# Hydrogen For Railways: Design and Simulation of an Industrial Benchmark Study

Luca Pugi*, Lorenzo Berzi, Michael Spedicato

Dept. of Industrial Engineering, University of Florence
Florence, Italy
luca.pugi@unifi.it, lorenzo.berzi@unifi.it, michael.spedicato@unifi.it

Francesco Cirillo
Hitachi Rail SPA
Pistoia, Italy
francesco.cirillo@hitachirail.com

**Abstract:** Electrified Railway System are probably the most sustainable way to move people and goods especially for ground connections over short and mid distances. Hydrogen & Battery-operated trains represents a feasible solution to increase sustainability of railway lines that are currently not electrified and consequently operated with fossil powered units. In this work authors investigate, on a benchmark test case, advantage and critical aspects of the proposed technology respect to near to realistic design constraints. Proposed train layout is quite innovative respect to current literature since the composition is longer and storage is arranged to make faster and easier system refuelling. Authors focused their attention on three aspects that has proven quite critical for the design: encumbrances of hydrogen storage, additional consumptions introduced by auxiliaries also during train stops and other preparation phases, real orography of Italian lines which deeply affects the autonomy of the train.

**Keywords:** Hybrid Railway Train, Fuel Cell Train, Hydrogen for Railway, Modelling, Mechatronics

**Biographical notes:**

Born in 1974, Luca Pugi is currently working at Dept. of Industrial Engineering at University of Florence where is responsible of various courses regarding mechatronics, vehicle dynamics and applied mechanic. These are also his current research interests and cooperation with other Industrial and academic partners.

Lorenzo Berzi is a member of the Moving Laboratory at dept. of Industrial Engineering, he is currently responsible of didactical activities related to construction of Hybrid and Electric Vehicles, also his research interests are aligned with performed didactical activities.

Michael Spedicato has obtained is master degree in mech engineering in 2022 participating to research activities of the team

Francesco Cirillo is currently working at Hitachi Rail SPA where is responsible of several activities concerning railway systems

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## 1 Introduction

Electrified Railway System are, one of the most sustainable means of ground transportation in terms of equivalent $CO_2$ emissions and more generally of overall sustainability (Zenith et al.,2020),(Logan et al, 2020). Reason of this advantage should be summarized in the following points:

- Almost Null vehicle emission associated to traction motors.
- High efficiency of both vehicle and infrastructure systems also in terms of energy management that is further increasing thanks to a further improvement of the regenerative braking.
- Very Low Motion Resistances respect to corresponding road vehicles.

- Long operational Life: Impact related to construction and withdrawal of railway vehicles can be compensated by a long service.

Electrification of railway infrastructures involves construction and maintenance costs that are often less justified on lines with a lower traffic intensity or in territories in which these interventions are also constrained by additional infrastructural, orographic, or economic limitations.

This “not electrified lines” represent almost the 40% of railway lines in Western Europe in terms of kilometric length. In other continents percentage of “not electrified lines” is often higher. Service on these lines is normally covered by Fossil operated units (mostly diesel) in which the power generated by the ICE powerpack is delivered to wheels with different kind of transmissions, mechanical, hydraulic, and electric.

In this sense recent solutions are a clear evolution of Diesel-Electric Transmission systems (Cipek et. al, 2020) in which the ICE source is helped by an electric storage (Magelli et al. 2021) realizing the so called Hybrid Trains.

Further Hybrid technologies also emphasize the substitution of Diesel units with hydrogen fuel cell systems (Corbo et. Al, 2005),( Murray-Smith et al.,2020).

If the electric storage is able to sustain the entire mission profile, the train is a battery operated one: (Ghaviha et al, 2020): in this case the train is fed only by an electrical storage that is periodically recharged (as example, at railway stations).

In this work authors focused their attention on passenger multiple units, a kind of fixed composition train that is often employed on local lines. Typically, these systems are modular and composed by smaller fixed compositions of two, three or four couches that should be assembled as a modular system to assure higher transportation capacities.

This is a sector that is potentially interesting from a commercial point of view considering products that are currently proposed by several industrial groups as visible in figure 1 and in Table I.

TABLE I. TECH . SPEC. OF RECENTLY PROPOSED FCMU

| | Alstom Coradia iLint (2018) | Siemes Mireo Plus H (2019) |
|---|---|---|
| **Max Speed** | About 140[kmh] | About 160[kmh] |
| **Capacity** | About 150 Seats | About 120 [Seats] |
| **Aut.** | About 650[ km ] | About 650[ km] |
| **$H_2$/cons.** | About 0.25[kg/km] | About 0.25[kg/km] |
| **F. Cells** | Hydrogenics (2x200kW) | Ballard (2x200kW) |
| **Batteries** | Li-Ion | LTO |

Fig. 1. Example of FCMU trains (Fuel Cell Multiple Units) recently developed by Alstom and Siemens

In previous research activities authors have proposed (Berzi et al., 2021) a simplified tool for preliminary simulation and design of this kind of FCMU (Fuel Cell Multiple Units) trains . Proposed tool solves a parametric model of train dynamics, also introducing some elements of eco-driving policy (Pugi et al.,2020) to automatically reproduce a smooth and realistic behavior of the train (Castagna et al., 2021).

