Renewable and Sustainable Energy Reviews 191 (2024) 114070

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

3E analysis of a virtual hydrogen valley supported by railway-based H_2 delivery for multi-transportation service

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A R T I C L E I N F O

Keywords:
Hydrogen valley
Hydrogen transport by rail
Multi-modal mobility
HRS
Green hydrogen production

A B S T R A C T

In Southern Italy, near the Mediterranean Sea, mobility services like cars, bicycles, scooters, and material-handling forklifts are frequently required in addition to multimodal local transportation services, such as trains, ferry boats, and airplanes. This research proposes an innovative concept of hydrogen valley, virtually simulated in Matlab/Simulink environment, located in Calabria. As a novelty, hydrogen is produced centrally and delivered via fuel cell hybrid trains to seven hydrogen refueling stations serving various mobility hubs.

The centralized production facility operates with a nominal capacity of about 4 tons/day, producing hydrogen via PEM electrolysis, and storing hydrogen at 200 bar with a hydrogen compressor.

As the size of vehicle fleets and the cost of acquiring renewable energy through power purchase agreements vary, the hydrogen valley is examined from both a technical and an economic perspective, analyzing: the values of the levelized cost of hydrogen, the energy consumption, and the energy efficiency of the energy systems. Specifically, the levelized cost of hydrogen reached competitive values, close to 5 €/kg of hydrogen, under the most optimistic scenarios, with fleet conversions of more than 60 % and a power purchase agreement price lower than 150 €/MWh.

Then, the benefits of hydrogen rail transport in terms of emissions reduction and health from an economic standpoint are compared to conventional diesel trains and fully electric trains, saving respectively 3.2 ktons/year and 0.4 ktons/year of carbon dioxide equivalent emissions, and corresponding economic benefits of respectively 51 and 0.548 million euros.

1. Introduction

Hydrogen-based technologies are living extraordinary growth throughout the globe [1], being promoted both at private and public levels, with the support of governors, organizations, and industry [2]. The main reasons associated with hydrogen technology momentum are: high efficiency of fuel cell technologies [3,4], low pollution [5] – close to zero if green hydrogen is adopted [6] –, flexibility and sector coupling [7], integration with renewable energy sources, applications in several energy sectors [8], from industry, mobility, and poly-generation energy systems [9,10].

The so-called "hydrogen valleys" play a crucial part in the growth of the hydrogen industry, both in terms of hydrogen production and demand [11], as they also act as model pilot regions, as these technologies become more widely used. The establishment and maintenance of a hydrogen value chain in the region depend on such valleys. This leads to having a precise location essential. The creation of these ecosystems, sometimes known as hydrogen valleys or hydrogen clusters, should have applications across the hinterland, such as ports [12,13], railway stations [14,15], industrial users [16,17], multi-mobility users [18,19], chemical applications [20,21], or power-to-gas applications [22], where they might have a more restricted national or global emphasis or a more local or regional one. In fact, hubs powered by hydrogen are ideally equipped to address transportation and industrial demands [23]. They qualify as ecosystems because many end-use applications in them share a common infrastructure [24,25].

Fig. 1 shows the main hydrogen valley projects worldwide, 36 overall, according to the Hydrogen Valley Map [26], developed by Fuel Cells and Hydrogen 2 Joint Undertaking. Germany is leading the implementation of such energy systems, followed by Spain, the Netherlands, China, and France.

Governors and states strongly support and plan to identify hydrogen valleys [27]. Europe [28–30], especially French [31,32], United Kingdom [33] and Germany [34–36], Japan [37–39], China [40,41], United States [42–44], South Africa [45], and many other countries

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https://doi.org/10.1016/j.rser.2023.114070
Received 8 November 2022; Received in revised form 27 October 2023; Accepted 5 November 2023
Available online 25 November 2023

Nomenclature Abbreviation

CAPEX	Capital Expenditures
ECMS	Equivalent consumption minimization strategy
FCB	Fuel cell bike
FCEA	Fuel cell electric aircraft
FCEB	Fuel cell electric bus
FCEF	Fuel cell electric ferries
FCES	Fuel cell electric scooter
FCEV	Fuel cell electric vehicles
FCF	Fuel cell forklift
FCHT	Fuel cell hydrogen train
HRS	Hydrogen refueling station
LCOH	Levelized Cost of Hydrogen
OPEX	Operational Expenditures
PEM	Polymer Electrolyte Membrane
PPA	Power purchase agreement
RES	Renewable energy source
TCO	Total Cost of Ownership

Symbols and Units

$\%_{loss}$	Percentage of losses [−]
AM	Annual mileage driven by FCHTs [km]
$c_{H_2,HRS,k}$	Cost of hydrogen [€ kg^{-1}]
C	Cost [€]
CoP	Cooling system coefficient of performance [−]
D	Annual depreciation [€]
d_{op}	Days of operation during the year [gg]
DC	Daily capacity [kg]
E	Energy demand [kWh]
e	Specific energy demand [kWh/kg]
F	Faraday constant [C mol^{-1}]
h	Enthalpy [kJ/kg]
i	Discount rate [−]
I	Direct current [A]
k	Index of summation [−]
$LCOH$	Levelized cost of hydrogen [€ kg^{-1}]
LHV	Low heating value [kJ kg^{-1}]
m	Mass [kg]
$\dot{m}$	Mass flow rate [kgs^{-1}]
MW	Molecular weight [kg $kmol^{-1}$]
n	Polytropic index [−]
N	Number of element [−]
OH	Daily operating hours [h]
p	Pressure [Pa]
R_g	Universal gas constant [kJ kg^{-1} K^{-1}]
T	Temperature [K]
TCO	Total cost of ownership [€ km^{-1}]
U_f	Utilization factor [−]
W	Power [kW]

Greek

α	Real gas law coefficient [K Pa^{-1}]
a_{00}	Non-linear regression coefficient a_{00} [kJ kg^{-1}]
a_{10}	Non-linear regression coefficient a_{10} [kJ $(kg\ K)^{-1}$]
a_{11}	Non-linear regression coefficient a_{11} [kJ $(kg\ Pa)^{-1}$]
a_{20}	Non-linear regression coefficient a_{20} [kJ $(kg)^{-1}$ $(K)^{-2}$]
a_{21}	Non-linear regression coefficient a_{21} [kJ $(kg)^{-1}$ $(Pa)^{-2}$]
a_{30}	Non-linear regression coefficient a_{30} [kJ $(kg\ K\ Pa)^{-1}$]
Δc_{H_2}	Cost margin [€ kg^{-1}]
ε	Interstage effectiveness [−]
η	Efficiency [−]
ρ	Density [kg m^{-3}]

Subscript

c	Parameter related to the cell
capex	Parameter related to the capital expenditures
comp	Parameter related to the compressor
cool	Parameter related to the cooling
FC	Parameter related to the fuel cell
FCHT	Parameter related to the fuel cell hydrogen train
H_2	Parameter related to hydrogen
HRS	Parameter related to the hydrogen refueling station
HUB	Parameter related to hydrogen hubs
in	Parameter in input to the system
inter	Parameter related to the interstage
k	Index of the summation
min	Minimum value
opex	Parameter related to operational expenditures
out	Parameter in output from the system
prod	Parameter related to the centralized production
ref	Parameter related to the refueling
rep	Parameter related to the cost of replacement
stage	Parameter related to the compressor stage
stor	Parameter related to the storage system
tank	Parameter related to the vehicle tank
WE	Parameter related to the water electrolyzer

[46–49] are committing millions of dollars to enter the market and ensure sustainable development. In the national and interregional plans, interaction with renewable energy power plants is included, to support the transition to green hydrogen production and use [50,51]. In addition, the clusters should include the entire value chain: from hydrogen production to its handling, storage, transport, and distribution [52–54]. In this context, many authors have addressed these aspects separately: production, storage, transport, and distribution/refueling.

For hydrogen generation, comprehensive studies can be found elsewhere [55–57]. Concerning hydrogen storage, several options are available, both already in the market or under research and development actions [58–60]. Hydrogen transport is also one of the main aspects to be addressed in a hydrogen valley feasibility analysis [61–64]. Jin et al. [65] investigated the possibility to blend hydrogen with natural gas, exploiting natural gas existing pipelines, and analyzing several scenarios of blending percentages, up to 20 %, both in economic and energy terms. They highlighted how blending applications may be helpful for the gas network, in terms of performance, if the hydrogen is produced by renewable energy sources (RESs) like solar and wind. Apostolou and Enevoldsen [66] reviewed several technical configurations of RES wind power-to-hydrogen, considering hydrogen as the best carrier for seasonal storage. Their analysis showed incredibly favorable economic conditions, with an LCOH ranging from 0.3 to 26.6 €/kg. Another important subject is the delivery and refilling of hydrogen. These facilities are crucial, and their size depends on the features of the mobility users, in terms of mileage, pressure levels, hydrogen needed for a full tank, and protocol and standard associated with the refueling. Apostolou [67] provided an exhaustive literature review on hydrogen refueling stations (HRSs). The author investigated different layouts, from liquid stations to gaseous hydrogen stations, including on-site and off-site hydrogen production. Processing several data, he concluded that the hydrogen cost to fuel the vehicles could range from 4 to 7 €/kg. Cal State LA Hydrogen Research and Fueling Facility Team offered several on-site analyses [68–70] and data sharing of its 700-bar fueling station [71,72], with an on-site unit producing hydrogen via water electrolysis, at 10 bar, with a capacity of 60 kg/day, and refueling with booster

