POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Local refilling infrastructure for hydrogen or electrical HD fleets

Project Work in Energy and Emissions in transportation systems

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Academic Year: 2021-2022

Abstract

The aim of this project work is to provide an answer to the question:

Could hydrogen be a good solution for substituting fossil fuels in HD transport?

This question will be answered analysing a case study related to a logistic depot located in northern Italy.

The first part of the report will be devoted to the description of the state of the art of heavy duty transport, the technologies used and the peculiarities of the current circulating fleet.

The subsequent section consists in the presentation of the current solutions used to exploit hydrogen in the energy and transportation sector.

A technical analysis will then be performed, to assess the possibilities and limits of different alternatives to provide the requested hydrogen to the depot, imagining the building of a local refilling infrastructure to respond to the needs of the vehicles that use the depot as a logistic base.

In the end, all those alternatives will be put to the test through an economical evaluation, using as unit of measure the total funds needed to run the refill facility for a year and the specific cost of H_2, also taking into consideration the possible CO_2 emissions.

The conclusion will present the results in a composite way, providing also an overview of the possible developments options of the different solutions.

Contents

1 | Introduction

Heavy duty transport can be seen as the backbone of today's economy: all commerce, from local retailers to big e-commerce brands, would not be possible without it. It's one of the most important links of the logistics chain, given that it makes possible to have the capillarity and the short lead times to which we are all used in today's world. But times like the ones we are living in oblige us to pose an important question: ***is all this sustainable?***

Given the report from ACEA[1], we can see that the circulating heavy duty fleets in EU have an average age of 13 years, with a predominance of diesel powered vehicles (Figure 1.1).

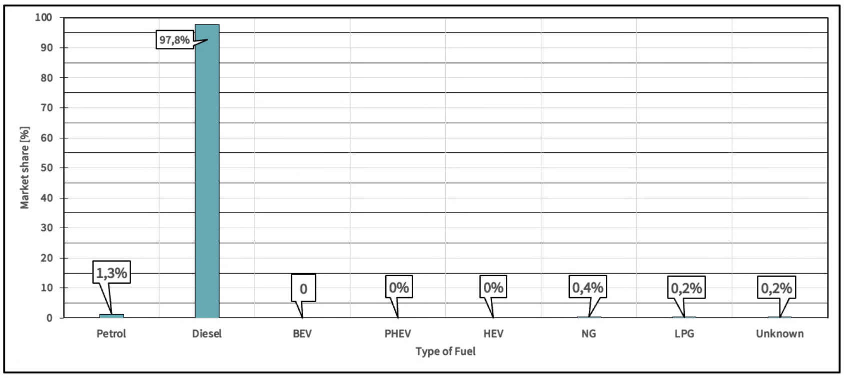

Figure 1.1: Market share (in percentage) for different types of fuel

The goods transportation sector has a prevailing weight on the energetic consumption of the European Union: in fact, over 40% of all the liquid fuels for road use are consumed by this sector[6]. So, in compliance with the UN sustainable development goals, the necessity to renew this field is evident. How to do this is an interesting question that puts on the table different solutions, ranging from hybrid trucks coupled with overhead contact lines to be powered with when on highways, to "simple" battery electric trucks and passing also from H_2 solutions. In Table 1.1 we can find the main options that can help us achieve this objective.

Fuel	PROS	CONS
Biofuels	Derivable from waste products	Still emit CO_2 during use
Electricity	100% clean during use; Possible to couple the vehicle with a fixed infrastructure (OVH contact line)	Cleanness depend on energetic mix; Charging infrastructure and time Weight of the battery
Hydrogen	100% clean during use; Higher energy density	Lower volumetric density

Table 1.1: *Pros and Cons of different alternative fuels*

Regarding the use of batteries, as stated in a recent book by Professor R. Mazzoncini[25], this is not so convenient, because of their size and type of use: to maintain a range which is compatible with a diesel solution, a BEV would weigh almost 5 **tons** more. Hence, the focus to produce HD vehicles that are green during use needs to pass from H_2 technologies, which will be the focus of this paper.

1.1. State of the Art

The field of hydrogen production is in continuous development. In the recent years, more and more attention is being put in these technologies, as they can offer a solution to a handful of problems, starting from their being a cleaner solution for transportation sector. The actual production technologies are the following[14]:

Oil: hydrogen is produced with steam reforming or partial oxidation from fossil or renewable oils;

Gas: natural or bio-gas can be used to produce hydrogen via steam reforming or partial oxidation;

Algae: methods for utilising the photo-synthesis for hydrogen production;

Wood: pyrolysis technology can be used for deriving hydrogen from biomass;

Electricity: water electrolysis using electric power from renewable sources;

Coal: with gasification technology hydrogen may be produced from coal;

Alcohols: like hydrogen and methanol derived from gas or biomass (rich in hydrogen and may be reformed to hydrogen).

The technology we chose to deepen is *electrolysis*, due to the good scalability of the plants, that range from few kW to several MW.

