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The Integration of Innovative Power Sources and Storage Systems in the Railway Sector: A Brief Perspective Analysis

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Abstract

Massive electrification of road vehicles is offering an unexpected possibility for revolutionary improvements in efficiency and sustainability of rolling stock especially on non-electrified lines: the automotive market with massive production numbers justifies the vast investments in key innovative technologies regarding storage systems, power management and generation that are substantially unaffordable for the railway sector. Research activities performed at Florence University in the last ten years and more generally by different international research groups can strongly correlate to these general assumptions. This work investigates how general past, current and future developments in power storage technology have influenced and can further influence the application of innovative power storage technologies to the railway sector.

Keywords: battery operated trains, multi-modal trains, hybrid trains, hydrogen propelled trains, longitudinal dynamics, energy efficiency.

1 Introduction

As shown in figure 1/a, in Western Europe, a significant part of railway lines (about 43% according to [1]) still needs to be electrified. EU, but if we extend our analysis worldwide[2] as shown in figure 2, it can be easily argued that there are sizeable existing railway markets (such as North, South America and Oceania) or emerging ones (such as Africa) in which non-electrified lines are more widely diffused.

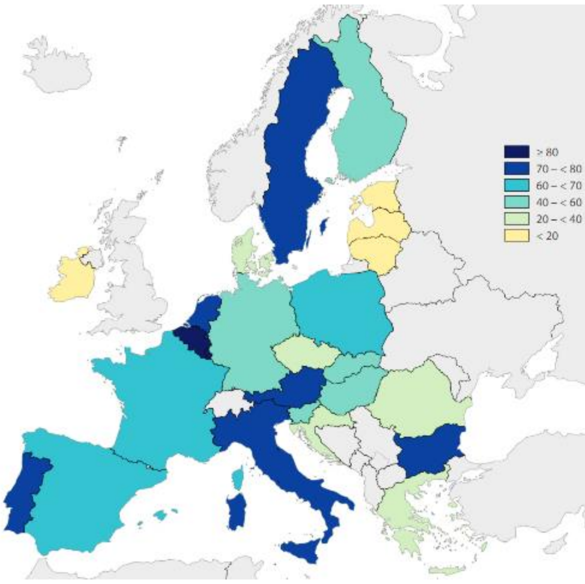

Figure 1: Electrified line in EU[1]

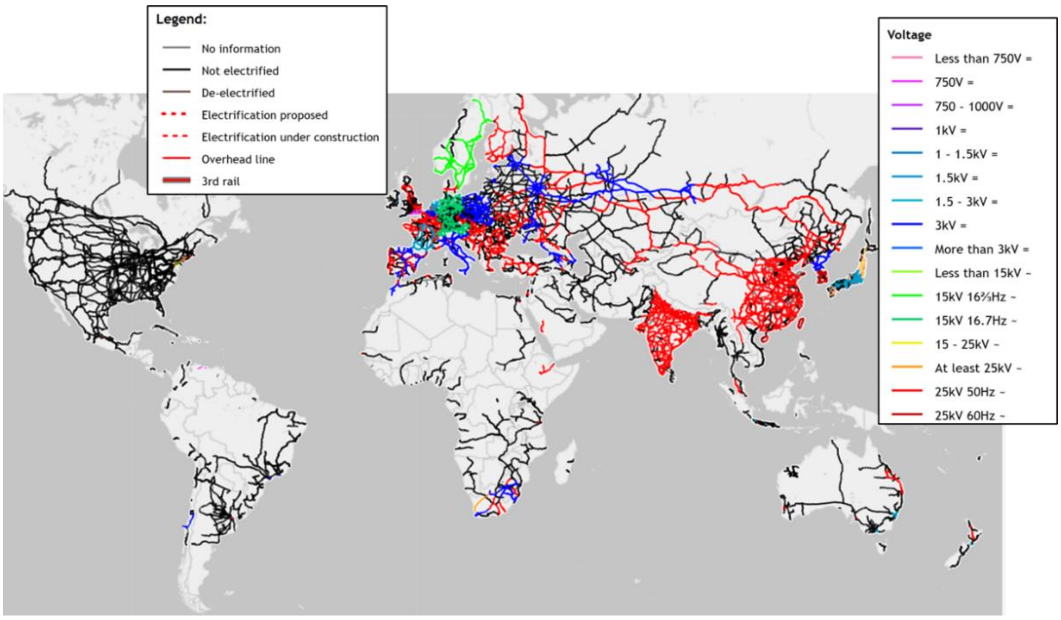

Figure 2: Mapping of Electrified Lines World Wide.[2]

So, it is clear that there is a broad potential market for the application of energy storage technologies that are alternatives to the conventional hydrocarbons fuel that are currently adopted for the propulsion of rolling stock on non-electrified lines. It should also be noted that Diesel-Electric Transmission is a widely diffused conventional technology applied to rolling stock since this kind of solution was successfully proposed in North America roughly from 1925-30. So also, the hybridization of rolling stock apparently requires a relatively minor technology jump for a corresponding evolution, as an example of the automotive sector.