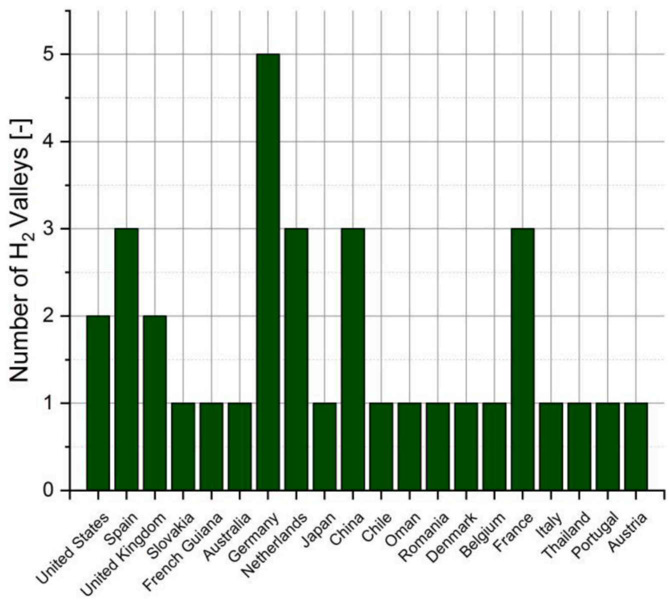


Fig. 1. Hydrogen Valley Projects under development in the world.

compressors. Piraino et al. [73] analyzed the technical and economic performance of an integrated hydrogen production facility and fuel cell hybrid train infrastructure, analyzing the Total Cost of Ownership and revenues of such integration.

As can be seen from the literature review presented, hydrogen production, storage, and distribution processes have been and are being extensively studied by the scientific community. However, to the best of the authors' knowledge, the literature lacks an overall analysis of a virtual hydrogen valley, and given the novelty of the topic, only project summaries or project proposals can be found.

Industry and research institutes are currently working on this, and a comprehensive analysis of these energy systems may be highly relevant as it can provide guidance and preliminary feasibility assessment for different sites and similar case studies.

In order to contribute to this trend, this work proposes a 3 E (energy, economic and environmental) analysis of a virtual hydrogen valley in Southern Italy, in Calabria, located near the Mediterranean Sea, where multimodal local transportation services are usually needed. The valley concept includes a centralized hydrogen production, and then several and various mobility users in different areas, where the performance of the related hydrogen storage and refueling infrastructure are investigated.

Moreover, hydrogen is delivered and transported by rail, with fuel cell hybrid trains (FCHTs). The valley is simulated in a Matlab/Simulink environment, where ad hoc modeling is implemented and used to analyze the performance of the involved plants.

The novelties of this research, therefore, can be summarized as follows.

- Analysis of an innovative concept of the Hydrogen Valley, which includes the production of hydrogen by electrolysis system larger than MW, distribution of the produced hydrogen by FCHTs, and subsequent use in local hubs in ports, in the marine and airport sectors, and also analyzing alternative solutions for public transport and urban mobility.
- Virtual simulation of this hydrogen cluster, thought to be installed in Calabria, in Southern Italy, as a cutting-edge technological system to analyze the performance of mobility technologies based on the hydrogen energy carrier, which includes managing small fleets of hydrogen fuel-cell vehicles and distributing hydrogen.
- Analysis of the revolutionary concept of the hydrogen transport system by rail, which, to the authors' best knowledge, has never been extensively studied in the scientific literature. This study will examine this concept from an energy, economic, and environmental point of view.
- Economic analysis of hydrogen distribution and refueling infrastructures as an energy vector that is beneficial for a variety of uses in mobility, particularly in sectors connected with the roles institutionally attributed to regions and local authorities, such as the port industry, airports, mobility, and local public transport, and overall territory development.
- Analysis of the levels of the levelized cost of hydrogen, as the size of the vehicle fleets, and the purchase price of renewable energy through power purchase agreements (PPAs), vary.
- Provision of methodologies and preliminary results for businesses and governmental organizations that require specialized knowledge in the design and construction of hydrogen facilities, as well as in distribution and environmental performance.
- Adoption of online resources to analyze how emissions reductions affect citizens' health outcomes in economic terms.
- Promotion of a concept of a "Hydrogen Valley" to recognize and showcase the potential of hydrogen use in the environmental transition process and interest in mobility activities.

It is worth mentioning that this research proposes a case study based on new technology analyses, related to the hydrogen industry. The case study includes a substantial review aspect in terms of findings and outcomes, which may be used for further analysis, comparison, or criticism. The case study is designed to be potentially expanded, combining it with systems from the larger category of renewable and sustainable energy, as well as to be re-adapted or relevant to other regions and different locations.

As a result, the manuscript is organized as follows: with the aim of introducing the research features, methodologies and instruments are presented in Section 2 "Materials and Methods"; in order to briefly describe the main model hypothesis and the primary equations underlying the model, Section 3 "Theory and Calculations" presents the main modeling features and the tool operation; all the information regarding the hydrogen valley under investigation as well as the various mobility users is provided in Section 4 "Case Study Description"; the key findings of the simulated virtual hydrogen valley are discussed in Section 5 "Results," along with their implications for the economy, the environment, and energy performance. The conclusions are presented in Section 6, which summarizes the key findings in relation to the research's novelties.

2. Materials and methods

2.1. Definition of the new concept of hydrogen valley

The present study focuses on the comprehensive examination of the "virtual hydrogen valley," encompassing multiple aspects ranging from hydrogen production to its utilization in end-use applications. The primary focus of this study centers around a tripartite framework known as the "3 E" analysis, which encompasses the dimensions of energy, economic, and environmental factors. The selection of this approach was made with the intention of offering a comprehensive viewpoint regarding the advantages and obstacles associated with the establishment of a hydrogen valley in the region of Calabria.

In the present context, the "Hydrogen Valley" refers to a centralized location where hydrogen is produced, followed by the establishment of distribution networks that serve the diverse transportation requirements within the given area. The utilization of rail transport, particularly fuel cell hybrid trains (FCHTs), as the primary means of hydrogen distribution, represents a unique and innovative approach.

An additional innovative element of the present research involves the development of a virtual simulation environment utilizing the Matlab/Simulink software. The provided setting facilitated a comprehensive examination of the system's performance across different scenarios, providing valuable perspectives on the effectiveness and viability of the proposed model.

Finally, the present study not only presents a novel framework but also thoroughly examines the practical implications of hydrogen utilization, evaluating its feasibility across various modes of transportation. The objective is to establish a foundation for future research and practical implementation by offering comprehensive analysis of refueling infrastructures designed specifically for different modes of transportation, ranging from fuel cell electric vehicles (FCEVs) to fuel cell electric aircrafts (FCEAs).

2.2. Structure of the simulation tool

In this work, a hydrogen valley, located in Southern Italy, is designed, modeled, and tested in different aspects, analyzing technical performance, and economic parameters. A central infrastructure for hydrogen production is placed in a strategic location, to easily fulfill the hydrogen demand of the whole valley.

As a novelty, the hydrogen produced is distributed, employing rail transport, to different regional points, to meet the hydrogen demand of each location, based on the transportation mode considered. The overall picture of the Hydrogen Valley is provided in Fig. 2.

The mobility end-users considered in this study are as follows.

- Fuel cell electric vehicles (FCEVs), with a refueling infrastructure at 700 bar;
- Fuel cell forklifts (FCFs), with a refueling infrastructure at 350 bar;
- Fuel cell bikes (FCBs), with a refueling point at 30 bar via a double-stage pressure reduction system;
- Fuel cell electric buses (FCEBs), with a refueling infrastructure at 350 bar;
- Fuel cell electric ferries (FCEFs), with a refueling infrastructure at 250 bar;
- Fuel cell electric scooters (FCESs), with a refueling infrastructure at 350 bar;
- Fuel cell electric aircraft (FCEAs), with an on-site liquefaction system and a refueling infrastructure at 20 K.

The methodology of the analysis and the operation of the simulation tool are summarized structure in Fig. 3. The tool can be divided into three main subsystems, which concern rail vehicles and hydrogen mobility applications, the hydrogen infrastructure, and the environmental-economic analyses; these main subsystems work in cascade, according to the simulation logic.

3. Theory and calculations

3.1. Fuel cell hybrid train for hydrogen transport

As the first step in the case-study evaluation, the hydrogen needed for the mobility applications in each location is estimated, taking into account the appropriate consumer base and specific consumption.