In this work, authors further investigate this topic applying the proposed tool to a benchmark test case whose main features are shown in figure 2 and table II. Design specifications are inspired to an existing train especially for what concern desired performances, allowable weight and volumetric limitations.

As visible in figure 2, two different compositions are considered.

The first one, called “A” is composed by three articulated car bodies that are sustained by four bogies with a wheelset arrangement $B_0$-2-2-$B_0$ (IRS 60650,2020). This layout corresponds to two motorized bogies at both train ends and two intermediate Jacobs, trailer bogies.

The second composition, the “B” one is longer than the “A” one: it composed by four articulated car bodies with a wheelset arrangement $B_0$-2-2-2-$B_0$ (IRS 60650,2020). Respect to the “A” composition an additional Jacobs trailer bogie is added. As visible in Table II, chosen specifications for what concern total installed power admit a range of possible values that are inspired to real configuration (Hitachi,2022). In this work both configurations are studied since they offer the possibility to investigate a wider range of design conditions.

In particular, axle load limitations imposed by current standards are investigated.

Respect to other works in literature (Aouzellag,2015), attention is focused on a cautious evaluation of auxiliary loads. These loads have a strong influence on vehicle autonomy on a real mission profiles especially for regional passenger trains.

HVAC (Heating, Ventilation and Air Conditioning) is probably the most demanding auxiliary load that contributes to consume large amount of power even when the train is stopped in a station or prepared for service.

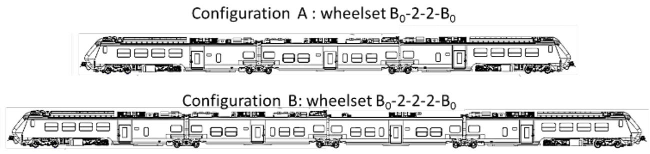

Fig. 2. Proposed benchmark test case, configuratio A and configuration B with correspondig wheelset description according UIC notation

TABLE II. TECH. SPEC. OF BENCHMARK TEST CASES

| | **Composition A** | **Composition B** |
|---|---|---|
| **Max Speed** | 140[kmh] | 140[kmh] |
| **Capacity** | 219 seats | 300 seats |
| **Max Long. Effort** | 140 kN | 160kNN |
| **Traction Power max *min*** | *778*- 1167[kW] | *889*- 1333[kW] |
| **Reg. Braking** | 1933[kW] | 1933[kW] |
| **Mean. Aux Power** | 90 [kW] | 120[kW] |
| **Ref. Power Management** | Hydrogen Fuel Cells with Regenerative Braking assured by high power LTO Modules. Power Management is performed as in hybrid series vehicles as a blended combination of Range Extender and Load Follower Strategies (Pugi,2013) | |

Work is organized as follows:

- Model description: proposed simulation model is briefly described. A particular attention is focused on updated features of proposed simulation tool respect to previous research activities. Major innovations regard the automated creation of large mission scenarios, the adoption of optimization procedures and the introduction of models able to predict aging of Fuel Cells and batteries respect to performed mission profiles.
- Design Optimization: the design of the system must take count of available encumbrances and weights. In this work authors introduce some practical methods to optimize the quantity of stored hydrogen and consequently train autonomy.
- Result Evaluation: proposed methodologies are applied to proposed benchmark case studies. Performances achieved with proposed optimization methods are discussed.

## 2 Proposed Model Innovative Features and Updates

Simulations are performed considering a modular model, developed in previous research activities (Berzi et Al.,2021) that is described in figure 3, the scheme is focused on introduced innovations:

- Generation of mission profile: data concerning speed limitations, design and orography of the simulated line can be automatically extracted (for Italian railway lines) from a public database (RFI,2022) that is published online according to open standards(RFI,2021). In this way it was possible to extend the analysis to multiple lines described in Table III. The first two lines (Firenze-Siena and Siena-Grosseto) are used as standard mission profiles for system design. Firenze-Siena line is partially electrified so batteries can be fully recharged at the beginning of each mission using a standard railway pantograph. the second line (Siena-Grosseto) is associated to a mixed mission profile that is quite useful for a robust design. The third one, the Sassari-Cagliari is introduced as worst case condition that is used only to assess the robustness of proposed solutions respect to very demanding operational condition (high line slopes for long distances).
- Battery and Fuel-Cells models: Performance data of batteries and Fuel cells are taken from technical documentation available on line (Hydrogenics, 2021), (GWC ,2021). Authors introduce an aging model respect to imposed mission profile for both batteries and fuel cells. The model doesn't consider the modelling of internal control loop of fuel cells (HEDDAD, O. et al.2021).
- Post Processing.

