Politecnico di Torino

Master of Science in Energy and Nuclear Engineering
"Renewable Energy System"

Hydrogen conversion of a diesel locomotive:

The rebirth of a Vossloh G2000

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Abstract

Today's society is constantly looking for solutions to reduce the continuous increase in emissions into the air and the train has always been seen as the most environmentally friendly means of transport for handling large quantities of people and goods on long journeys. In this work a description will be made of the current situation in Italy regarding the railway lines, especially those related to freight transport, and showing how locomotives with diesel propulsion still exist and continue to be produced, having regard to the non-electrification of almost 20% of the lines currently in use.

The analysis will focus on a locomotive in particular, the German Vossloh G2000 now always directed towards a lower use due to seniority but that has been the symbol of diesel transport on rail thanks to its power and regularity. After a technical description, the main problems or defects will be described.
The goal is to convert it to a hydrogen propulsion and analyse whether it could work on a practical level, while maintaining the same performance and trying not to impact the entire weight of the same.

We will then describe the main technologies available to achieve a hydrogen propulsion, in particular will be given a description of the main types of fuel cells currently on the market with a focus on the PEM type, that is the one suitable for the transport sector. And the main hydrogen storage solutions with their strengths and weaknesses will also be described.

Then, returning to the chosen locomotive, each unnecessary component will be removed in order to recover an acceptable volume of work. All the various components will be sized in such a way as to realize a conversion without changing its performance.

To make the best use of the spaces, the solution will be adopted is to divide the required power on four 560 kW electric motors mounted directly on each axis of the locomotive. It will be shown how the addition of all the various components, including a battery pack that can provide an autonomy of half hour, will not affect in a negative way the total weight.

At the end of all these analyses will be considered two real railway sections, the Sannazzaro-Alessandria and the Orbassano-Modane, two routes with completely different characteristics, one in the plain and one uphill, and by exploiting the data on locomotive performance and structure limits, an approximate calculation of possible hydrogen consumption will be made.
In the case of plains, consumption will be obtained in line with the European guidelines on hydrogen locomotives, that declare a consumption of about 0,9 [kg/km], while in the case of mountains consumption will be four times higher, justified by the fact that this section is never run with a single locomotive for the chosen load, of 1200 tons.

In conclusion, it has been demonstrated how it is possible to convert such locomotives to a new and clean propulsion, even if at an economic level it has not been possible to perform an analysis of the costs and the possible times of economic return.

Summary

1. Introduction

The idea of this argument born from the working experience performed at a private railway company that offer in the market both the goods transport on rail and the maintenance of their locomotives and for other competitors.

In particular, the maintenance branch had a very big specialization on the maintenance of diesel locomotive e this let me the possibility to know very well pros and cons of this vehicle. Having to analyse daily the dates of these vehicle, considering also damage or recurrent failures, I had the possibility to study in depth on the most disadvantages of this technology and think about a possible solution.

The essay purpose is to describe the actual structural situation of the Italian railway network, in particular the percentage not electrified, that force always the various railway company to adopt different solution respect the classical electrical locomotive with pantograph[1] in order to move inside this part of network. The successive part takes into account a diesel locomotive, will describe the defects or recurrent failures, and will try to remove all the traction section fuelled with diesel in order to substitute it with an innovative powertrain with fuel cell powered by hydrogen.

Actually, already exist different project of hydrogen locomotives, someone just in experimentation phase, but all consist of the construction of new means. In this essay, instead, the goals fixed is to take an old diesel locomotive and transform it to a new one in order to follow the way of recycling or re-utilization of that locomotive, considering that respect to car, motorcycle or camion they have a very long life and very high investment cost that can justify the cost of the project.

[1] Pantograph: device positioned on the upper part of a locomotive used to absorb electrical energy from the network. It composed by an articulated structure that let have a small mobility in order to guarantee a safe contact all the time and its operation are guaranteed by a small compressor.

The last point, as every project require, will be done an economical evaluation of all the work and decreeing if it is possible to save these locomotives from the demolition or is better to use them in this mode until the end.

2. The Italian railway networks

From always the rail transport is seen as a rapid, safe, ecological and relatively cheap way to travel.

In general, we can subdivide the usage of the railway in two categories:

- Passenger
- Goods

It is easy know them by the name, the first use locomotive with some passenger wagon, often integrated inside the locomotive, and let us to move rapidly between two localities. Meanwhile, the second is used to moves very huge amount of goods from the producer to the user, very important for the import and export of the country.

Watching the ISTAT data is possible to observe as the goods category makes less kilometres yearly respect the passenger one, it has a weight of around 13% moving almost 93 million tons of goods of different type ([01], 2021).

	Seleziona periodo	2019		
	Dimensione impresa	grandi imprese ferroviarie	piccole e medie imprese ferroviarie	tutte le voci
Tipo dato	Tipo di trasporto			
passeggeri trasportati	tutte le voci	883 300 306	15 171 992	898 472 298
passeggeri-Km (migliaia)		56 160 096	426 319	56 586 415
percorso medio di un passeggero in km		63.6	28.1	63
movimento di treni passeggeri - treni-km (migliaia)		337 121	10 243	347 364
movimento di treni merci - treni km (migliaia)		47 943	486	48 429
percorrenza media delle merci (Km)		225.9	232.5	226
merce trasportata - tonnellate	interno	33 187 539	995 998	34 183 537
	Internazionale (in entrata)	36 376 781	243 052	36 619 833
	Internazionale (in uscita)	23 375 513	115 699	23 491 212
	transito	0	0	0
	tutte le voci	92 939 833	1 354 749	94 294 582
merce trasportata - tonnellate-chilometro (migliaia)	interno	10 597 826	190 547	10 788 373
	Internazionale (in entrata)	6 558 719	89 269	6 647 988
	Internazionale (in uscita)	3 837 495	35 142	3 872 637
	transito	0	0	0
	tutte le voci	20 994 040	314 958	21 308 998

Figure 1: Italian railway transport in 2019 ([01], 2021)

From the table we can deduce as in Italy is common still exploit very little this type of good transport and I demonstrated also by some analysis in 2019 in which results that only the 17% of the goods is moved by rail, meanwhile the remaining 73% is moved by tyre respect a European average a bit higher ([02], 2019).

These data are not justified because there is a multiplicity of advantage respect to tyre:

- Reduced timing
- Convenience
- Elevated security
- Decongestion of highway
- Movement of big quantity of goods for long distance
- Reduction of emission

That last point will be one of the crucial points of the essay and below is shown a comparison between rail and tyre for a same quantity of good:

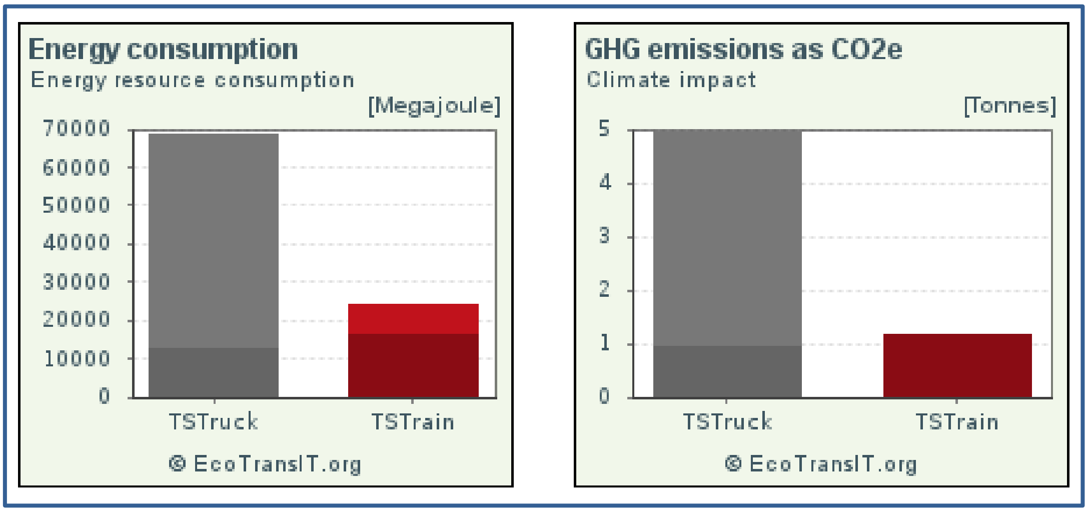

Figure 2: Emission comparison between tyre and rail ([03], 2021)

The data about rail's emission is not null both because the rail can be of electrical or diesel type and also transport produce small quantity of pollution from friction, product for lubrification of axle[2], etc.

[2] Axle: In a rail vehicle is defined as axle the part composed by two wheel and one axis used to let the locomotive move on the railway. They are generally characterized by the internal length, the radius of the wheel and the rate of fill.

Considering in general all types of transport and relating emission, a study of the European Environment Agency (EEA) of 2018 has relived that the 25% of the emission at European level is caused by the transport sector. In which the 72% of emission is due by the road transport, the 14% by marine transport, the 13% by air transport and the 0.4% by railway, that is composed almost for the total by the emission of diesel locomotive.

The reason why the usage today of diesel locomotive is not caused by economical fields, like the amortization of the investment cost on the larger time scale possible. In fact, still today are produced diesel type locomotive of last generation with device act to reduce the emission, already used in cars, like start&stop, eco mode or the usage of the diesel engine in order to produce electricity and power the electrical engine, for example 744 loco produced by CZ Loko or DE18 produced by Vossloh.

Figure 3: Locomotive 744.704 produced by CZ Loko ([04], s.d.)

The reason of the usage of these types of propulsion still now have to been searched at infrastructural level, in fact the electrical transport requires the presence of a railway electrified in order to connect with the pantograph and power the locomotive.
Actually, in Italy is present a very big rail network for a length of 16.782 km that arrives in each corner of our country, but only 12.065 km are electrified ([05], 2021).

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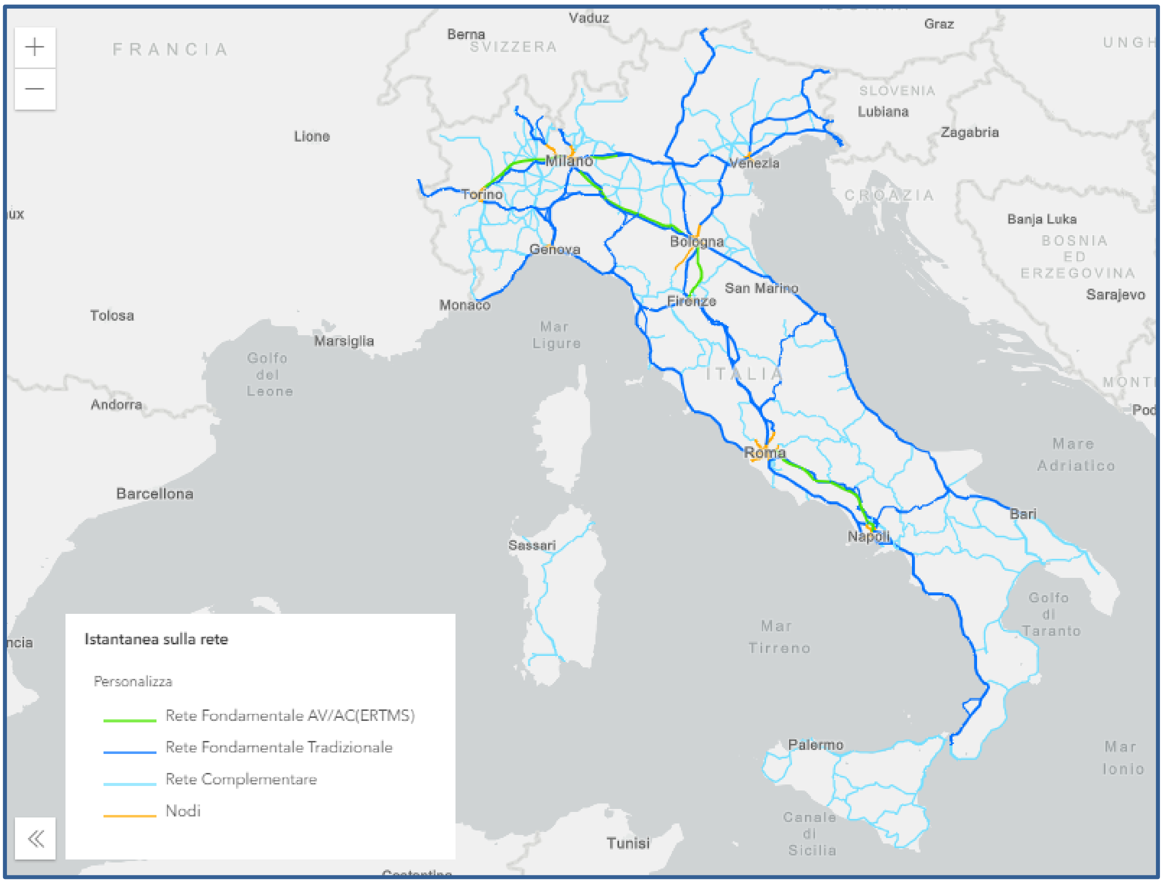


Figure 4: The Italian rail network ([05], 2021)

This means that the 18.11% of the actual used network is not electrified and require the usage of means with a propulsion system independent by the electrical network, and that bind us to the use of diesel engine.

Some vehicles of last generation try to reduce this infrastructural problem implementing new system called “LAST MILE”, that is a normal vehicle with a secondary system installed able to move the locomotive for short distance and powered by batteries or diesel.

In general, they are only small system with small autonomy e doesn’t guarantee the movement for long distance, fact that cause their name.

The distribution of the non-electrified wire is not homogenies on the entire Italian territory but exist also two regions without electrified rail at 100%.

	Chilometri di linee Diesel	Percentuale
Sardegna	430	100%
Val d'Aosta	81	100%
Molise	205	77,3%
Calabria	363	42,6%
Sicilia	578	41,9%
Abruzzo	206	39,3%
Basilicata	136	39,1%
Veneto	406	34,1%
Trentino Alto Adige	67	34%
Marche	118	30,5%
Piemonte	552	29%
Puglia	235	27,9%
Campania	240	21,9%
Toscana	503	18,8%
Friuli Venezia Giulia	84	17,7%
Lombardia	283	16,3%
Lazio	103	8,4%
Emilia Romagna	85	6,5%
Umbria	21	5,5%
Liguria	17	3,4%

Figure 5: non-electrified railway per region ([06], 2017)

3. Diesel locomotives e common problem

A diesel locomotive is a combustion engine vehicle, a very old technology after the steam one. They have been very common in the rail traction due to the old and known technology but also because they need only a railway to move.

Actually, they are used very much but the electrified version by a lot of year a become more famous. The reason is easy to deduce: old technology, high emission and a lot of issue.
As the car market impose, also in railway are growth law and classes on emission, also for gallery way and so a diesel locomotive finds its biggest problem. For example, the Vossloh/Imateq constructor have introduced a “Gallery mode” that is a modality in which the emission of the locomotive is reduced up to 50% reducing a bit the maximum power of the engine.

Another of the biggest problem is related to filters, in fact these sizes of engine require a lot of filters both for fuel and oil. In general, they have at least a ten of filter that require a constant substitution or clean that if not performed can cause the stop or not start of the vehicle. In addition, often the railway enterprise tends to use fuel of low cost that are always dirty and fill the filter quickly.

Other important problem is the cost of fuel that is subject to a variation during time and a fast increasing can compromise the usage. Or at structural level a heat engine requires, respect to an electrical engine, also the presence of a gearbox and transmission, all these parts together need a particular and regular maintenance and are subject with more probability to issue.

3.1. The Vossloh G2000

To proceed with the work, we need before to choose the locomotive that we want to modify, and this choice fell on the G2000. It is a locomotive designed in 1998 and the production stated from the 2000's years by the German Vossloh Lokomotiven, the reason why I have choice this model is due by two major reasons: the generously dimensions and simple that simplify the work and the seniority of the means in question.

Is possible to classify together rather vaguely as diesel- hydraulic locomotive, that is a propulsion powered by diesel and a hydraulic transmission. The first model presented was characterized by an asymmetry in the driver's cabin (as showed in picture).

Figure 6: The asymmetric first version of G2000 ([07], 2013)

Later the presentation will be produced a version for the Italian market characterized by the symmetry of the driver's cabin (see the picture below), and the successive production followed that standard for all other markets.

Figure 7: The common form of G2000 ([08], 2020)

The locomotive was designed with a length of 17400 [mm], a width of 3080 [mm] and a high of 4220 [mm], and is characterized by a particular squared form factor and very low aerodynamic.

It was born for a usage for good transport, will be produced with two different engines ([09], 2020):

- Caterpillar engine of 2240 kW
- MTU engine of 2700 kW (for the Scandinavian market)

The version that we will consider is the first. It can reach a maximum velocity of 120 km/h and has a weight of 87300 kg, considering 2/3 of the reservoir. A value relatively high considering that having 4 axis it means that each axle overcome the value of 20 t. This parameter is very important because is one of the parameters that characterized a possible limit in the performance imposed by RFI. The railway network is in fact subdivided by weight/axle that can support, and the groups are represent in the below table, were in red are highlight the value that are used in RFI railway ([10], 2013).

Categoria	Peso per asse in ton/asse	Peso per metro corrente in ton/metro
A	16	5,0
B1	18	5,0
B2	18	6,4
C2	20 (*)	6,4
C3	20 (*)	7,2
C4	20 (*)	8,0
D2	22,5	6,4
D3	22,5	7,2
D4	22,5	8,0
E4	25	8,0
E5	25	8,0

Figure 8: Classification of the railway lines in base of weight/axle ([10], 2013)

These types of categories are assigned to every body that move on railway, locomotive or wagon, but in general this type of analysis is much performed on the wagon. In the project will be kept in consideration also this aspect, and we hope to be able to keep the previous weight or limit the increase at much as possible.

3.2. Engine and hydraulic transmission

As anticipated in the previous chapter, we have taken in consideration the locomotive version equipped with the Caterpillar engine.

In particular the diesel engine is a four-stroke cooled with water and characterized by 16 cylinders with a positioned at V of 60°. The engine built by CAT is a 3516 B DI-TA HD that is able to provide a maximum power of 2240 kW with a rotational velocity of 1800 rpm. Finally, this engine is characterized by a direct injection with a electronic regulation, and as system for the supercharging two compressor that work with flue. The system act to the acoustic dissipation and absorption are installed on the cowling of the same engine.

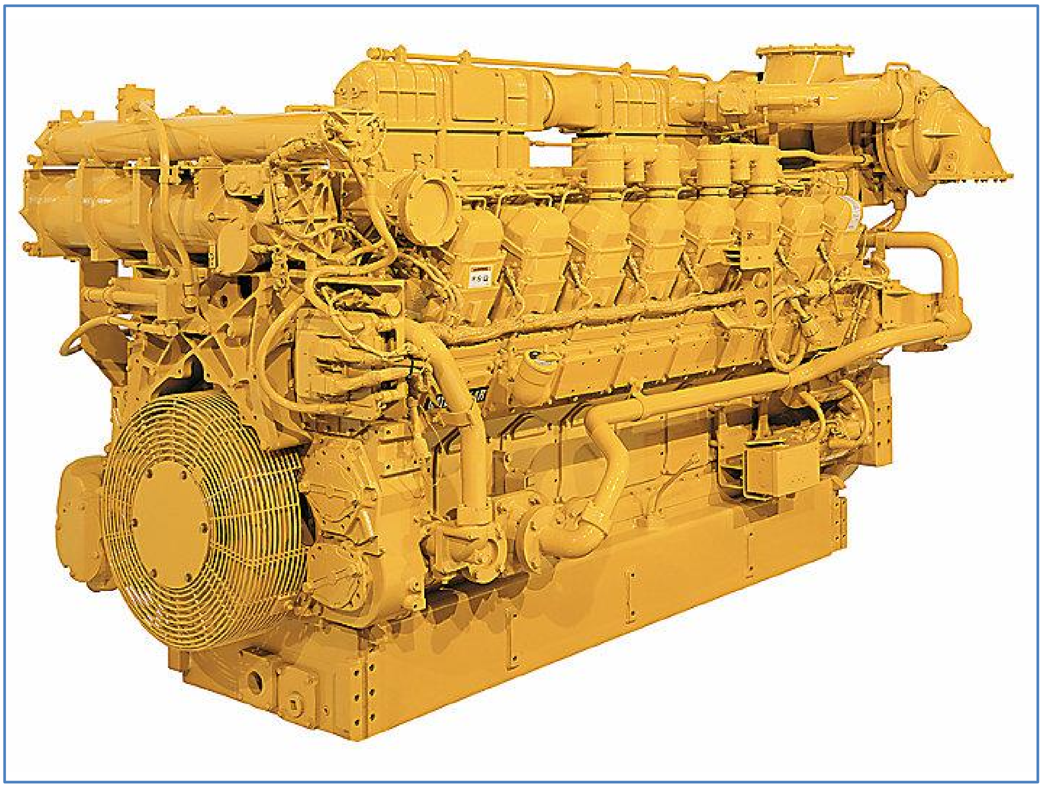


Figure 9: An example of engine of the line 3516 CAT ([14], s.d.)

Unfortunately, it was not possible recover information about the emission's class of this engine on manuals and during the visual inspection on the locomotive one. But it possible to deduce that this engine has a very high production of emission both for the age, the absence of system for the reduction or filtration of flue, like FAP and also for the color and smell of flue.

The power produced by the engine is transmitted to the carts by an automatic turbo-reducer. Produced by the Voith and is the model L620 re U2, that let have an entering power of 2100 kW and a rotational velocity equal to the engine, is composed by two torque converters hydrodynamic and a mechanical inverter of the direction of run. The regulation takes place mean the Voith Turbo Control system, also called VTC, and its logic CPU works in relation to the gear number of the engine and the velocity. At structural level it is positioned vertically in order to connect it directly to the engine with a cardan shaft, the remaining part of the body gets down between the two parts of the reservoir from which are connect the two carts with cardan shafts.

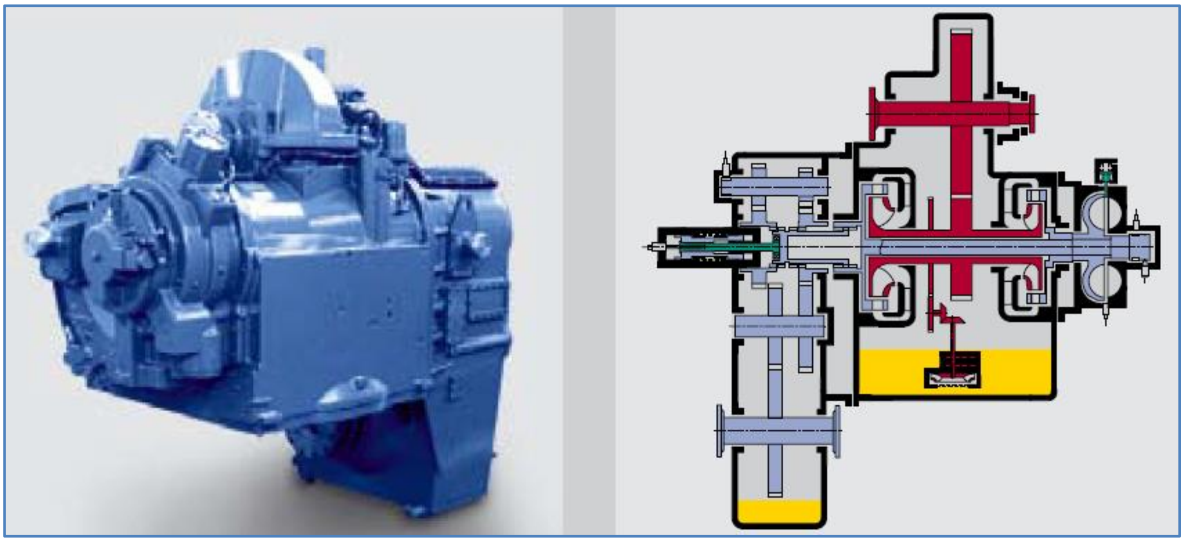


Figure 10: The Voith L620 re U2.