Along with these values, which influence the train features, the track morphology and the drive cycle are the inputs of the model. Utilizing numerical calculations, based on the Newton equation of motion, the

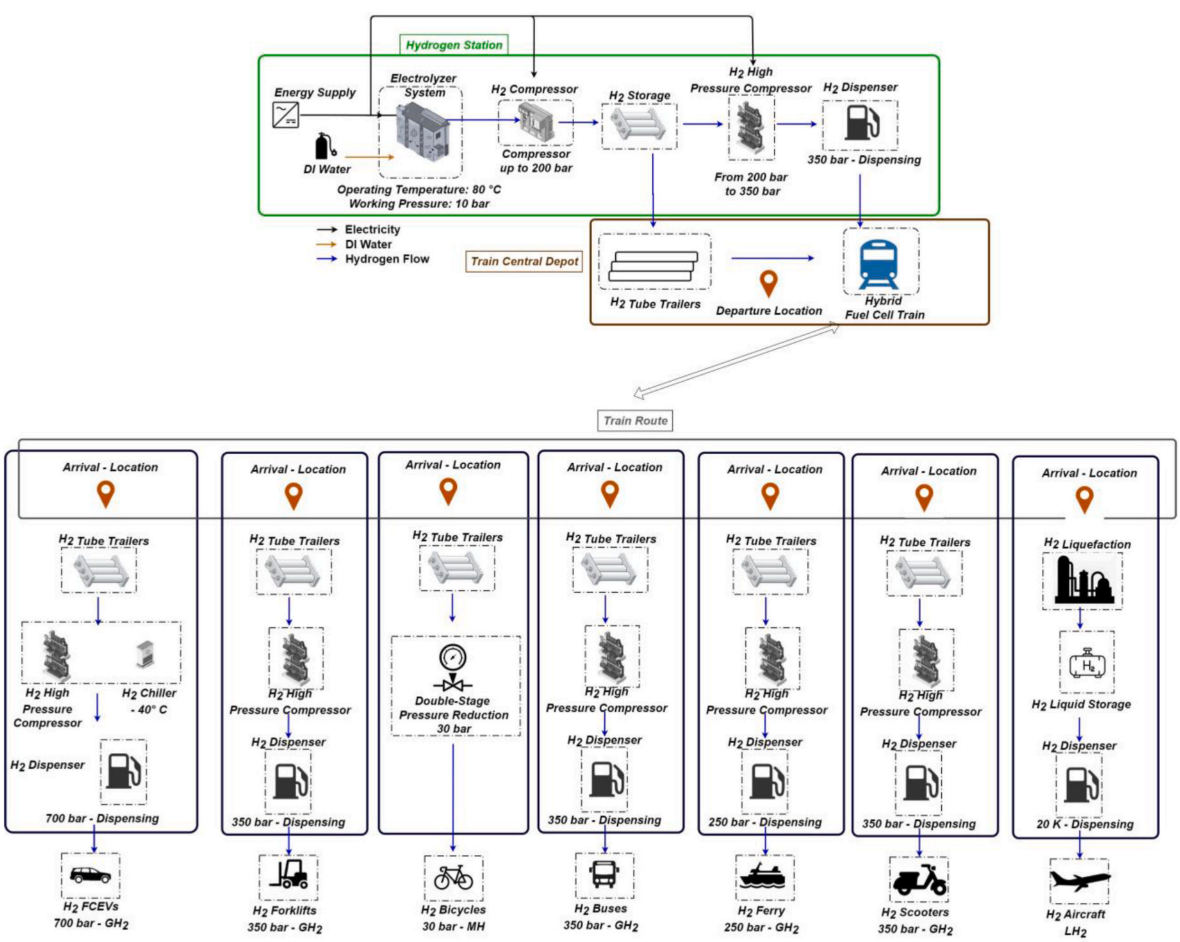


Fig. 2. Representative scheme of the simulated virtual hydrogen valley.

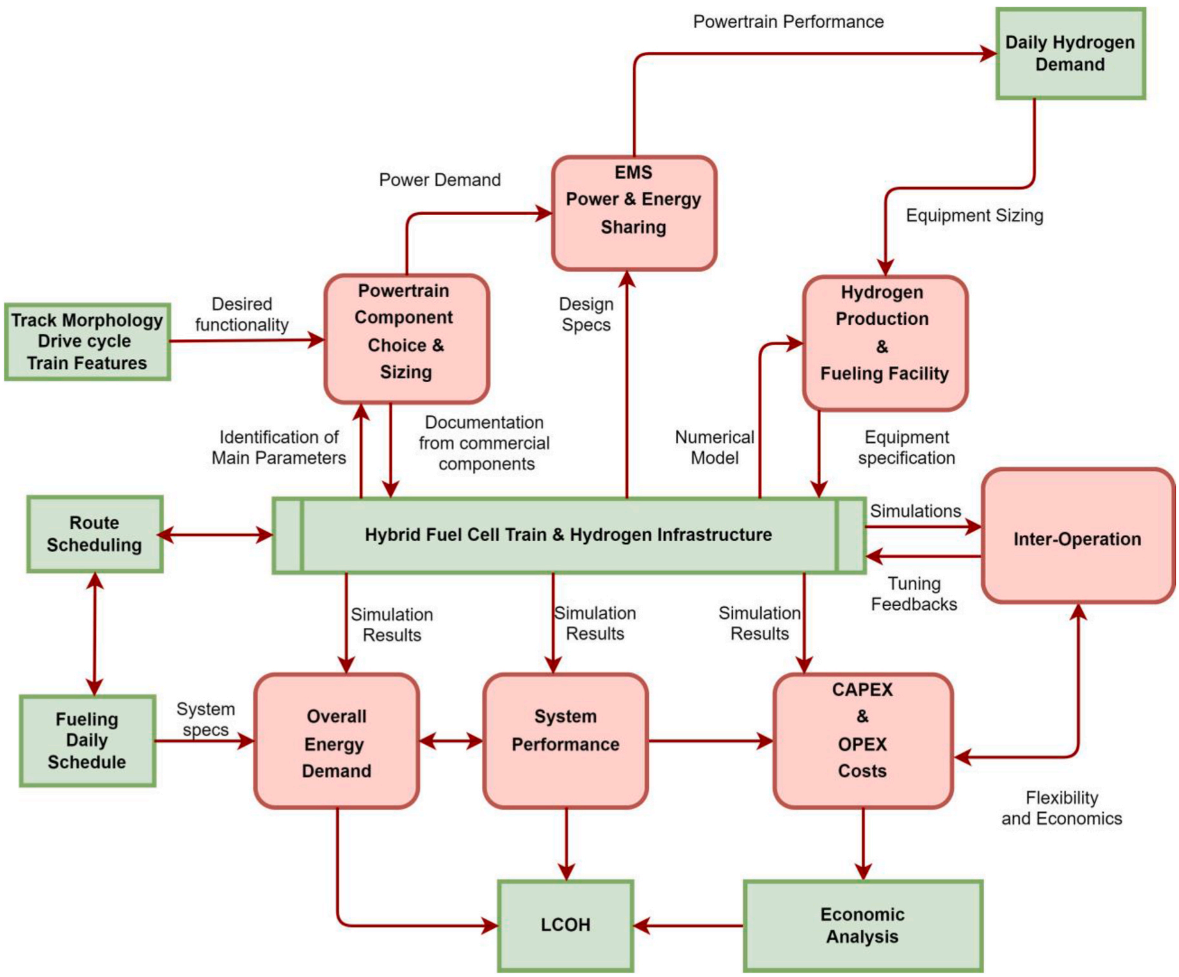


Fig. 3. Main structure of the simulation tool.

energy and power demand are calculated [74]. Starting from these parameters, a fuel cell hybrid powertrain (FCHT) is sized for each track, capable of fulfilling the standard train operations. Detailed and dynamic modeling of the whole powertrain is implemented, using electrochemical, physical, and logical relations. The parameter utilized for validation purposes was the relative error. When the simulation outcomes were compared with experimental data, there was a notable alignment between them. Specifically, the aggregate discrepancy or deviation was less than 1 %, highlighting the accuracy and reliability of the simulator's performance in relation to real-world experimental results [74–76]. The powertrain core is the fuel cell system, that implements the device behavior, modeling the Nernst's voltage and polarization losses. The voltage achieved determines the stack current (I_{FC}) which is the main parameter that affects the hydrogen consumption ($\dot{m}_{H2}$), as shown in Eq. (1). Consequently, the efficiency ($\eta_{el,FC}$) is obtained as the ratio of the fuel cell output power (W_{FC}) and the product of the hydrogen consumption and lower heating value (LHV_{H2}), as described in Eq. (2).

$$\dot{m}_{H2} = \frac{MW_{H2}\, N_c\, I_{FC}}{2FU_f} \quad \text{Eq. 1}$$

$$\eta_{FC} = \frac{W_{FC}}{\dot{m}_{H2} LHV_{H2}} \quad \text{Eq. 2}$$

Together with the fuel cell, the battery is the second source, used as energy storage; it is composed of a variable voltage source in series with a resistor. The power-sharing is performed by an equivalent consumption minimization strategy (ECMS), already tested by the authors [77], that chooses the fuel cell power optimizing the hydrogen consumption. In this way, the fuel cell is used to cover the energy request, while the battery provides the demand variations.

The energy management system controls the sources by means of the DC/DC converters, implemented in a simplified way, capable of increasing and maintaining constant the source voltage and protecting the energy sources from sudden voltage changes too.

The power flow reaches the motor block, composed of the inverter and motor. The latter is a Permanent Magnet Synchronous Motor, implemented with a second-order state-space model in the rotor reference frame [75]. Therefore, the inverter, built in a simplified mode, is fundamental to allowing the transformation from single-to three-phase currents. This powertrain configuration allows recovering a discrete amount of energy during decelerations, thanks to the battery, its bi-directional DC/DC converter, and the motor block that can work as a generator too.