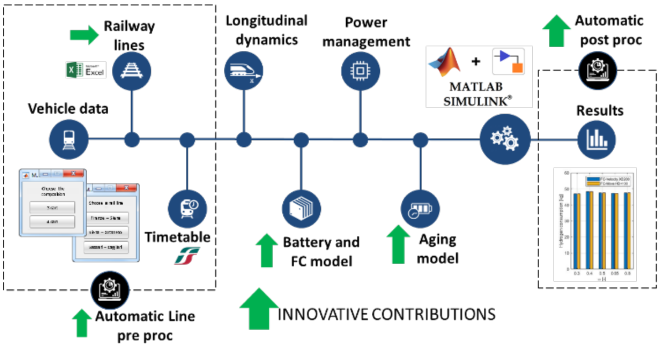

Fig. 3. Structure of the used model and recently introduced improvements.

TABLE III. REF. LINES FOR PERFORMED SIMULATIONS

| | **Firenze-Siena** | **Siena-Grosseto** | **Cagliari- Sassari** |
|---|---|---|---|
| **Length** | 93,5[km]* | 100,6[km] | 252,6[ km] |
| **Max Heigth Diff.** | 310[m] | 276 [m] | 740 m ** |
| **notes** | *about 30km are electrified so batteries are always fully charged at the beginnig of the mission by pantograph<br>**Sassary-Cagliari has a medium slope gradien of 22/1000 with additional curves that involve peaks of equivalent gradiet of 35/1000 | | |

### *A.* Introduction of Ageing Models for Battery Storage and Fuel Cell Modules

Power management of Fuel cells for traction applications is sustained by other storages, such as lithium batteries.

The resulting system is hybrid. This choice is justified several reasons: first fuel cells are single quadrant power sources, so batteries are needed for regenerative braking. Also, Fuel cells must be designed respect to a minimum expected life. To model aging of fuel cells authors implemented the approach originally proposed by Zang et al (2017): life/ duration of the cell is defined as the time $T_{cell}$. $T_{cell}$.is defined (1) as the time for which aging causes a 10% reduction of Fuel Cell output voltage respect to its nominal value $V_{rated}$

$$T_{cell} = {}^{0.1V_{rated}}\!/_{\dot{v}(\varphi)} \tag{1}$$

Derivative of fuel cell voltage $v$ is calculated according (2) as a linear function of $\varphi$. Coefficients of eq.(2) are calibrated according to experimental data provided by the manufacturer of Fuel Cells:

$$\dot{v}_{\varphi} = 11 + 50\varphi \tag{2}$$

$\varphi$ is calculated according (3) as a function of two weighting sub-functions $m_{cur}$ and $m_{vol}$ which respectively model degradation effects related to spectral composition of currents ($m_{cur}$) and statistical distribution of applied voltages ($m_{vol}$). In particular $m_{cur}$ and $m_{vol}$ are respectively defined according (4) and (5)

$$\varphi = m_{cur} m_{vol} \tag{3}$$

$$m_{cur} = \frac{1}{T} \int_{0}^{\omega_{\max}} F(\omega)(k_1\omega + 1)\, d\omega \tag{4}$$

$$m_{vol} = \frac{1}{v_{\max} - v_0} \int_{v_0}^{v_{\max}} H(v) w_{vol}(v)\, dv \tag{5}$$

In (4) the spectrum of loading current *F(ω)* is integrated respect to a range of frequencies between 0 and a cut-off frequency $\omega_{max}$. Adopted weighting function in (4) is a linear one with an angular coefficient $k_1$.

Calculation of $m_{vol}$ is performed respect to an interval of admissible voltage values respectively called $v_0$ and $v_{max}$.

Statistical distribution of voltage amplitudes *H(v)* is scaled according to a weighting function $w_{vol}$.

Corresponding behavior of power and voltage curves of a single cell is represented in figure 4.

Thanks to these modelling activities authors were able to perform some comparative analysis as the one visible in figure 5: efficiency $\eta$ and expected life are evaluated respect to adopted hybridization factor α (Lee,2014).

Hybridization factor α is defined (6) as the ratio between installed fuel cell power $W_{fc}$ and the total one $W_{tot}$.

$$\alpha = {}^{W_{fc}}\!/_{W_{tot}} \tag{6}$$

Results are referred to the Siena-Grosseto line considering both train compositions and different models of fuel cells. Reference data of compared fuel cells are described in Table IV.

