizing this global effect.

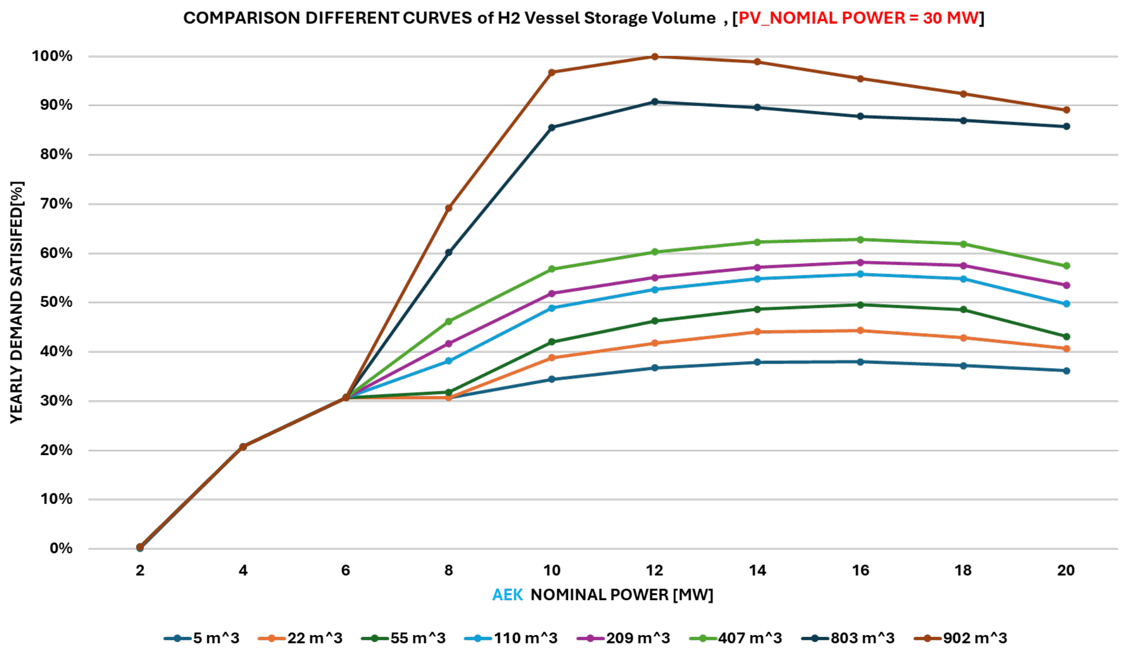

Figure 3.3: YDS, AEK

The design for which obtain the YDS=100% is PV=30 MW, Volume storage= 902 m^3 . This solution is unfeasible form an economic point of view, with LCOH=26,53 kg, in the figure is clear the weak approach to power a HRS(excluding compressors , cooler, dispenser) with only the PV plant. In figure (3.4) is represented the yearly behaviour for each hour of the year. The right axes refers to the blue curve, the hydrogen amount in the storage for each hours, and the left axes refers to the red curve, the Power absorbed by the electrolyzer. At the beginning of the year in the winter there is low production by the PV, so the PEM works at partial loads and the amount of H2 produced is low respect the demand , so the mass in the storage decrease but does not follow below the total buffer storage amount (of 367 kg). When there is more irradiance the PV gives more power and electrolyzer produce more, the mass in the storage increase until the storage is full. In summer season the storage is almost full, the oscillations due the demand are very low, for more than 3 mouths there is more than 40.000 kg$_{H2}$ not used in the Storage. During this period the Electrolyzer works at maximum load, but there are some hours that it works at partial load because the storage is full and there is not place to store the H2.