3.2. Hydrogen infrastructure

The hydrogen infrastructure modeling can be divided into three main subcategories.

- Hydrogen infrastructure for hydrogen production, which is a centralized facility;
- Hydrogen infrastructure for storing and refueling hydrogen in gaseous form;
- Hydrogen infrastructure for storing and refueling hydrogen in liquid form.

3.2.1. Hydrogen infrastructure for centralized production

Previously, the authors [78] have provided a mathematical model for a hydrogen generation plant, via a zero-dimensional model based on energy and mass conservation equations, developed in Matlab/Simulink by creating ad-hoc blocks. The model is based on polymer electrolyte membrane (PEM) electrolysis, and was presented in a meticulous manner in the previous publications, and comprehensive sensitivity analyses were performed to assess its robustness across different conditions and assumptions.

The electrolyzer daily capacity (DC_{WE}) is calculated employing Eq. (3), as the sum of each hydrogen demand $DC_{HRS,i}$ in the "N_{HUB}" hubs and the hydrogen m_{FCHT} required by the FCHTs, plus a certain value of hydrogen losses ($\%_{loss}$) studied by the authors in an operating hydrogen production plant [72], set to 10 % in this analysis.

$$DC_{WE} = \sum_{i=1}^{N}\left[(1+\%_{loss})\cdot\left(DC_{HRS,i}+m_{FCHT}\right)\right] \qquad \text{Eq. 3}$$

The energy demand of the electrolyzer, E_{WE}, is then calculated via Eq. (4) by assuming the most recent value of energy efficiency set by the European Union as the target for PEM electrolysis technology in 2023, e.g. 52 kW h/kg [79].

$$E_{WE} = LHV_{H_2}\cdot\eta_{WE}\cdot DC_{WE} \qquad \text{Eq. 4}$$

Finally, as shown in Eq. (5), the electrolyzer power W_{WE} depends on the daily operating hours of the electrolyzer system, OH_{WE}, considered to be 24 in the present analysis.

$$W_{WE} = \frac{E_{WE}}{OH_{WE}} \qquad \text{Eq. 5}$$

Once the hydrogen is produced, it is compressed in a 200-bar storage system using a multi-stage storage compressor system. This system is modeled assuming a polytropic process [80–82], as this has already been applied and validated by the authors [83]. The needed power is then calculated as in Eq. (6), as the sum of the power needed in the single stage. The electric power needed in the interstage for cooling the gas depends on the interstage effectiveness, ε, and the cooling system coefficient of performance, CoP, and is proportional to the enthalpy delta between the outlet and the inlet of each stage, as shown in Eq. (7).

$$W_{stor-comp} = \sum_{k=1}^{N_{stage}} \frac{DC_{WE}}{OH_{WE}}\cdot\frac{R_g\cdot T_{in,stage}}{\eta_{comp}}\cdot\left[\left(\sqrt[N_{stage}]{\frac{p_{stor}}{p_{WE}}}\right)^{\frac{n-1}{n}}-1\right] \qquad \text{Eq. 6}$$

$$W_{inter-cool} = \sum_{k=1}^{N_{stage}} \frac{\varepsilon\cdot\left(h_{out,k}-h_{in,k+1}\right)}{CoP} \qquad \text{Eq. 7}$$

The enthalpy is calculated by means of Eq. (8), retrieved via a non-linear regression of data belonging to the NIST database, with an R-square value of 0.999.

$$h(p,T) = a_{00}+a_{10}\cdot T+a_{20}\cdot T^2+a_{11}\cdot p+a_{21}\cdot p^2+a_{30}\cdot p\cdot T \qquad \text{Eq. 8}$$

Finally, the specific energy consumption of the storage compressor, $e_{stor-compr}$, is represented by Eq. (9).

$$e_{stor-compr} = \frac{\sum_{k=1}^{N_{stage}}\left(W_{stor-compr}+W_{inter-cool}\right)}{\frac{DC_{WE}}{OH_{WE}}} \qquad \text{Eq. 9}$$

3.2.2. Gaseous hydrogen storage and refueling station

For each facility including the refueling process, using the real gas law [84], the internal pressure of the storage tank is computed, as shown in Eq. (10).

$$\frac{p}{\rho} = R_g\cdot T\cdot\left(1+\alpha\frac{p}{T}\right) \qquad \text{Eq. 10}$$

Where $\alpha = 1.9155\times10^{-6}\ \frac{K}{Pa}$ is a coefficient, R_g is the gas constant of hydrogen with $R_g = 4124.3\,\frac{J}{kg\,K}$.

When higher pressure is required, the HRS includes a refueling compressor system, whose power is calculated utilizing Eq. (11), similar to Eq. (6), but with a different approach. In order to compute the power demand in the most demanding scenario, the minimum pressure level in the storage tank is considered, as well as the maximum flow rate for a fast refueling process, assuming as a general protocol the SAE J2601 [85, 86]. The interstage power and the specific energy consumptions of the refueling compressor are then calculated.

$$W_{ref-comp} = \sum_{k=1}^{N_{stage}} \dot{m}_{ref}\cdot\frac{R_g\cdot T_{in,stage}}{\eta_{comp}}\cdot\left[\left(\sqrt[N_{stage}]{\frac{p_{tank}}{p_{min}}}\right)^{\frac{n-1}{n}}-1\right] \qquad \text{Eq. 11}$$

Only for the FCEV HRS, a hydrogen chiller is considered, with a specific energy consumption of 1.4 kW h/kg of cooled hydrogen [87].

3.2.3. Liquid hydrogen storage and refueling station

Three phases make up a traditional technique for liquefying hydrogen and have been taken into consideration.

- Pure and dry hydrogen is drawn from the high-pressure trailers at pressures greater than the critical pressure (13 bar);
- cooling at low temperatures to chill down the gas close to 30 K;
- utilizing a throttle valve, expanding the hydrogen from high pressure to low, achieving 20 K.

To include complex phenomena such as hydrogen boil-off losses and ortho-to-para hydrogen conversion [88,89], its energy consumption is based on experimental data retrieved from the European database [79].

3.2.4. Energy balance

The energy flows associated with the proposed hydrogen infrastructure involve the various stages of production, storage, and refueling. The primary method of hydrogen production in a centralized system is heavily dependent on electricity, particularly from renewable sources. This electricity is used to power the electrolyzers. The storage of hydrogen in its gaseous state necessitates the utilization of energy for the compression process, which can result in potential losses within storage systems, particularly when operating under elevated pressures. Moreover, the refueling procedure in this particular configuration leads to energy consumption as a consequence of the refueling compressors. In the context of liquid hydrogen infrastructure, it is important to note that the process of liquefaction is characterized by a significant energy requirement.

The total energy balance of the hydrogen infrastructure is derived from the collective inputs, losses, and efficiencies throughout these stages. This analysis is crucial for ensuring the environmental and economic sustainability of the system. The overall energy balance is presented in Eq. (12), where it is possible to identify two main contributions: the first term is related to the centralized hydrogen production and compression system, while the second term is the sum of the energy requirements of the HRS system installed in each hub, $e_{HRS,i}\cdot DC_{HRS,i}$.

$$E_{tot} = \left(LHV_{H_2}\cdot\eta_{WE}+e_{stor-compr}\right)\cdot\sum_{i=1}^{N}\left[(1+\%_{loss})\cdot\left(DC_{HRS,i}+m_{FCHT}\right)\right] + \sum_{i=1}^{N}\left[\left(e_{HRS,i}\cdot DC_{HRS,i}\right)\right] \qquad \text{Eq. 12}$$

3.3. Economic assessment

The total cost of ownership (TCO) approach and a static analysis utilizing the levelized cost of hydrogen (LCOH) method are the foundations of the economic study in this work. The capital cost (CAPEX) and the operating cost (OPEX) of each component are required for both studies. They are included in Table 1 and were gathered from the most recent research and analysis. The lifetime of the system is considered to be 15 years.

Other three operating costs are considered in this analysis: labor cost (35 k€/year [93]), water cost (1.9 €/Sm^3 [94]), and renewable electricity cost, considered to be acquired via PPAs, with a variable price between 50 and 250 €/MWh, including tariffs and fees.