Finally, we found the hydrostatic plant composed by:

- Variable flow pump
- Reservoir with filter
- Hydrostatic module

The major part of the groups are positioned in the module for the cooling system and we can distinguish three circuits:

- Driver generator
- Driver compressor
- Driver fan of the cooling system

To power the three circuits is used the variable flow pumping system mentioned before and the latter is powered by the rotation of another cardan shaft connected horizontally to the turbo-reducer described before ([11], 2003).

3.3. Useful volume for the project

As we have already mentioned in the previous character the choice of the locomotive is due especially to the geometry really simply, that let reduce the difficulty on the placement of the components.

At interior level the simplified structure is repeated, in fact we can easily divide our locomotive in different macro-groups as in the draw:

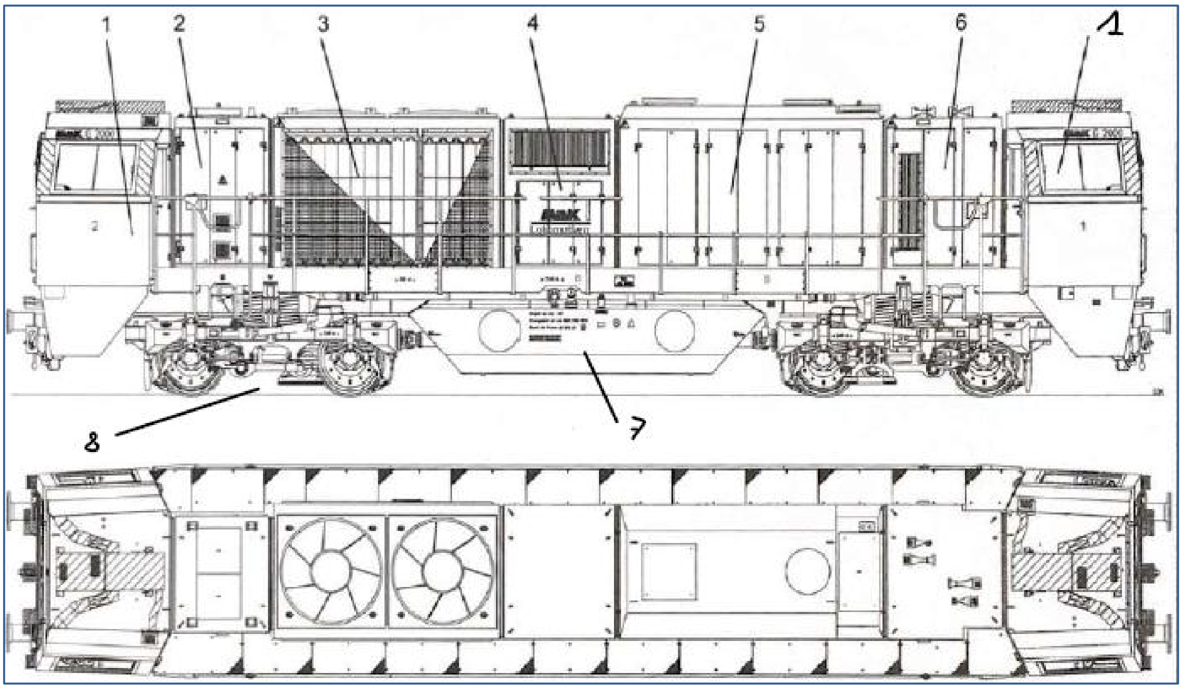


Figure 11: Lateral and top view of the G2000 ([11], 2003)

Below the macro-groups created by us:

1. DRIVER'S CABIN → Used by the driver to maneuver the locomotive. It can contain up to two people seats for each cabin and contains monitor and manipulator in order to control each parameter of the mean.
2. ELECTRICAL MODULE → The section in which are present all the required electrical control element like stotz of power or start and service battery.

3. COOLING MODULE → A sector totally dedicated to the removal of the heat and two fan of huge dimension that cover the entire imperial[3] of that module.
4. GEARBOX MODULE → Section in which is positioned the gearbox produced by the Voith.
5. ENGINE MODULE→ Section dedicated to the engine and various tubes.
6. COMPRESSOR MODULE → Module totally dedicated to air reservoir and compressor. The latter have the object to produce air for the brake system, meanwhile the reservoirs are dedicated to the principal pipe, charged at 8-10 bar, and the general pipe, charged at 5 bar.
7. DIESEL RESERVOIR → Reservoir for diesel of 5000 L, it is composed by two modules united and at the centre is positioned the gearbox at which are linked the carts by cardans shafts.
8. CART → Component composed by two axles whose task is to take the torque force form the gearbox and transmit it to the railway, in order to move the locomotive.

Now, that are been defined well the various parts is necessary to choose how to remove in order to recover as much space as possible.

First at all will be removed the diesel engine module and the gearbox because they will be replaced by an electrical engine. Another module that we can remove is that dedicated to the cooling system, because the heat produced is different and because is possible to implement more modern module with higher efficiency. The resultant space should be the following:

[3] Imperial: Which this word is called the external upper part of the locomotive's box, also called in informal way "roof".

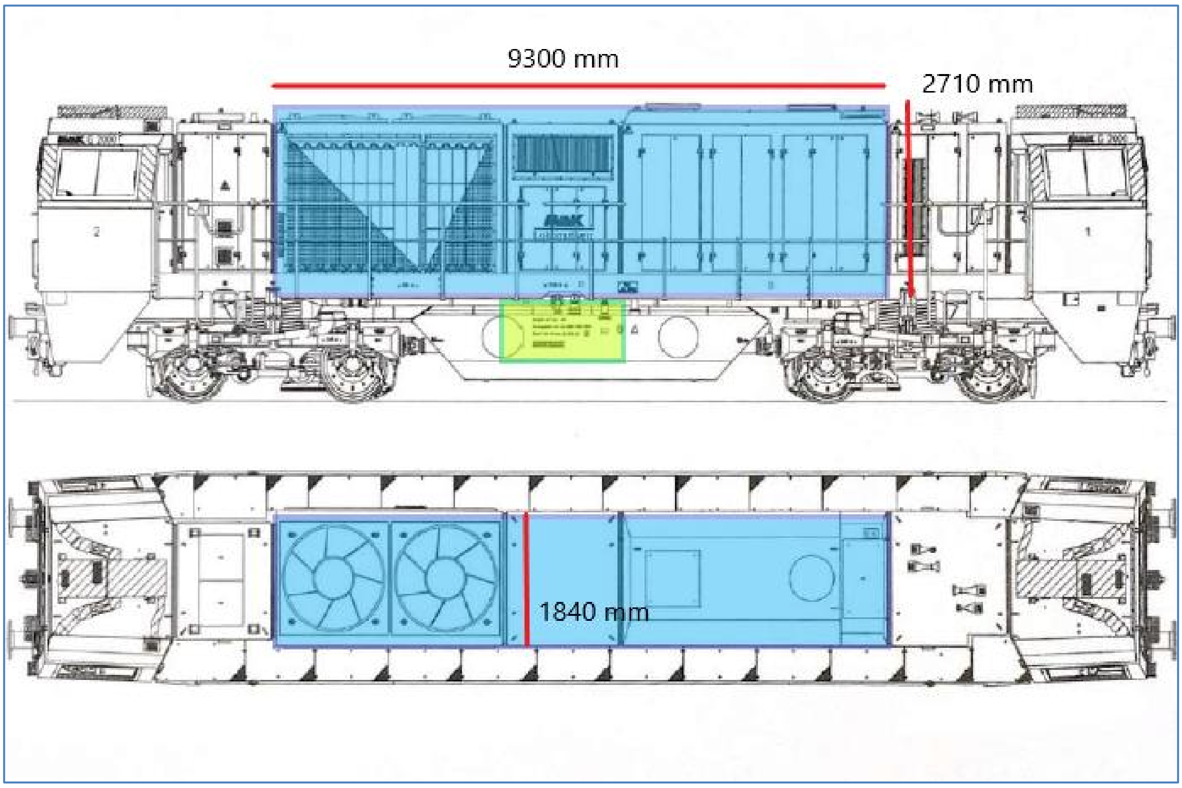


Figure 12: Measures of the useful space for the project ([11], 2003)

As you can see in the draws, we can recover a working area similar to a parallelepiped regular characterized by a length of 9300 mm, a width of 1840 mm and a heigh of 2710 mm that gives us a total volume of 46.37 m^3. In the figure 12 is possible to see a green rectangular, it is the area in which is positioned the gearbox Voith. Positioned in vertical and go down up to the reservoir in order to connect to the carts with cardan shaft, see figure 13.

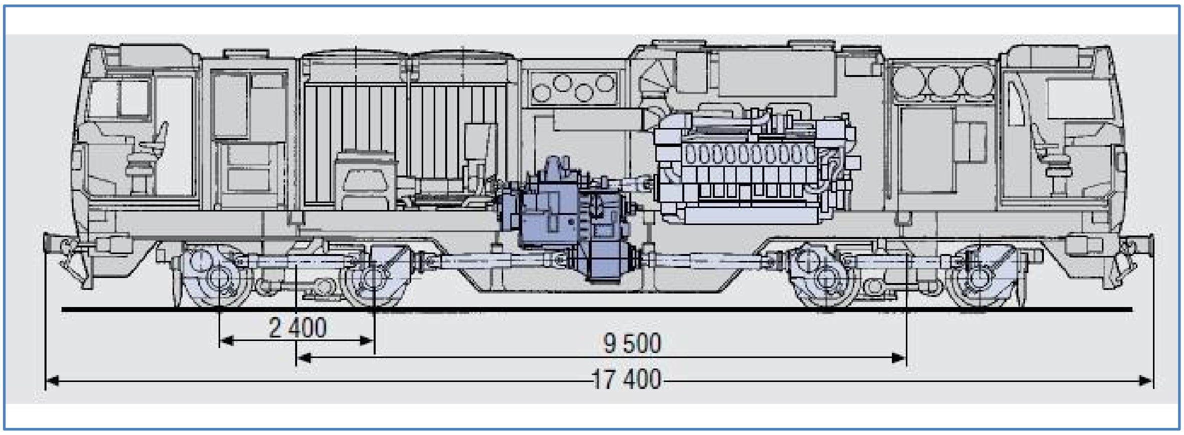


Figure 13: Internal view of the locomotive.

This is possible thanks to the reservoir that is not a single block, but it has a shape divided in two parts, or rather two reservoirs united at whose centre is positioned the gearbox and the cardan transmission, as shown in the following rendering:

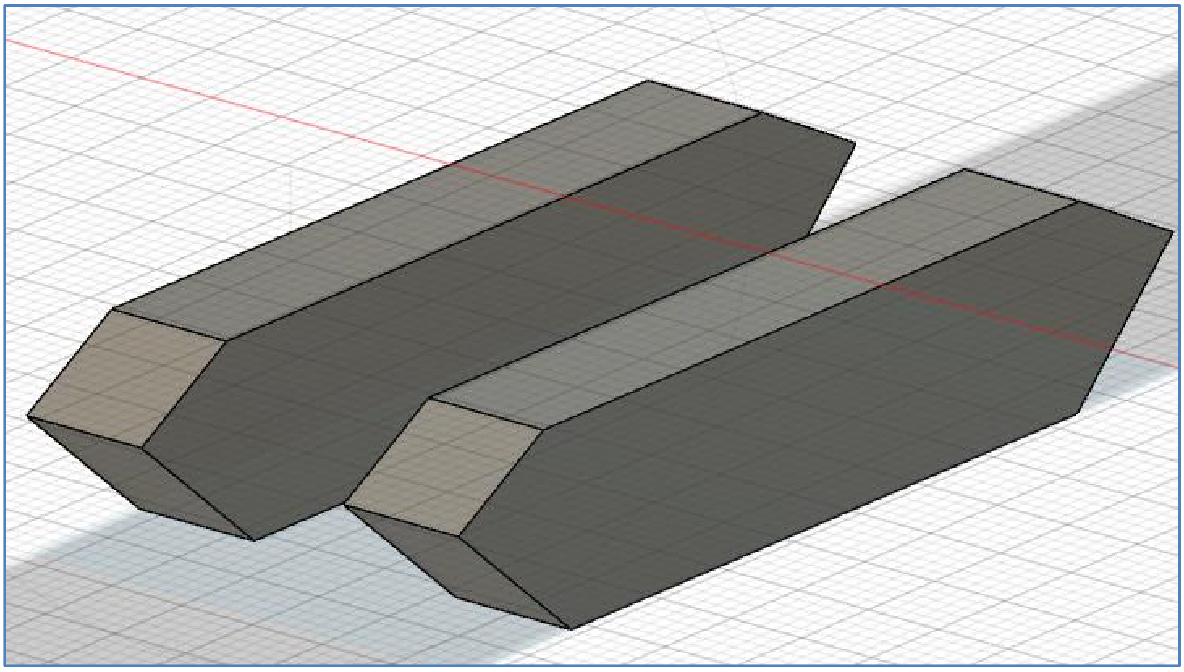


Figure 14: Self-made 3D model of the reservoir

During the experience will be evaluated if use this free space only for the cardan transmission as now or use it in order to have more space for some component.

4. Hydrogen system

In this chapter will be covered the entire system required to use hydrogen as energy vector for our project.

A general explanation of the fuel cells, their operation and finally the various solutions for hydrogen storage will be given. For each component will be given the pro and cons of the various typology actually available on the market.

4.1. The Fuel Cell

The Fuel Cell (or FC as abbreviation) is an electrochemical device used to produce electricity from the direct redox reaction of a fuel and an oxidant without actually having a combustion, despite the fact that heat is released during the process. They have become quite famous thanks to the fact that the use of hydrogen as fuel and air as an oxidant, makes it possible to produce electricity and as a residual water vapor.

The composition of these systems is very reductive by simplification, and we can generally divide it into three parts:

- Anode
- Cathode
- Electrolyte

Where a dense electrolyte is stored between two surfaces, respectively anode and cathode, forming a single cell. The fuel is flown to the anode while the oxidizer to the cathode. The term "flowing" has been used specifically to highlight the characteristic of these electrochemical cells, that is, it does not use an internal tank like the classic batteries but is powered externally for both fuel and oxidant.

Despite the high efficiencies, the powers involved on the single cell are not very high and it is for this reason that in practical use they are generally coupled in series forming a stack of cells with the power cut necessary for its application.

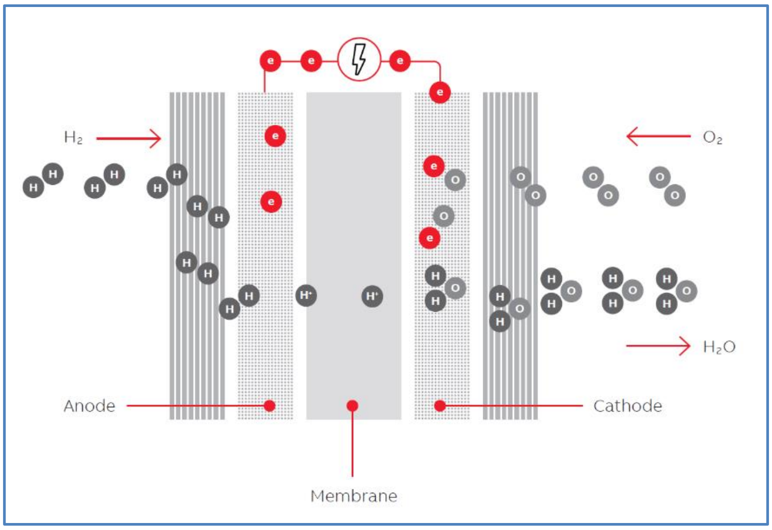


Figure 15: Fuel Cell representation ([12], 2020)

Generally, the fuel and the oxidant enter through two separate ducts, they are diffused up to a membrane that acts as a catalyst.

The electrode catalyst has the function of favouring the division of molecules to produce ions. At this point the ions are transmitted through the electrolyte and the electrons through a connection between the two electrodes, the electrons will produce a current flow to which a load must be connected, while the ions re-join to form the water as a residue.

The fuel cells are not all the same but vary depending on the electrolyte used, the reaction that takes place inside and the temperature. In particular, we will use this last feature to make a ranking as in the figure below.

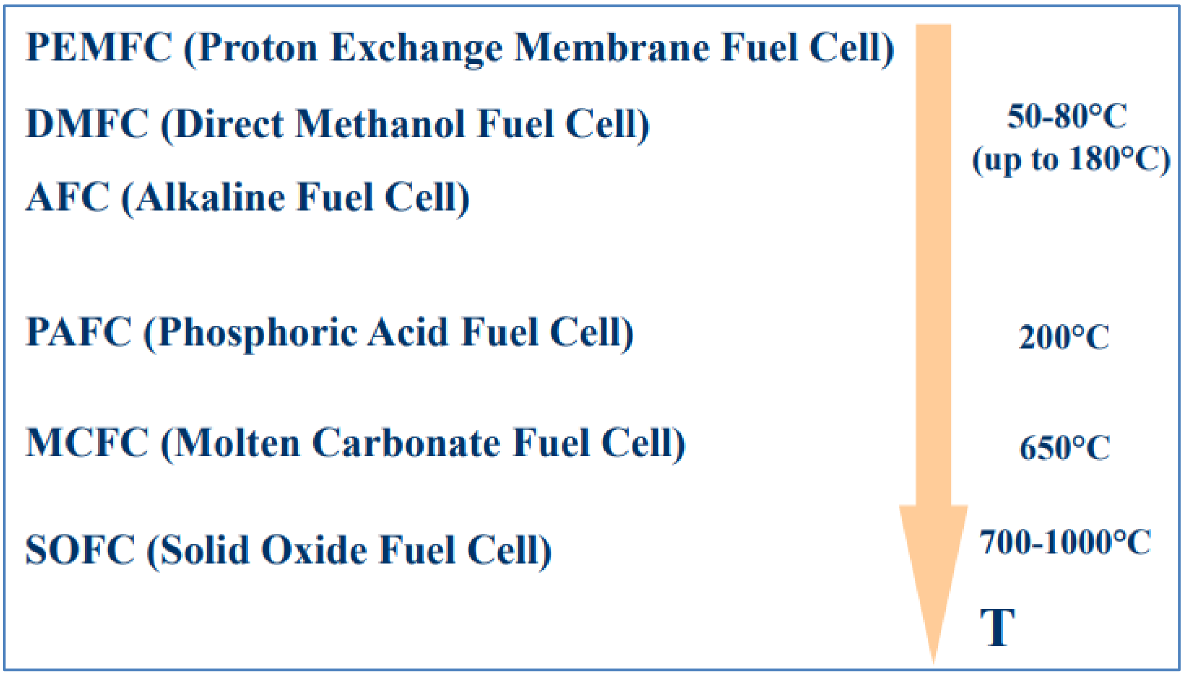


Figure 16: Scheme of various Fuel Cell respect to temperature ([13], 2014)

In particular, we will talk about:

- **Solid Oxide Fuel Cell (SOFC):** Fuel cells operating at temperatures around 500-1000 °C with a ceramic electrolyte. The transmitted ion is O^{2-} and the overall efficiency is about 65-75%.
  Given the high operating temperature, they require lower activation energy and consequently fewer valuable catalysts. In addition, it can also consume hydrogen in the form of compounds such as methane and this characteristic allows it to be introduced into gas cycles. Its applications are purely stationary, especially constrained by long ignition times.
- **Molten Carbonate Fuel Cell (MCFC):** Fuel cell with characteristics similar to the previous one, it differs from an electrolyte composed of molten carbonates and operating temperatures of about 600-700 °C.
  The ion traded is CO_3^{2-} and the efficiency reaches values up to 60%. The system can also burn hydrogen in the form of methane and the applications are generally stationary.

- **Phosphoric Acid Fuel Cell (PAFC):** In these types of you work with an electrolyte based on phosphoric acid and ion H^+ transport.

  The temperatures at which the cell works are about 150-220°C and reaches efficiencies of up to 45%. The fuel required is mainly pure hydrogen and the applications are generally stationary.
- **Alkaline Fuel Cell (AFC):** Electrolyte fuel cell composed of potassium hydroxide with ion OH^- transfer.

  The achievable efficiencies are relatively high and the temperatures at stake are around 50-200 °C. Hydrogen or "cracked ammonia" can be used, and applications can be both portable and stationary.
- **Proton Exchange Membrane Fuel Cell (PEMFC):** They are fuel cells that work at temperatures up to 60-70 °C and with efficiencies above 50%. They require the supply of pure hydrogen and whose applications can be used for automotive or stationary. In the next section an in-depth paragraph dedicated to this type will be made.

4.2. Proton Exchange Membrane Fuel Cell

The "Proton Exchange Membrane Fuel Cell", abbreviated as PEMFC, are a type of fuel cell invented in the early 1960s at General Electric by Willard Thomas Grubb and Leonard Niedrach ([15], 2019). As the name indicates, they are characterised by proton exchange through a polymer membrane; in fact, it is also called "Polymer Electrolyte Membrane". The ion transmitted by the polymer electrolyte is a proton H^+ from the anode to the cathode as shown in the figure.

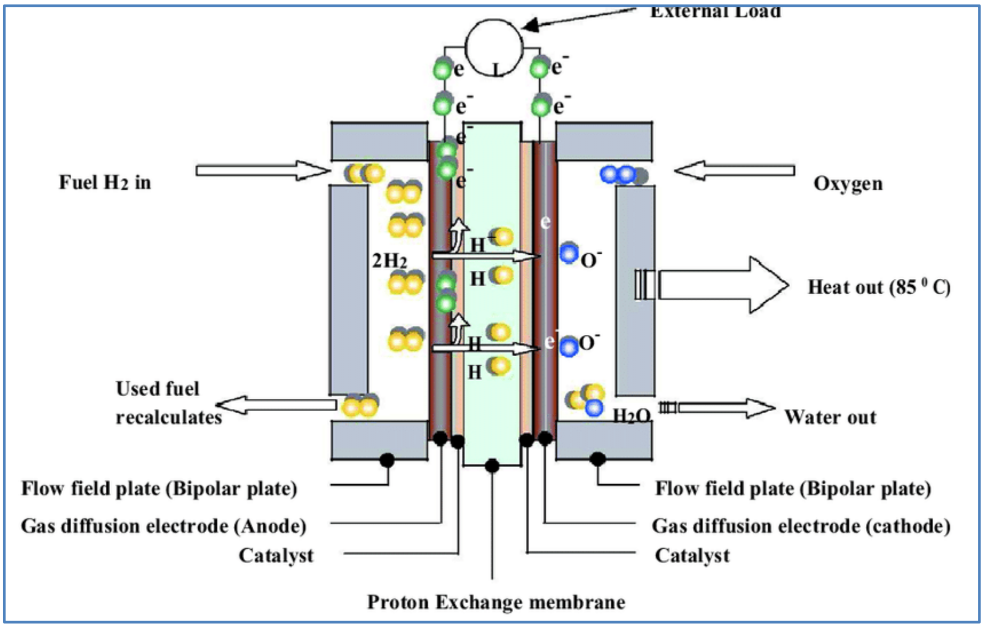


Figure 17: Schematic representation of the structure and functioning of a PEMFC ([16], s.d.).