Due to the physical and geographical characteristics of Italy and the very virtuous energetic mix, in which almost 40% of electric power comes from renewable sources, we chose to feed the water electrolysis with renewable energy. Namely, the two solutions we considered will be hydroelectric plants and photovoltaic plants. Both these solutions also address the problem of being independent from the foreign states. This theme, which is really important, started to spread in the last years in the case of oil and gas, with few countries controlling their extraction and production.

1.1.1. Electrolysis

With electrolysis water is split in hydrogen and oxygen, in an electrochemical cell. A distinction can be made based on the cell's temperature[14]:

- Low temperature cells that can be divided into:
  - Alkaline electrolysis (Figure 1.2) based on a liquid solution of $NaOH$ or KOH;
  - PEM (Figure 1.3) based on a polymeric electrolyte.
- High temperature cells (such as SOEC).

Low temperature cells are already a commercial solution, while high temperature ones are still in development; hence, our focus will be on the former.

1.1.2. Hydroelectric Energy

Hydroelectric power plants use the potential energy of water flowing down into the turbine to produce electrical energy. We can find two main configurations[23]:

- Dams with reservoirs (Figure 1.4), that can be classified into:
  - Small dams;
  - Large dams;
  - Pumped storage;
- Run-of-the-river.

This technology does not produce significant CO_2 emissions other than those emitted during the plant construction. It has also reached a significant degree of maturity: many of the plants that were built in the early decades of the 20^{th} century are currently still in operation. This reduces the costs of the facilities, because they consist simply in O&M.

Otherwise hydropower depends on rainfall and a reserve may be needed to compensate for

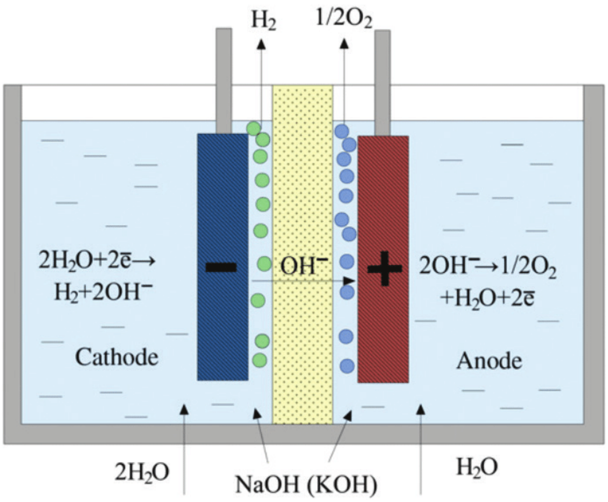

Figure 1.2: Schematic diagram of the alkaline electrolysis cell[21]

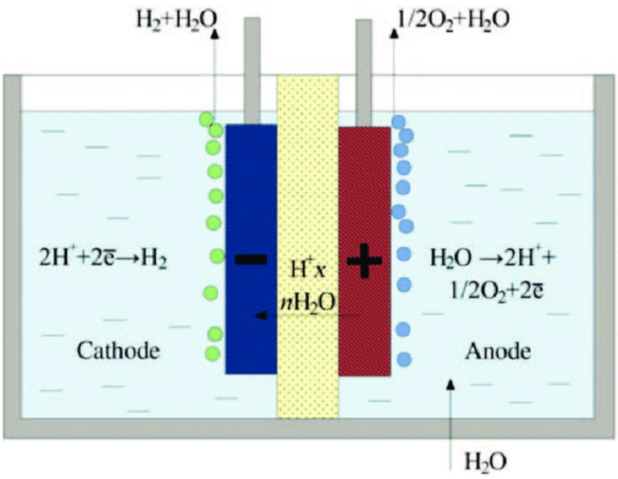

Figure 1.3: Schematic diagram of PEM electrolysis cell[21]

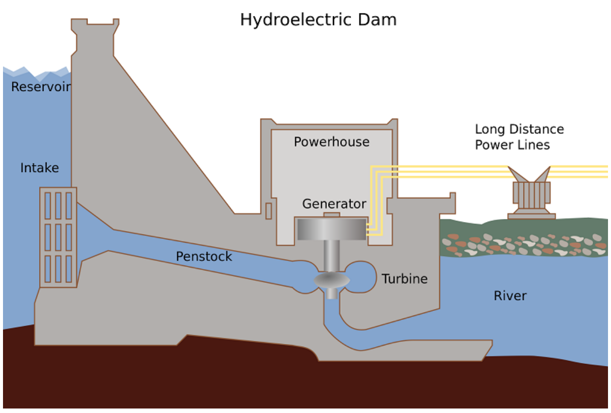

Figure 1.4: A diagram showing the main components of a conventional hydroelectric facility[15]

periods of low rainfall. So, it will be possible that climate change influences the efficiency of such technology. We also have to take into account the political, societal and economic risk usual of this type of infrastructures.

1.1.3. Photovoltaic Energy

The goal of a photovoltaic plant is to convert solar energy into electricity. To do that, a solar cell needs two main mechanisms[7]:

1. the light should be absorbed and electrons and holes should be generated in the conduction and valence band, respectively;
2. the generated electrons and holes should be separated and transported to their selective contact.