The LCOH method [95] is adopted for the calculation of the potential hydrogen price to be set in the centralized hydrogen plant, by considering a certain amount of days of operation during the year, d_{op}, set to 320 in this analysis, as shown in Eq. (13). No replacement costs are considered since the OPEX values already include the replacement cost averaged per year. A discount rate of 7 % is considered, and a lifetime of 15 years. The CAPEX includes the electrolyzer, the storage compressor, the tube trailers for the trains, the refueling compressor for the trains, and the four FCHTs.

$$LCOH_{prod} = \frac{\sum\left[C_{capex}\cdot\left(\frac{i\cdot(1+i)^l}{(1+i)^l-1}\right)\right] + C_{opex} + C_{rep}}{DC_{\mathrm{WE}}\cdot d_{op}} \quad \text{Eq. 13}$$

The costs of the integrated system (hydrogen infrastructure and trains) are compared to those of traditional technologies using the total cost of ownership (TCO). It is determined using Eq. (14). The sum of the annual CAPEX, annual depreciation D, and annual operating expenses, divided by the annual mileage driven by FCHTs, AM, expressed in kilometers, corresponds to the total cost of ownership (TCO).

$$TCO = \frac{\sum\left[C_{capex}\cdot\left(\frac{i\cdot(1+i)^l}{(1+i)^l-1}\right)\right] + \mathrm{D} + C_{opex}}{AM} \quad \text{Eq. 14}$$

TCO and LCOH are distinct metrics, but their applications to hydrogen systems are interdependent. TCO provides a more comprehensive view of the total costs associated with a hydrogen system or infrastructure over the course of its lifetime. LCOH, on the other hand, narrows the focus to the cost-effectiveness of hydrogen production. Consequently, while TCO may represent the overall financial implications of a hydrogen system, LCOH indicates the economic viability of the hydrogen produced by that system. While TCO helps stakeholders comprehend the entire cost continuum associated with a hydrogen system, LCOH provides insight into the competitiveness and prospective profitability of the hydrogen produced by that system.

The cost of hydrogen, sold to the refueling infrastructures of the several mobility hubs is then calculated employing Eq. (15), where the LCOH of the centralized infrastructure is averaged on the related daily capacity $DC_{HRS,k}$, and a value of cost margin Δc_{H_2} is added (3 €/kg), to guarantee certain profitability.

$$c_{H_2,HRS,k} = DC_{HRS,k}\cdot\frac{LCOH_{prod}}{\sum_{i=1}^{N} DC_{HRS,i}} + \Delta c_{H_2} \quad \text{Eq. 15}$$

Table 1
Economic parameters for the hydrogen valley.

Equipment	CAPEX	OPEX
PEM Electrolyzer [90]	0.7 k€/kW	30 €/kg/day
Storage Compressor [90]	1 k€/kW	0.03 €/kg/day
Tube Trailers [90]	0.45 k€/kg H_2	–
Hydrogen Storage [90]	0.75 k€/kg H_2	–
Gaseous HRS [90]	1 k€/kg H_2	0.35 €/kg/day
Hydrogen Chiller [91]	200 k€	0.0325 €/kg/day
Refueling Compressor [90]	5.6 k€/kW	0.07 €/kg/day
Liquid HRS [90]	1.4 k€/kg H_2	0.5 €/kg/day
Liquid Storage [90]	0.2 k€/kg H_2	–
Liquefaction System [92]	13.1 k€ @2300 kg H_2	–
Hydrogen Train [93]	5000	0.72 €/km

The LCOH of the single HRS is then calculated, using Eq. (13), but including in the OPEX also the cost of hydrogen needed in that specific hub.

Concerning the presented economic analysis, it is important to present the limits of its applicability. The feasibility and success of technology deployments are heavily influenced by economic risks, with special emphasis on capital expenditure and operational expenditure. Market circumstances that are subject to change may lead to fluctuations in the price of materials, labor, and other crucial components. Furthermore, the modification of governmental policies, tax structures, and laws may have a profound impact on the financial environment of projects, influencing both the original capital outlay and the continuous operating expenses. Unforeseen operational interruptions, such as equipment breakdowns or unexpected maintenance requirements, have the potential to bring unanticipated costs, hence increasing operational expenditures. The interconnected and worldwide structure of supply chains implies that disturbances, such as pandemics, geopolitical conflicts, or other global occurrences, might generate consequential impacts on the accessibility and expenses of resources and services. Financial fluctuations, such as swings in interest rates, currency exchange dynamics, and inflation, contribute to the introduction of uncertainty in long-term initiatives. Finally, it should be noted that external factors, such as natural catastrophes or societal unrest, have the potential to significantly affect project timetables and related costs in an unpredictable manner. It is important to acknowledge and effectively manage these economic risks in order to get a thorough comprehension and accurate projection of the expenses linked to any technical undertaking.

3.4. Environmental assessment

This study aims to analyze the environmental impact associated with hydrogen transport systems by rail, compared to two conventional approaches: transport via diesel trains or total electric trains.

Dual methods are employed to evaluate emissions and their environmental impacts. First, is the use of Co-Benefits Risk Assessment (COBRA) [96] to calculate the carbon footprint and health and quality of life advantages. The underlying principle that forms the basis of COBRA is to assess and measure the positive impacts on public health resulting from enhanced air quality. This is achieved by utilizing an extensive database that encompasses pollution levels in various cities and regions throughout the United States. COBRA performs a localized study for the given scenario. The authors have already applied this tool in a scenario implemented in Calabria [91]. The process of customizing this tool for the Calabrian region in Italy necessitated conducting a comparative analysis of air quality indices across different regions. According to a study conducted by IQ Air, it has been found that Calabria exhibits an average air-quality index (AQI) of 57, which closely corresponds to the AQI recorded in Montana, United States. Therefore, Montana is utilized as the standard for predicting emissions. In order to effectively use COBRA tool, it is essential to possess knowledge regarding variations in levels of specific pollutant species. These specific variations are outlined in Table 2. It is worth noting that although COBRA enables sector-specific analyses such as mobility, power production, and

Table 2
Specific emissions for the investigated scenarios.

Emission	Diesel Train [kg/ton of fuel] [98,99]	Total Electric Train [kg/kWh] [100,101]
PM 2.5	11	2.40404E-05
NO_x	63	0.00014016
NH_3	0.01	1.17934E-05
CO	18	–
VOC	48	5.4431E-06
SO_2	–	2.76691E-05
Equivalent CO_2	0.0069	0.224

buildings, it does not incorporate the health and societal consequences of carbon dioxide emissions.

The second method uses the European instrument "Carbon reduction advantages on health (CaRBonH)" [97] to examine benefits in the European Union and adjacent nations. The tool also analyzes carbon dioxide reduction, however, the regions are interconnected, and the European health benefits are averaged.

The energy required by the diesel trains and by the total electric trains is calculated by adopting the Newton equation of motion, as already described in Section 2.2. The overall fuel and electricity consumption are then calculated assuming average values of the powertrain efficiencies, respectively 30 % and 90 % for the diesel trains and the total electric trains. The emissions generated by the diesel trains and by total electric trains powered by the electricity retrieved from the national grid mix are presented in Table 2.

Concerning diesel trains, emission data from the European Environment Agency [98,99] have been retrieved, assuming a power train efficiency of 30 % [102]. The electricity needed for the total electric train has been assumed to be retrieved from the Italian national grid, with an average emission of 0.224 kg_{CO2eq}/kWh. The other component emissions have been calculated comparing the Italian situation to California, which has similar average emissions (0.246 kg_{CO2eq}/kWh), adopting tools such as AVERT [100] and eGRID Power Profile [101]. To be clearer, the carbon intensity value of 0.224 kg_{CO2eq}/kWh of the grid electricity serves as a benchmark for comparing the emission reductions achieved by implementing hydrogen trains to conventional electric trains. The generation of green hydrogen in this research is based on the premise that the whole energy need is fulfilled exclusively by renewable sources, which is made possible by the implementation of Power Purchase Agreements (PPAs). These partnerships guarantee that the power used for hydrogen generation originates only from renewable energy installations, including solar, wind, and hydroelectric sources. Therefore, under this theoretical framework, the carbon intensity linked to the generation of green hydrogen is essentially negligible, highlighting the environmental benefits of shifting towards hydrogen-based energy carriers in the transportation industry.

Within the framework of the present analysis, it is important to emphasize that although the European Environment Agency (EEA) offers a comprehensive perspective on emissions across Europe, it is crucial to acknowledge that emission factors can be influenced by regional variations within the continent. The transportation sector and energy mix in Italy, particularly in terms of electricity generation, may possess distinct characteristics that may not align precisely with the broader European averages. In order to capture the regional specificity, the present analysis juxtaposes the situation in Italy with that of California, utilizing tools such as AVERT and eGRID Power Profile. Both regions exhibit a heterogeneous energy portfolio, encompassing a substantial proportion of both renewable and non-renewable sources, rendering them suitable for comparative analysis within the context of the presented study. The main objective of this methodology was to provide a more nuanced and contextually relevant estimation of emissions, thereby strengthening the reliability and relevance of the findings within the Italian context.