The general reaction in the cell is the consumption of hydrogen and air to produce heat, electricity and water, in particular we will have a hydrogen oxidation and oxygen reduction.

However, we can analyse everything considering the partial reactions to the electrodes, in particular we will have:

$$\text{Anode} \rightarrow 2H_2 \rightarrow 4H^+ + 4e^-$$

$$\text{Cathode} \rightarrow O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$$

From a structural point of view, fuel cells are relatively simple devices, they are in fact mainly composed of the two electrodes, the catalysts and the electrolyte. The two electrolytes are created in such a way as to be highly permeable, so as to allow the complete diffusion of the gas up to the catalyst. As regards the catalyst, platinum has proven to be the most suitable material for this type of cell.

The reason is to be found in particular in the activation energy necessary to make the chemical reaction take place.

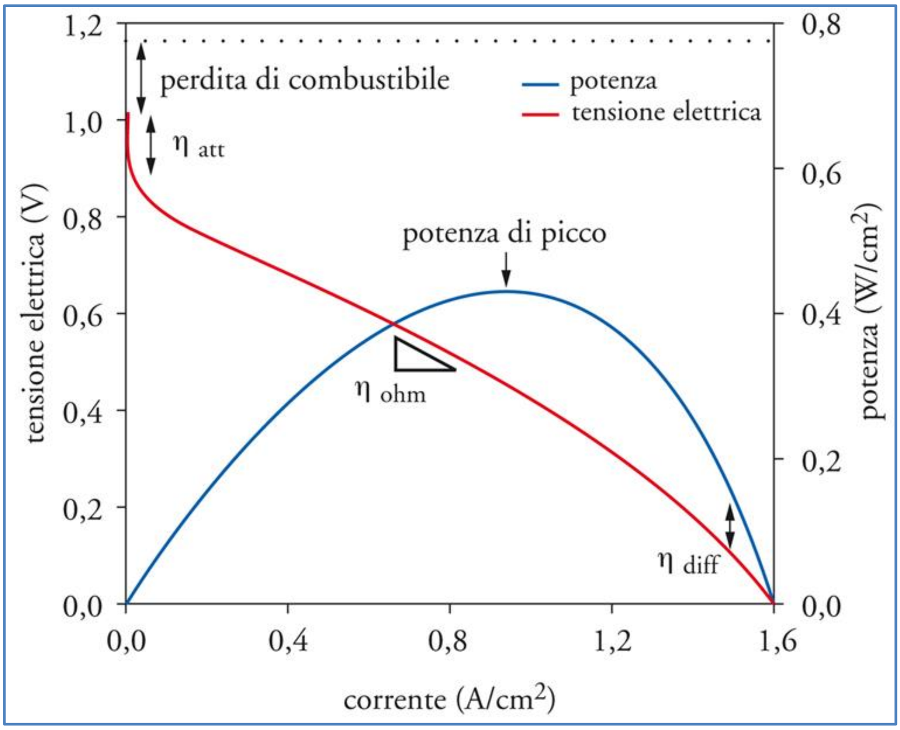


Figure 18: Polarization curve and Power curve of a generic PEMFC ([17], 2008).

As you can see in the graph above, the cell voltage changes dynamically once we place our cell in a circuit. This is due to the predominance of transport processes that change the balance of the cell, and we can enclose these transport processes in:

- Charge transfer
- Charge migration
- Mass transport

Processes that cause the change of the voltage of the cell compared to open circuit voltage, we can in fact summarise the voltage of the cell in the following formula:

$$V_C = OCV \pm \sum_{j=1}^{3} \eta_j(I)$$

Or in extended form:

$$V_C = \pm \frac{\Delta g_{react}}{zF} \pm [\, \eta_{act}(I) + \eta_{ohm}(I) + \eta_{conc}(I)]$$

Where components η are defined as "Overvoltage" and refer to different cell processes.

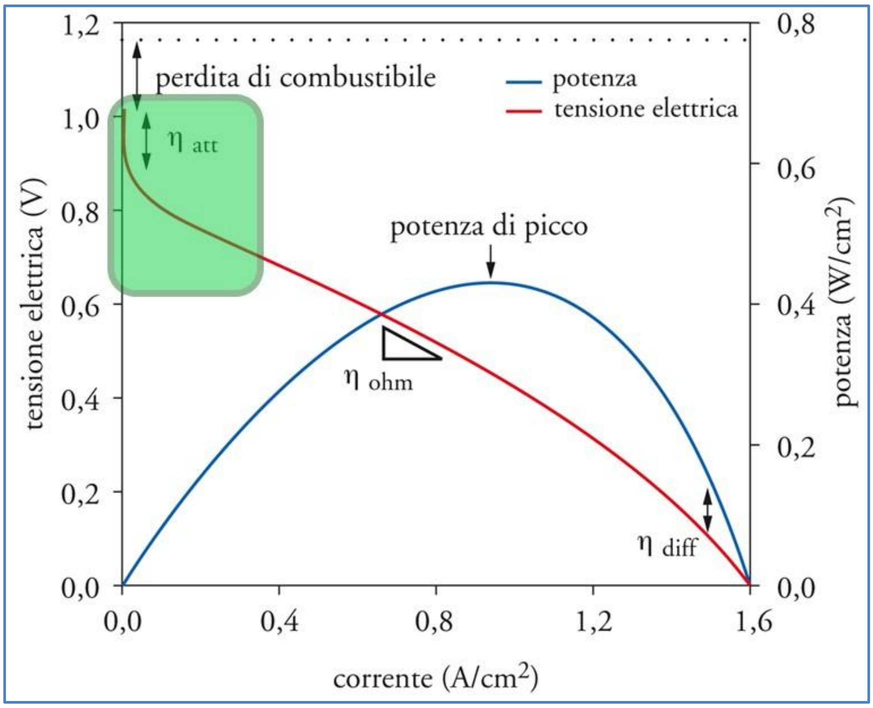


Figure 19: Focus on the activation overvoltage.

The first overvoltage (figure 17), the one relating to activation, refers to the charge transfer process that takes place in the electrodes by oxidation and reduction. In the case of PEMFCs it tends to be very accentuated, proving to require a lot of energy to start the reaction, also due to the low temperature at which the cell operates. In SOFCs, for example, these losses are very low, especially for high operating temperatures. Studies have shown how the operating temperature affects these losses.

All this explanation served to demonstrate the reason why the catalyst in platinum is chosen, despite it is a very valuable and expensive material. It has a strong power as a catalyst to facilitate reactions but at the same time has a very important disadvantage. It, in fact, if used at low operating temperatures, below about 150 ° C, tends to bind very easily to carbon monoxide and thus reducing the surface area useful for the reaction.
This is a very important problem considering that some studies have found that even a quantity of carbon monoxide of about 10 ppm causes a strong influence on the performance of the cell.

The solution was then found on two ways: the use of pure hydrogen that would therefore exclude any residue or the use of electrodes with catalysts composed of Platinum / Ruthenium able to tolerate carbon monoxide more.

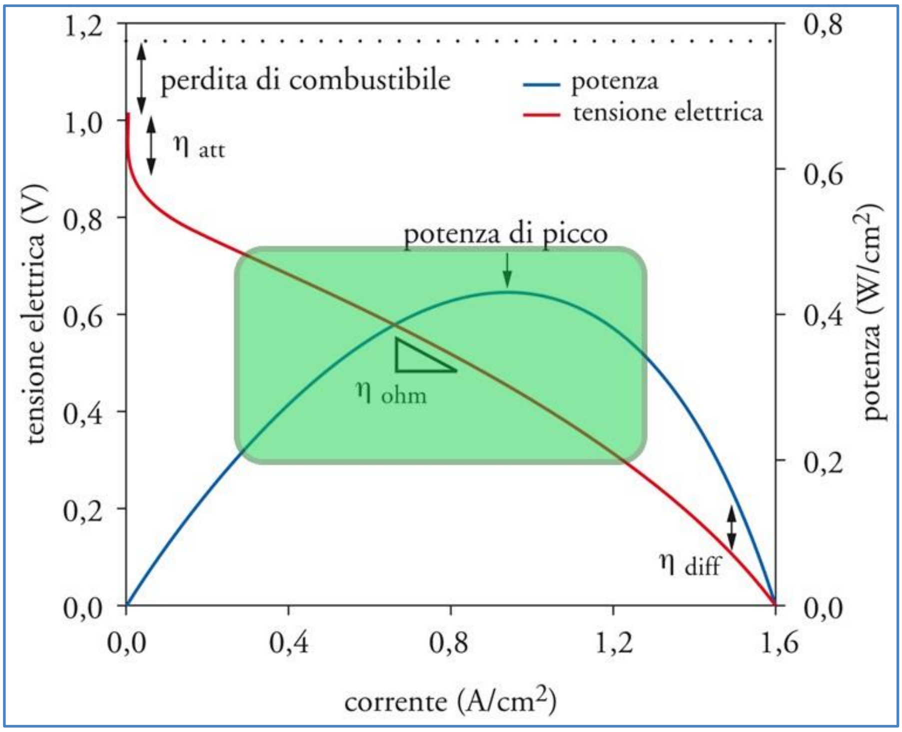


Figure 20: Focus on the ohmic overvoltage

In the case of ohmic overpotential we talk about losses related to the electrolyte layer and are related to Ohm's law.

In particular, we can obtain:

$$\Delta V = R\,I$$

$$\eta_{omh} = R\,I = \rho\,\frac{L}{S}\,i\,S = (\rho\,L)i = ASR\,i$$

Thus, a linear relationship is obtained with the "Specific Resistance Area (ASR)". The latter is one of the characteristics that must be minimised in the choice of electrolyte, but not the only one. In fact, as we all know, in the operation of the cell the electrons must pass through the load while the ions must pass through the electrolyte. We must therefore have a material that allows only the passage of ions.

Generally, a polymer electrolyte based on Fluro-sulphonated polymers is used, the famous Nafion is a patented molecule of this type. Its preparation starts from a polyethylene molecule modified by replacing hydrogen with fluoride, generating PTFE. The last step is to provide hydrogen sulphite, HSO3 to the previous molecule, thus adding a lateral chain whose term is a sulphonic group. The molecule thus generated will generally look like Figure 19, although there may be variations as needed.

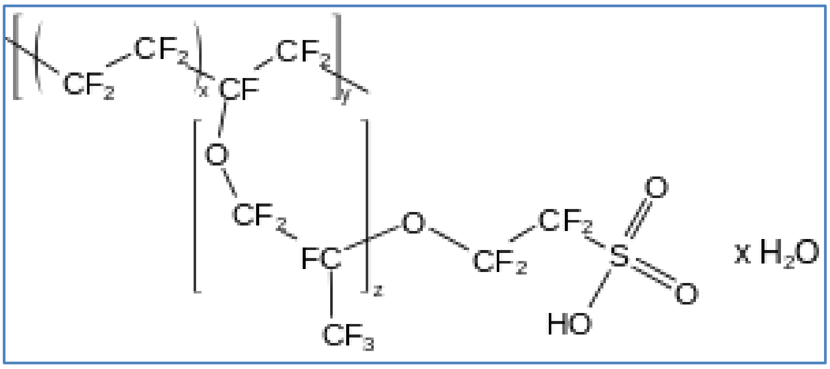


Figure 21: Molecule of Nafion ([18], 2018).

The thickness of this membrane varies according to the use required, but in general we can say that the average thickness is about a few thousandths of an inch.

The reason for such a thin thickness is explained in the previous part, namely the overpotential ohmic. As we have seen before, this parameter increases with the type of membrane but also with the thickness. We should therefore be able to have an electrolyte as thin as possible, in order to minimise this parameter always guaranteeing the non-passage of electrons through it.

A characteristic of this material, however, is that the HSO3 group attracts water; therefore, we will have a membrane with a water absorption zone inside a generally hydrophobic material. The absorption of water inside this membrane guarantees the free movement of hydrogen ions inside. This characteristic implies that for proper operation, the polymer membrane must be constantly humidified.

The humidification of this membrane could be carried out by exploiting the diffusion of the water molecules produced as a residue by the cell itself. We know that cathode water is produced and could spread through the layers, but an electrochemical phenomenon, called electroosmosis, has an inverse function and does not guarantee hydration.

Several studies and experiments have shown that this amount of water is not enough to moisturise the membrane and the causes are to be found in evaporation in electrodes, a phenomenon that increases with increasing temperature. The only solution is to guarantee humidification from the outside and the easiest way is the humidification of the incoming gas, which penetrates and humidifies the membrane, even if attention must be paid to the regulation of the amount of water.

4.3. Hydrogen storage

The idea of converting a diesel propulsion with a hydrogen one was born mostly for reasons related to emissions. We know that the use of hydrogen to feed fuel cells allows us to produce energy by eliminating carbon emissions.

This type of fuel, however, has advantages and disadvantages compared to the use of diesel fuel, first of all the advantages is the energy density inside it. Hydrogen in fact has an energy density, in normal form 143 [MJ/kg] against a value of 45.8 [MJ/kg] of diesel fuel.

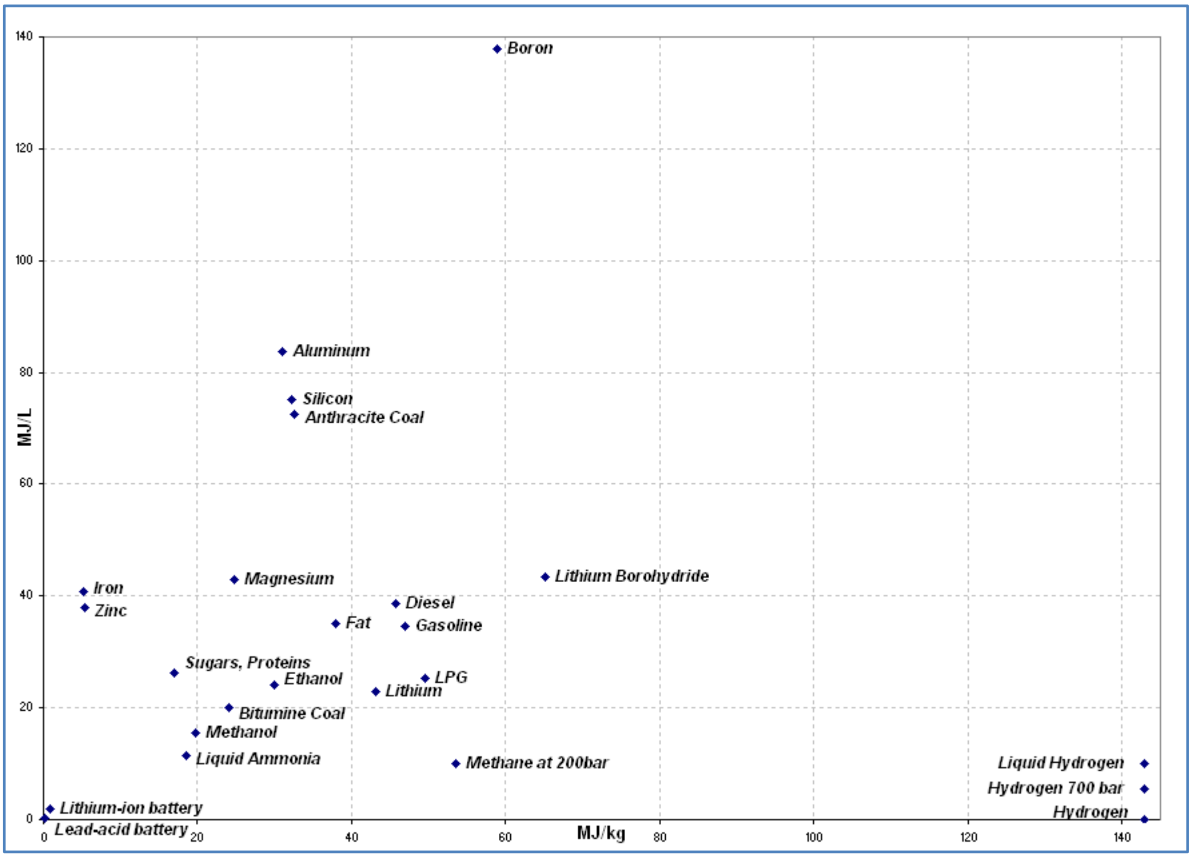


Figure 22: Different compound energetic density comparison ([19], 2021).

At the same time, it has the advantage of being a renewable and clean solution, and it is highly present all over the planet.

The disadvantages we can summarise in:

- Density
- Security
- Production

As mentioned above, hydrogen is very present in nature but tends to always be bound to other atoms in various compounds. Hydrogen production therefore requires the division of hydrogen atoms from these compounds and the most common processes are electrolysis and steam reforming from methane.

The first process consists of a difference in potential imposed on the water through electrodes, in order to generate an oxide-reduction reaction such as to absorb energy and release hydrogen and oxygen. The second process instead consists of a hot vapour that reacts with methane in order to produce hydrogen.

As far as density is concerned, it is a disadvantage because it is so low that it cancels the advantage in terms of energy density over diesel fuel. Hydrogen, under normal conditions, has a density of $0{,}0899 \left[\frac{kg}{m^3}\right]$ considering an environment at 0 [°C] and a pressure of 1 [atm]. It is therefore easily obtained that hydrogen, on the condition of the environment, has an energy density, in volumetric terms, of about $12{,}86\,[\frac{MJ}{m^3}]$ against diesel that in volumetric terms reaches the $38243\,[\frac{MJ}{m^3}]$.

The difference in volumetric terms is clearly high, the only solution to make this type of fuel available in tanks of acceptable volumes is to increase its density. There are two ways to do this, the compression and liquefaction of gas, a third possibility is the use of metal hydrides.

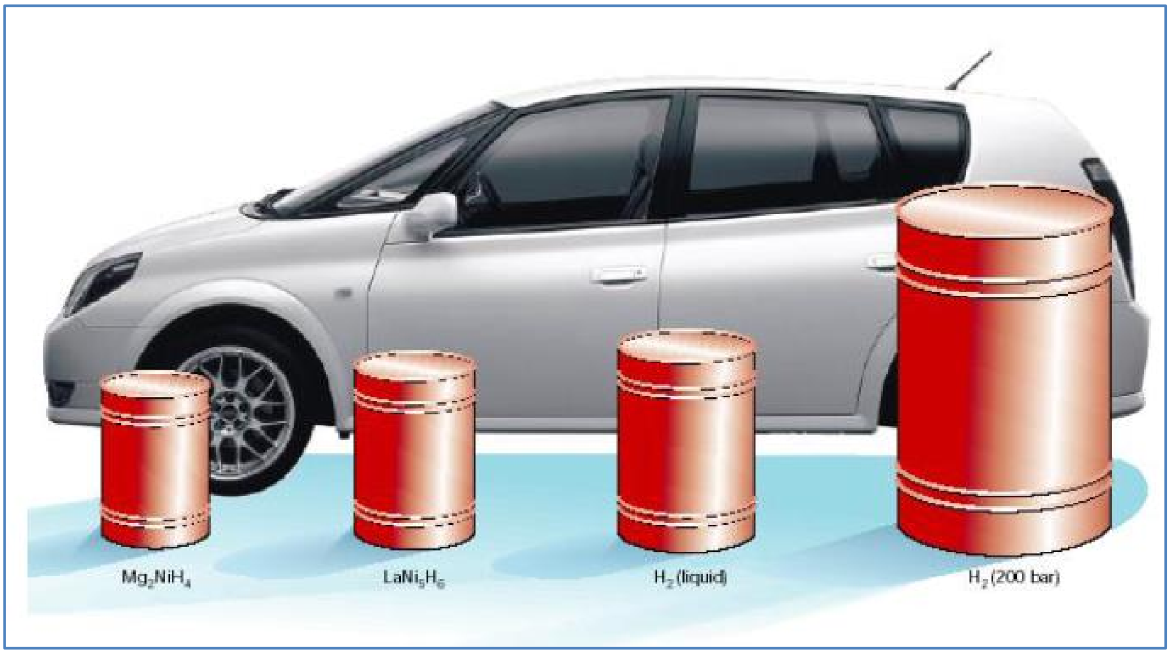


Figure 23: Volume comparison of different typology of storage ([20], 2021).

Hydrogen liquefaction requires that the gas be brought to a temperature equal to $20{,}39\ [K]$, which corresponds to the boiling point of hydrogen.

In general, to achieve this result, the systems need components such as: compressors, heat exchangers, turbines and valves are used. One of the most used processes is the Linde cycle, that is, the gas is compressed and cooled and then passed through an isenthalpic expansion valve producing liquid. The process therefore continues like a cycle.

Another version uses pre-cooled liquid nitrogen to cool the hydrogen before the valve and is called the pre-cooled Linde cycle.

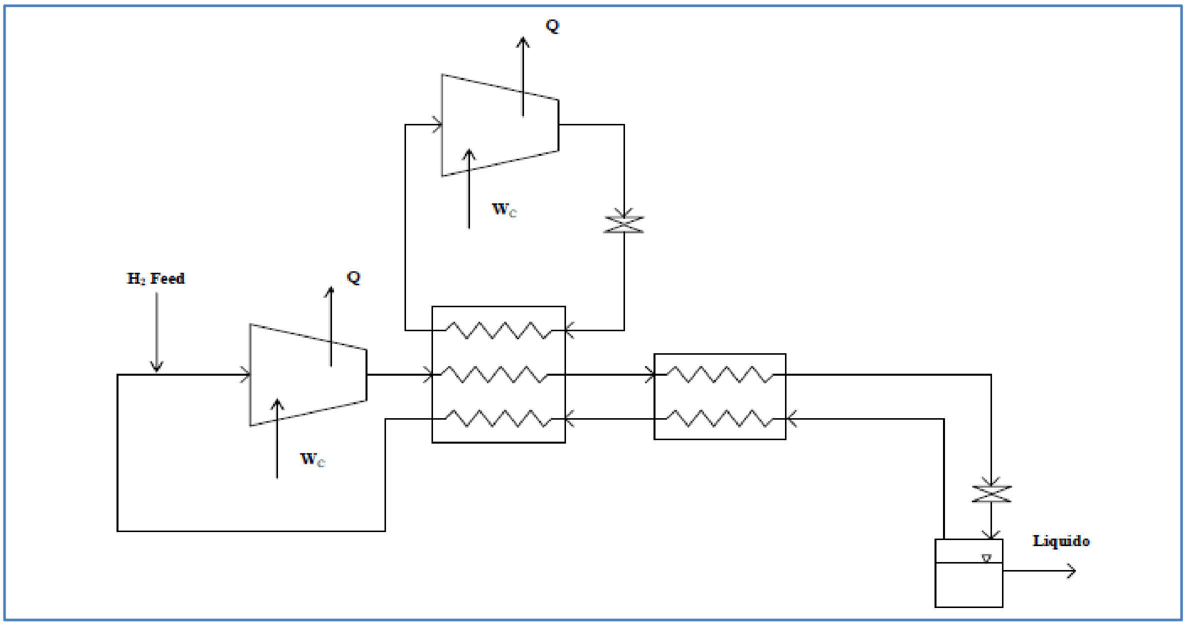


Figure 24: Scheme of the pre-cooled Linde process ([21], 2021).

Compression technology instead exploits gas compression in order to significantly increase its density, and consequently the amount stored in an acceptable volume tank.

Compared to all other technologies, it is the one with the worst result, in fact to obtain acceptable results it is necessary to reach really high pressures. The pressure levels normally used are 350 [bar] and 700 [bar], pressures in which we can reach volumetric density, respectively, of about 25 $\left[\frac{kg}{m^3}\right]$ and 35 $\left[\frac{kg}{m^3}\right]$.