More in detail (Figure 1.5), the light is absorbed in the Light Absorbing Layer (the photon have higher energy of the LAL energy gap) and generate electrons and holes that will diffuse in the layer. If an electron reaches the interface between LAL and the Electron Selective Layer (ESL) it is into ESL and can reach the electrode. On the opposite, if an electron reaches the LAL and Hole Selective Layer (HSL), the gap prevents the charge transfer and reflect back the electron. The same thing happens for holes that are forced to move towards the positive electrode.

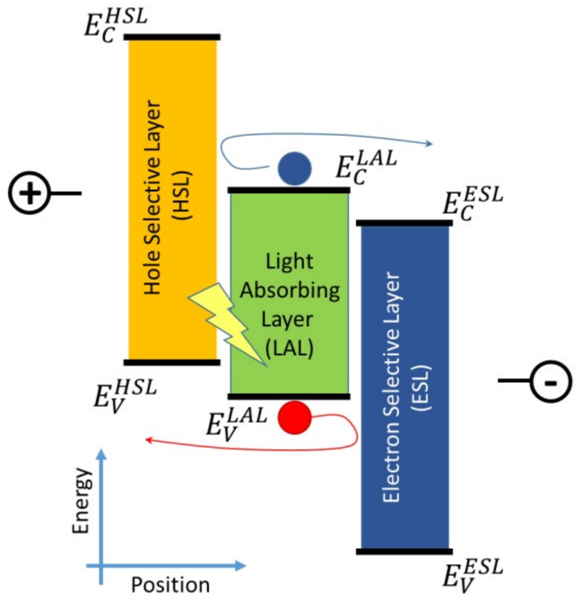

Figure 1.5: Schematic diagram of key elements for solar cells[7]

There are various generations of photovoltaic panels, that can be classified into two categories:

Wafer-based cells are fabricated on semiconducting wafers and can be handled without an additional substrate, although modules are typically covered with glass for mechanical stability and protection;

Thin-film cells consist of semiconducting films deposited onto a glass, plastic, or metal substrate. We can divide them into commercial and emerging thin-film technologies.

We can also say[7] that PV can adapt to the application requests by varying aspect and will spread in different sector but, at the same time, its future is still open for strong innovations with the aims to reach the maximum efficiency of 95% instead of the present record of 47, 1%.

1.2. Example Project

The creation of a grid of hydrogen refilling station is a great challenge that is going to require, in the near future, some great advancements in the field.

Regarding Italy, the actual H_2 refilling infrastructure is still way behind the level needed for a mass diffusion of this technology. Only one station is actually active, and a bunch of them are currently under development.

One virtuous example is H_2 *SÜDTIROL*[18].

H_2 Südtirol is a site located in Bolzano (Italy), where green hydrogen is produced locally by means of electrolysis powered by renewable energy. The main goal of this project was to find a way to store the surplus of clean energy provided by hydroelectric power plants in the form of hydrogen. The modular electrolysers on site are able to produce up to 180 Nm^3/hour. The hydrogen is than compressed and stored and can refill up to 15 urban buses (with 200/250 km of range) or up to 700 cars.

2 | Case Study Description

To this day, hydrogen trucks are starting to become a reality. What is proposed on the market or still under development offer values of chassis occupation comparable with the ones of diesel-powered solutions. Also, the range of such solutions is in line with what is offered today in the fossil-fueled market: H_2 tanks ranging from 30 to 100 kg can offer a range of more than 400 km[6].

A lot of effort in the development of hydrogen powered trucks is being currently spent by joint-ventures between industries and logistic partners, like the partnership between Scania and the food wholesaler Asko; given this fact, our case study will deal with the analysis of the truck fleet needed by a sample logistic depot.

The model of truck considered is based on the **Scania G-series** platform, produced by the aforementioned joint venture between the two Swedish companies; the vehicle has the characteristics showed in Table 2.1. We computed the size of an hypothetical hydrogen truck with an equivalent range with respect to the one powered with diesel engine.

Scania G-series (Asko)	
Size [tons]	$27,00$
Number of trucks	$10,00$
Range [km/day]	$500,00$
Motor power [kW]	$390,00$
Battery [kWh]	$56,00$
FC power [kW]	$90,00$
H_2 tank size [kg]	$33,00$

Table 2.1: *Truck data*[6]

Our case studies will focus on an Amazon Logistics depot in Milano (Via V. Toffetti, 108). Being a pretty small depot, we imagined it to be served by 10 trucks each day, with the required amount of hydrogen showed in Table 2.2 (note that the H_2 provision has been considered bigger of 10%).

Hydrogen Requirements	
H_2 daily needs [kg/day]	$363,00$
LHV H_2 [kWh/kg]	$33,31$
LHV H_2 [MJ/kg]	$119,92$
Electric energy required [MWh]	$20,46$

Table 2.2: *Hydrogen requirements*

The provision of hydrogen to serve the daily needs of the depot has been considered analysing different solutions. The focus is put on an **electrolysis system**, with the energy produced from **hydroelectric** and **photovoltaic** plants. In Figure 2.1 we can see the chosen PEM electrolyser, whose characteristics can be seen in Table 2.3.