TABLE IV. DIFFERENT FUEL CELL MODULES

| F.C. Model | FCVelocity-XD200 | FCMoveHD+100 |
|---|---|---|
| Power/module | 200[kW] | 100[kW] |
| Max eff. | 0.53 | 0.57 |
| Weigth | 1000[kg] | 275[kg] |
| Dimensions | 1800x2000x550[mm] | 1714x812x360[mm] |

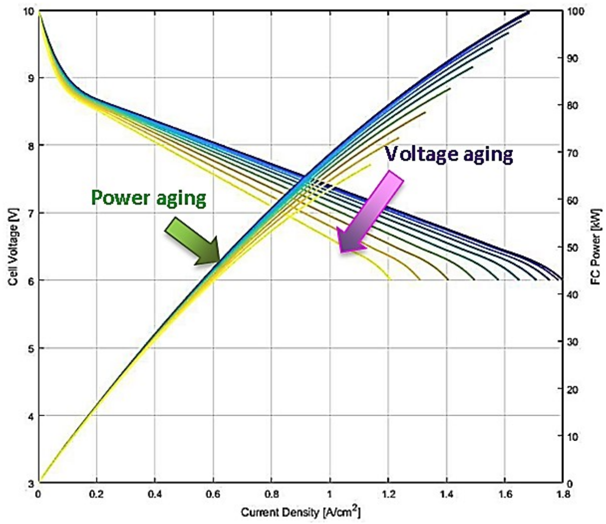

Fig. 4. Simulated aging behavior of a fuel cell.

According the model described by equations (1-5), aging of fuel cells is accelerated if delivered power is quite far from nominal conditions (coefficient $m_{vol}$) or alternatively if the system is subjected to fast transients (coefficient $m_{cur}$ ).

As a consequence, installed batteries are used as power buffers aiming to smooth the load profile to which are subjected the fuel cells.

LTO batteries (Lithium-Titanate or Lithium Titanium Oxide) are currently the most commonly used for this kind of applications since they tolerated repeated high power load with limited aging.

Authors modelled the aging of LTO batteries (Nemeth et al.,2020): life of the battery is calculated (7) in terms of FCE (Full Cycle Equivalents) as the ratio between ampere throughputs $A_{th}$ (the integral of currents) and the nominal capacity of the battery cell.

$$FCE = \frac{A_{th}}{2C_{nom}} = \frac{\int_0^t |I|\, dt}{2C_{nom}} \tag{7}$$

Aged battery is modelled only in terms of capacity loss neglecting complex poles migrations that are known from literature (Locorotondo, et al.,2021).

For future implementations also more performing battery/hybrid super-capacitors should be considered since their expected behaviour respect to aging seems very promising from literature data (Corti, et al.,2021).

Also a more accurate balancing of battery cells (WANG et al. 2020) should contribute to an extension of its life.

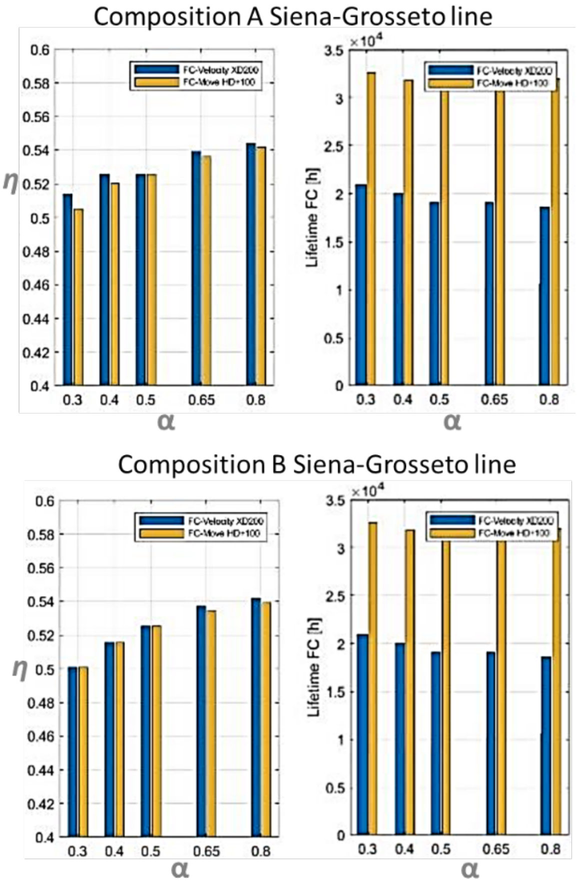

Fig. 5. Simulated efficiency and expected life respecto to hybrization factor an train composition for different models/generations of fuel cells