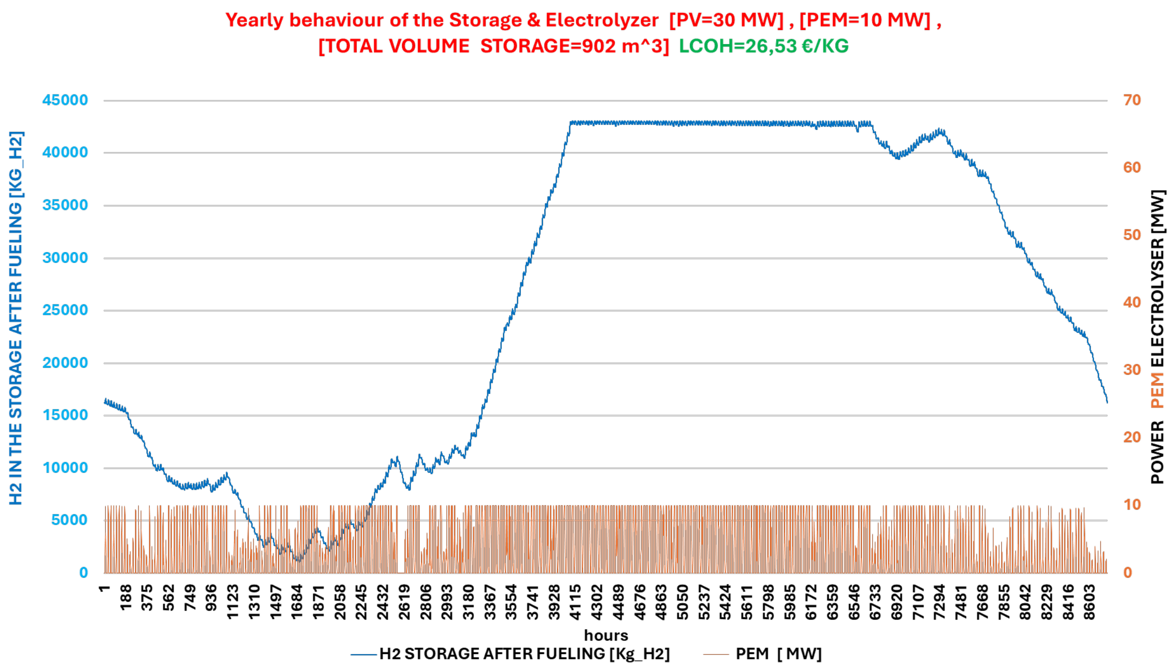

Figure 3.4: Yearly behaviour,PEM=15 MW, V=902 m^3

3.2 Scenario only PV + On wheel H2 supply

Green H2 from Facility

The station configuration, inside the dashed rectangular is not changed, figure (3.5). The green H2 form outside is transported form remote production, a facility dedicated in green H2 production, to the station. It's considered production cost and the transportation cost expressed in €/kg$_{H2}$.

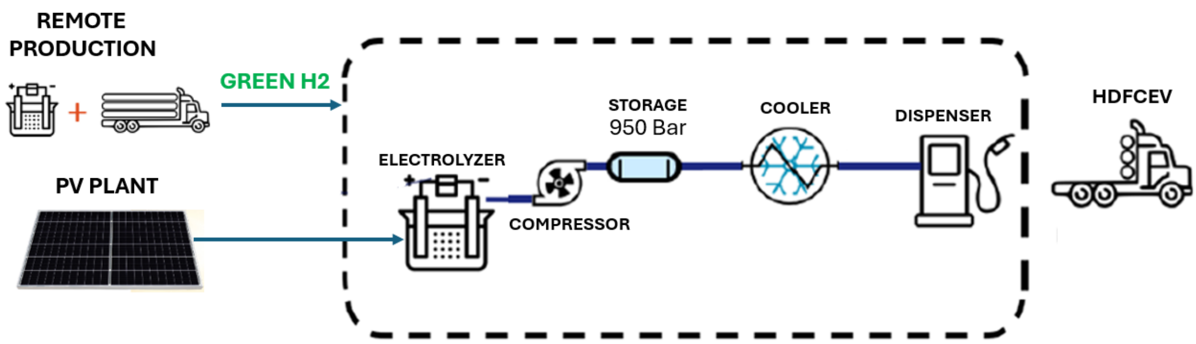

Figure 3.5: HRS green H2

3.3 Scenario only PV+GO

Green H2 produced from Renewable electricity

The other proposed solution is to produce the overall yearly H2 demand with the local eletrolyzer getting the electricity form PV plant and when there is low solar irradiance the electrolyzer get the renewable electricity from a dedicated IGO (Impianto garanzia di Origine) this plant have the guarantee to produce the renewable electricity, figure (3.6)

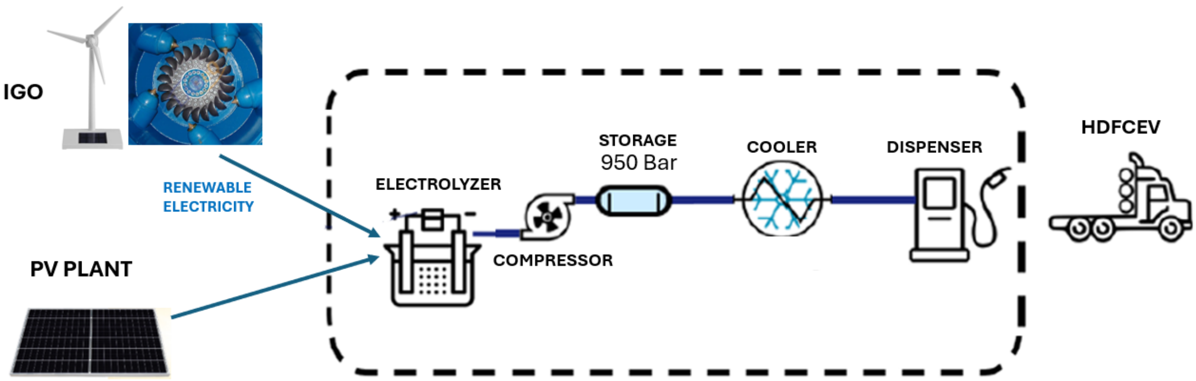

Figure 3.6: HRS PPA

It's a strong assumption to have the availability of a dedicated renewable plant that provide renewable electricity without time constraints, furthermore the electricity cannot be produced the by solar source, the plant it's not so far from the station, if mine PV plant produce low current due to low PV also another PV plant in the neighbour it's not able for production.