Figure 2.1: Hgas3SP electrolyser by **ITM power**[20]

Tech Specs	
Ectrolyser technology	PEM
Number of stacks	3
System packaging and size	1 x 20 ft & 1 x 40 ft ISO
Power supply	11kV AC (3 Phase - $50Hz$)
Control	PLC
Hydrogen generation pressure [bar]	20
Hydrogen purity (ISO standard)	Up to $99,999\%$
Maximum hydrogen production appx [kg/h]	$36,00$
Input power at maximum appx [kW]	$2.350,00$

Table 2.3: *Technical specifications of HGas3SP*

2.1. Hydroelectric Power

2.1.1. Electrolyser in the Depot

This first solution is based on these assumptions:

Electricity Production It is produced by the Hydroelectric PP in **Crodo** (VB) (see Table 2.4) and then is transferred to Milano via the electric grid;

Electrolysis It is performed on site in the depot, with a system **owned by the logistics company**.

Hydropower Plant - Crodo	
Efficient power [kW]	$52.800,00$
Distance from depot [km]	$160,00$
V_{Line} [V]	$200.000,00$
I_{Line} [A]	$264,00$
Power loss [%] (HV systems)	$0,02$
Effective power [kW]	$51.744,00$

Table 2.4: *Techinical data of Crodo's Hydropower Plant*

2.1.2. External Electrolyser, Transport of Hydrogen

The second solution is based on these assumptions:

Electricity Production It is produced by the Hydroelectric PP in **Trezzo sull'Adda** (MI) (see Table 2.5);

Electrolysis It is performed on site **in the Hydroelectric PP**; the system is **not owned by the logistics company**.

Hydroelectric Power plant - Trezzo Sull'Adda	
Efficient power [kW]	$10.500,00$
Mean producible energy [kWh]	$65.000.000,00$
Distance from depot [km]	$40,00$
V_{Line} [V]	$200.000,00$
I_{Line} [A]	$52,50$
Power loss [%] (HV systems)	$0,02$
Effective power [kW]	$10.290,00$

Table 2.5: *Techinical data of Trezzo sull'Adda Hydropower plant*[30]

The hydrogen is directly bought from the owner of the electrolyser, and is then delivered to the depot in Milano using diesel powered **Euro VI trucks**. The main characteristics of this power plant are reported in the table below. This hydroelectric power plant is different from the one considered in the first solution: in fact, it uses the flow of river **Adda** instead of the potential energy. The choice of this power plant was driven by its short distance from Milano, that could make transport of H_2 faster and more efficient.

2.2. Photovoltaic Power

2.2.1. PV Plant in Puglia, Transport of Hydrogen

In this case, we decided to place the hydrogen production in the already present solar park near **Troia (FG)** in **Puglia**. This solution allowed us to collect a greater amount of solar energy, thanks to a warmer and sunnier climate and a more favourable angle of incidence (the nearer to the equator, the better). The hydrogen is produced on site, so the problem would be to move it to the depot in **Milano**, with a consequent increase in **transportation costs** and CO_2 **emissions**. In Table 2.6 are showed some important cost values, while in Table 2.7 are shown the assumptions made about the efficiency of the system.

Constant	
Electricity cost [€/kWh]	0,22
Electricity Selling revenue [€/kWh]	0,10
Cost of battery [€/kWh]	122,13
Hydrogen transportation cost [€/kg]	3,00
Cost of a solar panel [€]	811,88
Hydrogen storage cost [€/kg]	0,04
Compression [kWh$_el$/kWh$_{H_2}$]	0,10

Table 2.6: *Useful cost constant*[4, 6, 10]

Efficiency assumptions	
BESS Charging efficiency [%]	$95,00$
BESS Self discharge [%]	$90,00$
BESS discharge [%]	$97,00$
Plant efficiency [%]	$80,00$
RTE efficiency [%]	$83,00$
Energy required [MWh]	$23,72$

Table 2.7: *Phototovoltaic and BESS efficiency assumptions*[9, 10, 14]

In Table 2.8 is possible to see the irradiation coefficients of the chosen plant.

Month	Days	H $[kWh/m^2 \cdot month]$
1	31	$105,68$
2	28	$108,01$
3	31	$125,45$
4	30	$176,99$
5	31	$193,44$
6	30	$187,80$
7	31	$215,53$
8	31	$204,94$
9	30	$165,46$
10	31	$135,13$
11	30	$121,34$
12	31	$112,82$

Table 2.8: *Irradiation coefficient per month in Puglia*[12]

2.2.2. PV Plant in Milano, Electrolyser in the Depot

In this other case study the PV plant is built on the roof of the depot in Milano: the situation will be reversed with respect to the previous one, having in northern Italy a lower irradiation coefficient (see Table 2.9). This will penalize the solution from the point of view of the collected solar energy, but at the same time it will have lower transportation costs, because the PV plant, the electrolyser and the depot are all in the same site.