## 3 Design Considerations

In figures 6 and 7, design of the system is described:
First, a pre-existing HMU (Hybrid Multiple Unit) is considered. Layout of the pre-existing train is investigated in order to evaluate volumes and weights that can be recovered eliminating the ICE (internal combustion) power pack. Also it's considered an optimization of the disposition of auxiliaries in order to maximize the encumbrances available for the installation of fuel cells and hydrogen tanks. Then the new system is designed with a particular attention to the way in which hydrogen plant can be managed reducing as much as possible the extension of piping by concentrating all the elements of the fuel cell plant on trailer coaches in which larger volumes are available for the hydrogen storage system. This solution offers advantages for what concern the management of Hydrogen re-fueling.
As visible in figure 8, proposed solution offers some interesting advantages in terms of industrial standardization: hydrogen plant is concentrated on trailer coaches and it is connected to the traction equipment on the other coaches with a stabilized DC bus. Intermediate trailer coaches occupied by fuel cell plants can be easily substituted with other coaches in which additional li-ion storage systems provide power to the rest of the train.
This is possible since both systems share almost the same electrical interface with the rest of the train. This is a big advantage in terms of industrial standardization realizing large scale economies in the management of a unique product line. Almost the same product platform can be configured to be a hybrid fuel cell system or a battery operated one. This solution helps to solve also uncertainties related to the development of both Fuel Cell and battery technologies: an upgrade of the whole train is possible by focusing all the intervention only on intermediate trailer coaches.

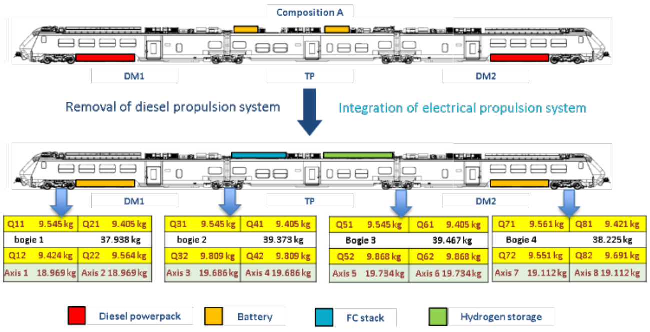

Fig. 6. Three Step design process for configuration A, localization of functional volumes occupied by traction and power management systems, update with the new hybrid solution and weigt,axle load verifications

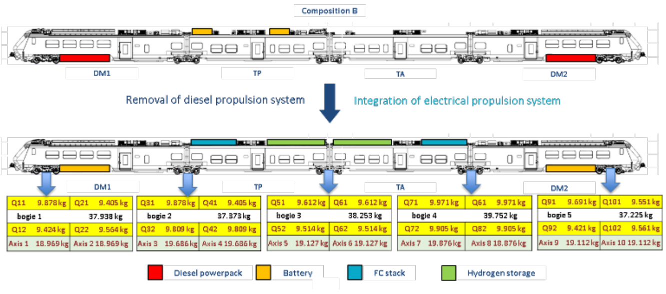

Fig. 7. Three Step design process for configuration B, localization of functional volumes occupied by traction and power management systems, update with the new hybrid solution and weigt,axle load verifications

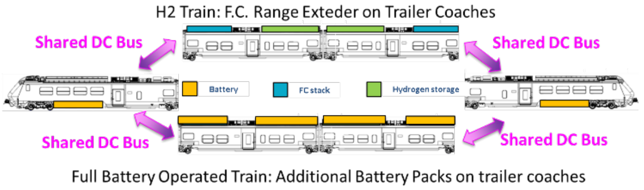

Fig. 8. Standardization and interchangeabilty of proposed solution respect to a fully operated battery train

Design procedure described in figures 6&7 is completed by a third step in which after the optimization of functional layout and available encumbrances is also verified the distribution of weight in terms of axle loads.
The procedure is iterative; volumetric optimization is performed before the weight one because the most critical parameter is represented by the low volumetric efficiency of Hydrogen tanks: respect to stored energy encumbrances of pressurized tanks are still relevant.
This trouble is mainly related to two concurring causes: first hydrogen has molar mass of 2gr/mole which involve in standard temperature and pressure conditions a very small density (0.09gr/liter). So, even implementing a high-pressure storage (350-700 bar), mass density of stored hydrogen is very low. This enormous drawback is partially balanced by energy density of hydrogen (about 120MJ /Kg). Also the use of high storage pressure involves high structural stresses for tanks.
In this work are considered the data of most performing tanks that are currently available on the market, the class 4 ones (Bosch,2021),( Luxfer,2021).
Due to high pressure, the shape of the tank is constrained to be cylindrical; Also despite to the usage of innovative materials and structural optimization tools, tanks are constrained to be robust enough to resist to high pressure, penalizing their weight and their maximum diameter.
As a consequence, the hydrogen to tank weight ratio is still undesirable (1/20-1/15): the tank is much heavier than the stored hydrogen. As visible in figure 9, cylindrical shape of tanks involves a further reduction of volumetric efficiency of the system: this shape is not well suited respect to encumbrances available on trains which have a typical trapezoidal section visible in figure 9.
Trapezoidal shape of the train roof is imposed by limitations of standard loading gauge.
In figure 9 authors show the optimized tank layout that was chose for the benchmark train considering a storage pressure of 350 and 700bar. These results lead to optimized storage

configurations for both A and B train compositions that are described in Table V: advantages of a higher pressure (700 bar) are partially compensated by the increase of tank weight and overall costs; so, any further increase of storage pressure is limited by severe technological constraints.