Despite this evidence, the advance of these new technologies is currently delayed compared to other sectors, like the automotive one, by some key factors:

- A pre-existing, well-consolidated technology that allows a very highly sustainable railway service represented by electrified lines.
- Interoperability between rolling stock and infrastructure must be granted.
- The operational life of rolling stock often adopted in recent studies [3] is typically between 25 and 45 years, corresponding to a mileage reaching several million km. The expected operational life of a car, for example is much shorter (around 10 years) and corresponds to expected mileages of 150000-200000 kilometres. This exceptionally long operational life is a critical factor considering the current evolution trend of some key technologies, such as high energy NMC batteries proposed for the automotive sector, as shown in figure 3 [5], that depicts an exploding scenario in which the chemistry of a battery lithium cell becomes obsolete in less than 10 years with a linear increase of performances between 10 and 20% each year. Improvements in lithium-ion battery cell technology are too fast for the foreseen life of rolling stock, which should be designed to support a continuous upgrade of installed storage systems that will become obsolete during the expected service life of the rolling stock. Prolonged vehicle life and extended mileage also involve a more cautious exploitation of the storage system, which implies a reduced expected performance for batteries compared to applications such as the automotive one, where the overall service life is much shorter.

Continuous improvement of battery cell technology also affects the potential comparison in terms of equivalent autonomy and performances with other hybrid solutions, such as the hydrogen fuel cells in terms of specific power W_{spec} and specific energy E_{spec}, respectively affecting peak power performances and autonomy.

Specific power W_{spec} is defined as the ratio (1) between the power exerted by the storage W_{stor} and its weight m_{stor}

$$W_{spec} = \frac{W_{stor}}{m_{stor}} \left[W / kg \right] \tag{1}$$

In the same way specific energy or energy density E_{spec} is defined as the ratio(2) between stored energy E_{stor} and corresponding weight m_{stor}

$$E_{spec} = \frac{E_{stor}}{m_{stor}} \left[Wh / kg \right] \tag{2}$$

For hydrogen fuel cell systems, the mass of the storage is the sum of the mass of fuel cells and hydrogen tanks: fuel cells are responsible for power delivery and their power density W_{fc} is currently between 3 and 5 kW/kg. Otherwise, energy is stored in tanks which energetic density is calculated according to (3) as the product of the specific energy of hydrogen *PCI*, the expected efficiency of the fuel cell η, and the tank ratio ρ, which is defined as the ratio between the mass of stored H_2 respect to the total mass that includes the weight of tanks.

$$E_{tank} = PCI \eta \rho \tag{3}$$

Tank weight ratio ρ is the most critical factor for the design, since for a pressurized hydrogen tank at 350 bar, the weight of the tank is about 10-14 times higher compared to the one of the stored hydrogen, as stated by various academic [6] and industrial sources [7]-[8]. This constraint is quite critical since it is related to the structural limits of materials adopted for tank walls. Possible alternatives are represented by chemical and physical carriers and vectors for hydrogens [9][10]; however, performances and TRL level of these solutions are still not enough for an extensive application in the railway sector.

So specific energy and power of the whole system will be described respectively by (4) and (5) where m_{fc} and m_{tank} are respectively the masses of fuel cells and tanks.

$$W_{spec} = W_{fc} \frac{m_{fc}}{m_{fc} + m_{tank}} \tag{4}$$

$$E_{spec} = E_{tank} \frac{m_{tank}}{m_{tank} + m_{fc}} \tag{5}$$

So, the resulting specific power and energy of a fuel cell system are decided mainly by the ratio between fuel cell mass and hydrogen tank masses, as shown in figure 4: currently, battery-operated trains are mostly equipped with thermally stable LTO or LiFePO4 batteries, which assure an autonomy (70-100km) which is about one-tenth of the hydrogen fuel-cell solutions (800-1000km).

High-performance Li-NMC cells currently proposed for the automotive sector or more performing versions of other Lithium cells can halve this gap, as stated by recent autonomy records of battery-operated trains over 200 kilometres [11].