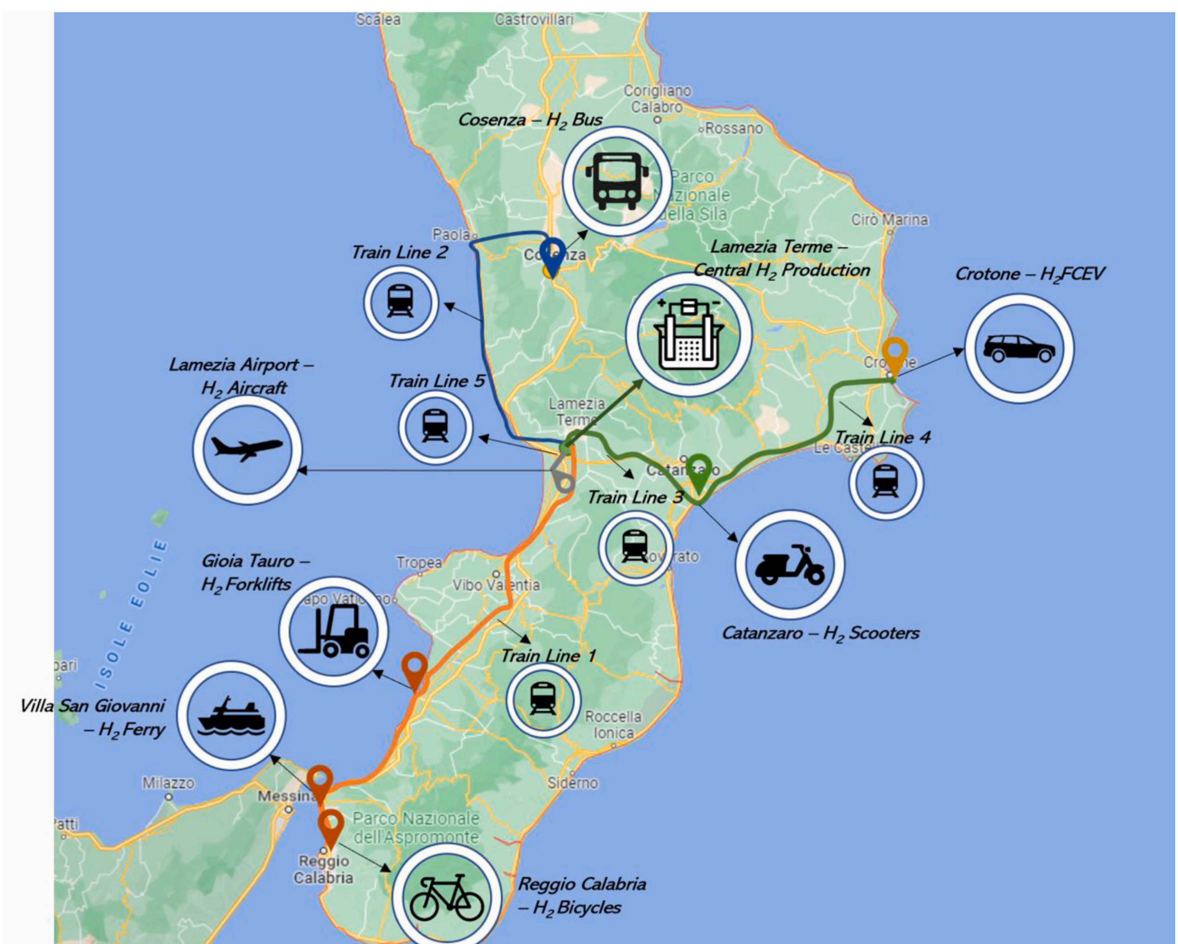


Fig. 4. Graphical representation of the simulated virtual hydrogen valley in calabria (IT).

4. Case study description

The case study examines an innovative concept for a hydrogen valley in Calabria, a region in southern Italy, which envisions the penetration of hydrogen in the mobility sector in the region's major localities. Seven locations are considered with varying mobility applications. The total amount of hydrogen required is produced at a central facility in Lamezia Terme, located in the heart of the Calabria region, and then distributed to the various communities via five train lines. The structure of the hydrogen valley, shown in Fig. 4, is as follows.

- 100 forklifts operate in Gioia Tauro, which has one of the largest ports in Italy, consuming 90 kg/day of hydrogen supplied by Train Line n. 1;
- 10 ferries travel from Villa San Giovanni to Sicily and consume approximately 295 kg/day of hydrogen transported from Lamezia by Train Line n. 1;
- 130 bicycles move in Reggio Calabria's city center, for tourist purposes, consuming nearly 5 kg/day of hydrogen supplied by Train Line n. 1;
- A bus service, composed of 98 vehicles, is used in the city of Cosenza, an industrial city, consuming roughly 170 kg of hydrogen, provided using Train Line 2;
- 130 scooters are useful to link the city center of Catanzaro, with the hospital and university, requiring approximately 34 kg of hydrogen, transferred from Lamezia on Train Line n. 3;
- A car fleet of 100 vehicles is planned in Crotone, to link the city with the most important spots of the Ionian coast, demanding 500 kg of hydrogen, transported with Train Line n. 4;
- 5 aircraft take-offs from Lamezia airport, consuming nearly 2270 kg/day of hydrogen, which will be delivered by Train Line n.5.

The amount of hydrogen needed for the different uses, reported in Table 3 and described in the Sankey plot (Fig. 5), represents the nominal scenario presented in this work, corresponding to the maximum hydrogen demand from the valley. Starting from these values, five scenarios are investigated, as shown in Fig. 6. The nominal demand corresponds to the 100 % scenario, while the other cases take into account a demand fluctuation and the production infrastructure works at partial load, namely producing 20 %, 40 %, 60 % or 80 % of the hydrogen nominal value. For each train line, the hydrogen consumption is associated with a percent value, according to the scenario considered.

5. Results

Considering 4 % gravimetric density for hydrogen tanks, the FCHT of Line 1 carries almost 390 kg/day of hydrogen with a payload of 9700 kg; approximately 170 kg/day are moved on Line 2, with 4200 kg payload; the FCHT travels towards both Catanzaro (Line 3) and Crotone (Line 4), therefore the amount of hydrogen is about 540 kg/day and its payload is 13,350 kg; while Line 4 links the Lamezia central infrastructure with the Airport, transporting almost 2270 kg/day with 56,670 kg payload.

For each line, the vehicle weight and length are calculated according to the payload; these values, together with the track morphology and drive cycle, are used to achieve the power and energy demands, using the developed tool and numerical simulations. Fig. 7 shows the power request at the wheels and the drive cycle for the round-trip journeys, while the main parameters of the train lines are summarized in Table 4.

In detail, in Line 1, the vehicle stops 3 times between the fueling spot and Reggio Calabria center, refueling the stations for forklifts, ferries, and bicycle fleets, while a direct journey is considered for the return trip, when all the hydrogen amount is dispensed, with a maximum speed of 60 km/h. The power at wheels varies in a wide interval, between 2730 kW and −2324 kW, while the energy request in acceleration mode is around 1800 kW h and the deceleration one assumes a maximum value of 850 kW h, part of this potentially recoverable using an appropriate regenerative braking strategy. Line 2 has just one stop in the industrial center, reaching approximately 65 km/h. It requires energy and power values respectively of 1544 kW and 727 kW h, lower than Line 1, mainly owing to the lower hydrogen amount transported and, consequently, to fewer tanks installed on board. Merging Line 3 and Line 4, which are consecutive between each other, the overall line has two stops for one way, dispensing hydrogen for vehicles and scooters. Its energy values are the higher ones between the four lines, 2062 kW h in acceleration and 1229 kW h in deceleration since it reaches the maximum payload and also because its slope values are very high, with maximum values of approximately 60 ‰. Line 5 transports hydrogen to the Airport, located near the production infrastructure, at a distance of 5 km; in addition, given the considerable hydrogen amount, 3 journeys are considered during the day. Therefore Line 5 is the shortest in terms of length and duration and, given the high amount of hydrogen transported for each journey, limited speed and acceleration levels are used, in a track with low slope variations.

For these reasons, the energy values achieved are the lowest compared to the other lines, both in terms of power, in an interval between 833 kW and −282 kW, and energy, 153 kW h and −45 kW h for one round-trip. The respective hydrogen consumptions, required by the FCHTs in each line, are presented in Fig. 8, for each scenario, from 20 % to 100 % of the nominal capacity of the hydrogen valley.

FCHTs showed high performance in terms of energy efficiency, too. The FCHT in Line 1 performed the drive cycle with a fuel cell efficiency of about 50 % under the 100 % Scenario constraints, and 47 % under the 20 % scenario constraint. In the drive cycle required in Line 2, the FCHT showed an energy efficiency of the fuel cell system of 51 % in the best scenario, dropping to 46 % in the 20 % Scenario. The FCHT driving in the consecutive lines Line 3 and Line 4, reached a maximum efficiency of 52 %, and a minimum efficiency of 48.6 %, respectively in the 100 % Scenario and 20 % Scenario. Line 5, which is the shortest in terms of length, as presented in Table 3, presented the highest efficiency, 52 %, for the 100 % Scenario, and the highest efficiency for the 20 % Scenario,

Table 3
Location and hydrogen demands.