As visible in figure 9 tanks with different diameters are adopted: these are real tanks that are commercially available for railway applications. Tanks are sustained by thin transversal frames, so the structure is relatively stiff and light.  Also this solution is innovative respect to literature.

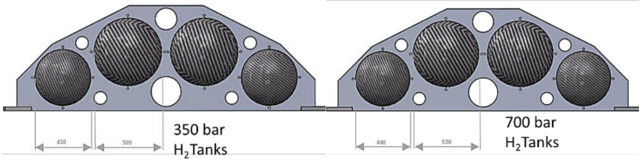

Fig. 9.  Avalialable sections on benchmark train roof and chosen tank layout for 350 and 700 bar storage pressure

TABLE V. OPTIMIZED ENCUMBRANCES OF $H_2$ TANKS

| | **Composition A** | | **Composition B** | |
|---|---|---|---|---|
| **$H_2$Pressure[bar]** | 350 | 700 | 350 | 700 |
| **$H_2$Capacity[kg]** | 76 | 92 | 152 | 184 |
| **Energy[kWh]** | 2533 | 3067 | 5067 | 6134 |
| **Tank Vol. /Roof Vol.** | 23% | 23% | 23% | 23% |
| **H2 Mass/ Roof Vol[kg/m$^3$]** | 5.8 | 8.9 | 5.8 | 8.9 |
| **Tank Weight[kg]** | 1103 | 1862 | 2206 | 3724 |

## 4 Simulation Results

Using the model and the design optimization criteria described in previous sections, authors performed a simulation campaign iterating various design parameters.

Some results of performed calculations are shown in figure 10: simulations are repeated on different lines considering both train compositions (A&B). In particular, in figure 10, simulations are iterated respect to the hybridization factor α. Considering the same amount of stored hydrogen (same tanks) a different value of α involves a different relative sizing of cells respect to buffer batteries.

Results are presented showing Specific Energy Consumption in terms of consumed hydrogen respect to travelled distance and train mass.

Specific Energy Consumption is an efficiency index that is represented respect to hybridization factor α and respect to achieved autonomy.

Autonomy is calculated considering the energy stored in Hydrogen Tanks, neglecting the contribution of energy stored in batteries: for a hybrid train batteries are recharged by fuel cells so they are considered only as a power buffer.

As visible in figure 10, composition B is preferable in terms of autonomy to higher availability of space for hydrogen tanks respect (Composition B has two trailer coaches so respect to the A one, available hydrogen volume is doubled).

Variations of efficiency respect to installed fuel cell power can be appreciated for normal mission profiles such as the Siena-Grosseto line; however, when the train is employed on the Sassari-Cagliari line (worst case mission profile) trains with lower installed power are not able to complete the mission.

So it can be concluded that a higher installed power involves a reduction of autonomy and efficiency but at the same time a higher robustness respect to worst case mission profiles.

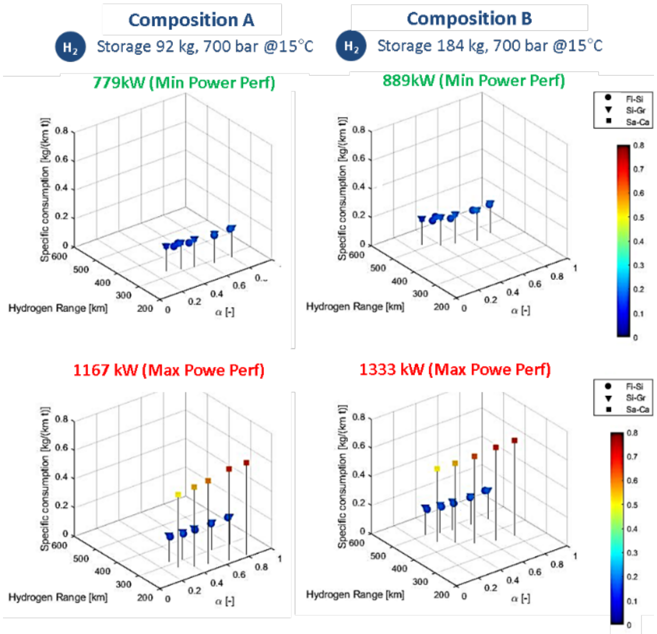

Fig. 10. Results of Simulation Campaign considering hybridization factor, autonomies simulated lines, tran configurations and values of total installed power.