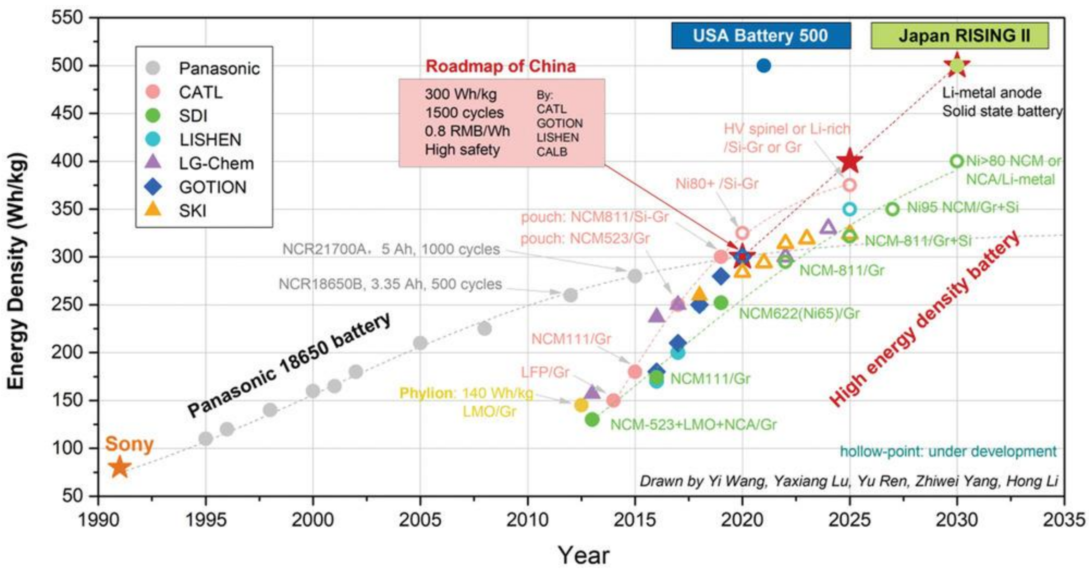

Figure 3: roadmaps for battery development (focused on high perf. Solutions for automotive marked) as foreseen by different industrial and academic groups in China, Japan and USA[5]

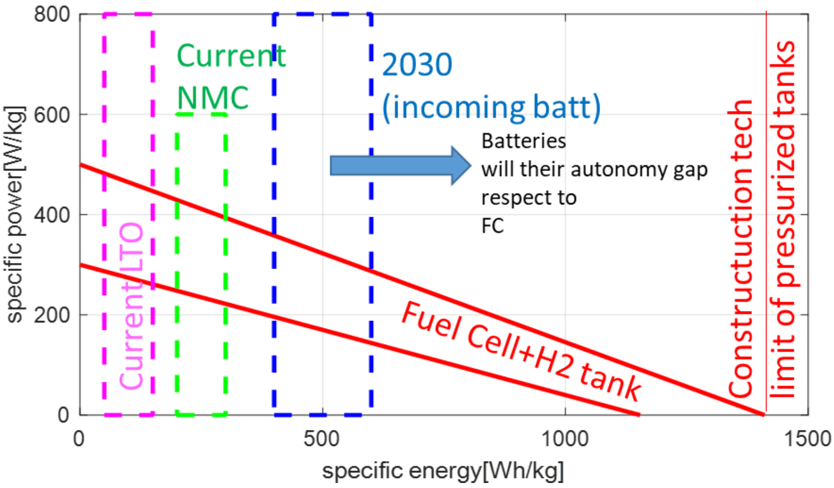

Figure 4: comparison between power and energy density of different batteries with current performances of Hydrogen Fuel Cell Systems

However, the performance of incoming Lithium cells that are foreseen in a short time from 2025 to 2030 poses a severe threat to fuel cell systems since potential autonomy can further increase by about three to five times.

Further improvements related to the exploitation of more performing electrochemical reactions [12], such as metal-air batteries, are currently foreseen for a long-term scenario (2050), which is compatible with the mean expected life (30-35 years) of rolling stock build at present time. Further uncertainties related to technological developments can also be addressed to fuel cells [13] as an example of what concerns power density or the development of more compact and efficient hydrogen storage systems.

All the above-performed considerations introduce and describe a scenario of heavy technological uncertainties and continuous developments that should negatively affect the extended application of these new storages to the railway sector.

Considering the expected operational life of rolling stock, updating and revamping the installed system will probably be mandatory. So, in this work, the authors investigate and propose a modular approach aiming to simplify the simulation and consequently, design construction and revamp of the future multimodal rolling stock.

2 A General Simulation Framework

Considering different possibilities for the hybridization of Multimodal trains, a general model [14] capable of simulating a wide variety of different hybrid layouts is designed. As visible in figure 5, a series hybrid layout is supposed in which each storage system (batteries or supercapacitors) and power sources (Internal combustion Engines, Fuel Cell or a pantograph connected to an external power source) are connected through power converters to a common DC voltage bus. Many simulation environments, such as Simulink/Simscape™ or Modelica [15], can easily assemble this kind of model.