In the following parts the main results will be analyzed.

3.4 Comparison

In the results section are showed and analysed the main results of the different configurations, the best configuration will be discussed the once that provide the lower LCOH. At first there is a summary of the best configuration obtained without incentives.

Dynamic behaviour of the station

In the following figures it's showed the dynamic behaviour for all the hours of the first two days of the year in the case when there is the need to get H2 from outside and the case in which the storage to support the demand.

In figure,(3.7) the demand(orange curve) it's constant as showed at the beginning. The storage curve express each hour the remaining amount of hydrogen in the storage after the charging and the discharging due to the demand; so it's express the difference(Production-Demand). This difference cannot go under the minimum amount imposed in the volume storage(corresponding to 5 bar), if the mass in the storage goes under this level the green H_2 from outside will be requested. In the first hours of the morning at 7.00 there is the demand but the solar irradiance is still to low so an low external amount is requested for the first hour, then the PV panel provide great amount power and electrolyzer produce a sufficient amount of hydrogen to satisfy the demand of 1 HDVs per hour and the remaining part fill the storage, it's visible the blue curve rise. When blue curve rise means that production is higher then demand, it reach the peak at the same moment when electrolyzer reach the maximum production following the bell PV shape. When the HDFCEV are 2 the demand is 90 kg in 1 hour, the electrolyzer production decrease so the demand is higher then production and the storage level follow until the storage is not able to sustain the demand and the external H_2 request traces the demand.

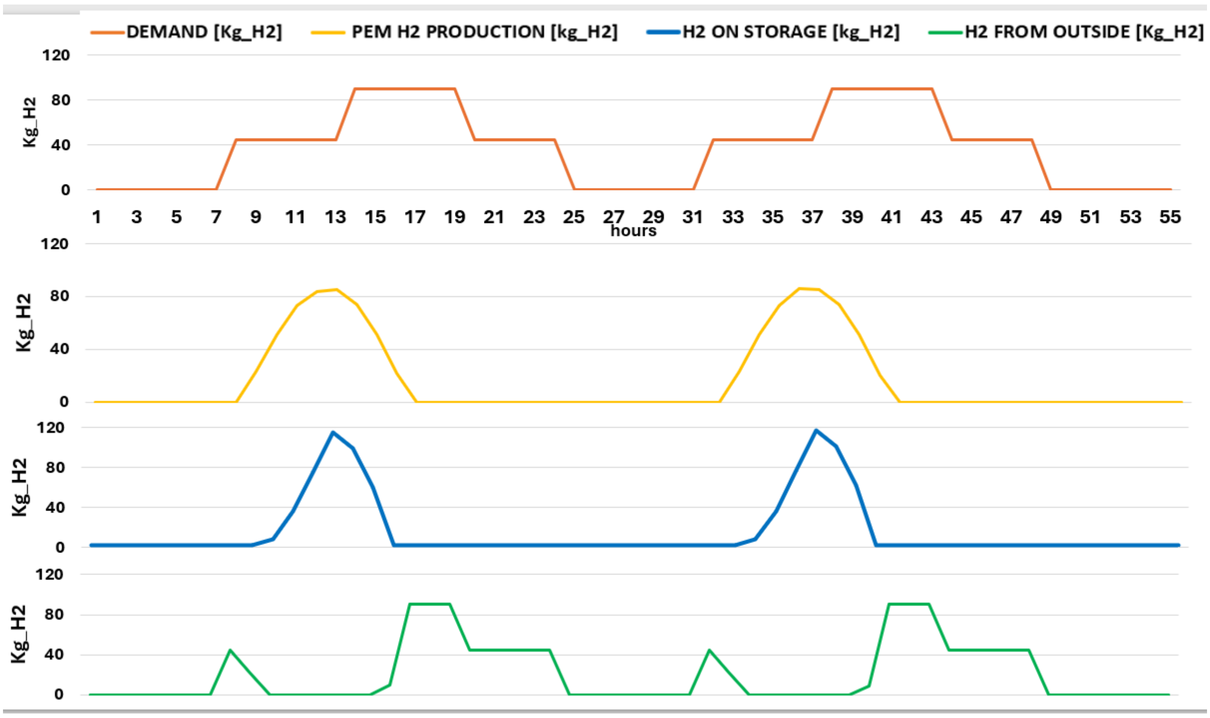

Figure 3.7: Dynamic behaviour

In this figure (3.8) is showed for the best configuration(PV=15 MW, PEM=6 MW, total volume storage) the yearly behaviour of the h2 mass content in the Hydrogen vessel storage(blue curve,left axes) and the amount of green H_2 gets from outside or produced with renewable electricity (green curve,right axes).