Obtained results for B configurations should be considered surprising since achieved autonomy is apparently equivalent to declared values of existing commercial trains in which the hydrogen storage is at 350 bars; Some data for these existing trains are shown in TableVI.

TABLE VI. ALSTOM I-LINT SOME PERF. INDEXES ON BUXTEHUDE- CUXHAVENN (119KM)

| **Line** | **Buxtehude- Cuxhavenn** | **Cuxhavenn -Buxtehude** |
|---|---|---|
| **$H_2$ cons.** | 30[kg] (0.25g/km) | 40[kg] (0.34g/km) |
| **Range** | 800[km] | 600[km] |
| **Power** | FC. 400kW Batteries 110kWh,  α=0.78 | |

However, these results are strongly justified by the following considerations:

- Choice of a higher storage pressure (700 vs 350bar) involves a modest increase of stored energy (no more than 30%) and a small but not negligible increase of weight.
- Studied mission profiles are generally cautious and demanding in terms of line slope. Most of current literature for fuel cell trains is referred to plain lines of the northern Europe so energy efficiency is often over-estimated.
- In this work cautious values of auxiliary loads are considered. Consumptions due to auxiliaries are evaluated also when the train is stopped in stations.  This

is a realistic condition. Cautious auxiliary loads are justified by the hot climate of southern Europe which involves high power demands to refrigerate both passengers and on board power systems.

- Chosen benchmark compositions correspond to layouts that are very compact respect to fuel cell trains that are currently proposed on the market. For this reason, available space for hydrogen storage is reduced.
  In particular, proposed benchmark trains adopt Jacobs bogies; coaches are short respect to the number of transported passengers so less space is available on the train roof. Available encumbrances for tank installation are lower respect to train mass.
- Finally proposed solution involve the modification of trailer coaches without affecting the other ones. Further space for tanks on trailer coaches can be found with an integrated design allowing, as example, that some auxiliary systems are moved from trailer coaches to motorized ones.

As visible in Tables VII & VIII. line profile strongly influences train efficiency: kilometric consumptions strongly depends from the direction of the train among the same line due to the mean slope which is not null.

Consumptions are nearly doubled when the train must reach Siena which is higher respect to the starting stations of Firenze and Grosseto.

Calculations of table VII & VIII are repeated also considering different consumptions of auxiliaries.

TABLE VII. Consumption On Different lines respect to Auxiliarry Consumptions (Conf B, Low Power Spec.)

| | | **Firenze Siena** | **Siena Firenze** | **Siena Grosseto** | **Grosseto Siena** |
|---|---|---|---|---|---|
| **Length** | | 94[km] | | 100[km] | |
| **$H_2$ Cons.** | **Aux. 120[kW]** | 50[kg] | 30 [kg] | 31 [kg] | 51 [kg] |
| | **60[kW]** | 44[kg] | 26[kg] | 27[kg] | 46[kg] |
| | **0[kW]** | 39[kg] | 22[kg] | 23[kg] | 41[kg] |
| **Range** | **120[kW]** | 348[km] | 581[km] | 590[km] | 360[km] |
| | **60[kW]** | 390[km] | 673[km] | 683[km] | 401[km] |
| | **0[kW]** | 442[km] | 793[km] | 801[km] | 451[km] |
| **Avg.$H_2$ Cons. [kg/km]** | **120[kW]** | 0.53 | 0.31 | 0.31 | 0.51 |
| | **60[kW]** | 0.46 | 0.27 | 0.27 | 0.46 |
| | **0[kW]** | 0.41 | 0.23 | 0.23 | 0.42 |
| Fuel Cell Power 1100kW, 2x Battery 330, $\alpha$=0.65 | | | | | |

TABLE VIII. Consumption On Different lines respect to Auxiliarry Consumptions (Conf A, Low Power Spec.)

| | | **Firenze Siena** | **Siena Firenze** | **Siena Grosseto** | **Grosseto Siena** |
|---|---|---|---|---|---|
| **Lenght** | | 94[km] | | 100[km] | |
| **$H_2$ Cons.** | **Aux. 90[kW]** | 35[kg] | 22 [kg] | 24 [kg] | 36 [kg] |
| | **45[kW]** | 32[kg] | 18[kg] | 20[kg] | 33[kg] |
| | **0[kW]** | 29[kg] | 16[kg] | 16[kg] | 30[kg] |
| **Range** | **90[kW]** | 250[km] | 400[km] | 394[km] | 257[km] |
| | **45[kW]** | 268[km] | 467[km] | 470[km] | 278[km] |
| | **0[kW]** | 297[km] | 554[km] | 567[km] | 310[km] |
| **Avg.$H_2$ Cons. [kg/km]** | **90[kW]** | 0.37 | 0.23 | 0.24 | 0.36 |
| | **45[kW]** | 0.34 | 0.19 | 0.20 | 0.33 |
| | **0[kW]** | 0.30 | 0.17 | 0.16 | 0.30 |
| Fuel Cell Power 600kW, 2xBattery 330kWh, $\alpha$=0.5 | | | | | |

High consumptions of auxiliaries strongly affect train autonomy and efficiency.