Transport application	Forklift	Ferry	Bicycle	Bus	Scooter	Vehicle	Aircraft
End user hub	Harbor	Ferry terminal	Touristic center	Industrial city	Hospital & University	Not served city with regional public transportation	Airport
Location	Gioia Tauro	Villa San Giovanni	Reggio Calabria	Cosenza	Catanzaro	Crotone	Lamezia Terme
Train line	Line 1	Line 1	Line 1	Line 2	Line 3-4	Line 3-4	Line 5
Line Length from Central H_2 Production [km]	69.68	105.95	119.93	82.73	43.22	103.28	4.7
Vehicle number	100.00	10.00	130.00	98.00	130.00	100.00	5.00
Vehicle Operation	6.00 h/day	16.00 km/day	100.00 km/day	20.00 km/day	100.00 km/day	600.00 km/day	2000.00 km/day
Fuel Economy	*0.*1500 kg/h	*1.*8359 kg/km	*0.*0004 kg/km	*0.*0860 kg/km	*0.*0026 kg/km	*0.*0083 kg/km	*0.*2267 kg/km
Hydrogen required [kg]	90.00	293.74	4.55	168.56	33.93	500.00	2266.67

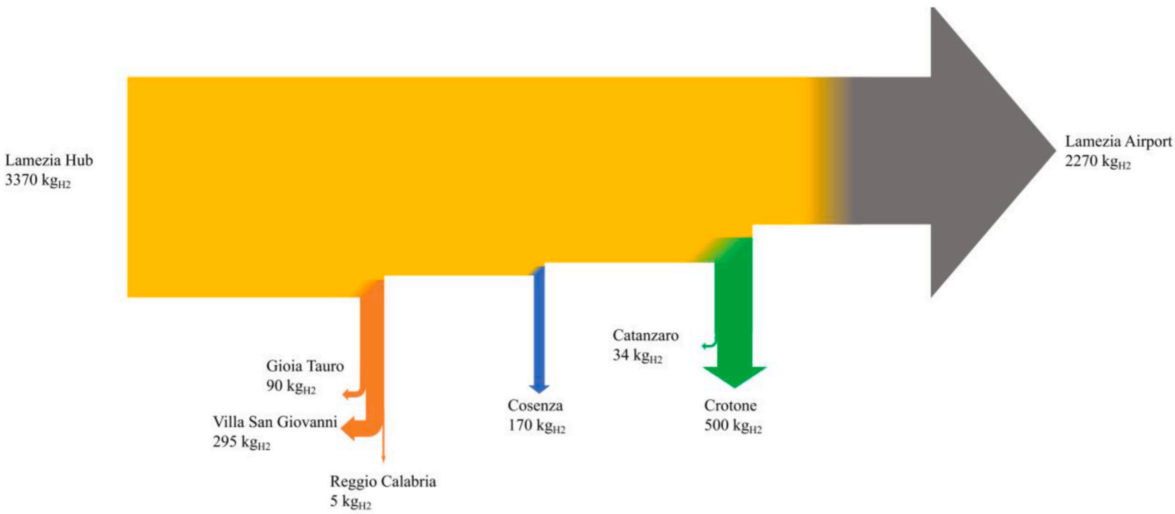


Fig. 5. Sankey plot of the hydrogen demand according to the line simulated.

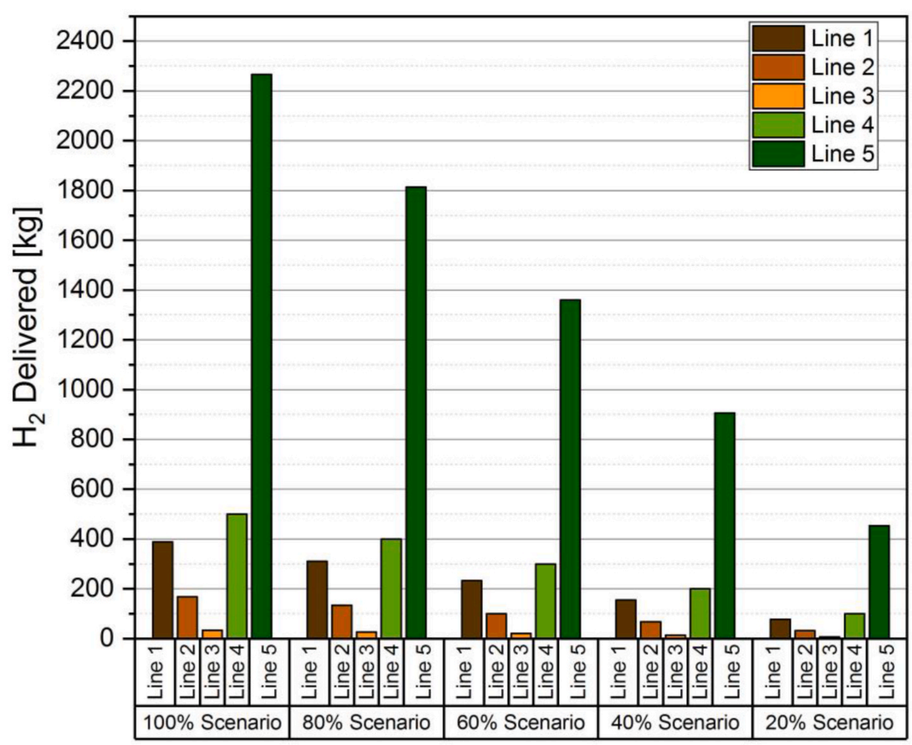


Fig. 6. Hydrogen Delivered and Transported via FCHTs for each line and according to five scenarios corresponding to a percentage of the hydrogen demand of 20 %, 40 %, 60 %, 80 % and 100 %.

when compared to other lines, with a value of 49.5 %.

Having identified the daily necessary quantities for each location of the Hydrogen Valley, plus the required hydrogen needed for transporting and distributing it at 250 bar via FCHTs, the centralized hydrogen production facility has been sized, along with the 7 hydrogen refueling stations (HRSs) for the several mobility users. The production facility's daily capacity includes also potential hydrogen losses during its operation, already evaluated by the authors [72], with a conservative value of 10 % of the distribution target.

The equipment sizes and performance are reported in Appendix A, for the sake of clarity and for the easiness of reading. The facilities have been sized by considering the most stringent condition, 100 % Scenario, e.g. the highest hydrogen demand from the hydrogen valley, and with operating constraints, e.g. minimum pressure levels in the storage tanks, which require the highest power demand for the compression equipment.

Fig. 9 shows the specific energy consumption, expressed in kWh per kg produced or dispensed. The hydrogen production center has the highest rate, with an overall value of 53.8 kW h/kg, mainly associated with the high energy requirement belonging to the PEM electrolyzer energy system. The daily consumption, shown in Fig. 10a, reaches 213 MW h/day, in the 100 % Scenario, and drops down to 45 MW h/day under the 20 % Scenario constraints.

The second highest specific energy consumption belongs to the hydrogen liquefaction and dispensing system, for the aircraft facility, with an overall value of 12.5 kW h/kg, and a daily energy demand

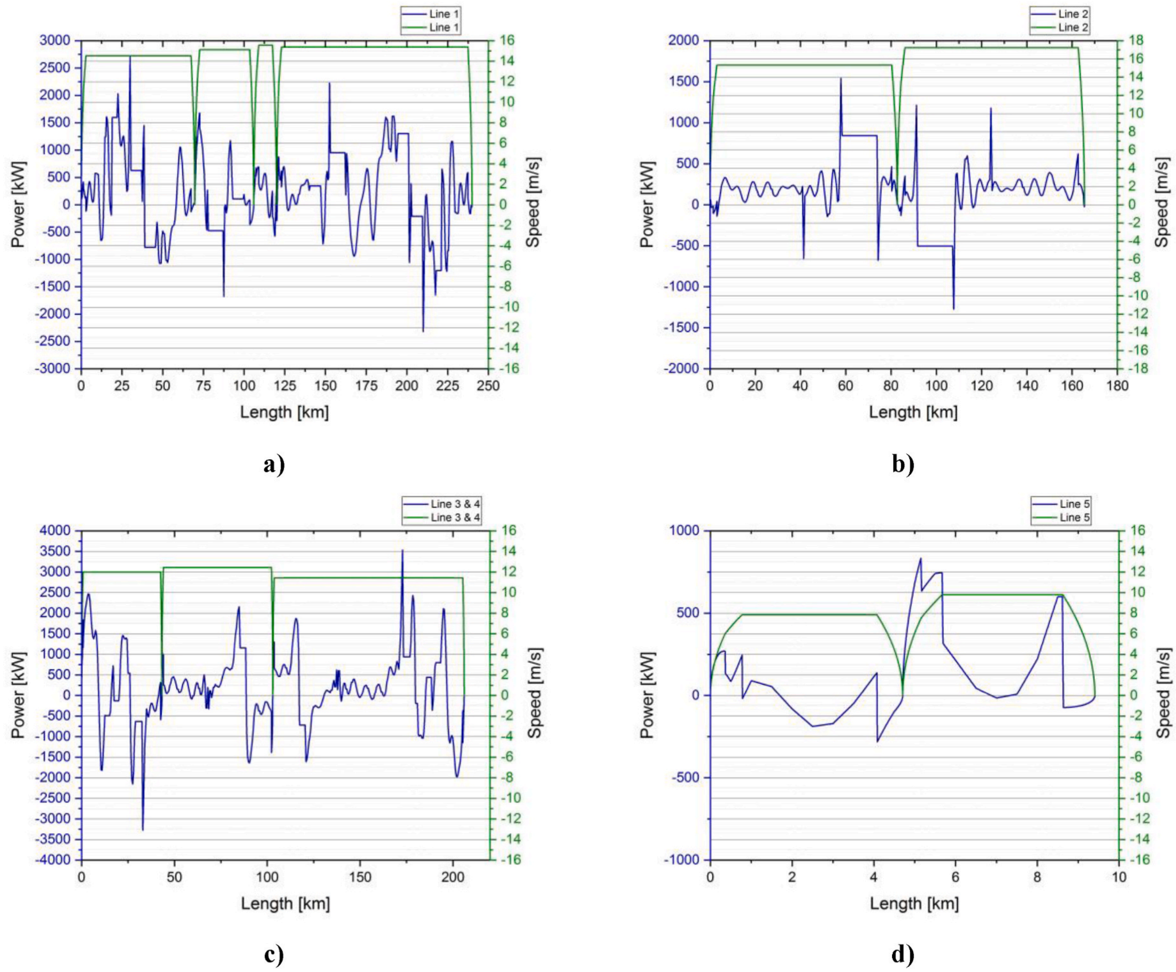


Fig. 7. Fcht power and speed profiles for line 1 (a), line 2 (b), line 3 & 4 (c), and line 5 (d).