This way, conventional hybrid series powertrains powered by internal combustion engines, such as the Italian Hitachi Blues, can be simulated [16].

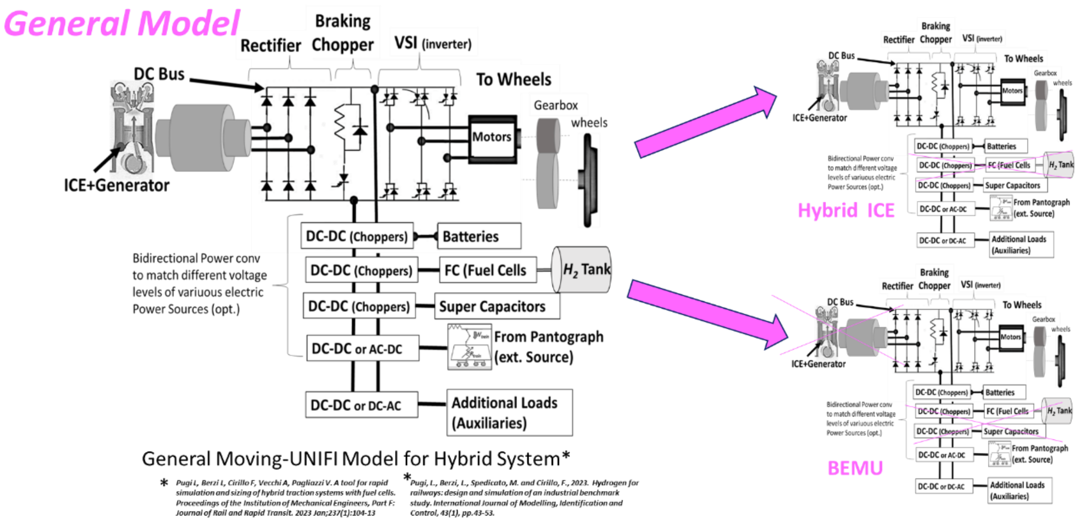

Figure 5: Modular Model for Multi-Modal Trains [14]

The concept of modularity can be extended to the design of multimodal rolling stock shown in Figure 14, which refers to a series of different powertrains that have been investigated starting from the same EMU platform inspired by the existing Hitachi Masaccio-Blues: the chosen example is an EMU (about 200tons with about 0.9-MW of installed traction power) with four articulated coaches and a wheelset B0-2-2-2-B0 which implies that motorized bogies are located at both ends of the train: for performed studies, all the traction equipment including a small number of high power batteries that work as power buffer for the traction system are located on this two pilot articulated coaches placed at both ends of the composition. So, applying the general powertrain described in figure 5, it is possible to connect to the same DC bus to different storages or power sources that are be located on the two intermediate coaches: intermediate coaches can be equipped with tanks and fuel cells to feed the DC bus, or they can be filled with batteries to obtain a battery-operated train with extended autonomy.
As shown in Figure 6, intermediate coaches can be equipped with a railway pantograph to ensure the possibility of current collection under partially electrified lines for the battery-operated solution.
Otherwise, it is possible to think of a specialized pantograph for a static current collection that can be used in stations to perform a parking recharge of train batteries and to extend the autonomy even of the hydrogen-fuelled solution by feeding auxiliaries when the train is performing a prolonged parking at terminus station [18]. This concept can also be extended to more conventional train compositions designing, for example, electrical locomotives able to carry a limited amount of buffer batteries that can be connected through a high power link to other wagons/tenders [19] in which power sources or alternative storage systems are implemented.