Let's immediately notice a clear difference compared to liquid hydrogen in which the density reached is $70 - 75$ $\left[\frac{kg}{m^3}\right]$, moreover in general a tank at this pressure greatly increases the danger of explosion.

For this reason, it is necessary to use tanks with really high safety coefficients and sensors able to signal any minimum loss, in order to act immediately. An example of the use of this technology is found in the Toyota Mirai, a fuel cell car that is produced by few years. The machine in question is equipped with two compact tanks at a pressure of 700 bar and are designed to withstand up to pressures of 225% compared to operating pressures and super-sensitive sensors ([22], 2019).

Figure 25: Toyota Mirai ([23], 2021)

The latest technology, metal hydrides, are the latest novelty of hydrogen storage technologies. The principle of operation is based on the ability of some metals to absorb a large amount of hydrogen atoms inside their crystalline lattice, generating a metal hydride.

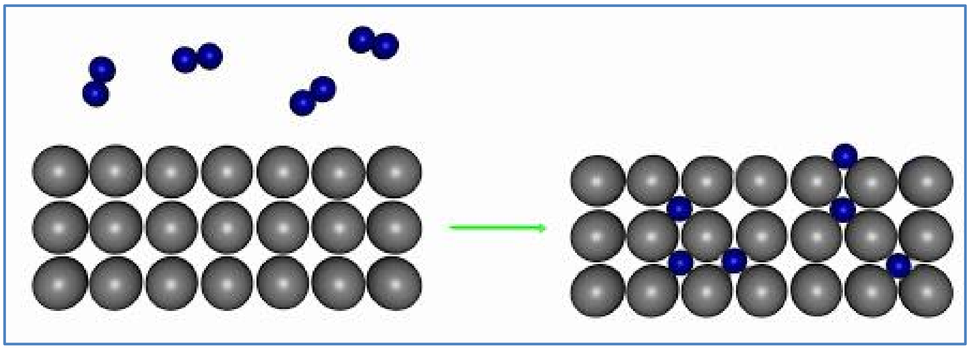


Figure 26: Metal hydrides formation process.

The absorption process is exothermic, so it releases energy during the reaction. While the reverse process, the release of hydrogen, takes place through an endothermic reaction and therefore requires energy to be provided to release it. If on the one hand you could think of this thing as a disadvantage, it's actually a huge advantage. The reason is on the safety side, in fact we are sure that without heat supplied there will be no leaks without control.

The main advantage of this technology, and above all the characteristic that makes the study of these materials important, is the high ability to store hydrogen. It is possible, in fact, to reach a volumetric density equal to twice the liquid hydrogen.

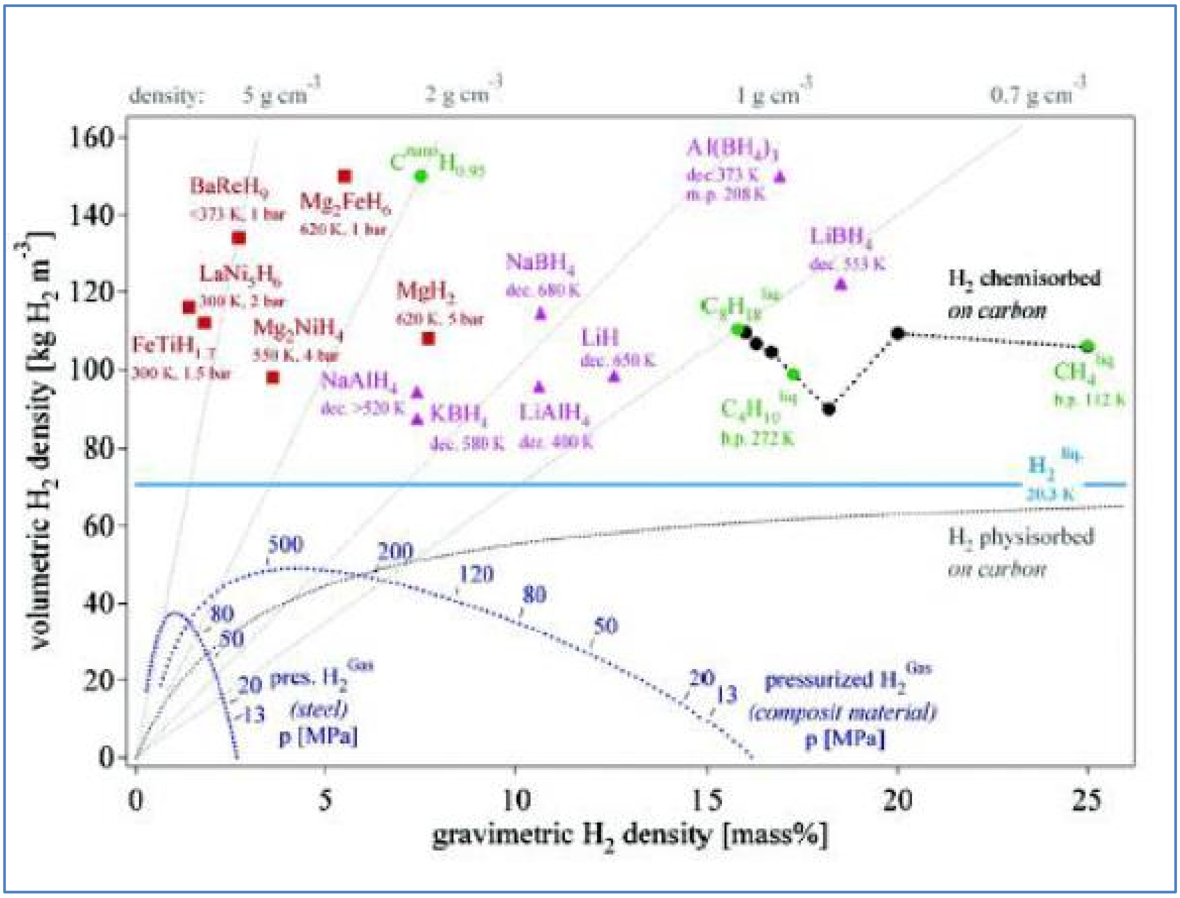


Figure 27: Technology comparison respect to volumetric density ([20], 2021).

As you can see in Figure 25, in fact, the types of metal hydrides are many and varied, but in general they can achieve really high hydrogen densities compared to other technologies described above (liquid hydrogen represented by the blue line).

Volumetric density assumes very different values depending on the technology chosen, but in general we can still define with certainty that these values are greater than other technologies. For example, in the case of Mg_2FeH_6 the value obtained is the double of the value obtained for the liquid hydrogen.

The whole advantage of this technology is reduced by another important aspect of these materials, the weight. In fact, at the moment for any type of metal chosen there are high weights for the storage of a few kilograms of hydrogen.

Hydride	Compound	Gravimetric H_2 content (wt%)
Metal hydrides	LiH	12.6
	NaH	4.2
	CaH_2	4.8
	MgH_2	7.6
Complex metal hydrides	$LiAlH_4$	10.6
	$NaAlH_4$	7.4
	$Mg(AlH_4)_2$	9.3
	$LaNi_5H_6$	1.4

Figure 28: Gravimetric H2 content comparison.

As can be seen from figure 26, depending on the type of metal hydride chosen, the values fluctuate between 1% and 10% on a weight basis. This means that considering a value of about 4%, for every 1 [kgH2] we will have 25 [kg] of tank.

This feature is currently the limit of this technology, especially in the automotive field, but studies are underway to develop tanks with light metal hydrides. That is, hydrides with the use of light metals that would consequently lower the total weight of the tank.

5. Hydrogen powertrain dimensionalization

This chapter will deal with the sizing of the various components necessary for the project. Mainly, the operating parameters of the current diesel propulsion will be analysed, and the alternative hydrogen traction will be dimensioned. Given the sizing of the system, a numerical simulation of consumption will be carried out on two routes, one in the plains and one in the mountains. Finally, the change in the weight of the locomotive will be analysed following the change implemented

5.1. Electric engine

As already analysed above, the current locomotive configuration includes a 2200 kW CAT 3516 B DI-TA HD diesel engine, a Voith L620 re U2 turbo-reducer. From the manual of the locomotive in possession there are no operating curves of the engine itself, but there is information on the maximum effort to the rim of the locomotive compared to the driving speed.

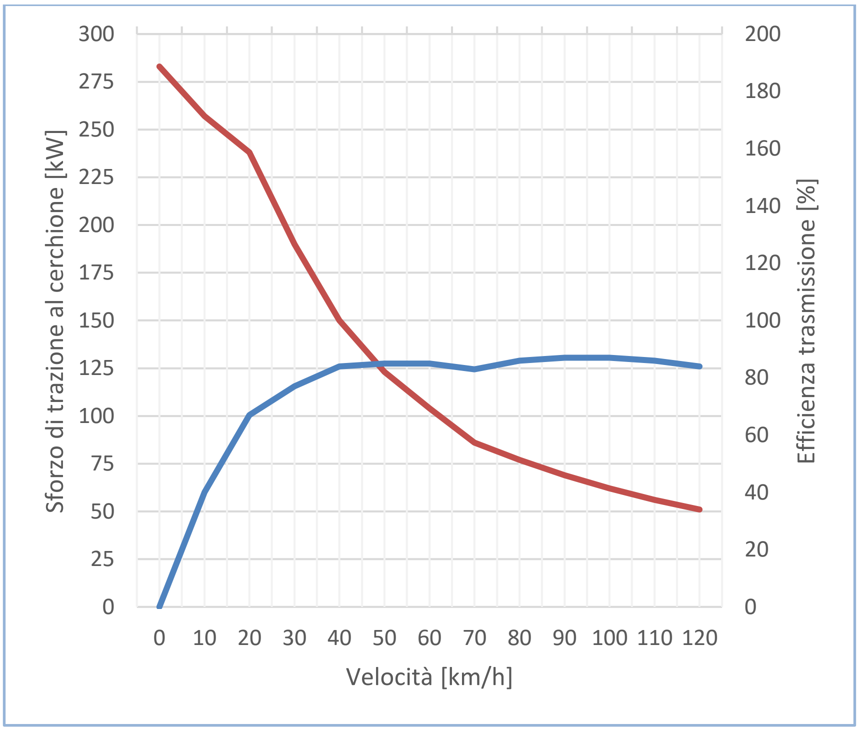


Figure 29: Traction stress diagram ([11], 2003).

The idea is to take advantage of the figure of the rim diameter, equal to 960 mm, and derive from the maximum effort, the maximum power developed by the wheels. This is possible using the following formula,

$$T_c = \frac{F_{TraxMax}}{r_c} \quad [kNm]$$

$$\omega_r = \frac{v}{2\,\pi\,r_c} \quad [\frac{round}{s}]$$

$$P_c = T_c\,\omega_r\,2\,\pi \quad [kW]$$

At this point, using the transmission efficiency graph with respect to the running speed, it is possible to derive the maximum engine power relative to the speed. The results of this processing are shown in the following table and graph.

v [km/h]	rps [round/s]	Transmission efficiency [%]	F_trax [kN]	Torque [kNm]	Power_cerc [kW]	Power_engine [kW]
0	0,00	0	283	135,84	0,00	0,00
10	0,92	40	257	123,36	713,89	1784,72
20	1,84	67	238	114,24	1322,22	1973,47
30	2,76	77	190	91,2	1583,33	2056,28
40	3,68	84	150	72	1666,67	1984,13
50	4,61	85	123	59,04	1708,33	2009,80
60	5,53	85	104	49,92	1733,33	2039,22
70	6,45	83	86	41,28	1672,22	2014,73
80	7,37	86	77	36,96	1711,11	1989,66
90	8,29	87	69	33,12	1725,00	1982,76
100	9,21	87	62	29,76	1722,22	1979,57
110	10,13	86	56	26,88	1711,11	1989,66
120	11,05	84	51	24,48	1700,00	2023,81

Table 1: Data and result of the elaboration.

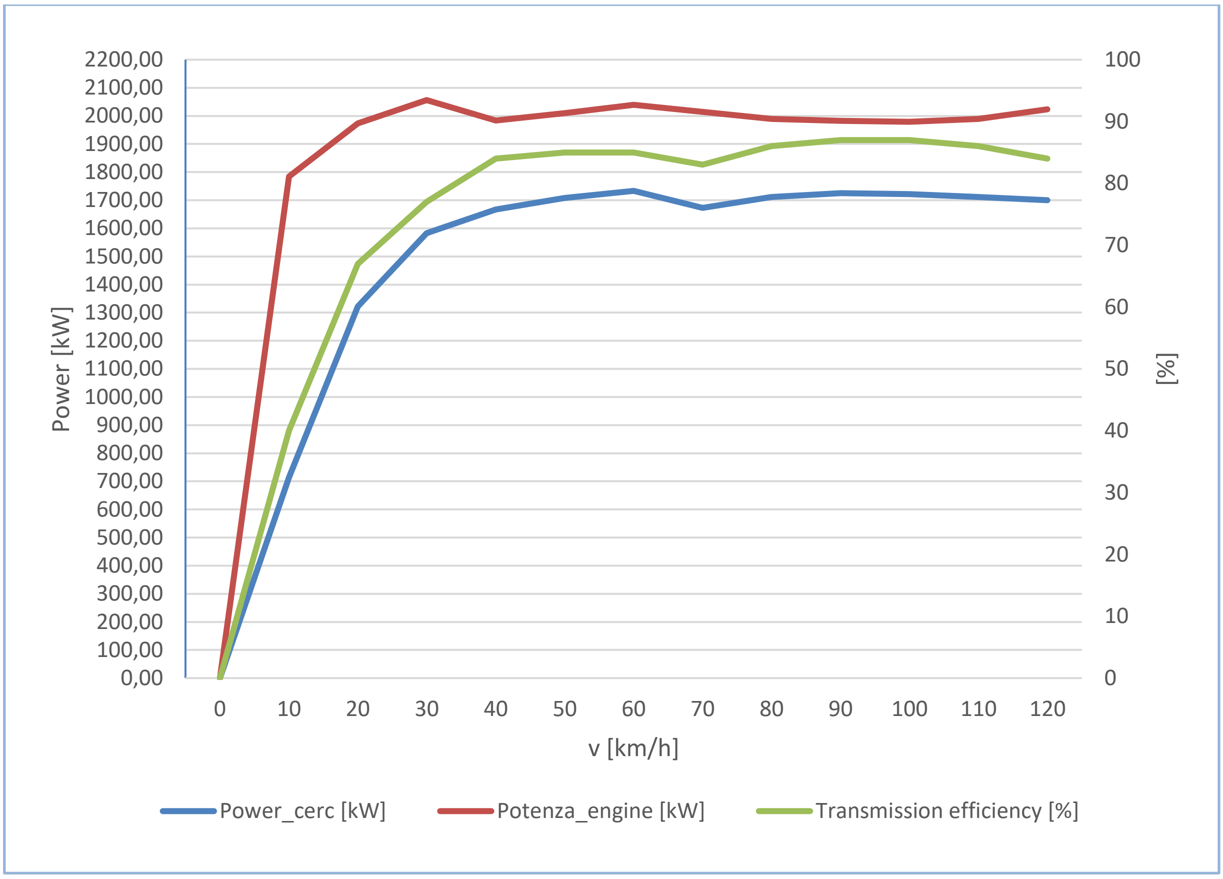


Figure 30: Power comparison and transmission efficiency.

These rim power values will serve us later to simulate the consumption of the new propulsion on real line sections, that is, the engine power necessary for the speed of the locomotive in that particular partial stretch will be defined.

According to our calculations, the maximum power required for the rim is 1725 [kW]. The idea, to optimise space, is to avoid the single internal motor with relative transmission and to divide the necessary power on four electric motors applied directly on the axes. Consequently, for our process we need 4 electric motors with a power of about 560 kW each and torque at least equal to that already present with the old propulsion.

Figure 31: Danfoss EM-PMI540-T4000 electric engine ([24], 2021).

The EM PMI540-T4000 model produced by Danfoss was chosen as a reference for the engine. This type of engine, as for the manufacturer's website, is available in a power range of 284 kW and 896 kW, and our power cut falls within this range.

Moreover, this motor makes it possible to develop these powers in a small volume and with an efficiency of 96%. The dimensions of this engine are, in fact, 1040 mm long and 665 mm high ([24], 2021).

Finally, to make sure you can deliver an adequate torque, a gearbox will be equipped between the motor and the axle, the efficiency of which has been estimated at about 0,8 in order to have a precautionary approach in calculations.

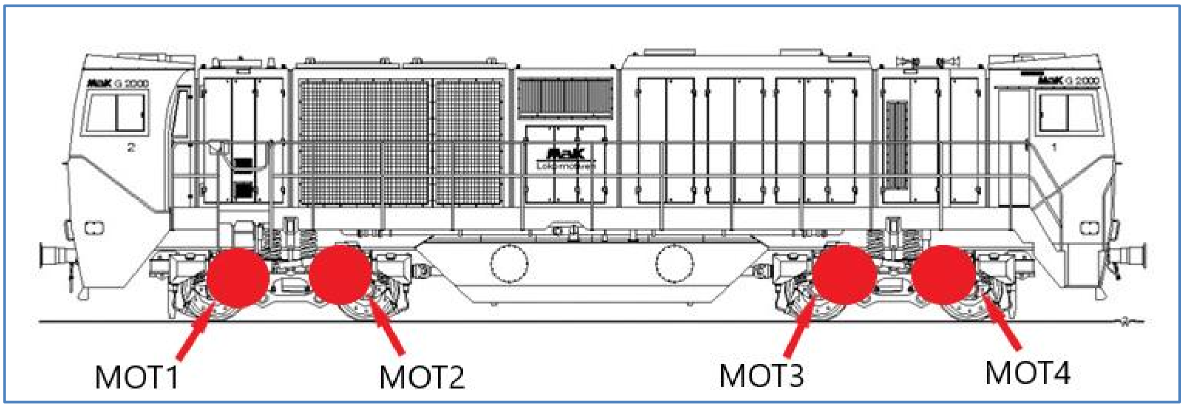


Figure 32: Positioning of engines on the locomotive.

In figure 31 it is possible to see how the positioning of the motors on the individual axes has been studied, where the red spot represents the electric motor in correct proportion to the drawing. This configuration allows the system to greatly save space for the project and avoid long motion transmission systems, such as cardan transmissions present on the diesel locomotive.

5.2. Fuel Cell

Once the new engines have been positioned, it is necessary to size the fuel cells necessary for energy production. Before doing this, we must consider introducing a power unit between engines and fuel cells, whose purpose is to adjust the electrical values required by motors and transform direct current, produced by fuel cells, into alternating current useful for motors.

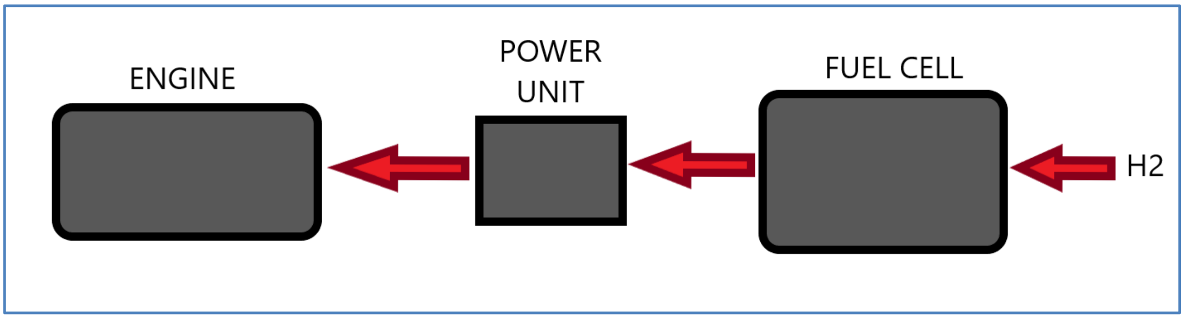


Figure 33: Simplification of the flux of energy from hydrogen to engines.

Not having enough information to define a power unit in the individual components and operations, it will be considered as a simple block in the energy flow with an efficiency of 0,9. Consequently, we can calculate the necessary power output from the fuel cell in this way,

$$P_{OUT\_FC} = \frac{P_{IN_{ENG}}}{\eta_{PU}}$$

From which we get a maximum required output power of about 2500 [kW].

Regarding the choice of fuel cell, there are currently many good products of different types on the market. Our choice, however, fell on the PEM type and in particular the systems produced by Ballard.

Figure 34: Ballard FCgen®-HPS ([25], 2021).

The model, in particular, is FCgen®-HPS, a stack composed of 309 cells whose dimensions are 484 mm long, 555 mm wide and a height of 195 mm. The stack thus composed delivers a nominal voltage of 202 V and a nominal current of 645 A, with the generation of a power of about 130 kW ([25], 2021).

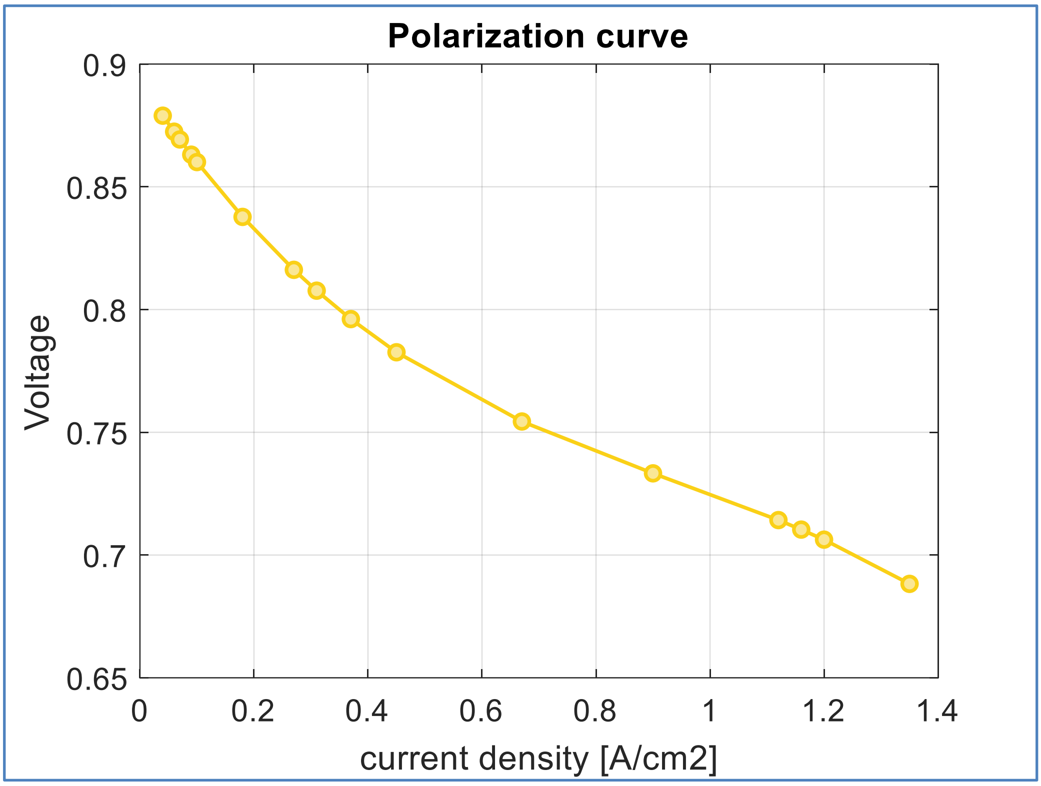


Figure 35: Polarization curve of Ballard FCgen®-HPS ([26], 2021).

The stack, whose weight is about 55 kg, has been designed for use in the automotive field and is able to implement a cold start, in figure 35 it is possible to see its polarisation curve.