Month	Days	H $[kWh/m^2 \cdot month]$
1	31	$20,60$
2	28	$33,90$
3	31	$57,40$
4	30	$90,90$
5	31	$136,50$
6	30	$145,20$
7	31	$184,80$
8	31	$184,40$
9	30	$147,90$
10	31	$85,40$
11	30	$32,10$
12	31	$22,50$

Table 2.9: *Irradiation coefficient per month in Milano*[12]

In both cases we will face out with the problem of storing energy as electricity (with a BESS) or as hydrogen, producing more hydrogen of the necessary, to eventually sell it.

3 | Technical Evaluation

We will now describe in detail, for each main case, the different results of the proposed solution. Firstly, we computed the requested energy and hydrogen to run **10** trucks per 500 km/day, as we can see in Table 3.1.

Energy Requirements	
Number of trucks	$10,00$
Km per day	$500,00$
Total daily request of H_2 per depot [kg]	$363,00$
LHV H_2 [kWh/kg]	$33,31$
LHV H_2 [MJ/kg]	$119,92$
PEM efficiency	$65,00$
Energy request [MJ]	$47.882,46$
Energy input [MJ$_{el}$]	$73.665,32$
Energy input [MWh$_{el}$]	20.46
Energy input per truck [MWh$_{el}$]	2.05

Table 3.1: *Computation of requested energy to move the trucks*

3.1. Hydroelectric PP

3.1.1. Crodo

This solution is based on the use of electric energy provided by the hydroelectric power plant in Crodo (VB). The analysis has been based on a well-to-wheel methodology, whose main steps are the following:

- Production of green electricity in Crodo;
- Transmission of electricity from Crodo to Milano;
- Production of H_2 on site, with **PEM electrolyisis**;
- Compression of H_2;
- Storage of H_2

In Table 3.2 is possible to see how the chosen electrolyser can be exploited to produce all the needed H_2 by the depot in **11 hours**. This production has been performed during the night, offering a lower cost of electricity to the owner of the depot. The needed electric energy has been transmitted from Crodo to Milano via the existing grid. The 363 **kg** of H_2 have then been stored in a tank inside the depot to refuel the trucks. This solution offered the advantage to be with **0 emissions**, not considering the CO_2 needed to produce the electrolyser and the tank. However, as will be discussed in the next section, this solution implied that the depot owner is the owner of the electrolyser, a huge investment that will strongly influence the specific price of hydrogen.

PEM electrolyzer near the depot	
Maximum H_2 production [kg/h]	36,00
Hours to satisfy demand	10,08
Working hours [h]	11,00
Maximum power [kW]	2.350,00
Production to satisfy demand in 11h [kg/h]	33,00
Actual Power [kW]	2.154,17
Energy (considering compression) [MWh]	23,72

Table 3.2: *PEM Electrolyser exploitment and consumption*

3.1.2. Trezzo sull'Adda

This second solution is based on a more straightforward approach with respect to the first: hydrogen is bought directly from the producer, so the owner of the depot did not have to sustain any type of cost related to the electrolysis process. The 363 **kg** of hydrogen have been transported daily from the production site in Trezzo sull'Adda, at **40 Km** from Milano.

The transport has been performed using **Euro VI** trucks, with an emission factor of 94 $\mathbf{g}_{CO_2}$**/km**; travelling for **80 km** each day, so the total emission would be of $7,5$ kg$_{CO_2}$/km. Of course, this solution is not with **0 emissions**, but at the present time it is more easily applicable with respect to the first one proposed for three main reasons:

1. the transmission of energy that's completely renewable is easier, being the electroyser located in the production site;
2. the transport of gaseous hydrogen is something that is already a reality on the market;
3. the investment cost of this solution is 0 for he logistics company;

3.2. Photovoltaic PP

We decided to use photovoltaic panels provided by EnelX, which specifications can be seen in Table 3.3.

Solar panel data	
Nominal power [W]	375,00
Surface [m_2]	1,84
Weight [kg]	18,50
Efficiency of the panel [%]	20,10
Cost of the panel [€]	811,88

Table 3.3: *Solar panel technical specifications* [10]

3.2.1. Puglia

We now start the discussion about the installation of a PV plant in Puglia, recalling Table 2.7 and 2.8 for details about the input data. First of all, we sized the PV plant: we computed the energy generated (Table 3.4) and then we sized the plant (Table 3.5).