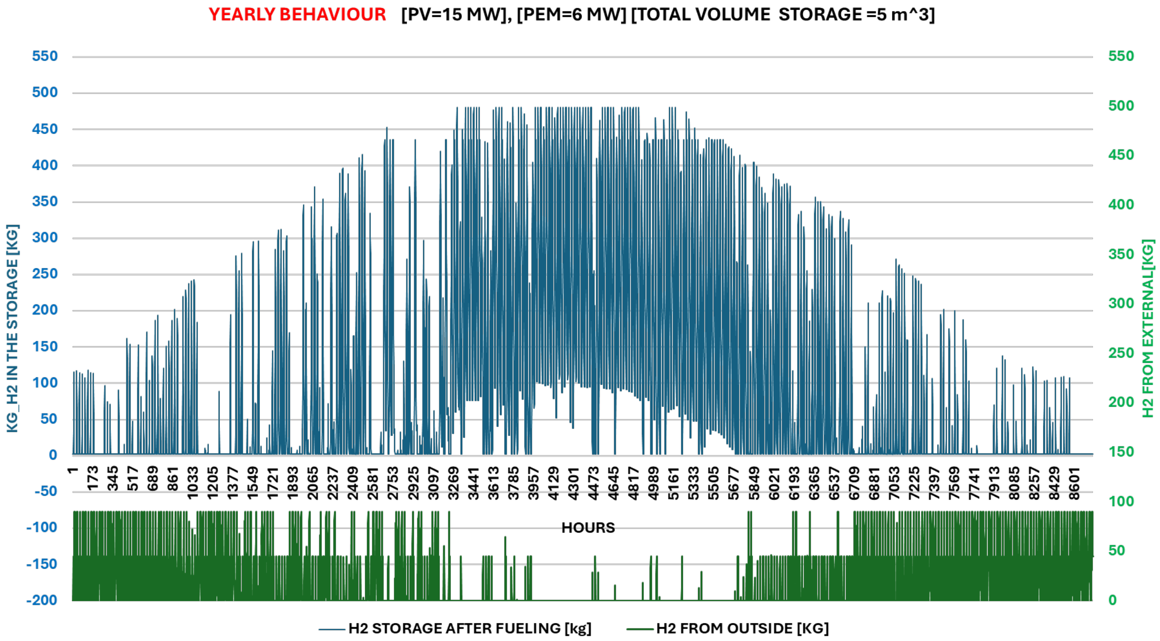

Figure 3.8: Yearly behaviour H2 from outside

With hyphothesis price of:

- Green PPA = 200 €/MWh
- Green H_2 from faicility = 10,21 €/kg$_{H2}$

and also without incentives , the configurations are compared in the following table.

Table 3.1: COMPARISON BEST CONFIGURATIONS

Configurations	PV size [MW]	Electrolyzer size [MW]	Storage size [m^3]	LCOH [€/kg$_{H2}$]
only PV	30	10	902	26,5
PV + PPA for integration	15	6	5	9,5
PV + green H2 integration	15	6	5	8,96

It's easy to understand that the only PV solution is not feasible and the outside support is needed. The minimum LCOH is achieved with the green H2 integration from a remote production, this is obtained under the costs assumptions, if the green PPA price and production costs plus transport cost change the choice could be different. for both the best volume size minimize the LCOH, in case of otside support, it's the minimum volume of 5 m^3, the reason why it's that having the possibility to get H_2 from outside or producing by the electrolyzer during vulnerable moments, the storage function fails, so the function cost tend to minimize the volume. It cannot be removed because it's needed a vessel to compress H_2. This behaviour is also present in these curve, in figure (3.9) for PEM and in figure (3.10) AEK electrolyzer, the two types do not show great difference in terms of LCOH and shape. Decreasing the storage volume the LCOH for the reason expressed before. Notice also the U curve, for low and high electrolyzer power size the LCOH. In case of lower size the local h2 production is very low so it's higher the amount of hydrogen get from outside, aslo the PV power is not used at all. For higher Power design the electrolyzer base erected cost for electrolyzer is higher but the demand self satisfied does not increase due that the Power provided by PV plant is not changed(fixed to 15 MW) and it's always needed the outside support.