The performances of the system are in line with the overall efficiency of the cell type, with a deviation relative to the normalised power at that moment. This yield can be calculated using the following relation:

$$\eta_{FC} = a\, e^{(b\, x)} + \, c\, e^{(d\, x)}$$

Where 'a', 'b', 'c' and 'd' are constants and apply respectively:

- a = 0,6208
- b = -0,3142
- c = -0,2984
- d = -22.4459

The trend of stack efficiency is then shown on the graph below.

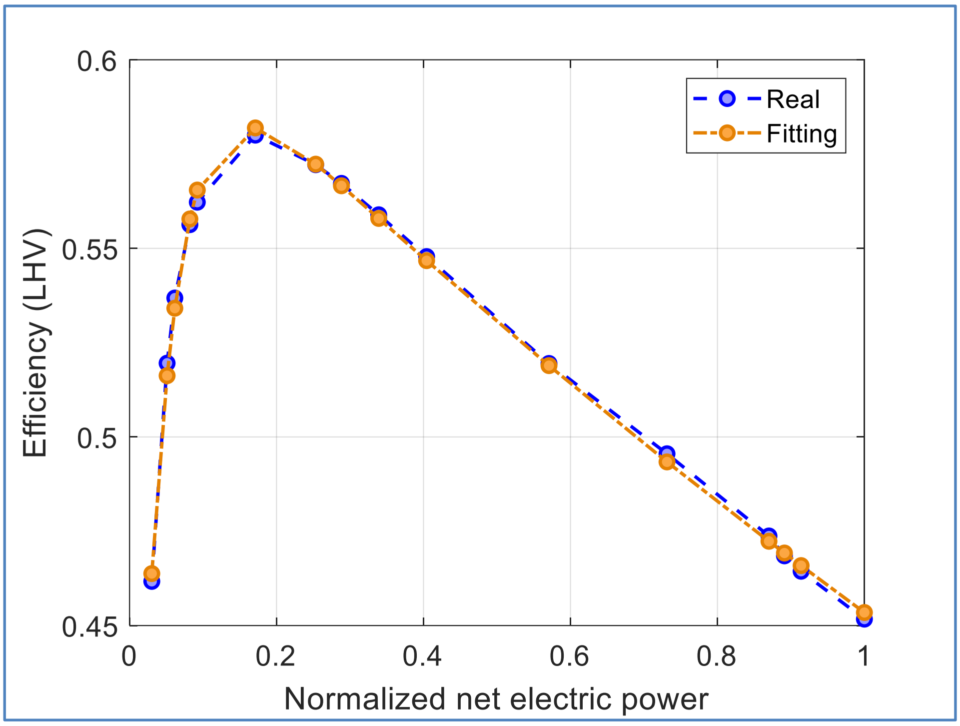


Figure 36: Ballard FCgen®-HPS performance ([26], 2021).

Analysing the graph, we can then say that our stack works with an efficiency ranging from 0.45 to 0.57, based on the normalized net electric power work ([26], 2021).

Going back to sizing, we previously calculated that our system requires a power output from the fuel cell of at least 2500 kW. Below are the data of the fuel cell chosen,

FC stack	
Type	Ballard Fcgen* -HPS
P_rated [kW]	130
Length [m]	0,484
Width [m]	0,555
Height [m]	0,195
Specific weight stack [kW/kg]	2,51
Specific weight system [kW/kg]	1,19

Table 2: Ballard FCgen®-HPS features.

So, considering the nominal stack power, we can calculate with a simple division the number of stacks needed for our project.

We know that our stack has a nominal power of 130 kW; therefore, to get the required power we will need 19.23 stacks. The value obtained we use it for excess in order to ensure a surplus of useful power for any critical moments, consequently we will install 20 stacks. We will then be able to deliver a nominal power of about 2600 kW, considering that in addition to the engine there are other loads, such as cabin lighting, air conditioning and the compressor of the braking system, we can deem adequate the obtained sizing.

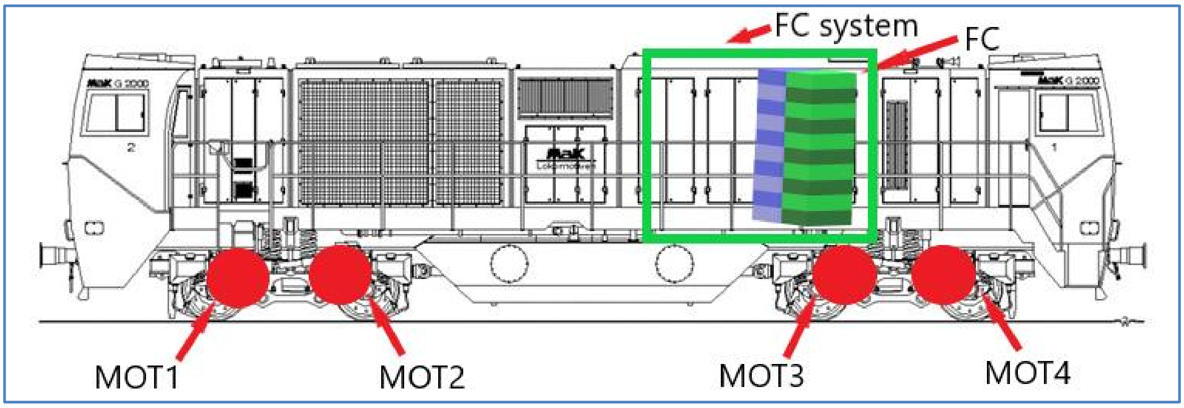


Figure 37: FC stack positioning on the locomotive.

As for its placement inside, we know that the single stack has the following dimensions: length of 0.484 m, width of 0.555 m and height of 0.195 m. While inside the locomotive is still available a volume of length of 9,300 m, width 1,840 m and height of 2,710 m.

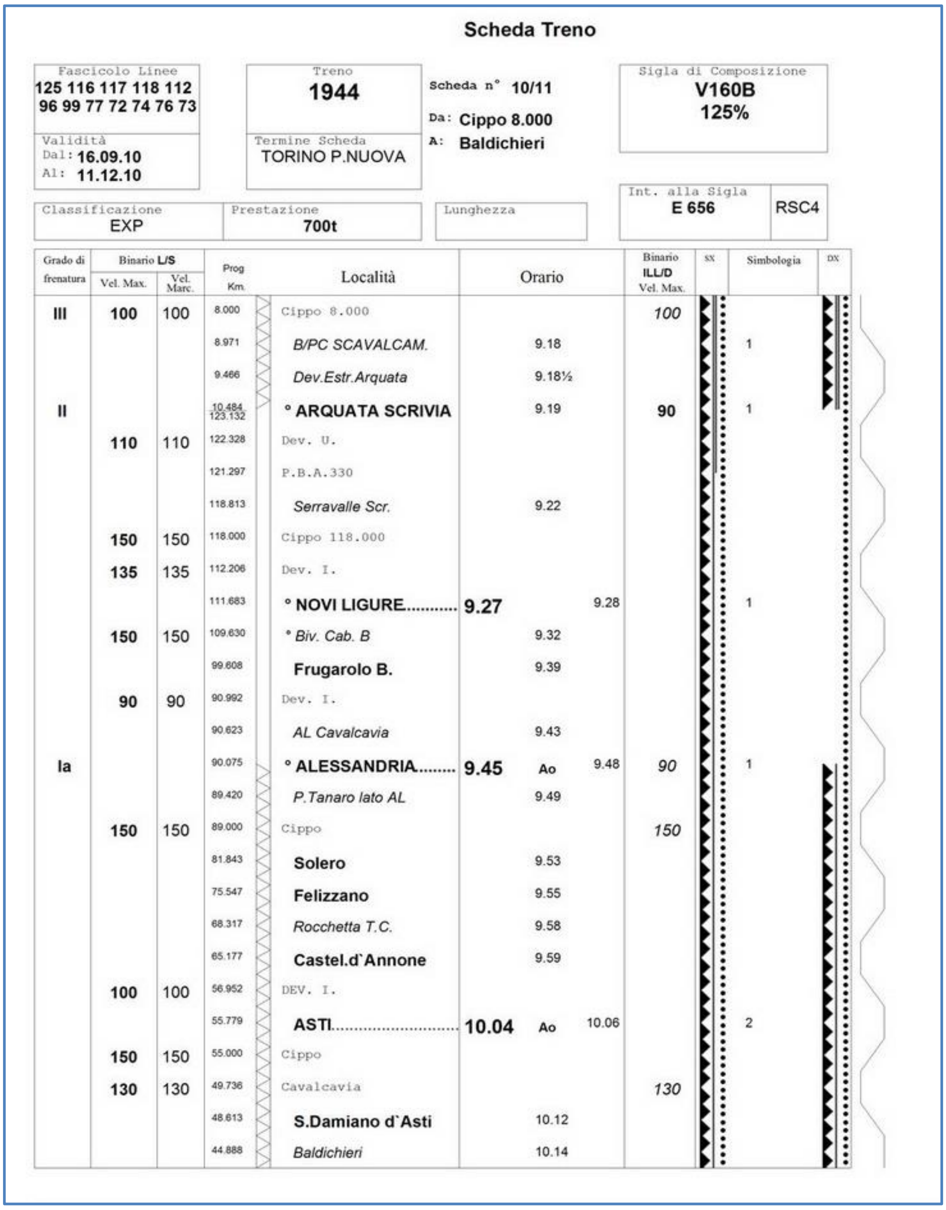
It follows that a row arrangement of all the necessary stacks is not possible, the ideal solution is the choice to place two columns of 10 stacks each. This arrangement means that a volume of 1,0476 [m 3] will be occupied with a length of 0,484 m, a width of 1,110 m and a height of 1,950 m. Considering also the entire volume of the system auxiliary to the fuel cell, we have calculated that is need a volume of 9.63 [m^3]. For the arrangement, at the moment there are no constraints and therefore it will be positioned as shown in figure 37.

5.3. On-road modelling

At this point in which we sized the traction motors, gearboxes, power units and fuel cells and chose their placement within the space recovered inside the locomotive, all that remains is to simulate the possible consumption on real sections and consequently to size the hydrogen tanks, in order to choose how much autonomy to ensure our vehicle.

For the simulation on real routes were chosen two completely different paths, the first is the stretch from Sannazzaro to Alexandria and the second stretch is that from Orbassano to Modane. The following paragraphs will describe in detail both the physical characteristics of the strokes and the calculations made.

In order to be able to perform a consumption analysis, train cards have been generated for each route through the collaboration of drivers currently in service. The train fiche is nothing more than an information sheet generated by the service staff at the start of each transport in such a way as to know the characteristics of the section to be covered with particular attention to gradients and maximum speed, with an indication of the arrival time at each point of the route.
An example of a train card, not related to our routes in the studio, is shown in figure 38 for a passenger train for a journey from Genoa to Turin Porta Nuova.


Scheda Treno

Fascicolo Linee	Treno	Scheda n°	Sigla di Composizione
125 116 117 118 112 96 99 77 72 74 76 73	1944	10/11 Da: Cippo 8.000 A: Baldichieri	V160B 125%
Validità Dal: 16.09.10 Al: 11.12.10	Termine Scheda TORINO P.NUOVA		Int. alla Sigla E 656 RSC4
Classificazione EXP	Prestazione 700t	Lunghezza	

Grado di frenatura	Binario L/S Vel. Max.	Vel. Marc.	Prog Km.	Località	Orario			Binario ILL/D Vel. Max.	Simbologia
III	100	100	8.000	Cippo 8.000				100	
			8.971	B/PC SCAVALCAM.		9.18			1
			9.466	Dev.Estr.Arquata		9.18½			
II			10.484 123.132	° ARQUATA SCRIVIA		9.19		90	1
	110	110	122.328	Dev. U.					
			121.297	P.B.A.330					
			118.813	Serravalle Scr.		9.22			
	150	150	118.000	Cippo 118.000					
	135	135	112.206	Dev. I.					
			111.683	° NOVI LIGURE...........	9.27		9.28		1
	150	150	109.630	° Biv. Cab. B		9.32			
			99.608	Frugarolo B.		9.39			
	90	90	90.992	Dev. I.					
			90.623	AL Cavalcavia		9.43			
Ia			90.075	° ALESSANDRIA........	9.45	Ao	9.48	90	1
			89.420	P.Tanaro lato AL		9.49			
	150	150	89.000	Cippo				150	
			81.843	Solero		9.53			
			75.547	Felizzano		9.55			
			68.317	Rocchetta T.C.		9.58			
			65.177	Castel.d`Annone		9.59			
	100	100	56.952	DEV. I.					
			55.779	ASTI...........................	10.04	Ao	10.06		2
	150	150	55.000	Cippo					
	130	130	49.736	Cavalcavia				130	
			48.613	S.Damiano d`Asti		10.12			
			44.888	Baldichieri		10.14			

Figure 38: Example of train form ([27], 2011).

In the figure above it is possible to analyse a well-known passenger route. The second column shows the maximum speed that can be reached on the line on time, in order to respect the limits of the structure and the locomotive. The third column shows the locations along the route used as reference points, with on the left a kilometric numbering able to trace us precisely to the point of the line and to the progressive kilometric. The first column, on the other hand, gives us information about the slope of the route with the parameter "braking degree". That is, a scale of ten parameters can tell us the slope of our path with values between 0‰ and 35‰. The problem with such train schedules is that the indicated limit speed is a consequence of the interpolation of the line speed limits and the locomotive used.

Unfortunately, the train cards in our possession are generated considering the locomotives generally used in such lines, for example for the line Orbassano-Modane the locomotive considered is the French E436. The inconvenience solution takes into account the fact that the locomotives, inserted in the train cards in our possession, are much more performing than our Vossloh G2000. As a result, the speed limits of our locomotive will be lower than those of the inserted locomotive; therefore, no errors will be generated in the processing. Returning to the degree of braking, in subsequent calculations will not be considered, in its place the slope of the individual sections of the line in ‰ points shall be calculated. The values shall then be combined with the locomotive performance table based on the gradient and towed mass, and the results shall be the maximum speeds of the locomotive on each section.

v [km/h]	Massa rimorchiabile [t] rispetto alla pendenza							
	2,5 ‰	5 ‰	7,5 ‰	10 ‰	12,5 ‰	15 ‰	20 ‰	25 ‰
0	>3000	>3000	>3000	2485,00	2010,00	1690,00	1265,00	1010
5	>3000	>3000	>3000	2475,00	2005,00	1685,00	1260,00	1007
10	>3000	>3000	>3000	2460,00	2000,00	1680,00	1255,00	1004
15	>3000	>3000	>3000	2340,00	1900,00	1590,00	1195,00	955
20	>3000	>3000	2725,00	2110,00	1710,00	1435,00	1085,00	860
25	>3000	>3000	2430,00	1870,00	1520,00	1275,00	960,00	760
30	>3000	2950,00	2115,00	1640,00	1320,00	1110,00	830,00	650
35	>3000	2590,00	1850,00	1430,00	1160,00	975,00	725,00	575
40	>3000	2250,00	1620,00	1260,00	1120,00	850,00	640,00	500
45	>3000	1990,00	1430,00	1110,00	900,00	750,00	560,00	440
50	2760,00	1750,00	1275,00	985,00	790,00	660,00	490,00	385
55	2435,00	1540,00	1115,00	860,00	710,00	590,00	440,00	345
60	2150,00	1375,00	1000,00	775,00	630,00	525,00	385,00	300
65	1900,00	1220,00	895,00	695,00	560,00	465,00	345,00	260
70	1655,00	1090,00	795,00	615,00	500,00	420,00	305,00	240
75	1465,00	965,00	710,00	550,00	445,00	370,00	270,00	205
80	1310,00	870,00	640,00	500,00	405,00	340,00	245,00	180
85	1180,00	790,00	570,00	455,00	365,00	305,00	215,00	165
90	1060,00	715,00	535	415	335	280,00	200,00	150
95	955,00	650,00	480	375	305	250,00	175,00	140
100	865,00	590,00	445	345	275	235,00	155,00	115
105	780,00	540,00	400	315	250	210,00	150,00	105
110	710,00	495,00	365	290	240	190,00	135,00	95
115	645,00	455,00	340	260	215	175,00	120,00	85
120	580,00	410,00	310	245	195	155,00	110,00	75

Figure 39: Table of velocity, mass trained and track slope ([11], 2003).

5.3.1. Line Sannazzaro - Alessandria

The first section of the line analysed is the Sannazzaro - Alessandria, part of the railway line from Pavia to Alessandria Smistamento. This route is used for the transport of fuels, from the Eni refinery in Sannazzaro to Alessandria Sorting where they will be sorted to the various destinations. Generally run with diesel locomotives, such as CZ DE753 or CZ DE520, as for the most part not electrified and therefore impossible to build with the classic electric locomotives, crosses places such as Lomello, Mede, Torre Beretti, Valenza and Valmadonna.

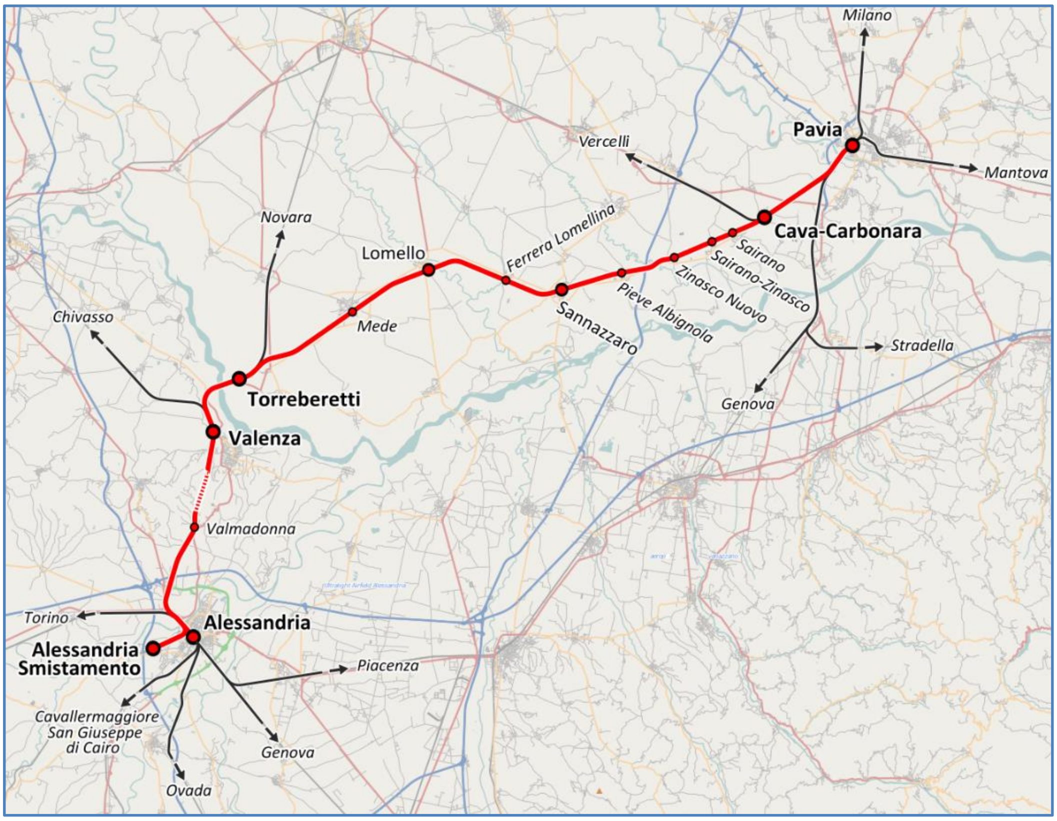


Figure 40: Railway path from Pavia to Alessandria SM ([28], 2021).

The reason for this choice is due to the decision to make a first simulation on a flat path, so as to obtain results in "standard" conditions that can be considered as nominal values of the machine. The route is in fact totally flat with only a small drop of 20 m, just before the resort Valmadonna, distributed over a distance of 6 km.

Below is a reconstruction of the altitude profile of the route using the data in our possession.

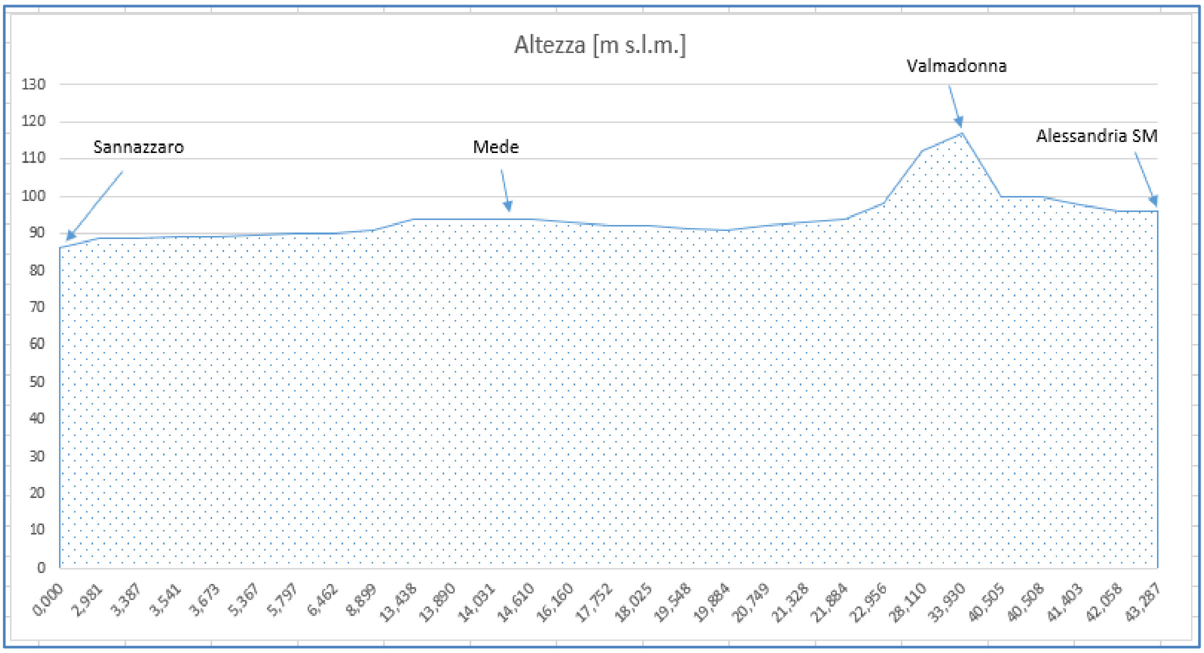


Figure 41: Route elevation profile.

In figure 41, the difference in height seems to be very marked but attention must be paid to the plane of the abscise, in which the kilometres of reference assume an increase not constant.

The next step is to get the maximum speed on each section of the line. To do this, the progressive kilometres of the various locations with relative altimetric profiles were reported, and then derive the gradients of the individual sections expressed in ‰. When this is done, the maximum physical speed of the locomotive is set according to the slope according to the procedure described in the previous paragraph, and then the minimum value between the latter and the limit values of the line is considered. Below are the values developed with representative graphs.