Month	E_{req} [kWh]	$E_{gen_{PV}}$ [kWh]	ΔE [kWh]
1	904.902,26	668.557,89	-207.334,01
2	817.331,07	683.298,04	-111.802,08
3	904.902,26	793.627,81	-88.517,58
4	875.711,86	1.119.682,63	248.410,76
5	904.902,26	1.223.749,41	320.097,94
6	875.711,86	1.188.069,37	313.378,16
7	904.902,26	1.363.496,23	452.857,41
8	904.902,26	1.296.501,26	389.212,20
9	875.711,86	1.046.740,99	179.116,20
10	904.902,26	854.865,89	-30.341,41
11	875.711,86	767.626,93	-86.042,16
12	904.902,26	713.727,30	-164.423,07

Table 3.4: *Energy generated from the PV plant in Puglia*

As we can see, in the months of January, February, March, October, November and December we produced less energy than the required amount: this is reasonable, because in winter months the solar radiation is lower with respect to the summer months. We tried to store the energy in excess to avoid to buy it from the grid, but the dimension of the batteries was above 250.000 kWh, which corresponded to approximately 2 million €, as we will see in the next chapter. This would have led to a large outlay in economic terms, in addition to having to look for a large enough area where to place all the batteries.

PV Plant Sizing	
Installed PV power [kW]	28.755,67
Oversized PV power [kW]	31.631,24
Number of panels	84.350,00
Battery Capacity [kWh]	249.995,79

Table 3.5: *Size of the PV plant in Puglia*

For these reasons, we decided to switch to a storage of hydrogen. We computed the hydrogen that we could produce with the available energy from the PV plant (see Table 3.6) and we obtained that, each year, we produced a surplus of 24.860 kg of hydrogen. In this way we could store the surplus that we need to fill our depot (9.220 kg) and sell the remaining amount (13.010 kg). Then the hydrogen was sent to the depot in Milano, via a truck that can transport the needed 363 kg.

Month	$H_{2_{req}}$ **[kg]**	$H_{2_{gen_{PV}}}$ **[kg]**	ΔH_2 **[kg]**
1	17.312,31	13.046,01	-4.266,30
2	15.636,92	13.333,65	-2.303,28
3	17.312,31	15.486,58	-1.825,72
4	16.753,85	21.849,11	5.095,26
5	17.312,31	23.879,83	6.567,52
6	16.753,85	23.183,58	6.429,74
7	17.312,31	26.606,80	9.294,49
8	17.312,31	25.299,48	7.987,18
9	16.753,85	20.425,75	3.671,90
10	17.312,31	16.681,56	-630,75
11	16.753,85	14.979,21	-1.774,64
12	17.312,31	13.927,43	-3.384,88

Table 3.6: *Hydrogen request and generation for the PV plant in Puglia*

3.2.2. Milano

As before, we started with the sizing of the plant, so we recall Table 2.7 and 2.9. The result can be seen in Table 3.8 and 3.7. Again, we faced out with the problem of low production in the winter months, and also with the batteries that in this case reach a cost of approximately 6 million €. Again, we decided to switch to hydrogen storage (see Table 3.9): more in detail, we stored 33.264 kg of hydrogen and sold 9.643 kg.

Month	E_{req} [kWh]	$E_{gen_{PV}}$ [kWh]	ΔE [kWh]
1	904.902,26	211.484,62	-641.553,61
2	817.331,07	348.025,66	-430.310,85
3	904.902,26	589.282,39	-282.645,74
4	875.711,86	933.201,55	71.253,73
5	904.902,26	1.401.342,26	488.811,14
6	875.711,86	1.490.658,58	600.837,91
7	904.902,26	1.897.201,83	959.877,73
8	904.902,26	1.893.095,33	955.976,56
9	875.711,86	1.518.377,44	627.170,82
10	904.902,26	876.737,21	-9.563,65
11	875.711,86	329.546,42	-502.218,64
12	904.902,26	230.990,48	-623.023,04

Table 3.7: *Energy generated from the PV plant in Milano*

PV Plant Sizing	
Installed PV power [kW]	46.664,74
Oversized PV power [kW]	51.331,22
Number of panels	136.884,00
Battery Capacity [kWh]	773.561,96

Table 3.8: *Size of the PV plant in Milano*

Month	$H_{2_{req}}$ [kg]	$H_{2_{gen_{PV}}}$ [kg]	ΔH_2 [kg]
1	17.312,31	4.126,84	-13.185,47
2	15.636,92	6.791,25	-8.845,67
3	17.312,31	11.499,06	-5.813,25
4	16.753,85	18.210,18	1.456,33
5	17.312,31	27.345,32	10.033,01
6	16.753,85	29.088,20	12.334,36
7	17.312,31	37.021,35	19.709,04
8	17.312,31	36.941,22	19.628,91
9	16.753,85	29.629,10	12.875,25
10	17.312,31	17.108,35	-203,96
11	16.753,85	6.430,66	-10.323,19
12	17.312,31	4.507,47	-12.804,84

Table 3.9: *Hydrogen request and generation for the PV plant in Milano*

4 | Economic Evaluation

In this chapter we will provide an economic evaluation of the proposed solutions, focusing on the specific cost in €/kg_{H_2} and in €/MJ_{H_2}. The purchase cost of the HD trucks has been considered for each case study: hydrogen trucks, provided by Nikola, cost 268.782 €, while Scania diesel trucks (Euro VI) costs around 153.000 €. The cost of the compressor is included in the cost of compression.

4.1. Hydroelectric PP

4.1.1. Crodo

The first assumption of this analysis regards the costs to be sustained to provide the electricity to the electrolyser in the depot. As already said, there is the need to consider both a specific cost for kWh and a transmission cost. Those costs are summarised in Table 4.1[14].