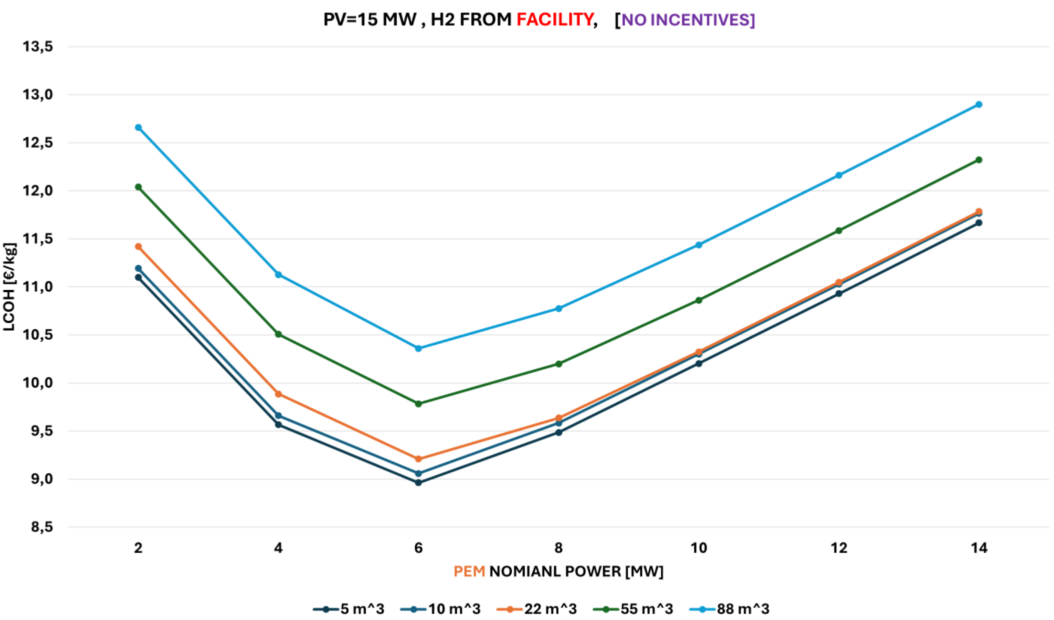

Figure 3.9: LCOH PEM different volume

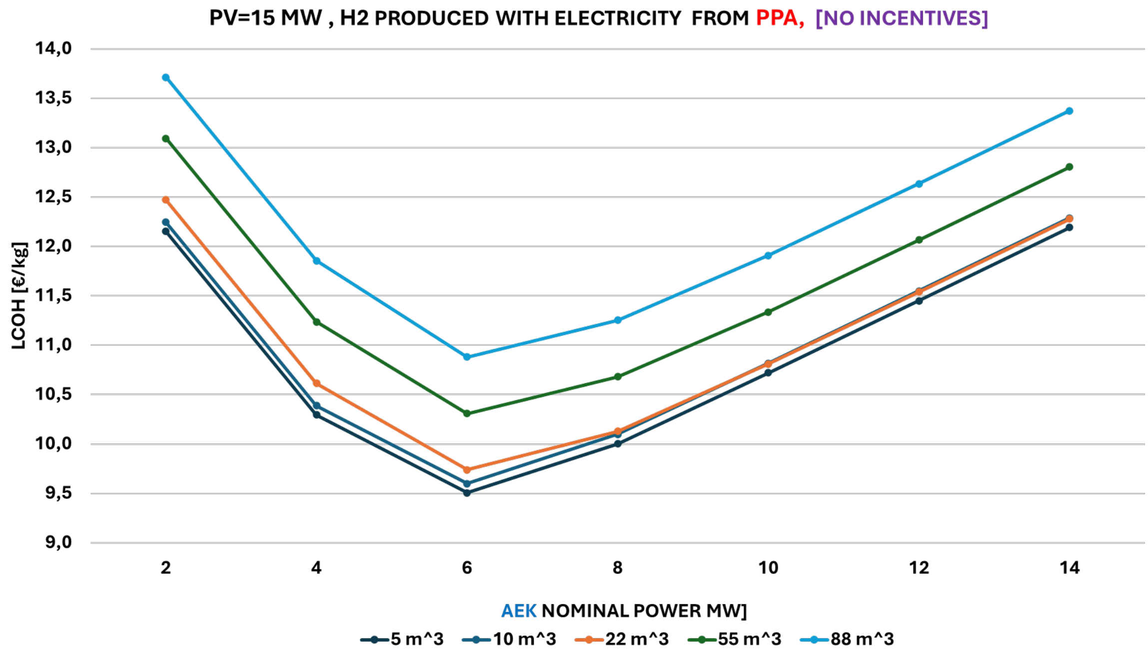

Figure 3.10: LCOH AEK different volumes

The two following figures refer to the best configuration(15 MW, total volume storage= 5 m^3) referring about the different way to meeting the demand. Figure (3.11) refers to the case when I get green h2 from remote facility, the columns indicate LCOH (left axes) the orange columns refer to the case with incentives(Incentive for the HRS and incentive for green H2 production) and the blue column refer to case with any incentives. Of course the LCOH is lower in the case with incentives but change the LCOH reduction in different PEM size. The green curve(left axes) express the LCOH percentage reduction between incentive and not incentive case, for different electrolyzer size. In this case the only incentive is the incentive for the HRS and the green H2 self produced, the green H2 amount taken form outside does not benefit for the green incentives, it is the producer who eventually has the incentives. For low PEM size(2-4 MW) the LCOH reduction is low because HRS self produce low amount of H2 and the incentives proportionally tot the low self production, the maximum LCOH reduction is achieved for the best configuration, 6 MW, reaching a LCOH reduction of 22,5%. Increasing the PEM size its CAPEX increase but always as said before the H_2 produced does not increase to much due to fixed Power provided from PV.