Distanza [km]	Progressivo	Località	Altezza [m s.l.m.]	Base [m]	Salita [‰]	Velocità_max_loco [km/h]	Velocità_max_road [km/h]	Velocità_eff [km/h]
0	0,000	Sannazzaro	**86**	0,00	0,00	0,00	95	0
2,981	2,981	P.L.A. km 18+633	88,52555775	2981,00	0,85	90,00	95	90
0,406	3,387	P.L.A. km 18+227	88,86952838	406,00	0,85	90,00	95	90
0,154	3,541	Ferrara Lomell.	**89**	154,00	0,85	90,00	95	90
0,132	3,673	P.L.A. km 17+941	89,04927212	132,00	0,37	90,00	95	90
1,694	5,367	P.L.A. km 16+247	89,68159761	1694,00	0,37	90,00	95	90
0,430	5,797	P.L.A. km 15+817	89,84210526	430,00	0,37	90,00	95	90
0,665	6,462	P.L.A. km 15+152	90,09033221	665,00	0,37	90,00	95	90
2,437	8,899	Lomello	**91**	2437,00	0,37	90,00	95	90
4,539	13,438	P.L.A. km 8+176	93,65335152	4539,00	0,58	90,00	95	90
0,452	13,890	P.L.A. km 7+724	93,91757599	452,00	0,58	90,00	95	90
0,141	14,031	Mede	**94**	141,00	0,58	90,00	95	90
0,579	14,610	P.L.A. km 7+274	93,70322911	579,00	-0,51	90,00	95	90
1,550	16,160	P.L.A. km 5+724	92,90876474	1550,00	-0,51	90,00	95	90
1,592	17,752	P.L.A. km 4+132	92,09277294	1592,00	-0,51	90,00	95	90
0,273	18,025	P.L.A. km 3+859	91,9528447	273,00	-0,51	90,00	95	90
1,523	19,548	P.L.A. km 2+338	91,17221937	1523,00	-0,51	90,00	95	90
0,336	19,884	Cippo	**91**	336,00	-0,51	90,00	95	90
0,865	20,749	P.L.A. km 1+135	92,2975	865,00	1,50	90,00	90	90
0,579	21,328	Segn. Di . Protez.	93,166	579,00	1,50	90,00	90	90
0,556	21,884	Torreberetti	**94**	556,00	1,50	90,00	90	90
1,072	22,956	Dev. U.	**98**	1071,99	3,73	70,00	95	70
5,154	28,110	Valenza	**112**	5153,98	2,72	70,00	95	70
5,820	33,930	Valmadonna	**117**	5820,00	0,86	90,00	95	90
6,575	40,505	Cippo 0,00/88,52	100,0124262	6574,98	-2,58	90,00	95	90
0,003	40,508	Segn. di Protez.	100,0046752	3,00	-2,58	90,00	95	90
0,895	41,403	Ponte Tanaro	97,69229823	895,00	-2,58	90,00	75	75
0,655	42,058	Alessandria	**96**	655,00	-2,58	90,00	75	75
1,229	43,287	Alessandria SM	**96**	1229,00	0,00	90,00	60	60

Figure 42: Data elaboration.

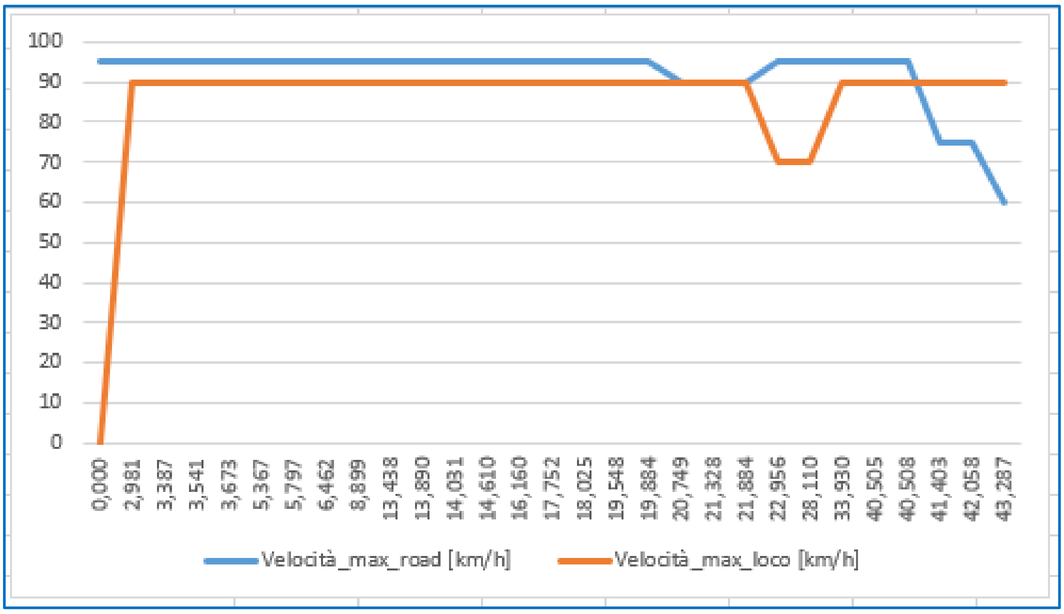


Figure 43: Velocity analysis.

As predicted, it is allowed a speed almost always up to 90 km/h, mainly due to the little difference in height that allows traction with reduced need for thrust.

Subsequently, the table of traction effort was taken into account and for each section, based on the maximum possible speed, the required power at the rim was defined. This value, however, considers a demand for constant maximum traction, therefore it was considered a transient acceleration based on experience, in this case it takes 8-9 km to reach the required speed with the chosen load, where full traction is effectively required. Later a partial traction is enough for the simple maintenance of the speed, this phase has been estimated with a use of reduced power to 50%; while for the sections in descent it has been considered a reduced power of 75%.

Finally, to obtain the required power output from the fuel cell, the values obtained were divided by the efficiency of the reducer, estimated at 0.8, the efficiency of the electric motor, fixed at 0.96 and finally the efficiency of the power unit, estimated at 0.9.

Distanza [km]	Progressivo	Località	Velocità_eff [km/h]	Pot_cerc_real [kW]	Pot_FC_out [kW]
0	0,000	Sannazzaro	0	0	0
2,981	2,981	P.L.A. km 18+633	90	1725	2495,659722
0,406	3,387	P.L.A. km 18+227	90	1725	2495,659722
0,154	3,541	Ferrara Lomell.	90	1725	2495,659722
0,132	3,673	P.L.A. km 17+941	90	1725	2495,659722
1,694	5,367	P.L.A. km 16+247	90	1725	2495,659722
0,430	5,797	P.L.A. km 15+817	90	1725	2495,659722
0,665	6,462	P.L.A. km 15+152	90	1725	2495,659722
2,437	8,899	Lomello	90	1725	2495,659722
4,539	13,438	P.L.A. km 8+176	90	862,5	1247,829861
0,452	13,890	P.L.A. km 7+724	90	862,5	1247,829861
0,141	14,031	Mede	90	862,5	1247,829861
0,579	14,610	P.L.A. km 7+274	90	862,5	1247,829861
1,550	16,160	P.L.A. km 5+724	90	862,5	1247,829861
1,592	17,752	P.L.A. km 4+132	90	862,5	1247,829861
0,273	18,025	P.L.A. km 3+859	90	862,5	1247,829861
1,523	19,548	P.L.A. km 2+338	90	862,5	1247,829861
0,336	19,884	Cippo	90	862,5	1247,829861
0,865	20,749	P.L.A. km 1+135	90	862,5	1247,829861
0,579	21,328	Segn. Di . Protez.	90	862,5	1247,829861
0,556	21,884	Torreberetti	90	862,5	1247,829861
1,072	22,956	Dev. U.	70	836,125	1209,671586
5,154	28,110	Valenza	70	836,125	1209,671586
5,820	33,930	Valmadonna	90	862,5	1247,829861
6,575	40,505	Cippo 0,00/88,52	90	431,25	623,9149306
0,003	40,508	Segn. di Protez.	90	431,25	623,9149306
0,895	41,403	Ponte Tanaro	75	422,915	611,8561921
0,655	42,058	Alessandria	75	422,915	611,8561921
1,229	43,287	Alessandria SM	60	866,665	1253,855613

Figure 44: Required power from the FC.

The final step is the calculation of the energy required for each section and consequently the hydrogen consumption per kilometre and for the total journey.

To do this the power required in output from the fuel cell has been normalized to 1 so as to derive the instantaneous efficiency, or at least on each section, of the fuel cell. Applying the principle of transient acceleration to speed again, we therefore have everything we need to derive consumption. It will be sufficient to derive the energy from the power applied for the journey time and then divide it for the efficiency of the cell, as follows:

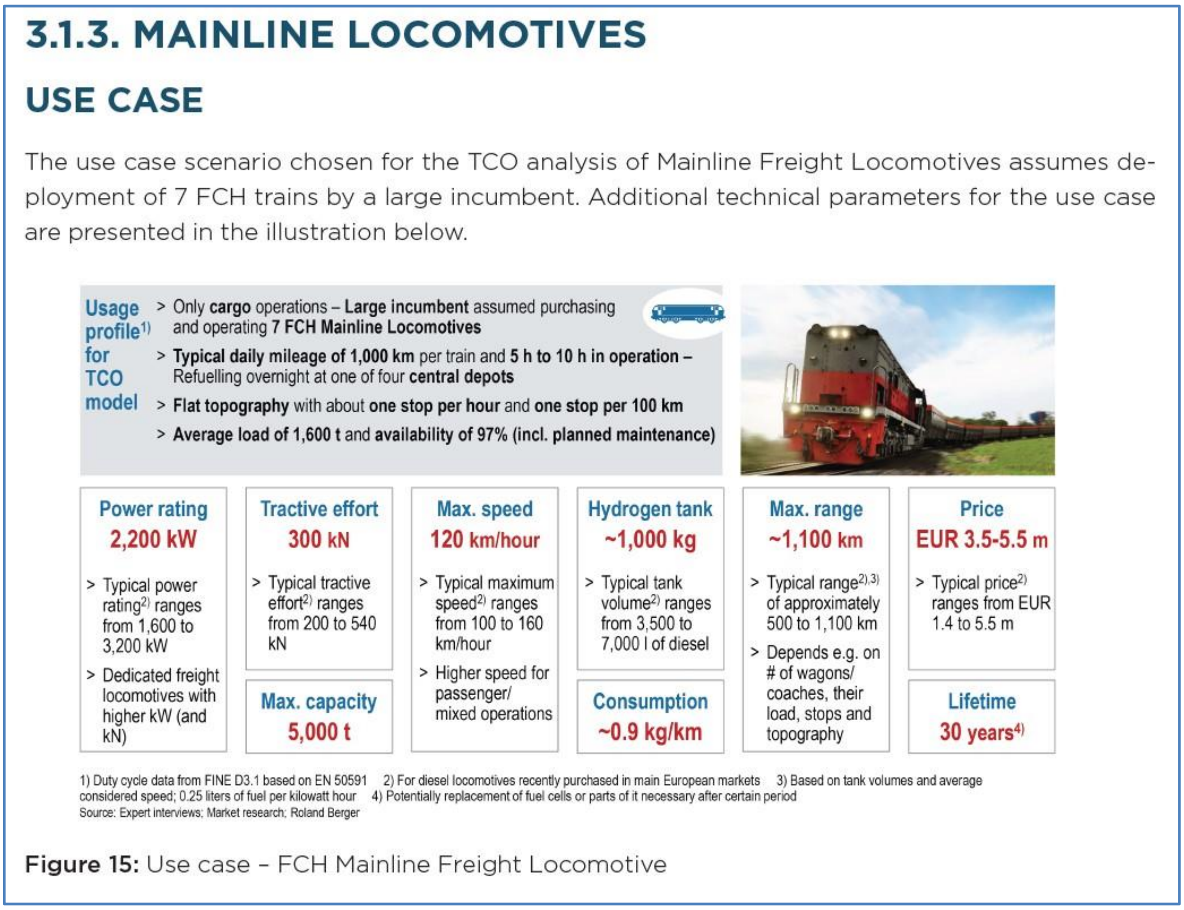
$$E_{req} = \frac{P_{req}(\frac{distance}{velocity})}{\eta_{FC}}$$

The hydrogen consumption can be obtained with a simple division by the energy density of the fuel, 143 [MJ/kg]. Here are the results obtained.

Distanza [km]	Progressivo	Località	Pot_FC_out [kW]	Vel_real [km/h]	P_out_norm	Eff_FC	Energia_real	Consumo [kgH2/km]
0	0,000	Sannazzaro	0	0	0	0,3224	0	0
2,981	2,981	P.L.A. km 18+633	2495,659722	52,08982433	0,663461538	0,503986334	283,3842391	2,393206534
0,406	3,387	P.L.A. km 18+227	2495,659722	55,52384116	0,663461538	0,503986334	36,20871728	2,245192432
0,154	3,541	Ferrara Lomell.	2495,659722	56,77208812	0,663461538	0,503986334	13,43236431	2,195827423
0,132	3,673	P.L.A. km 17+941	2495,659722	57,82057004	0,663461538	0,503986334	11,30467735	2,156009667
1,694	5,367	P.L.A. km 16+247	2495,659722	69,89364703	0,663461538	0,503986334	120,0168746	1,783591403
0,430	5,797	P.L.A. km 15+817	2495,659722	72,63961856	0,663461538	0,503986334	29,31308383	1,716166885
0,665	6,462	P.L.A. km 15+152	2495,659722	76,69293912	0,663461538	0,503986334	42,93711626	1,625465256
2,437	8,899	Lomello	2495,659722	89,99999974	0,663461538	0,503986334	134,0848253	1,385130092
4,539	13,438	P.L.A. km 8+176	1247,829861	90	0,331730769	0,559178485	112,5440642	0,624207345
0,452	13,890	P.L.A. km 7+724	1247,829861	90	0,331730769	0,559178485	11,20729611	0,624207345
0,141	14,031	Mede	1247,829861	90	0,331730769	0,559178485	3,496081307	0,624207345
0,579	14,610	P.L.A. km 7+274	1247,829861	90	0,331730769	0,559178485	14,35624877	0,624207345
1,550	16,160	P.L.A. km 5+724	1247,829861	90	0,331730769	0,559178485	38,43209948	0,624207345
1,592	17,752	P.L.A. km 4+132	1247,829861	90	0,331730769	0,559178485	39,4734854	0,624207345
0,273	18,025	P.L.A. km 3+859	1247,829861	90	0,331730769	0,559178485	6,769008489	0,624207345
1,523	19,548	P.L.A. km 2+338	1247,829861	90	0,331730769	0,559178485	37,7626371	0,624207345
0,336	19,884	Cippo	1247,829861	90	0,331730769	0,559178485	8,331087371	0,624207345
0,865	20,749	P.L.A. km 1+135	1247,829861	90	0,331730769	0,559178485	21,447591	0,624207345
0,579	21,328	Segn. Di . Protez.	1247,829861	90	0,331730769	0,559178485	14,35624877	0,624207345
0,556	21,884	Torreberetti	1247,829861	90	0,331730769	0,559178485	13,78596601	0,624207345
1,072	22,956	Dev. U.	1209,671586	70	0,321586538	0,560919744	33,02657194	0,775595312
5,154	28,110	Valenza	1209,671586	70	0,321586538	0,560919744	158,7863356	0,775595312
5,820	33,930	Valmadonna	1247,829861	90	0,331730769	0,559178485	144,3063348	0,624207345
6,575	40,505	Cippo 0,00/88,52	623,9149306	90	0,165865385	0,582077825	78,30645643	0,2998253
0,003	40,508	Segn. di Protez.	623,9149306	90	0,165865385	0,582077825	0,035729182	0,2998253
0,895	41,403	Ponte Tanaro	611,8561921	75	0,162659615	0,582134408	12,54260837	0,352802204
0,655	42,058	Alessandria	611,8561921	75	0,162659615	0,582134408	9,179227356	0,352802204
1,229	43,287	Alessandria SM	1253,855613	60	0,333332692	0,558903155	45,95275988	0,941295929

Figure 45: Hydrogen consumption analysis.

The calculations show that for the entire journey our locomotive should need about 37 kg of hydrogen, defining an average consumption of about 0.858 kg/km. A value that is slightly different from the European reference values for hydrogen freight trains, fixed at 0.9 kg/km, as shown in the next figure.



3.1.3. MAINLINE LOCOMOTIVES

USE CASE

The use case scenario chosen for the TCO analysis of Mainline Freight Locomotives assumes deployment of 7 FCH trains by a large incumbent. Additional technical parameters for the use case are presented in the illustration below.

Usage profile[1] for TCO model

- Only **cargo** operations – **Large incumbent** assumed purchasing and operating **7 FCH Mainline Locomotives**
- **Typical daily mileage of 1,000 km** per train and **5 h to 10 h in operation** – Refuelling overnight at one of four **central depots**
- **Flat topography** with about **one stop per hour** and **one stop per 100 km**
- **Average load of 1,600 t** and **availability of 97% (incl. planned maintenance)**

Power rating 2,200 kW
- Typical power rating[2] ranges from 1,600 to 3,200 kW
- Dedicated freight locomotives with higher kW (and kN)

Tractive effort 300 kN
- Typical tractive effort[2] ranges from 200 to 540 kN

Max. capacity 5,000 t

Max. speed 120 km/hour
- Typical maximum speed[2] ranges from 100 to 160 km/hour
- Higher speed for passenger/ mixed operations

Hydrogen tank ~1,000 kg
- Typical tank volume[2] ranges from 3,500 to 7,000 l of diesel

Consumption ~0.9 kg/km

Max. range ~1,100 km
- Typical range[2),3] of approximately 500 to 1,100 km
- Depends e.g. on # of wagons/ coaches, their load, stops and topography

Price EUR 3.5-5.5 m
- Typical price[2] ranges from EUR 1.4 to 5.5 m

Lifetime 30 years[4]

1) Duty cycle data from FINE D3.1 based on EN 50591 2) For diesel locomotives recently purchased in main European markets 3) Based on tank volumes and average considered speed; 0.25 liters of fuel per kilowatt hour 4) Potentially replacement of fuel cells or parts of it necessary after certain period
Source: Expert interviews; Market research; Roland Berger

Figure 15: Use case – FCH Mainline Freight Locomotive

Figure 46: Guide-line European about hydrogen locomotive for cargo ([29], s.d.).

For completeness, but above all to show the results from another point of view, below will be reported the values of real speed, consumption "instantaneous" and energy required compared to the altitude profile of the route. Again, the graphs do nothing but increase the consistency of the values used and the results obtained.

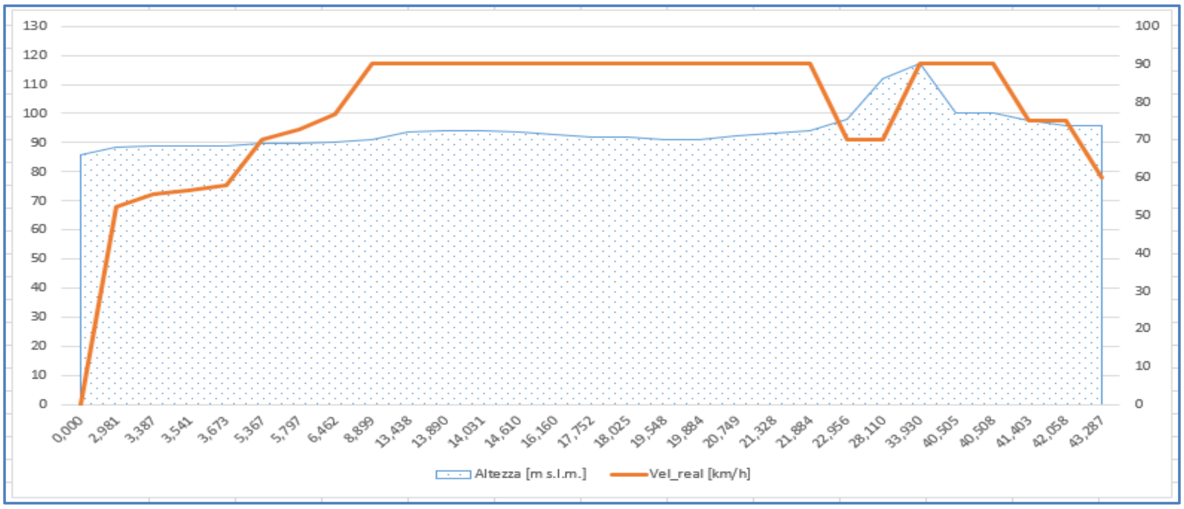


Figure 47: Velocity profile respect to altitude.

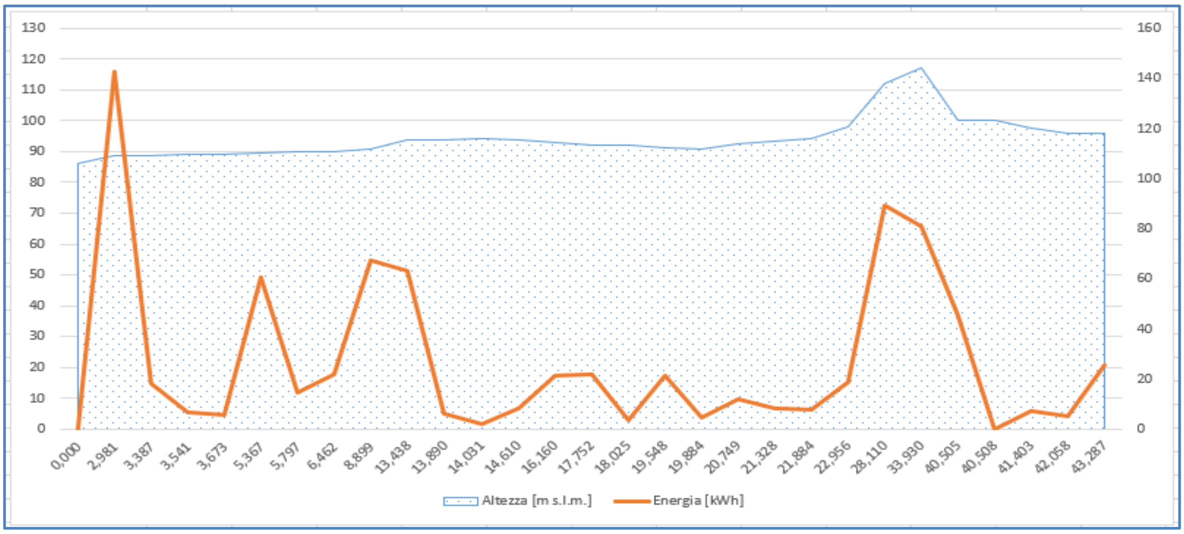


Figure 48: Energy consumed respect to altitude.

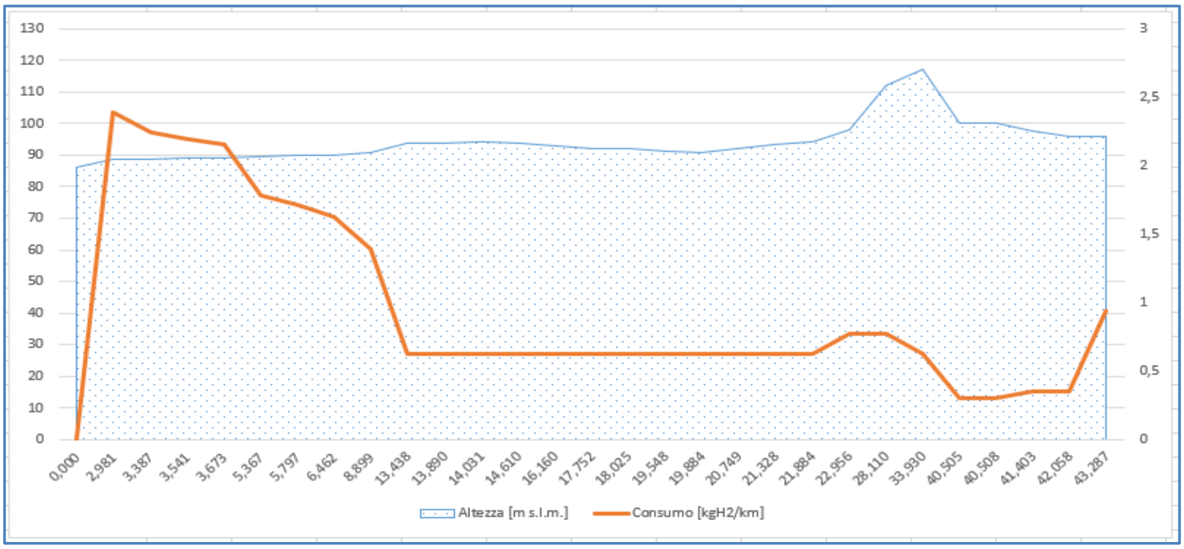


Figure 49: Hydrogen consumption respect to altitude.