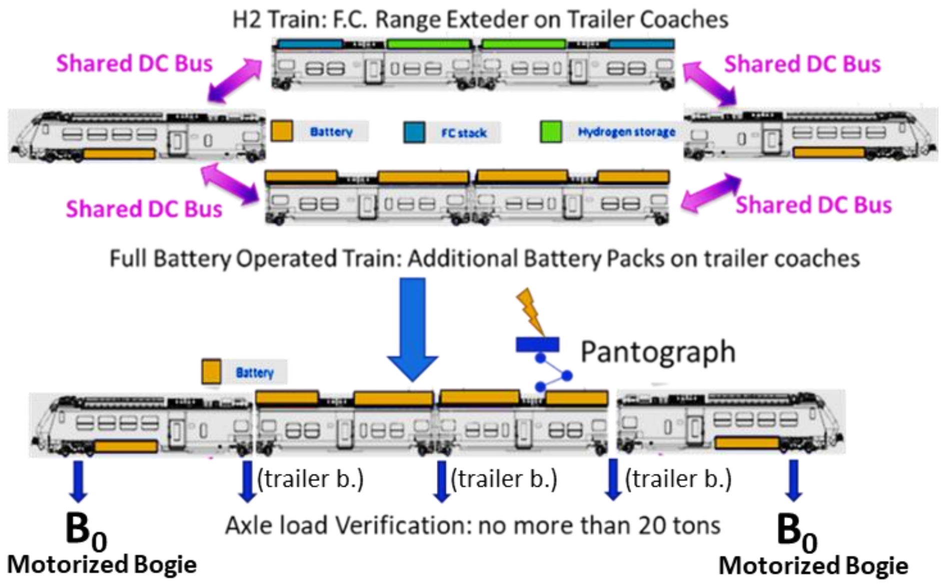

Figure 6: Modular Layout Applied to the Multimodal BEMU(Battery Electric Multiple Unit) or HFCMU(Hydrogen Fuel Cell Multiple Unit) [17],[18].

3 A Benchmark Test Case (Firenze-Faenza Italy)

Exploiting all these different features, authors were able to compare the performances of three different systems on the same benchmark test line, the Firenze-Faenza line (a non-electrified line on the Apennines mountains in Italy).

In these examples, which have been the object of previous publications [14],[17],[18],[20], three different scenarios are considered:

- Solution 1, a hybrid hydrogen fuel cell solution: intermediate coaches are filled with fuel cells and hydrogen tanks. Due to the limited encumbrances available on intermediate coaches, the quantity of stored Hydrogen is limited to about 185 [kg] and consequently from simulations foreseen autonomy is limited to about 500 kilometers. The reference model adopted for this test case is described in [20].
- Solution 2, Hydrogen fuel cells with parking device: a significant part of the energy consumption of the train is caused by auxiliaries (like HVAC, for example), so in [18] it is proposed to add to the train a static pantograph that allows a to perform a parking recharge at each stop. In this way, feeding the auxiliaries during stops is possible without consuming stored hydrogen. Further savings are assured by buffer batteries being recharged at each station, storing a total quantity of energy that is not negligible considering the high number of intermediate stations along a local line.
- Solution3, Battery Operated Train with dynamic recharge on partially electrified sections: this last scenario was the object of another recent study [17]. The battery-operated version of the same simulated benchmark train is equipped with a standard railway pantograph that allows current collection from catenaries of electrified lines. Installed batteries are supposed to be updated, state of the art products for railway applications but with performances in terms of specific energies (117[Wh/kg]) that are quite cautious compared to the increasing trends that is currently foreseen as shown in figure 3. So, the resulting total stored capacity is limited to about 1 MWh

to respect axle loading limits. With this limited amount of stored power, some short, intermediate electrified sections are added to the line (30 kilometres of the line are electrified, about 30% of the total length with respect to a mission length of 100km).

- Solution 4, Battery Train with static recharge in railway stations: in this case, authors suppose the availability of a battery with an energy density of 200Wh/kg (about 1.8MWh of total stored energy), which is relatively high but aligned to performances that are feasible for batteries currently adopted in the automotive sector. In this last scenario, the train can perform a complete roundtrip between Firenze and Faenza, and the vehicle is recharged only with dedicated static recharge devices at terminus stations.