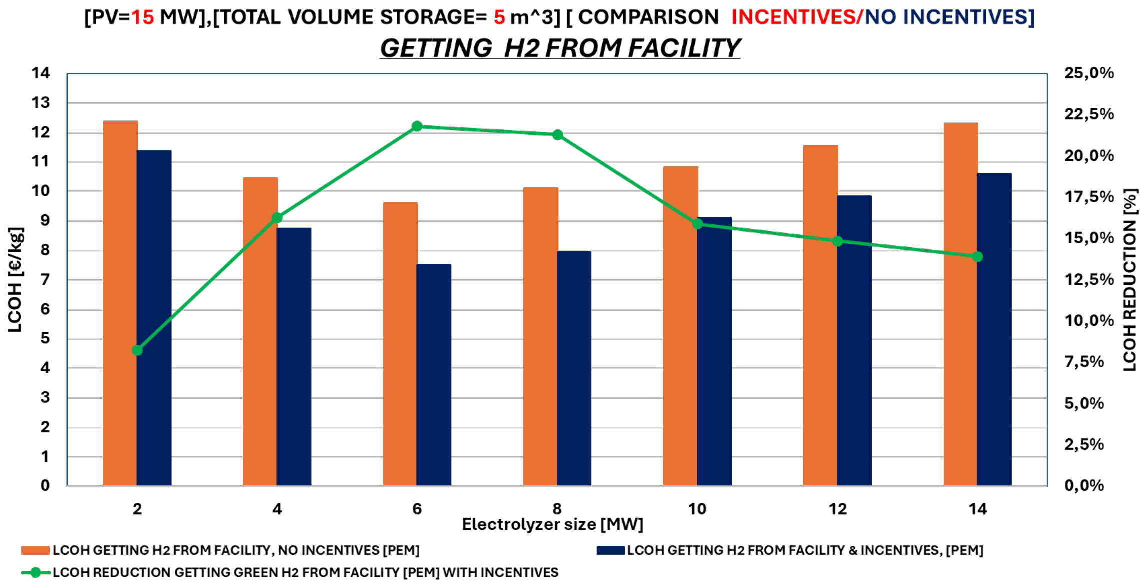

Figure 3.11: Comparison Incentives no incentives green H2

The figure (3.12) refers to the case in which the missing demand is satisfied producing H2 with electrolyzer taking renewable electricity from the IGO. As in the previous plot the columns express LCOH in case of incentives and not incentive(left axes), green curve indicates the LCOH percentage reduction(left axes). The green curve show almost the same behaviour of the previous , reaching the maximum reduction for the 6 mW(best configuration). The different is underlined in the fact that the reduction in this case is higher then when I get green H2 from remote, in fact at 6 MW reach 30% reduction and also for lower size (4-6 MW) the reduction is significant, around 25% (higher then the best case of the previous 22,5%). This behaviour it's due to the fact that in this case the overall hydrogen is produced by the electrolyzer and it's incentivized. More amount of hydrogen produce and more will be the incentives gained.