5.3.2. Line Orbassano – Modane

The second route that we will analyse is the Orbassano-Modane, part of the railway line that connects Italy to France and that has always been one of the fundamental points for the import and export of goods to and from Europe.

It is a route used for various goods, but in our case, we will analyse a very frequent transport, that is clay and passes through places such as Alpignano, Salbertrand and Bardonecchia. It is commonly run with the electric locomotives e436, very old vehicles but with a high operational continuity and low maintenance cost, and it is easy to deduce the total electrification of the route.

Figure 50: Railway path from Torino to Modane ([30], 2021).

Being therefore electrified is not required the use of locomotives with alternative traction, was in fact chosen for the conformation altimetric in order to simulate a situation of extreme use. The line is in fact immediately constituted by more slopes than the previous case, up to Alpignano where there is a path from the steep slope up true Bardonecchia. The total difference in altitude of the route goes from an initial altitude of about 280 m until reaching 1300 m after the town of Bardonecchia.

Below the reconstruction of the altitude profile of the route,

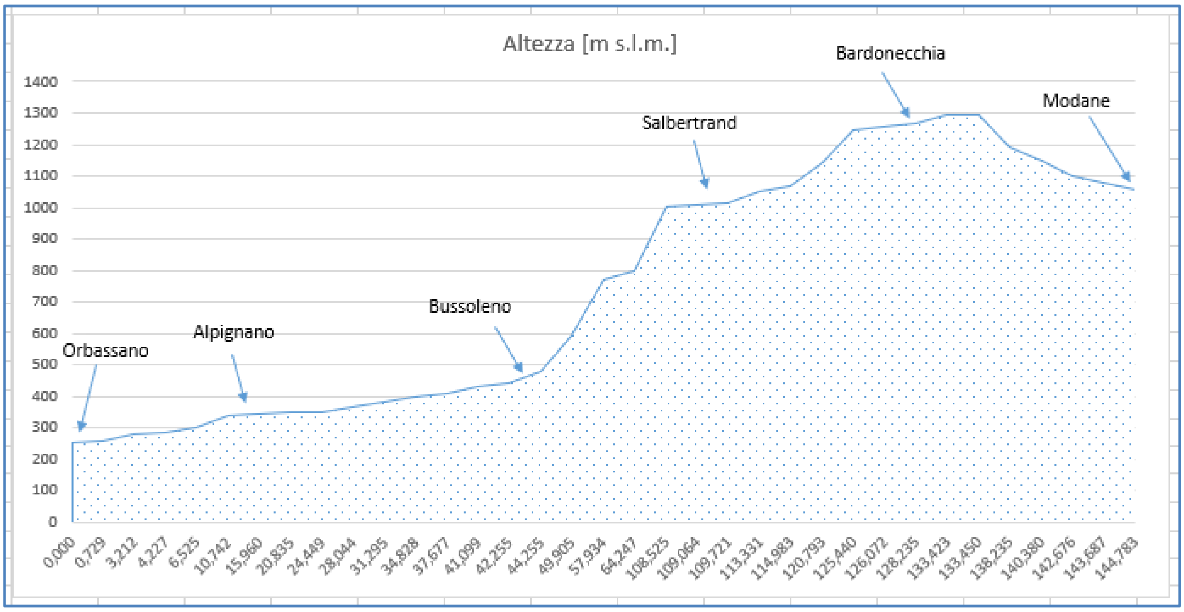


Figure 51: Route elevation profile.

It should be remembered that attention must be paid to the progressive mileage reported on the horizontal axis of the graph as it does not present a constant step.

As in the previous case, in the following steps the slope of the individual sections is first calculated and transformed into. Once these values have been obtained, the table in Figure 39 has been taken into consideration again and keeping always equal to 1200 t the transported load, the maximum speeds of the locomotive have been fixed with respect to the present slopes. These values were again compared with the line speed limits and the minimum between the two limits was taken as the reference value.

Below is the table of values and its representative graph.

Distanza [km]	Progressivo	Località	Altezza [m s.l.m.]	Base [m]	Salita [‰]	Velocità_max_loco [km/h]	Velocità_max_road [km/h]	Velocità_eff [km/h]
0,000	0,000	Orbassano	**254**	0	0,00	0,00	30	0,00
0,729	0,729	P.Inizio RSC	259	729	7,10	55,00	60	55,00
2,483	3,212	Biv. Pronda	277	2483	7,10	55,00	60	55,00
1,015	4,227	Grugliasco	**284**	1015	7,10	55,00	100	55,00
2,298	6,525	Collegno	**300**	2298	6,96	55,00	100	55,00
4,217	10,742	Alpignano	**338**	4217	9,01	45,00	100	45,00
5,218	15,960	Rosta	**343**	5218	0,96	90,00	100	90,00
4,875	20,835	Avigliana	**348**	4875	1,03	90,00	100	90,00
3,614	24,449	S. Ambrogio	**352**	3614	1,11	90,00	100	90,00
3,595	28,044	Condove	**367**	3595	4,17	70,00	100	70,00
3,251	31,295	S. Antonino Vale	**380**	3251	4,00	70,00	100	70,00
3,533	34,828	Borgone	**399**	3533	5,38	55,00	100	55,00
2,849	37,677	Bruzolo	**408**	2849	3,16	70,00	100	70,00
3,422	41,099	Cippo	433	3422	7,21	55,00	100	55,00
1,156	42,255	Bussoleno	**441**	1156	7,21	55,00	90	55,00
2,000	44,255	Cippo (Sx)	481	2000	20,13	20,00	90	20,00
5,650	49,905	P.C. Meana	**595**	5649	20,13	20,00	100	20,00
8,029	57,934	Chiomonte	**771**	8027	21,93	20,00	100	20,00
6,313	64,247	Exilles	800	6313	4,62	70,00	100	70,00
44,278	108,525	Sb.G. Voute (Dx)	1005	44278	4,62	70,00	100	70,00
0,539	109,064	Salbertrand	**1007**	539	4,62	70,00	100	70,00
0,657	109,721	Imb. Gal. Carenda	1014	657	10,14	40,00	100	40,00
3,610	113,331	Cippo	1050	3610	10,14	40,00	60	40,00
1,652	114,983	Oulx Ce.Cl.Ses.	**1067**	1652	10,14	40,00	100	40,00
5,810	120,793	Beaulard	**1145**	5809	13,43	30,00	100	30,00
4,647	125,440	Segn. Di Protez.	1244	4646	21,41	20,00	95	20,00
0,632	126,072	Bardonecchia	**1258**	632	21,41	20,00	75	20,00
2,163	128,235	Cippo	1269	2163	5,01	70,00	75	70,00
5,188	133,423	P.C. Frejus	1295	5188	5,01	70,00	100	70,00
0,027	133,450	Confine Francese	**1295**	27	5,01	70,00	85	70,00
4,785	138,235	Cippo	1195	4784	-21,01	90,00	85	85,00
2,145	140,380	P.C. Terres Froi.	1149	2145	-21,01	90,00	70	70,00
2,296	142,676	P. Fine RSC	1101	2295	-21,01	90,00	70	70,00
1,011	143,687	Dev. I.	1080	1011	-21,01	90,00	70	70,00
1,096	144,783	Modane	**1057**	1096	-21,01	90,00	30	30,00

Figura 52: Data elaboration.

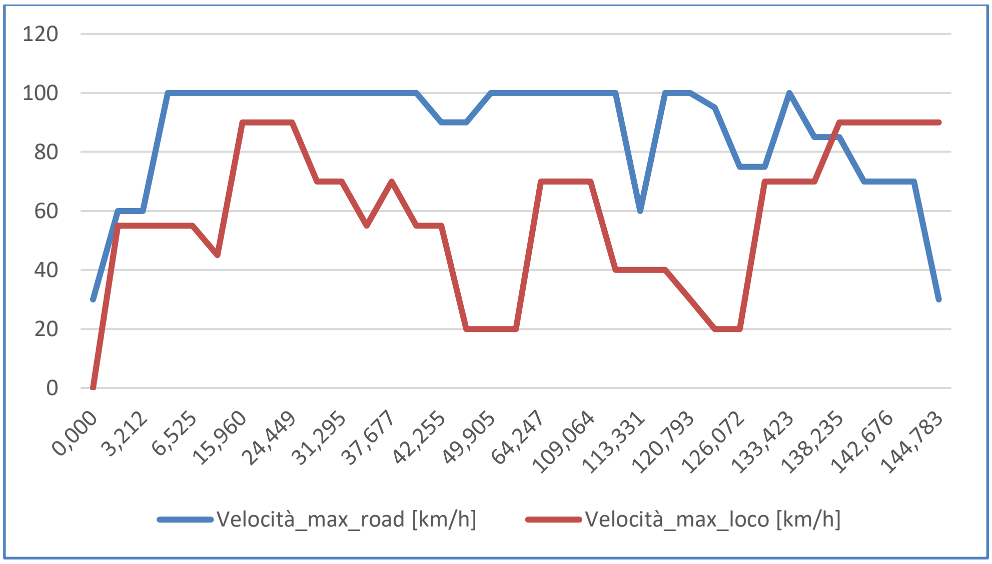


Figure 53: Velocity analysis.

Compared to the previous case, we notice a very variable speed profile with even relatively low values, because in certain sections you reach slopes too high for the traction of the chosen load, limiting the speed to 20 km/h.

Following the procedures of the case in plain, the graph of the traction force to the rim with respect to the speed is resumed and derived accordingly the power required to the rim. Compared to before, however, we are faced with a path for almost all uphill, this feature involves a continuous demand for traction at maximum power to be able to overcome the altitude difference. The only situation of reduced power is relative to the last section, after Bardonecchia, where the steep slope downhill and it is possible to consider a reduced engine power of 75%.

The obtained values must then be divided, as before, for the efficiency of the transmission, set to 0.8, the efficiency of the electric motors, fixed to 0.96, and finally for the efficiency of the power unit that regulates the whole, the value of which is 0.9.

Distanza [km]	Progressivo	Località	Velocità_eff [km/h]	Pot_cerc_real [kW]	Pot_FC_out [kW]
0,000	0,000	Orbassano	0,00	0	0
0,729	0,729	P.Inizio RSC	55,00	1720,83	2489,626736
2,483	3,212	Biv. Pronda	55,00	1720,83	2489,626736
1,015	4,227	Grugliasco	55,00	1720,83	2489,626736
2,298	6,525	Collegno	55,00	1720,83	2489,626736
4,217	10,742	Alpignano	45,00	1687,5	2441,40625
5,218	15,960	Rosta	90,00	1725	2495,659722
4,875	20,835	Avigliana	90,00	1725	2495,659722
3,614	24,449	S. Ambrogio	90,00	1725	2495,659722
3,595	28,044	Condove	70,00	1672,22	2419,299769
3,251	31,295	S. Antonino Vale	70,00	1672,22	2419,299769
3,533	34,828	Borgone	55,00	1720,83	2489,626736
2,849	37,677	Bruzolo	70,00	1672,22	2419,299769
3,422	41,099	Cippo	55,00	1720,83	2489,626736
1,156	42,255	Bussoleno	55,00	1720,83	2489,626736
2,000	44,255	Cippo (Sx)	20,00	1322,22	1912,934028
5,650	49,905	P.C. Meana	20,00	1322,22	1912,934028
8,029	57,934	Chiomonte	20,00	1322,22	1912,934028
6,313	64,247	Exilles	70,00	1672,22	2419,299769
44,278	108,525	Sb.G. Voute (Dx)	70,00	1672,22	2419,299769
0,539	109,064	Salbertrand	70,00	1672,22	2419,299769
0,657	109,721	Imb. Gal. Carenda	40,00	1666,67	2411,270255
3,610	113,331	Cippo	40,00	1666,67	2411,270255
1,652	114,983	Oulx Ce.Cl.Ses.	40,00	1666,67	2411,270255
5,810	120,793	Beaulard	30,00	1583,33	2290,697338
4,647	125,440	Segn. Di Protez.	20,00	1322,22	1912,934028
0,632	126,072	Bardonecchia	20,00	1322,22	1912,934028
2,163	128,235	Cippo	70,00	1672,22	2419,299769
5,188	133,423	P.C. Frejus	70,00	1672,22	2419,299769
0,027	133,450	Confine Francese	70,00	1672,22	2419,299769
4,785	138,235	Cippo	85,00	429,51375	621,4029948
2,145	140,380	P.C. Terres Froi.	70,00	418,055	604,8249421
2,296	142,676	P. Fine RSC	70,00	418,055	604,8249421
1,011	143,687	Dev. I.	70,00	418,055	604,8249421
1,096	144,783	Modane	30,00	395,8325	572,6743345

Figure 54: Required power output from FC.

The final step is to transform the values obtained in terms of hydrogen demand. Before doing this, however, it is necessary to consider the transitional periods in which the locomotive accelerates to reach the required speed. In this situation we find a path with a very marked difference in height, this variation compared to the case in the plain involves the possibility of not considering the same acceleration spaces. In order to remain cautious in the calculations, we will assume that our new locomotive will employ spaces from two to three times more extended. This assumption means that to reach the speed of 80-90 km/h it will be necessary up to 24 km of distance, values not too far from reality.

Below is the table of values used in the calculations and the results obtained.

Distanza [km]	Progressivo	Località	Pot_FC_out [kW]	Vel_real [km/h]	P_out_norm	Eff_FC	Energia_real	Consumo
0,000	0,000	Orbassano	0	0	0	0,3224	0	0
0,729	0,729	P.Inizio RSC	2489,626736	18,21464202	0,661857692	0,504240368	197,6075422	6,824053949
2,483	3,212	Biv. Pronda	2489,626736	38,23355177	0,661857692	0,504240368	320,6481242	3,251011063
1,015	4,227	Grugliasco	2489,626736	43,8604416	0,661857692	0,504240368	114,2588032	2,83393635
2,298	6,525	Collegno	2489,626736	54,49380509	0,661857692	0,504240368	208,2090098	2,28095101
4,217	10,742	Alpignano	2441,40625	45,00	0,649038462	0,506275409	451,9020441	2,697783959
5,218	15,960	Rosta	2495,659722	60,06	0,663461538	0,503986334	430,1967894	2,075532573
4,875	20,835	Avigliana	2495,659722	71,32	0,663461538	0,503986334	338,4960452	1,748016156
3,614	24,449	S. Ambrogio	2495,659722	78,63	0,663461538	0,503986334	227,6087944	1,585504042
3,595	28,044	Condove	2419,299769	70,00	0,643161538	0,507211106	244,9637289	1,715415591
3,251	31,295	S. Antonino Vale	2419,299769	70,00	0,643161538	0,507211106	221,5235279	1,715415591
3,533	34,828	Borgone	2489,626736	55,00	0,661857692	0,504240368	317,1593918	2,259958178
2,849	37,677	Bruzolo	2419,299769	62,36	0,643161538	0,507211106	217,9075069	1,925511895
3,422	41,099	Cippo	2489,626736	55,00	0,661857692	0,504240368	307,1948596	2,259958178
1,156	42,255	Bussoleno	2489,626736	55,00	0,661857692	0,504240368	103,7747685	2,259958178
2,000	44,255	Cippo (Sx)	1912,934028	20,00	0,508546154	0,529121232	361,5303851	4,55073212
5,650	49,905	P.C. Meana	1912,934028	20,00	0,508546154	0,529121232	1021,323338	4,55073212
8,029	57,934	Chiomonte	1912,934028	20,00	0,508546154	0,529121232	1451,363731	4,55073212
6,313	64,247	Exilles	2419,299769	48,11	0,643161538	0,507211106	625,8916676	2,495915303
44,278	108,525	Sb.G. Voute (Dx)	2419,299769	70,00	0,643161538	0,507211106	3017,108202	1,715415591
0,539	109,064	Salbertrand	2419,299769	70,00	0,643161538	0,507211106	36,7275243	1,715415591
0,657	109,721	Imb. Gal. Carenda	2411,270255	40,00	0,641026923	0,507551397	78,03173074	2,990007884
3,610	113,331	Cippo	2411,270255	40,00	0,641026923	0,507551397	428,7588249	2,990007884
1,652	114,983	Oulx Ce.Cl.Ses.	2411,270255	40,00	0,641026923	0,507551397	196,2076396	2,990007884
5,810	120,793	Beaulard	2290,697338	30,00	0,608973077	0,512688761	865,3041594	3,749377097
4,647	125,440	Segn. Di Protez.	1912,934028	20,00	0,508546154	0,529121232	840,0158497	4,55073212
0,632	126,072	Bardonecchia	1912,934028	20,00	0,508546154	0,529121232	114,2436017	4,55073212
2,163	128,235	Cippo	2419,299769	32,50	0,643161538	0,507211106	317,488047	3,695194674
5,188	133,423	P.C. Frejus	2419,299769	51,28	0,643161538	0,507211106	482,5837687	2,34174287
0,027	133,450	Confine Francese	2419,299769	51,36	0,643161538	0,507211106	2,507617633	2,338105019
4,785	138,235	Cippo	621,4029948	63,94	0,165197596	0,582092729	79,88525087	0,420292001
2,145	140,380	P.C. Terres Froi.	604,8249421	68,84	0,160790385	0,582149354	32,37168038	0,37993072
2,296	142,676	P. Fine RSC	604,8249421	70,00	0,160790385	0,582149354	34,07760907	0,37364889
1,011	143,687	Dev. I.	604,8249421	70,00	0,160790385	0,582149354	15,00542804	0,37364889
1,096	144,783	Modane	572,6743345	30,00	0,152243269	0,582029686	35,94610868	0,825672447

Figure 55: Hydrogen consumption analysis.

The consumption obtained shows very high values, even higher than expected. With an average mileage consumption of around 2,389 [kgH2/km] for a total of 346 kg of hydrogen for the entire journey. This value, almost threefold compared to the flat case, is due to a very demanding route and that in reality requires the use of at least two locomotives in multiple traction.

The results from the elevation profile will be shown below.

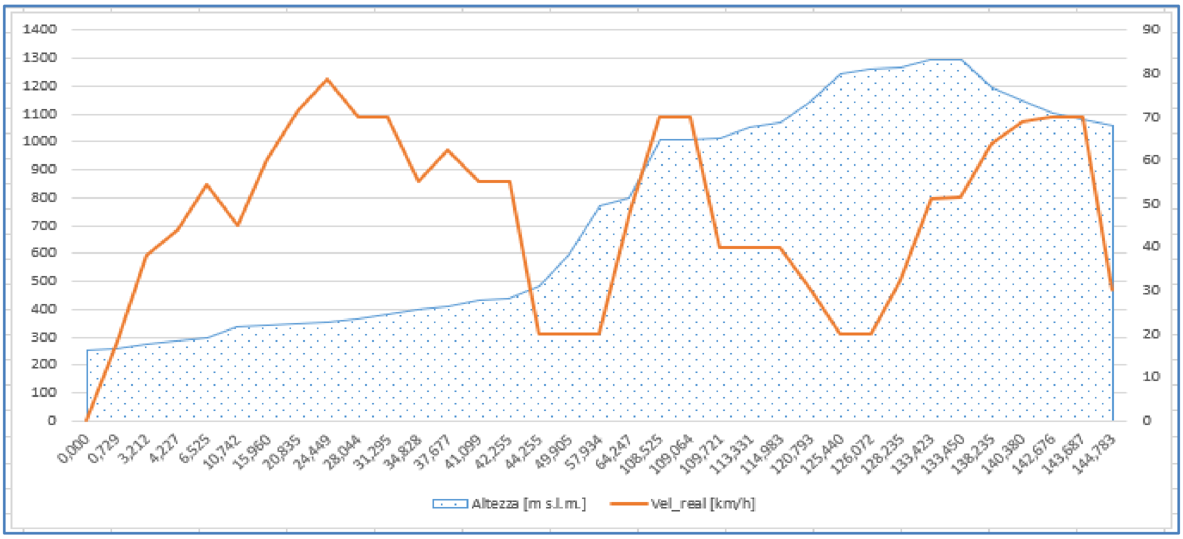


Figure 56: Velocity profile respect to altitude.

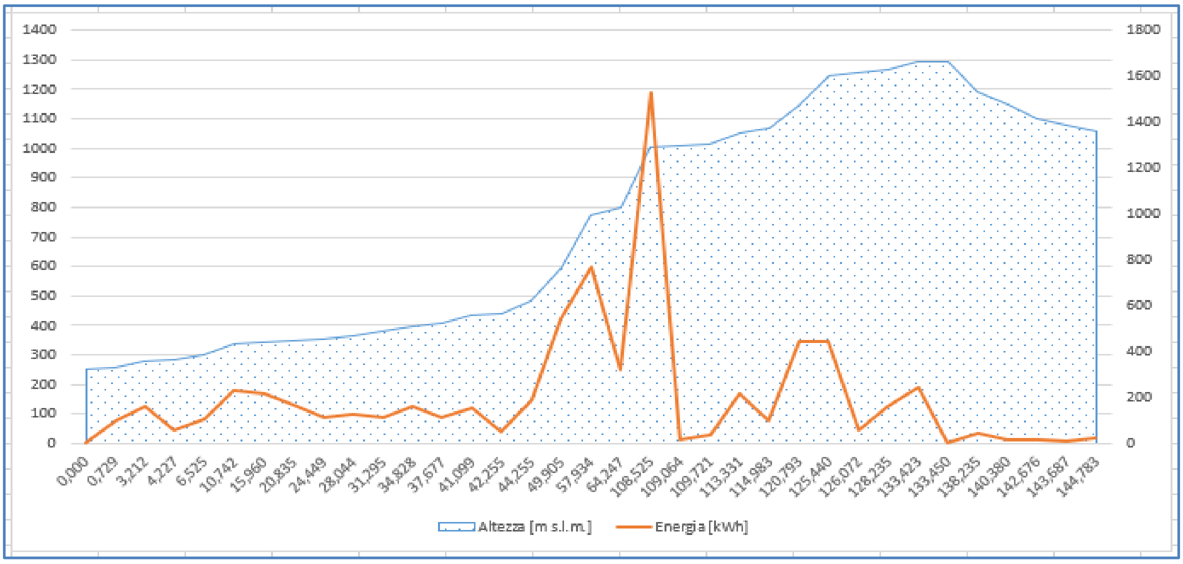


Figure 57: Energy consumed respect to altitude.