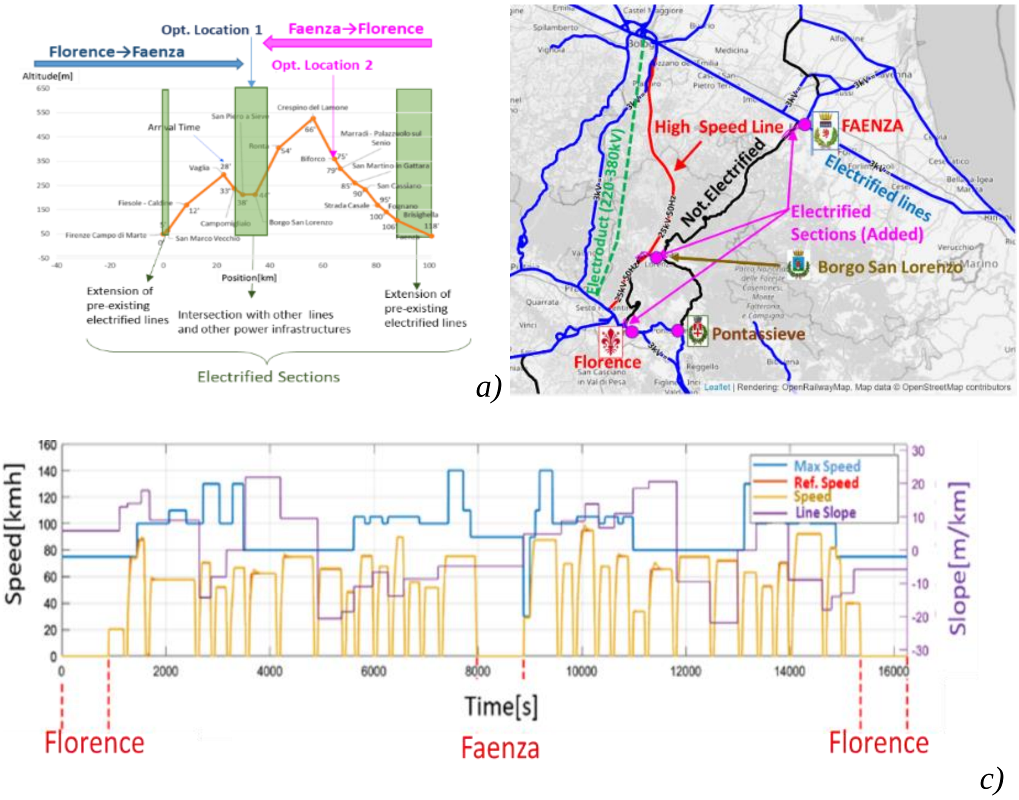

Figure 7: Example of Benchmark Test Line, the Firenze-Faenza line, altimetric profile (*a*), proposed electrified sections (*a*,*b*), simulated mission profile (*c*)

Some results concerning performed simulations are summarized in SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis that are listed in Tables 1-4: the third solution (Battery Operated Trains) should be the favourite choice, at least in short-midterms scenarios since it's feasible in a short-term scenario, maintaining the possibility of a conversion to fully electrified infrastructure if the traffic increases.
Some simulation results performed with UNIFI tools that have produced significant results able to justify the conclusions of performed SWOT analysis are shown in figures 8,9 and 10.

	HELPFUL	HARMFUL
INTERNAL	STRENGTHS **45 pts** (0/50) -Higher Autonomy respect to Battery Operated Solutions. -No Self Discharge, long term Energy Storage -Fast Refuelling (5-10minutes)	WEAKNESSES **-20pts** (-50/0) -Costs and Tech Limits associated to the storage of pressurized (350bar) or liquified (700bar) hydrogen -low overall efficiency of the well to wheel efficiency of the system -Autonomy is less then expected with heavy consumptions of auxiliaries or considering mission profiles that are penalized by the absence of regenerative braking
EXTERNAL	OPPORTUNITIES **50 pts** (0/50) -Long Term Storage, Transportable in different ways: Good Sinergy with Renewable Energy Sources -Politically and Financially Sustained by a large public consent -Continuous Tech Improvement of Fuel Cell Technology	THREATS **-20pts** (-50/0) -Fast Continuous Improvement of Concurrent Solutions (Batteries) -Currently heavy affected by the injection of public incentives-resources -A major limit is represented by technology of pressurized tanks
		Total Score: 55 (-100/100)

Table 1: Comparative SWOT for the simulated solution 1, the hybrid hydrogen fuel cell train

	HELPFUL	HARMFUL
INTERNAL	STRENGTHS **50 pts** (0/50) -The same strength points of Solution 1 -Enhanced Autonomy -Unlimited duration of parking (fundamental for train preparation)	WEAKNESSES **-35pts**(-50/0) -The same weakness points of Solution 1 -Additional Costs and Maintenance for the electric infrastructure for static parking recharge -Buffer Batteries are probably overstressed by additional charging-recharging cycles
EXTERNAL	OPPORTUNITIES **50pts**(0/50) -The same opportunities of solution 1 -Size and robustness of buffer batteries can be easily improved the concurrent improvements of batteries developed for the automotive sector	THREATS **-25 pts** (-50/0) -The same Threats of Solution 1 -Unconventional solution respect to what is proposed in other sectors, cost reductions deriving from tech. transfer or scaled production can be negatively affected
		Total Score: 40 (-100/100)

Table 2: Comparative SWOT for solution 2, hydrogen hybrid train with static parking recharge in railway stations