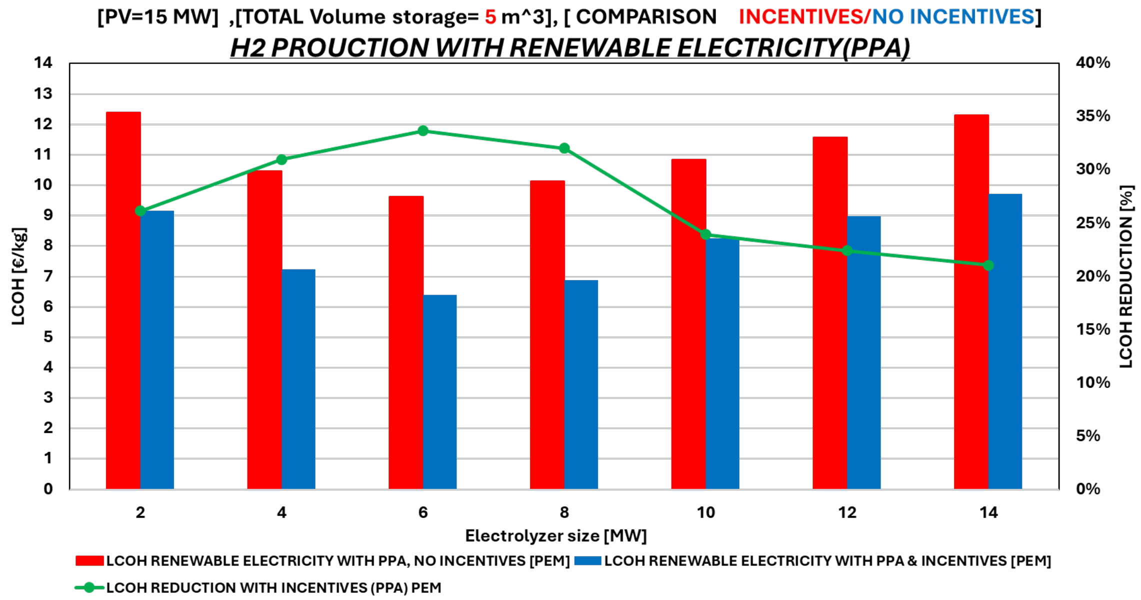

Figure 3.12: Incentives no incentives PPA

As expressed before the choice between the 2 different way to satisfy the overall demand depends by the by the green PPA price and also by the production and transport cost of green H2. In the tables are summarized which are the best configuration in terms of lower LCOH(without incentives) changing the costs. green PPA price is varied from (100 to 250 €/MWh) with step of 50 €/MWh, green H2 cost is varied from 8 to 14 €/kg with 2 €/kg, the 10 is rounded to 10,21(the standard case analysed).

looking at the first table (3.2), keeping fixed the green H_2 cost from Facility,when the green PPA price is equal to 100 €/MWh the PV size is equal to 5 MW the electrolyzer equal to 2 MW and the best way to integrate H2 from outside is getting the renewable electricty from outside due the fact that the price is very low. Increasing the PPA price at 150 €/MWh the best design include PV=15 MW, electrolyzer size of 6 MW, LCOH=8,14 €/kg and now it's more convenient integrate H2 from outside with green H2 from remote production, because it has a lower specific cost(8€/kg) respect the green PPA price, Furthermore it's convenient to have a larger PV plant to produce in situ the H2. Over the PPA price of 150 €/kg the best solution does not change it's always convenient get H2 by transport.

The same considerations are valid in the other tables((3.3),(3.4), (3.5)), when the green H2 cost from facility increase, for lower PPA price the best solution is to produce H2 in situ with renewable electricity until the PPA price is to much higher to switch the solution and choose the Green H2 transported form remote.

Table 3.2: GREEN H2 COST FROM FACILITY 8 [€/Kg_{H2}]

Cost green PPA [€/MWh]	PV nominal power [MW]	PEM electrolyzer nominal power [MW]	Total volume storage [m^3]	Minimum LCOH [€/kg_{H2}]	Solution H2 from outside
100	5	2	5	6,55	PPA
150	15	6	5	8,14	GREEN H2
200	15	6	5	8,14	GREEN H2
250	15	6	5	8,14	GREEN H2

Table 3.3: GREEN H2 COST FROM FACILITY 10,21 [€/Kg$_{H2}$]

Cost green PPA [€/MWh]	PV nominal power [MW]	PEM electrolyzer nominal power [MW]	Total volume storage [m^3]	Minimum LCOH [€/kg$_{H2}$]	Solution H2 from outside
100	5	2	5	6,55	PPA
150	15	6	5	8,42	PPA
200	15	6	5	8,96	GREEN H2
250	15	6	5	8,96	GREEN H2

Table 3.4: GREEN H2 COST FROM FACILITY 12 [€/Kg$_{H2}$]

Cost green PPA [€/MWh]	PV nominal power [MW]	PEM electrolyzer nominal power [MW]	Total volume storage [m^3]	Minimum LCOH [€/kg$_{H2}$]	Solution H2 from outside
100	0	6	5	6,55	PPA
150	15	6	5	8,42	PPA
200	15	6	5	9,5	PPA
250	15	6	5	9,63	GREEN H2

Table 3.5: GREEN H2 COST FROM FACILITY 14 [€/Kg$_{H2}$]

Cost green PPA [€/MWh]	PV nominal power [MW]	PEM electrolyzer nominal power [MW]	Total volume storage [m^3]	Minimum LCOH [€/kg$_{H2}$]	Solution H2 from outside
100	0	6	5	6,55	PPA
150	15	6	5	8,42	PPA
200	15	6	5	9,50	PPA
250	15	6	5	10,35	GREEN H2

Once interesting consideration regards the the table (3.6) also represented in the plot (3.13). in the previous tables are indicated the best solution for different price of PPA and green H_2. In the table (3.6) is represented the prices for which from an economic point of view it's the same convenience to choose one or the other external solution, both of theme gave the same LCOH.

Table 3.6: Equal Condition

PPA[€/MWh]	GREEN H2[€/Kg$_{H2}$]	LCOH[€/Kg$_{H2}$]
137	8	8,14
150	8,75	8,42
175	10,21	8,96
200	11,7	9,5

In the figure (3.13) it's represented the Green H2 cost from outside and the PPA cost, in the straight line are represented the points in the table (3.6), based on the PPA and green H_2 price is indicated the respective LCOH. The points above the straight line indicate that became economically convenient the choose of use renewable electricity because it means that the green H_2 price is higher respect the case in which the choice is economically the same, the straight line. The opposite consideration is valid for the points below the straight line indicating that the green PPA price is lower respect the indifferent condition(straight line) and so it's economically convenient to get green H_2 form remote production.