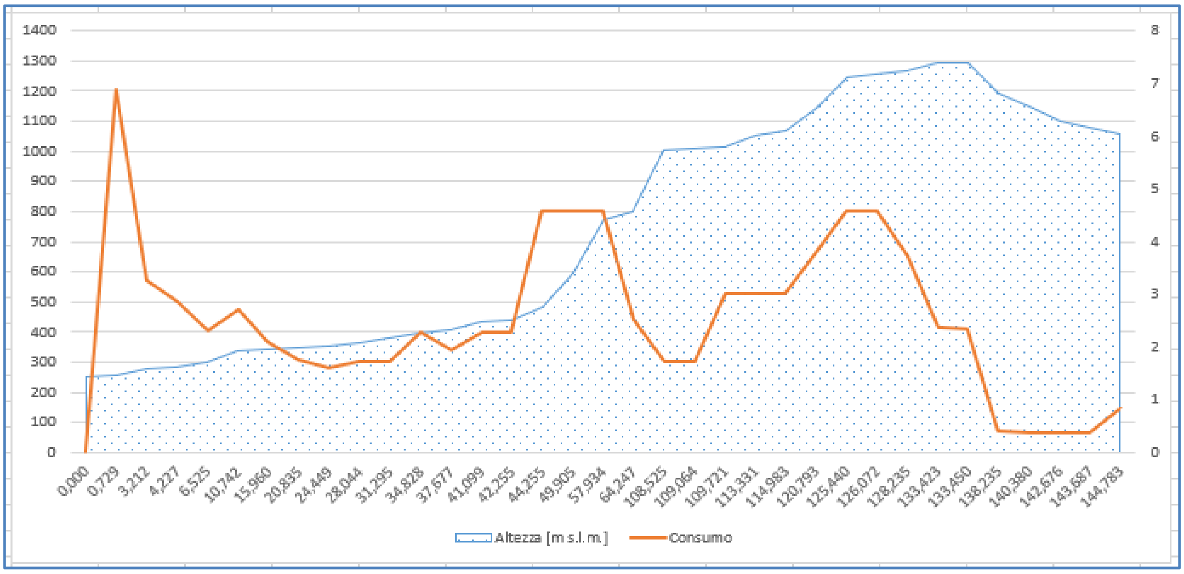


Figure 58: Hydrogen consumption respect to altitude.

In any case, despite very high consumption, correlation graphs show a clear consistency of the results obtained compared to the study. In the specific consumption of hydrogen, Figure 58, we notice in fact a peak of consumption in initial phase, where a high effort is required to pass from the standstill to the required speed recording a peak consumption of about 6.82 [kg/km]. And two peaks of consumption, lower than the first, relating to the two climbs with greater inclination present along the route with peak values at about 4.55 [kg/km].

5.4. Hydrogen storage

After analysing our locomotive on real-world routes, we have to go to size the tank to contain the hydrogen needed for the process. In Section 4.3. all the different types of hydrogen storage systems were examined. In this case we will analyse for our sizing only the types of compressed hydrogen, liquid hydrogen, carbon nanostructure and metal hydrides.

Method	Gravimetric Energy Density (wt %)	Volumetric Energy Density (MJ/L)	Temperature (K)	Pressure (barg)	Remarks
Compressed	5.7	4.9	293	700	Current industry standard
Liquid	7.5	6.4	20	0	Boil-off constitues major disadvantage
Cold/cryo compressed	5.4	4.0	40–80	300	Boil-off constitues major disadvantage
MOF	4.5	7.2	78	20–100	Attractive densities only at very low temperatures.
Carbon nanostructures	2.0	5.0	298	100	Volumetric density based on powder density of 2.1 g/mL and 2.0 wt % storage capacity.
Metal hydrides	7.6	13.2	260–425	20	Requires thermal management system.
Metal borohydrides	14.9–18.5	9.8–17.6	130	105	Low temperature, high pressure thermal management required
Kubas-type	10.5	23.6	293	120	
LOHC	8.5	7	293	0	Highly endo/exothermal requires processing plant and catalyst. Not suitable for mobility
Chemical	15.5	11.5	298	10	Requires SOFC fuel cell.

Figure 59: Hydrogen storage features comparison ([26], 2021).

A schematic summary of the gravimetric and volumetric densities in energy terms of certain types of storage is given in the figure above.

Before proceeding with the dimensioning, it is required to define the quantity of hydrogen necessary for transporting and consequently set the autonomy that we want to give to our locomotive. In order to guarantee an adequate autonomy also on demanding or long distances, it has been chosen to consider the hydrogen necessary to cover at least once the Orbassano - Modane section, or about 356 kg of hydrogen. A quantity that on the Sannazzaro - Alessandria route would guarantee the possibility of making at least nine or ten times the route.

Serbatoio	
H2 [kg]	356
Energy_H2 [MJ]	50849,5725

Table 3: Reservoir data.

The last necessary step is the calculation of the volume occupied and the weight generated by the individual types of tanks. To do this, just refer to the values shown in the table in Figure 56, For the calculation of the weight it is necessary to consider that the gravimetric density gives us information on what percentage occupies the weight of the hydrogen stored in relation to the total weight of the tank required. The values obtained from the calculations are reported below.

	Volume [L]	Peso [kg]
Compressed 700 bar [L]	10377,5	6238,446
Liquid [L]	7945,2	4741,219
Carbon nanostructures [L]	10169,9	17779,57
Metal hydrades [L]	3852,2	4678,834

Table 4: Reservoir results.

Leaving aside the case of liquid hydrogen, which would require a dedicated system for maintaining gas at the liquefaction temperature with a high cost, and carbon nanostructures, of which there is little information and however have the worst results, Compressed gas and metal hydrides remain. Given the results, the ideal tank would be to metal hydrides seen the volume really reduced and not excessive weight, also guarantees greater safety.

5.4.1. Safety of hydrogen reservoir

The question of safety is a fundamental issue in any field, but I would say vital if such safety is related to the storage of a gas such as hydrogen, in huge quantities, on a mobile vehicle (among other things, often used for the transport of flammable and explosive goods).
For these reasons it is necessary to make an assessment dedicated to the tank, in our case the current tank used for diesel has a shape that extends to the two lateral ends of the shape of the locomotive, as shown in the figure below.

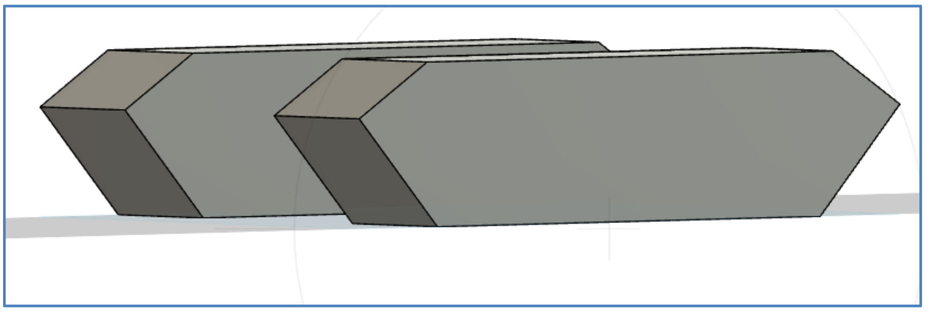


Figure 60: Rendering of the actual diesel reservoir.

The volume currently available is 5000 L, which is more than sufficient in the case of metal hydrides.

At the level of form instead you could increase the level of safety; in fact, in case of side collision has too high exposure to damage. A real example we can take from an accident occurred in manoeuvre at Casalpusterlengo during a manoeuvre with a CZ 753, that is an exchange of position of the locomotive at a maximum speed of 6 km/h. In this manoeuvre the Polish locomotive collided with the wagons engaged in the manoeuvre, cutting the fuel tank with relative fuel loss and all the consequences of the case.

Figure 61: Self-made picture of reservoir damage at Casalpusterlengo.

Although the locomotive we use is different, it must be considered that the fuel currently used is more dangerous, especially in the case of compressed hydrogen tank in which the pressures at stake reach 700 bar.

Therefore, it is proposed to modify the shape of the tank in such a way as to fit more and therefore be more shielded from other components in case of damage. The proposed template is shown in the next figure.

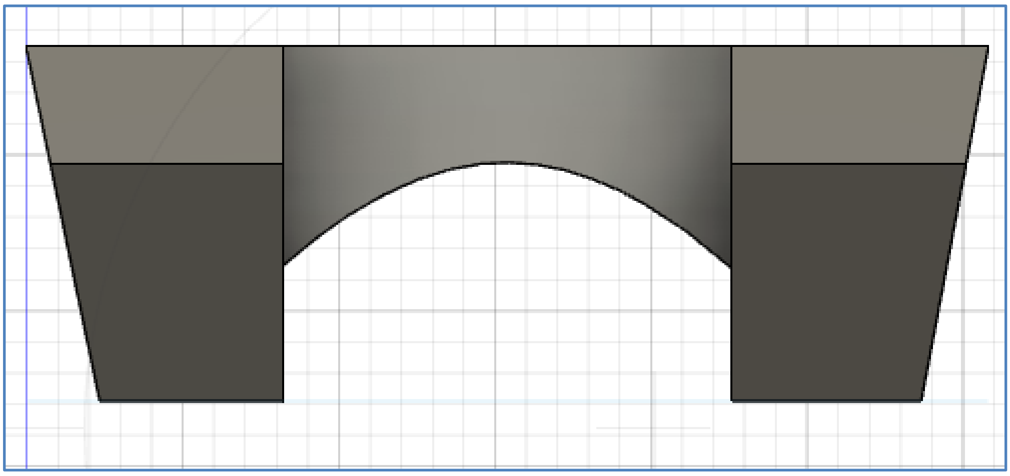


Figure 62: Front view of the new reservoir.

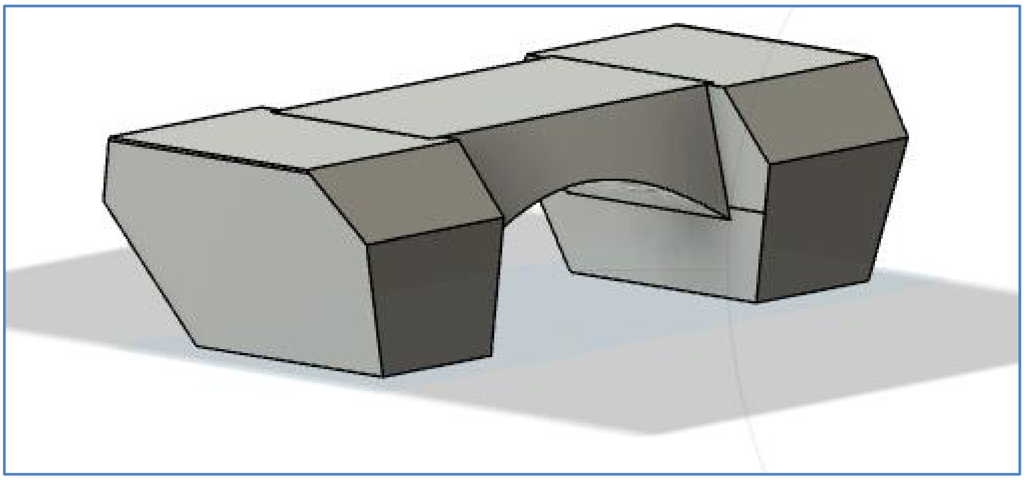


Figure 63: 3D view of the new reservoir.

The new tank, thanks to the more recessed shape, provides greater safety levels for any storage technology chosen and also allows a modulation of the volume necessary with the simple change of the size of the connection between the two extremes. Finally, in case metal hydrides are chosen, we will have a higher degree of safety guaranteed by the non-release of hydrogen in the absence of a heat source supplied to the system, even in case of impact.

5.5. Battery pack

In the initial design idea, the introduction of a battery pack as an emergency system was not considered. This auxiliary system was in fact excluded a priori thinking of having to devote the entire space available to the positioning of the components previously analysed, such as engine, fuel cell and tank. The only battery pack in the project would be the one related to general support batteries, with very limited size. Following the total sizing, the space deferred is such as to allow the introduction of further systems, so it was decided to proceed with the installation of a battery pack.

First of all, we need to identify the type of battery you want to install. In fact, there are different variants, depending on the chemical composition used, with different operational characteristics and durability.

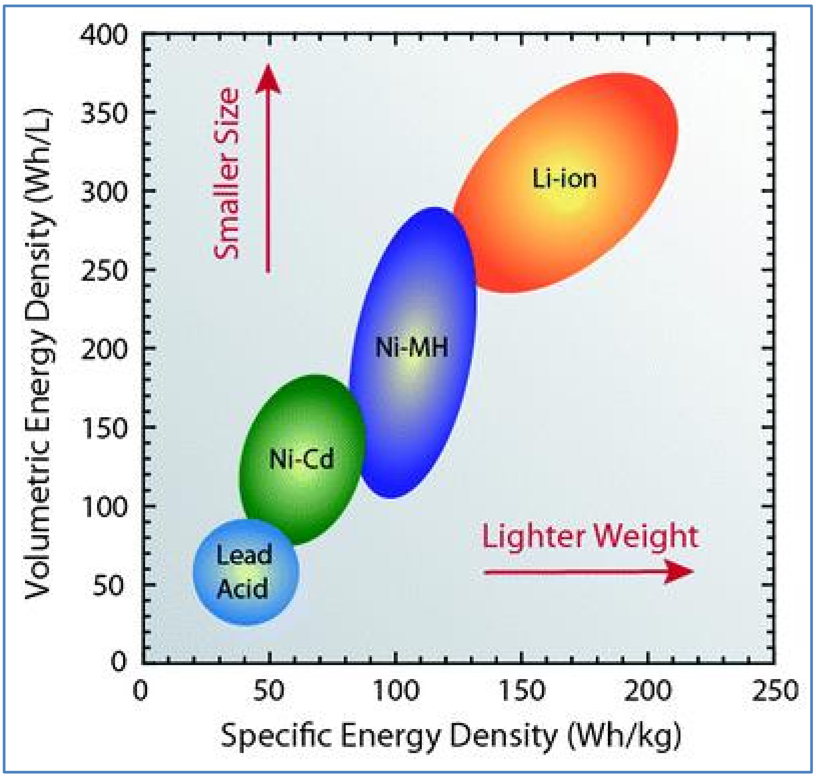


Figure 64: Batteries comparison ([31], 2021).

Figure 64 shows a comparison of the most common batteries used, Lead, Nickel-Cadmium, Nickel-Mercury and Lithium, relative to their volumetric and massive energy density. As we can see the most common lead batteries guarantee a volumetric energy density ranging from 30 [Wh/L] to 80 [Wh], these values for our interests are too low to obscure the positive aspects such as greater knowledge and experience. Therefore, the Li-ion type that offers a specific energy content of 250-380 [Wh/L] and 120-220 [Wh/kg] will be used. These values result in a lower volume occupied and weight generated with the same energy stored.

To size it we consider the maximum values of the energy density ranges above and that our engines require a power of 2500 kW upstream of the power unit. The system is consequently dimensioned in such a way as to ensure an autonomy of half hour with the engines at full power.

Batteria supporto	
Autonomia [h]	0.5
Capacità [kWh]	2500
Densità_litio [Wh/L]	370
Densità_litio [kWh/mc]	370
Densità_litio [Wh/kg]	220
Peso [kg]	5682
Volume [m3]	3.3784

Table 5: Battery pack features.

As shown in Table 5, we have been obtained that the battery pack will have a weight of 5.68 t and will occupy a volume of 3.3784 [m^3]. For a more precise sizing of shape and size, it was decided to occupy the entire available height and width, and then develop into length as shown below.

Length [m]	2,7100741
Width [m]	1,84
Height [m]	1,355

Table 6: Battery pack dimension.

As for the other components, an idea of the possible positioning of the battery pack is shown.

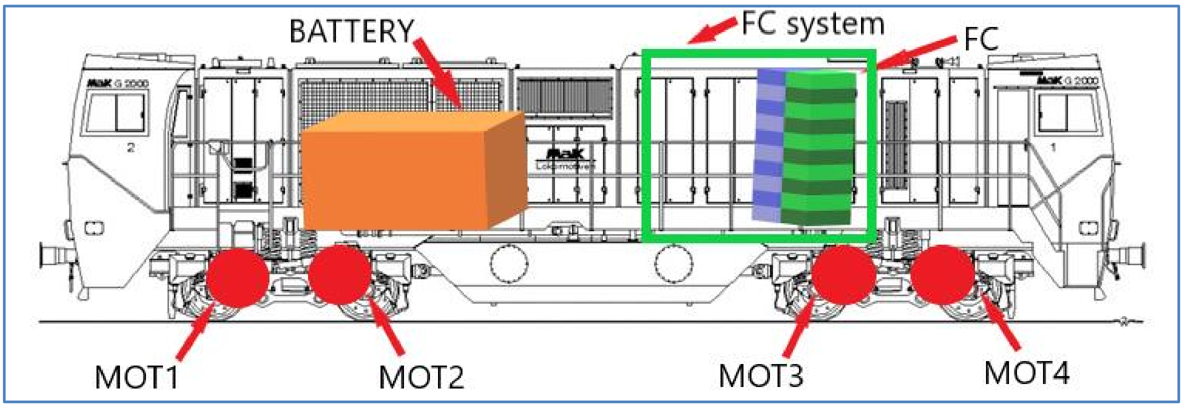


Figure 65: Position of the battery pack.

This positioning does not take into account the need for heat dissipation and various accessories; therefore, measurements may vary to ensure the introduction of the missing parts. However, it takes into account the proximity to the module E, where there are all the switches for the management of the electrical part of the vehicle.

5.6. Weight and volume control

One of the main points mentioned at the beginning of the work was the objective of being able to maintain equal or little different the weight of the locomotive before and after the intervention. It is therefore necessary to proceed with an analysis of the weights of the various components removed and introduced.

First, we'll analyse the weights removed. We know that the initial locomotive declared a total weight of 87 tonnes, recital 2/3 of the reserve. Only some data could be obtained from the removed components. The CAT diesel engine is declared to have a weight of about 8 tons, while the gearbox Voith 4.7 tons. The weight of the tank has been estimated at 500 kg considering the mass of metal used and added to the fuel quota included in the total weight. Finally, a general estimate was made of the weight removed with the elimination of the cardan shafts, the muffler and the old cooling system, considering a value of 2 t.

Weight data original		
Locomotive	87300	kg
Engine	8000	kg
Gearbox	4700	kg
Fuel	3283	kg
Cooling system, muffler, cardanic transmission, reservoir structure	2000	kg
NET	69317	kg

Table 7: Weight data before project.

At this point we proceed with the evaluation of the weights introduced. First, the fuel cells, of which we know the specific weight compared to the power cut related to the entire cell contour system, from which we derive a weight of 2.1 t. The tank, considering the use of metal hydrides, would have a weight of 4.68 tons. As for electric motors, we know from the data provided by the manufacturer that each engine has a weight of 950 kg. Multiplying this value by the number of engines and increasing by a 20% the weight so as to also include the reducers, you get a weight of 4.5 t. The greatest impact is related to the newly dimensioned battery pack, whose weight is around 5.68 t.

These components therefore lead to an overall increase in weight from the initial 87 tonnes to about 86.4 tonnes. The value is perfect, we have not introduced other weight to the locomotive, also we have reduce it a bit. So, the new locomotive can have lower limitation during the run.

Weight data new		
NET	69317	kg
FC system	2185	kg
Reservoir	4679	kg
Battery	5682	kg
Engine	4560	kg
TOTAL	86422	kg

Table 8: Wight data post project.

In order to give an idea of the volume pre and post project, below is reported a table with the initial available volume and the volume of the component sized in the previous chapters.

Volume data		
Initial available volume	46,374	m^3
Initial reservoir volume	5,000	m^3
FC + system	9,630	m^3
Battery	3,378	m^3
Reservoir	3,852	m^3

Table 9: Volume data pre and post project.

6. Economic analysis

The size of the design is a substantial modification of the propulsion of a locomotive. Such modifications, besides being studied in order to render the medium highly efficient and "green", generate a great economic impact to level of investment in the intense activities of modification.

The interventions proposed in the project are divided into:

- Installation of electric motors with gearboxes
- Fuel cell stack installation
- Installation of battery
- Installation of new reservoir

The cost of investment for every single intervention is difficult to find, in the literature there are, in fact, few information about it; therefore, it would be difficult to carry out an economic analysis without having direct information from companies. Given the impossibility of obtaining concrete data from companies operating in the sector, a rough and highly cautious estimate of the possible costs of the project was made.

Component	Unit	Value	Specific cost [€/-]	Cost [€]
Engine	[kW]	2240	100	224.000,00
FC	[kW]	2600	100	260.000,00
Battery	[kWh]	1250	140	175.000,00
Reservoir	[kg]	4678,83	80	374.306,75
Extra			2,5%	25.832,67
			TOTALE	1.059.139

Table 10: Cost analysis.

For electric motors, the estimate was made taking into account the costs of significantly lower power electric motors found on the market. The specific cost was therefore increased by 25% to protect itself more. The cost of fuel cells is the result of a range found in the literature in which it spoke of 100-115[$/kW].

For the battery was considered the cost of lithium-ion batteries, the price indicated was 140 [$/kWh] but to be safer was increased by 16%. Finally, for the tank it was necessary to make an estimate without references, making assumptions between the cost of the metal used and the technology, was considered a value of 80 [€kWh]. In order to introduce in the calculation also the ancillary expenses, it is introduced an "extra" voice pairs to the 2,5% that included the costs of installation, techniques and other.

The resulting cost is around 1 million of euros. This amount is first of all an estimate without solid foundations; therefore, this value could also vary a lot at the actual design stage. Moreover, considering that the intervention consists in a complete revamping of the locomotive and that the initial cost of the locomotive itself was around 3-4 million €, this design cost is relatively acceptable. In fact, considering that the locomotive studied had a useful life of 15-20 years and the initial cost, we can deduce that it has a high return value. Therefore, any proposed change to the estimated investment cost would allow for a new operating locomotive with acceptable return on investment times.

7. Conclusion

The elaboration has reached the end of the entire phase of planning and technical and economic analysis. Before drawing conclusions, it is right to make some observations of a relatively important nature.

The first observation relates to simulations on real-world routes in general. Such analyses were carried out under ideal conditions. In the work experience carried out in this field it has been possible to visualize real variables that in the phases of planning have not been considered.

For example, we know in fact that traction is given by an iron-iron coupling, whose friction is much lower than the classic pneumatic-road coupling of cars. This condition generates a high risk of slippage in case of slopes with heavy load or adverse weather conditions, these conditions cause higher consumption and slowing down in the path. Another phenomenon is the obligatory stops for priority of other trains that cause the need to start sometimes uphill, not easy if the load and the slope are high.

The second observation is related to acceleration in simulations. This value, in the case of Sannazzaro-Alessandria, was derived from the experience of acquaintances working in the sector for years. The same value was then divided by three, by approximation, as the slope of the second path increased. And it was also considered a uniformly accelerated motion, only ideal condition.

The third observation concerns the simulation on the Orbassano-Modane route. First of all, this section is electrified and consequently is carried out with the best-performing electric locomotives. In addition, such gradients with loads of this size are traversed with the use of several locomotives, usually one in front and one behind. And this solution is also adopted for simpler slopes. From this it follows that the results are for test purposes only but have no real relevance.

The last point concerns the economic part. This calculation is in fact the result of a pure estimation based on literature, web and precautionary factors. The data recovered through knowledge and firms did not allow the development of an economic analysis, it was however carried out by placing a maximum possible expenditure ceiling, based on the purchase costs of such locomotives.

Having made the necessary observations and following all the results obtained in the work, it can be concluded that the proposed project has a high interest in the development of sustainable transport. The results obtained during sizing allow to deduce the feasibility of the project both in terms of size and performance. In fact, in terms of size, there is still an important useful volume. This result makes it possible to say that this project can also be proposed a locomotive with smaller dimensions. At the economic level, it is difficult to draw conclusions without real data, but it is assumed that costs cannot increase significantly to such an extent that intervention is unjustified.

The conversion of an old diesel locomotive with a new hydrogen propulsion, resulting in a reduction in emissions, is therefore possible. Giving the possibility to avoid piles of abandoned locomotives always increasing.

Figures

Tables

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