Specific Costs	
Electricity cost [€/kWh]	$0,11$
Mean EU distribution cost [€/kWh]	$0,03$

Table 4.1: *Specific costs*

One of the most impacting factors of this solution is the **electrolyser** Since it needs to be bought by the logistics company, its cost has a non negligible impact on the final cost of H_2. The considerations done on this aspect are summarised in Table 4.2[6].

PEM investment	
Mean investment cost PEM [€/kW]	$1.921,50$
Investment cost [€]	$4.139.231,25$
Mean life of the plant [h]	$40.000,00$
Mean life of plant [days]	$1.666,67$
Daily investment cost [€/day]	$2.483,54$

Table 4.2: *PEM investment cost [6, 8, 14]*

Another step to be considered is the compression of H_2 after its production by the electrolyser. This has been assumed in 0.03 €/kWh[14]. The last aspect to be considered is storage; the tank has a cost of 945 € and the specific cost of storage has been considered to be **2.61 €/kg**. After all of the considered steps, the final costs are computed on a daily basis and summed together. The results are resumed in Table 4.3.

Daily costs	
Total cost of electricity [€/day]	$3.361,42$
Daily investment cost [€/day]	$2.483,54$
Total cost of storage [€/day]	$217,80$
Cost of tank [€]	$945,78$
Total daily cost [€/day]	$6.065,35$

Table 4.3: *Daily costs*

The last step is to arrive to specific costs, considering the daily request of H_2. In Table 4.4 is possible to see how the cost of H_2 per MJ is higher than diesel ($0,03$ €/MJ considering a price of $1,55$ €/l), making this solution not convenient in the present times. The main variable that can make this solution more convenient is the specific cost of the electrolyser, which is one of the most impacting factors in this economic evaluation.

Unitary costs	
Unitary cost for each truck [€/day]	$606,54$
Specific cost [€/kg$_{H_2}$]	$16,71$
Specific cost [€/MJ$_{H_2}$]	$0,14$

Table 4.4: *Specific costs*

4.1.2. Trezzo sull'Adda

This solution avoids the most critical cost considered in the previous one, the electrolyser. In fact, it is considered as an asset of the H_2 dealer, and not of the logistics company. The chain here starts with the purchase of green hydrogen produced in Trezzo sull'Adda. The cost of green hydrogen on the market is, as of today, 4 €/kg. At first, this value is very intriguing since if we consider it in €/MJ, H_2 has a cost of 0.03, the same of diesel. However, in our solution, the value chain that needs to be considered needs to take into account also hydrogen transport and storage.

For this two steps, the considered costs are summarised in Table 4.5[8].

Costs of transport and storage	
Cost of transport [€/kg]	3,00
Cost of tank [€]	945,78
Cost of storage [€/day]	13,44
Total cost [€/day]	2.676,03

Table 4.5: *Costs of the solution*

Considering all the value chain, the specific cost of H_2 rises, arriving to a value of 0.06 €/MJ, higher than diesel but lower than the previous solution. The most impacting factors here are, of course, transport and purchase of hydrogen. Since, however, the actual solutions for transporting hydrogen will pretty much not change in the future, a sensitivity analysis can be made on the price of green hydrogen. The sensitivity analysis, reported in Table 4.6, shows what the cost of green H_2 per MJ on the market should be for it to be competitive with diesel. The fact that the price needs to drop of almost the 80% makes this solution **unfeasible**, at least in the present times.

How much should H_2 cost to be comparable with diesel?		
Cost of green H_2 [€/kg]	Specific cost [€/kg]	Specific cost [€/MJ]
0,95	**4,18**	**0,03**
1,00	4,23	0,04
1,50	4,75	0,04
2,00	5,28	0,04

Table 4.6: *Sensitivity analysis*

4.2. Photovoltaic PP

4.2.1. Puglia

The computation, as showed in Table 4.7, started with the cost of the main facilities such as the photovoltaic panels, a life time of 20 years, resulting in a cost per year of 1.159.840 €/year. The total cost of the storage process (compression from 20 to 700 bar) was of 10.941 €/year. Due to the transportation of the produced hydrogen it is necessary to take into account the cost of transport of 397.485 €, and also the indirect cost connected with the emission of 53 tons of CO_2. The obtained surplus of hydrogen has been sold with revenues of $52.040, 86$ €, obtained considering a cost of green H_2 on the market of 4 €/kg[28]. The direct use of the hydrogen as an energy carrier, instead of the electricity, avoided the use a BESS and produced yearly savings of $2.035.465, 73$ €.

Specific cost computation - Puglia	
Daily investment cost	11.930,46 €
Total cost of storage per day	29,97 €
Cost of transportation per day	1.089,00 €
Total daily cost	12.906,85 €
Daily cost for each truck in the depot	1.290,69 €
Specific cost [€/kg_{H_2}]	36,56
Specific cost [€/MJ_{H_2}]	0,30

Table 4.7: *Specific cost computation for the PV plant in Puglia*

4.2.2. Milano

The reasoning for this solution is pretty the same as for the photovoltaic plant in Puglia: we had a cost of 1.882.155 € for the PV plant , while the revenues from hydrogen was 52.040 €. In this case there were no transportation costs and no emissions. In Table 4.8 the specific costs can been founded.