	HELPFUL	HARMFUL
INTERNAL	STRENGTHS **50pts** (0/50) -Autonomy and Performances of Battery-Operated Trains can be increased even using storage with relatively modest performances. -Dynamic recharge is performed with standard pantographs under conventional catenaries, the system can be interfaced to with electrical infrastructures used in railway sector. -Recharge is performed in Motion, no time is wasted for recharge	WEAKNESSES **-15pts** (-50/0) -If performances of batteries are modest electrified sections should be quite extended (higher costs) -Aging of batteries due to fast recharge may reduce the life of installed battery storage. -if traffic intensity increases costs of a fully electrified should be cheaper than a partial electrified one with battery-operated trains
EXTERNAL	OPPORTUNITIES **50 pts** (0/50) -Performances and costs of Battery Storage Systems are improving thanks to the mass production of batteries for the automotive sector -If the traffic increases a partially electrified line can be converted in a fully electrified one. -A dynamic recharge of the train along intermediate sections of the line is compatible with the integration of the system in local grids sustained by renewable energy sources	THREATS **-20pts** (-50/0) -Hydrogen Powered Solution can be a more valid competitor -Evolution of storage technologies should involve further interventions on the recharge infrastructure
		Total Score: 65 (-100/100)

Table 3: Comparative SWOT for the 3rd proposed solution, battery-operated train with dynamic recharge along the line.

	HELPFUL	HARMFUL
INTERNAL	STRENGTHS **45pts** (0/50) -Respect to Solution 3 recharge infrastructures are confined to a limited number of railway plants/ Limited or null Catenaries are involved.	WEAKNESSES **-30pts** (-50/0) -Static Recharge involves that the train is not moving while recharging. -higher performances in terms of energy and power densities of batteries are required since recharge should be as fast as possible, and it should be performed in a limited number of sites. -Aging of batteries due to fast recharge may reduce the life of installed battery storage. -Fast recharges involve power peaks that should increase the cost of the recharge infrastructure also penalizing its integration in local energy grids
EXTERNAL	OPPORTUNITIES **40 pts** (0/50) -Performances and costs of Battery Storage Systems are improving thanks to the mass production of batteries for the automotive sector -	THREATS **-25pts** (-50/0) -Hydrogen Powered Solution can be a more valid competitor -Dynamic Recharge of Battery-Operated Trains allows the usage of components and subsystems that are also standardized for conventional electrified trains and lines (solution 3rd can be cheaper)
		Total Score: 30(-100/100)

Table 4: Comparative SWOT for the 4th solution, battery operated train with dedicated static recharge stations

For what concerns the comparison between proposed solutions 1 (hydrogen hybrid train) and 2 (hydrogen hybrid train with a static electric recharge when the train is stopped in stations): it is interesting to notice that a large amount of the energy provided by fuel cells is used by auxiliary loads. When the train is stopped, auxiliaries are fed by an external line (120kWh saved) and buffer batteries are recharged, allowing reduced energy consumptions of Hydrogen during the traction phase.

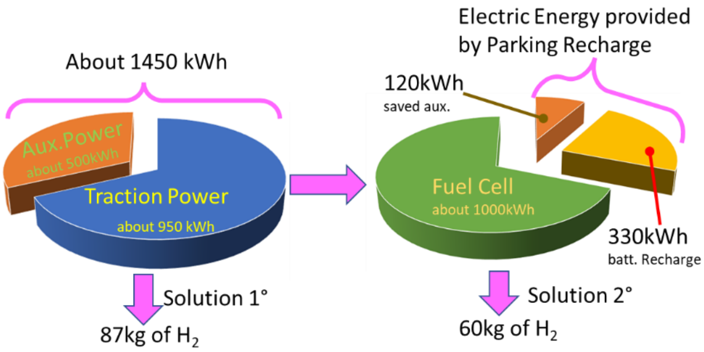

Figure 8: simulated/calculated H_2 consumptions for a complete roundtrip for solution 1(left) and for solution 2(right)

As regards solution number 3 (the battery-operated train with dynamic recharge), in figure 9, SOC behaviour of the chosen battery is shown: the system is energetically stable since the battery is fully recharged at each roundtrip, reaching the maximum value of 85%. Also, during the whole mission, the minimum level of the SOC is well over the minimum allowed value of 20%. In this way, the proposed solution is also robust against battery ageing, typically associated with a capacity loss of about 20%.