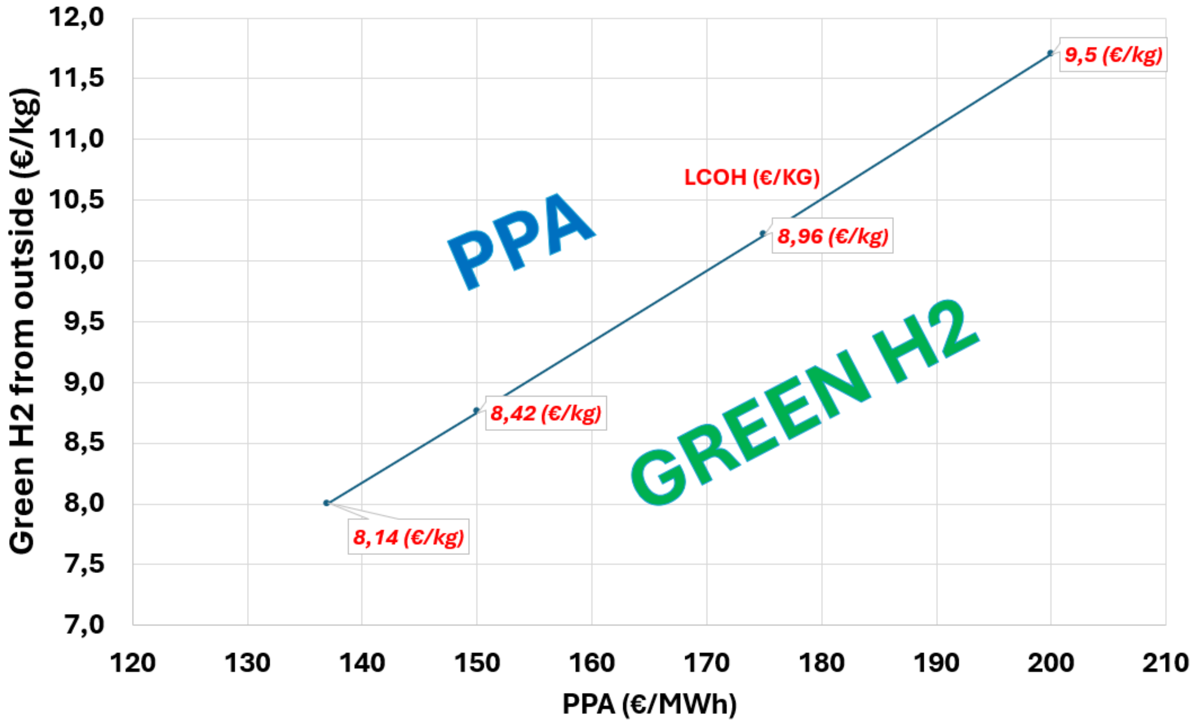

Figure 3.13: GREEN H2 and PPA

Chapter 4

Conclusions

Thesis address the issue of the transport sector decarbonization, with the substitution of the usual ICEs using fossil fuel with a new type of sustainable mobility with no emission on road adopting xEVs(Electric power train vehicles). The FCEVs(Fuel Cell Electrict vehicles) have in the power train of the vehicles a fuel cell that with the incoming hydrogen produces electric power for the electric motor. hydrogen is the fuel for this new alternative vehicles,of course during the vehicles travel there are not CO_2 and other pollutant emission coming form the combustion, but to ensure a sustainable and "green mobility " the hydrogen as a fuel must be produced in a green way avoiding CO_2 emissions, otherwise the emissions are not reduced but they are only shifted from the road to the production site. This is the reason why in the thesis has been considered only the green/renewable hydrogen production, in loco or in a remote facility, to satisfy the HDFCEV demand. The advantage of Heavy duty is that in most of the cases they have a fixed roots respect the Light duty, especially the PCs(Passenger Cars) that show a more random rote and as a consequence a not fixed fuel demand in space and time. Once the demand is scheduled became easier analyse and construct an infrastructure for the fueling. The most challenge is the production of green H_2, at the moment the most of hydrogen is produced with SMR (Steam Methane Reforming) using methane CH_4,the technology does not produce green H_2 due the fact that is used methane. The production H_2 is produced with electrolyzer, to ensure the green H_2 the electricity used must be renewable otherwise the hydrogen is not considered as green. In a first approach the renewable electricity is provided by the Photovoltaic plant, the analysis show that this solution is not economic feasible so other complementary solutions are provided to reduce the LCOH. the final LCOH obtained is not completed but must be considered the auxiliary equipment and their energetic request, the compressor is the once that require the higher amount, so the final LCOH at the pump will be higher than the results obtained. It's also showed that the public incentives reduces the LCOH making more affordable the green Hydrogen, at the beginning it's fundamental the public economic support to push the new technology from economic point of view but also for the public acceptance. People are not prone to change their vehicle if the costs is higher and even if they are constrained to low refueling site. It's crucial a coordinated efforts between governments, industry and civil society are needed to overcome the challenges and fully realize the potential of hydrogen cars as an integral part of the transportation landscape of the 21st century.

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