Specific cost computation - Milano	
Daily investment cost	17.944,74 €
Total cost of storage per day	108,11 €
Total daily cost	17.947,16 €
Daily cost for each truck in the depot	1.794,72 €
Specific cost €/kg_{H_2}	49,44
Specific cost €/MJ_{H_2}	0,41

Table 4.8: *Specific cost computation for the PV plant in Milano*

5 | Conclusions

In order to assess which of the previously developed cases is the most convenient, we compared their relative economic costs and the eventual CO_2 emissions. Moreover, we also considered a realistic situation where only diesel trucks are employed (corresponding to the most common solution preferred nowadays), so to understand if there are any possible improvement margins and where to act, with the aim of making green solutions comparably convenient to the traditional ones. For sake of simplicity we calculated emissions in standard diesel case as produced by the logistic service provided by trucks, so not comprehensive of the WTT analysis (not being the purpose of our project).

	Unitary cost [€/MJ]	**Unitary cost [€/kg]**	**Total cost [€/year]**
Crodo	0,14	17,72	2.348.244,67
T. S. Adda	0,06	8,39	1.111.140,57
PV - Puglia	0,30	36,57	4.845.392,65
PV - Milano	0,41	50,46	6.685.106,18
Diesel	0,03	1,86	1.019.416,67

Table 5.1: *Resume of total and unitary costs*

	CO_2 emissions [kg]	**CO_2 reduction [%]**
Crodo	2.390.043,74	99,13
T. S. Adda	5.134.843,74	98,13
PV - Puglia	53.729,46	99,98
PV - Milano	0,00	100,00
Diesel	273.969.000,00	0,00

Table 5.2: *Resume of CO_2 emissions*

In Table 5.1 and 5.2 are provided all the resumed information. It can be immediately noticed that, among green hydrogen production solution, hydroelectric cases appear to be cheaper with respect to the PV plant ones. This result is given by two factors: hydroelectric plants are already built, while in the case of photovoltaic systems we need to install new panels in order to feed our logistic node, but also because solar energy provision is not constant during the year, so a storage of energy (in form of electricity or hydrogen) is required. In fact, winter production can only partially respond to the demand of trucks, that we assumed to be constant along the year. Since a storage of electricity represented an excessive cost, we turned to gaseous hydrogen storage, that is more convenient, but requires also additional expenses for compression. This issues does not appear in the electricity production from dams, because the dams themselves are potential energy storage that can be spilled when needed.

What makes the Trezzo sull'Adda solution even more convenient than the Crodo one, is the external production of hydrogen from other private parties (who can make economy of scale for their processes costs) that we just buy. Assuming a shipment of the gas using traditional HD trucks, we show how emissions significantly increase. It must be specified that even though electricity production from hydroelectric plants is fully sustainable, the consumption done by our fictitious company would force actual consumers to buy their power supply from the national grid (ecological worst case scenario), so our first two solutions cannot be said to be fully eco-friendly, but a significant reduction of CO_2 emissions would be achieved.

Analysing the PV plant solutions, only the Milano plant would grant zero emissions, because it is the one of the two not requiring a hydrogen transportation, which is a very impacting aspect also when calculating the annual cost. It can be reasonably assumed that a local production and usage of hydrogen in Puglia, not requiring shipment costs, would be even more convenient thanks to the higher irradiation factor available, but it could not be coupled with alternative green energy sources as it can be done in Milano.

In the Crodo solution we can see that the higher reducible cost is the electrolyser's but it appears that even a reduction of its cost of 100% would not make this case as convenient as the diesel one; the only other relevant feature is the cost of electricity bought from the grid, but it cannot easily be forecasted.

The most relevant cost in Trezzo sull'Adda case is the hydrogen purchase. By the way the annual cost of this case is already comparable with the one of the diesel case, making this solution already competitive for commercial purposes. Unfortunately this model is applicable only in the specificity of our location because what makes it convenient is a combination of short distance Hydrogen shipment, hydroelectric plant coupled with an electrolyser big enough to produce green Hydrogen at reasonable costs.

Finally, the main cost of the PV plants, as it can be easily guessed is the panel's one, but only a reduction of 100% (obviously not a realistic case) of the cost would make these solutions comparable with the traditional one.

In conclusion, we assessed that conventional technologies nowadays are still more convenient than most of hydrogen production strategies and the gap can be filled only by **reducing economical costs** of many different features, since we assessed that acting on just a single element is not enough to reach the goal.

More research must be done, and in order to foster societal use and private investments, a public intervention is required. Moreover, it must be kept into account that in the nowadays renewable landscape no technology is outperforming others; consequently the optimal solution must be evaluated time by time taking into account location and goals.

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List of Figures

List of Tables