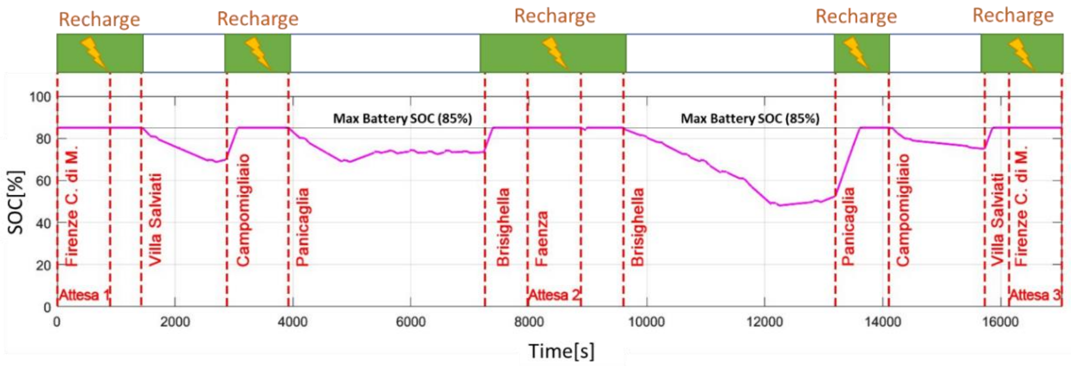

Figure 9: simulated behaviour of battery SOC (Energy density of 117Wh/kg) for the Solution 3 (battery-operated train with dynamic recharge on partially electrified sections)

Collected currents during the dynamic recharge are shown in figure 10: currents are calculated considering different line impedances for a 3kV DC line (Italian electrification standard). Collected currents during train motion are inferior to 2000A, typically considered the upper limit for a power collection with a single pantograph [22] when the train moves. Also, current limits in standstill conditions (200[A]) are imposed to protect both line and catenary against thermal runaway.
The mean level of recharging currents is about 1000[A], so it can be concluded that proposed infrastructure cannot be used to recharge a train with a power demand that

is roughly double that of the simulated train. So, the maximum mass of a train that can perform the same mission profile is about 400tons (mass of the simulated train is about 200tons).
These brief calculations suggest that for the dynamic recharge of longer or heavier compositions with the same mission profile there are two possibilities:

- A further increase of the length of the electrified sections of the line; this solution is quite suboptimal in terms of infrastructural costs.
- It's possible to use multiple pantographs, but this practice can be acceptable only for relatively slow compositions such as long freight trains.
- Otherwise, a feasible solution is represented by adopting higher AC voltage electrification standards or, better, by adopting innovative medium voltage DC standards. This idea has recently been revived in recent publications [23].

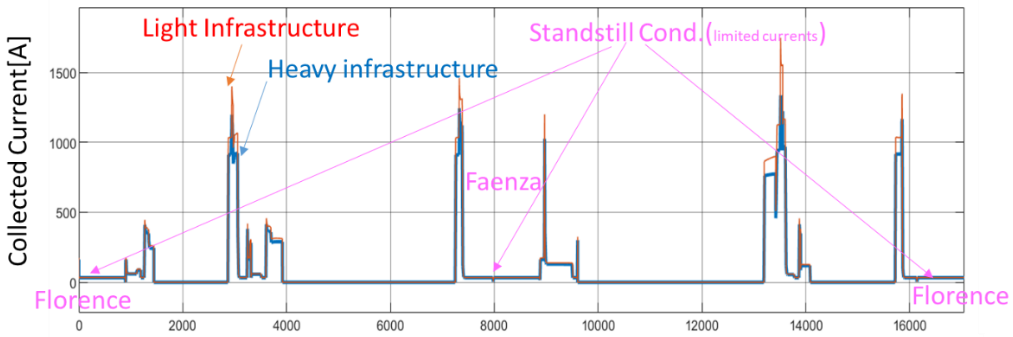

Figure 10: behaviour of collected current during dynamic recharge considering light (0.1Ω/km)or heavy catenary(0.05 Ω/km)

4 Conclusions and Contributions

Fuel cell systems are currently able to assure a relatively long autonomy, which can be negatively affected by heavy consumptions of auxiliaries and or by mission profiles with specific features that penalize efficiency of this kind of systems:

- frequent stops (regenerative braking is typically not allowed or very limited)
- high altitude gradients (increased traction efforts, no reg. braking)

A further increase of foreseen autonomy (about 15-20%) can be obtained by allowing an electric parking recharge at train stops to sustain consumptions of auxiliaries, further exploiting the capacity of buffer batteries. However, the drawbacks of this approach must be carefully evaluated (reduced life of buffer batteries and increased infrastructural costs).
For what concerns batteries, partial electrification of the line can significantly improve train autonomy even when adopting batteries with relatively modest performances. The length of partially electrified sections strongly depends on the specific power of the adopted batteries. However, at the same time, a distributed dynamic recharge favours a smoothed power interaction with fixed infrastructures and connected energy grids. This is an exciting consideration even for future battery trains with higher autonomy since a distributed dynamic recharge can contribute to optimising the size of recharging infrastructures and prolonging the life of onboard batteries. In the end, in a short-medium-term scenario, battery-operated trains supported by dynamic

recharge on partially electrified lines should represent a valid alternative to ICE-powered rolling stock, especially if the train is relatively short and the installed power is relatively small.

Acknowledgements

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