Power demand of auxiliaries is constant, so it penalizes system efficiency even when consumptions of the traction system is null or negligible. This is a statistically common situation (train stopped in a station, coasting or braking maneuvers).

For the same reason, auxiliary loads are applied also during peak demands of the traction system contributing to overloads that penalize efficiency of fuel cells.

Energy losses are the integral of corresponding power losses, so at the end, a small increase of auxiliary loads produces a relevant effect in terms of system autonomy.

Results of table VII & VIII are respectively referred to compositions “B” and “A”: due to the lack of space for hydrogen tanks, configuration A is penalized in terms of autonomy respect to the B one. This is an unavoidable consequence of the different volume available for hydrogen tanks. For this reason, a lower hybridization factor is adopted for configuration “A”: a lower hybridization factor allows a slight higher efficiency in the usage of fuel cell modules. This choice is preferred to preserve a minimum autonomy of the system.

For what concern the “A” composition, it’s possible to increase the autonomy by providing some fast recharge devices along the line since adopted LTO Batteries supports recharge rates between 3C and 9C (batteries can be completely recharged in 10-20 minutes). In this way “A” composition can be managed as a hybrid-battery operated train: fuel cell module is added only to provide a limited range extension to batteries that are periodically recharged along the line.

For what concern the real transportation efficiency of proposed solutions authors also evaluate the consumption of both compositions respect to transported passengers.

Results as visible in table IX are quite interesting: both A and B configurations assure an overall transportation efficiency that is 20-30% better respect to declared performances of existing fuel cell trains. These results are quite encouraging since they are obtained considering a simulation scenario which is quite cautious (Firenze-Siena line with maximum consumptions of auxiliaries).

So it should be concluded that the more interesting feature of the proposed systems is their overall efficiency respect to the number of transported passengers.

TABLE IX. Comparison of consumptions For Transported Passenger

| **Train Composition** | **$H_2$ Consumption for Transported Passenger** |
|---|---|
| Composition A | 0.0014 kg/[km * Passenger] |
| Composition B | 0.0014 kg/[km * Passenger] |
| Alstom Coradia | 0.0017 kg/[km * Passenger] |
| Siemens Mireo | 0.0020 kg/[km * Passenger] |
| ***Firenze-Siena Line with max consumptions of auxiliaries, mean consumption in both direction is considered** | |

## 5 Conclusions and Future Developments

In this work authors have demonstrated the utility of proposed tools and methodologies to design a hybrid fuel cell train by updating a pre-existing DMU one.

Proposed models and methodologies offered the possibility of an extended simulation campaign that was used to optimize an innovative layout for a hybrid fuel cell trains respect to different mission profiles. The study is quite innovative since it takes count of several aspects that are often neglected in current literature, such as the consumptions of auxiliaries and the service on lines with demanding elevation profiles.

Proposed train layout is very innovative since the same platform is designed to be easily adapted not only for fuel cell installation but also for battery operated systems.

Thanks to performed optimizations proposed train configurations are able to assure an efficiency respect to the number of transported passengers that is higher than existing commercial product. This is a quite interesting result, also considering the cautious hypothesis that have been adopted to assure the robustness of performed optimization.

Finally performed design optimizations give clear indications of technological issues that should be the object of future research activities.

Volumetric encumbrance of the hydrogen tanks seems to be the more critical aspects for rail applications. So, the way in which hydrogen is stored should play a critical role in future. For this reason, any form of volume reduction of auxiliaries or improvement in terms of their power management should be greatly appreciated (Alstom,2021) in order to increase available space for hydrogen storage.

Improvements of both fuel cell and battery technology is very important since it affect both system performances and its durability.

Finally considering the nonlinear nature of controlled systems authors are investigating the application of innovative control (Xu et al. (2021)) and optimization (Ghadiri H et al. (2021)) techniques to further improve the power management of the proposed hybrid system.

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## Acknowledgment

Authors wish to thank all the unmentioned engineers and technicians of various suppliers of batteries, fuel cells and traction equipment that have supplied data and often direct feedback from their previous experience supporting this research work.

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