Table 4
FCHTs model results.

	Line 1	Line 2	Lines 3-4	Line 5
Time travel [h]	5	3	5.2	0.45x3
Maximum power [kW]	2730	1544	3537	833
Minimum power [kW]	−2324	−1276	−3274	−282
Acceleration energy [kWh]	1836	727	2062	153x3
Deceleration energy [kWh]	847	−159	1229	−45x3

between 5 and 23 MW h/day, according to the aircraft fleet hydrogen demand. The HRS, installed for the vehicle fleet, required the highest rate among the gaseous hydrogen-based facilities. The presence of the 700 bar refueling compressor, along with the −40 °C hydrogen chiller, affects the energy consumption, which showed a specific value of about 9 kW h/kg, and daily energy demand of 1.35 MW h in the most demanding scenario, shown in Fig. 10b.

The bicycle HRS, serving a bicycle fleet for touristic purposes, does not have a significant energy consumption, given the only presence of a refueling point at 30 bar via a pressure double-stage reduction system, without compressors. The scooter, bus, and forklift HRSs presented comparable specific energy consumption, of about 0.9 kW h/kg, having a similar layout and operating conditions: a refueling compressor, with a maximum delivery pressure of 350 bar. Their daily energy demands, however, differ: Fig. 10b shows respectively values of 0.03, 0.15, and 0.08 MW h/day in the 100 % Scenario, while 6, 30, and 16 kW h/day in the 20 % Scenario. The ferry HRS has different operating conditions: a refueling compressor, but with a maximum pressure level of 250 bar, which is the maximum pressure allowed in the ferry storage. The facility has a specific energy consumption of 0.7 kW h/kg, and a maximum daily energy demand of 205 kW h/day, as shown in Fig. 10b.

In terms of economic performance, CAPEX and OPEX have been calculated, and they are discussed in Appendix B. Their values have been used to calculate the LCOH and TCO values for the centralized hydrogen production facility, shown respectively in Fig. 11a and b, as well as for the HRSs serving the several mobility applications considered in the simulated virtual hydrogen valley, shown in Figs. 12 and 13.

The centralized hydrogen production facility showed a minimum value of about 5.4 €/kg of LCOH, with a PPA price of 50 €/MWh while serving the whole fleets of the hydrogen valleys, e.g. 100 % Scenario, as depicted in Fig. 11a. The LCOH increases with the increase of the PPA price, and under very critical conditions, e.g. PPA of 250 €/MWh and the production of only 20 % of the fleet nominal capacity, the LCOH reaches values more than 20 €/kg, which will impose a non-competitive hydrogen price and business case. On the contrary, the TCO, shown in Fig. 11b, reaches competitive values, lower than 10 €/km with RES PPA price under 160 €/MWh, and even with production at full nominal capacity, e.g. 100 % Scenario. The predicted TCO is consistent with a recent analysis of the European Union [103], which assessed a TCO of 12 €/km. Compared to other railway technologies [104], the total cost of ownership of the studied system is very close to the diesel train (8.8 €/km) and is preferable to the electric train with a full battery (14.8 €/km) and possible new electrification of the overhead line (44.9 €/km).

Fig. 12 presents the economic performance of: the HRS serving FCFs, with a refueling infrastructure at 350 bar (Fig. 12a); the HRS serving FCEFs, with a refueling infrastructure at 250 bar (Fig. 12b); the HRS

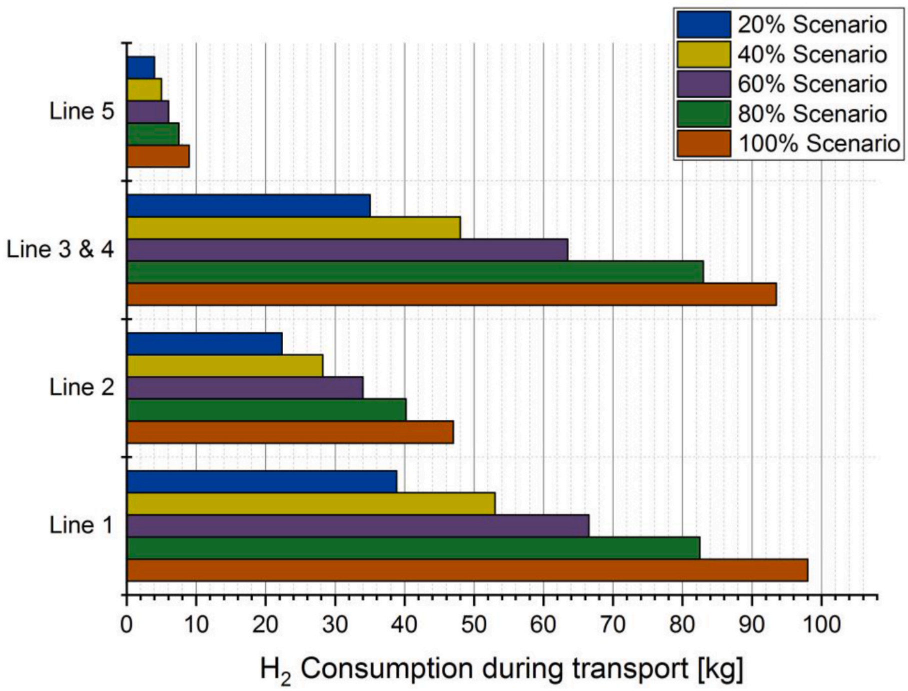


Fig. 8. FCHTs: Hydrogen consumption.

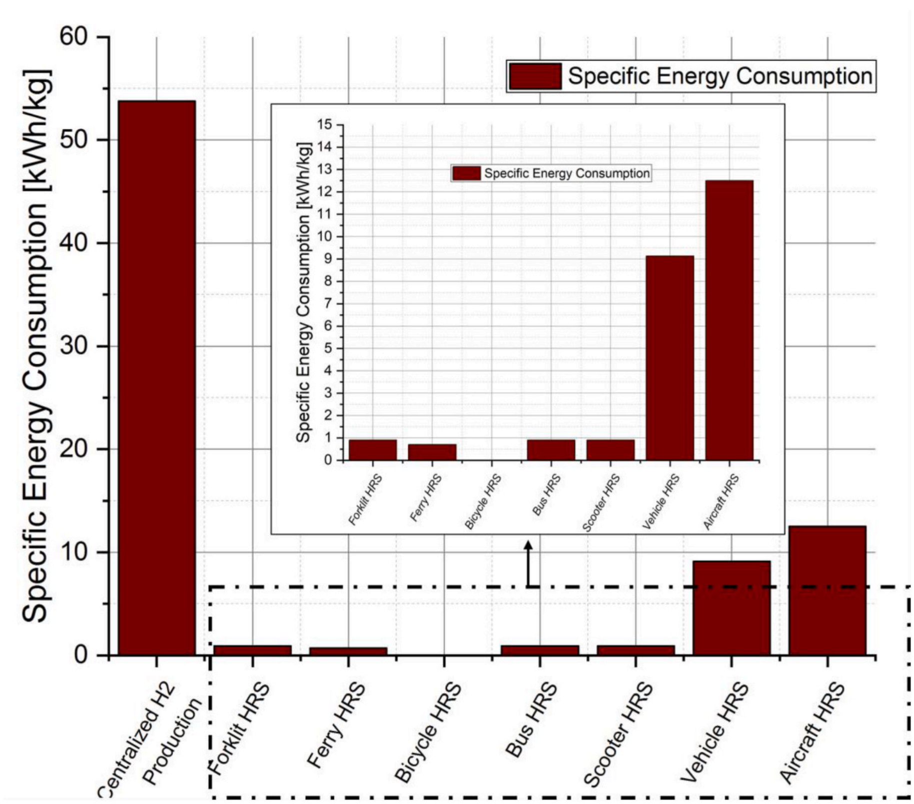


Fig. 9. Hydrogen infrastructures, specific energy consumption.

serving FCBs, with a refueling point at 30 bar via a pressure double-stage reduction system (Fig. 12c); and the HRS refueling at 350 bar a fleet of FCBs, shown in Fig. 12d.

In addition to the LCOH of the centralized hydrogen production infrastructure, all facilities acquire hydrogen with a 3 €/kg margin. Since the facilities are designed for the most demanding circumstances, as shown in Appendix A, CAPEX rates stay constant across all scenarios. The cost of hydrogen, the price of purchasing energy, the cost of maintenance activities, and the cost of labor all change depending on the scenario being studied.

The HRS for FCFs features a storage capacity of 90 kg/day and a compression system to fuel the vehicle at 350 bar for use with port

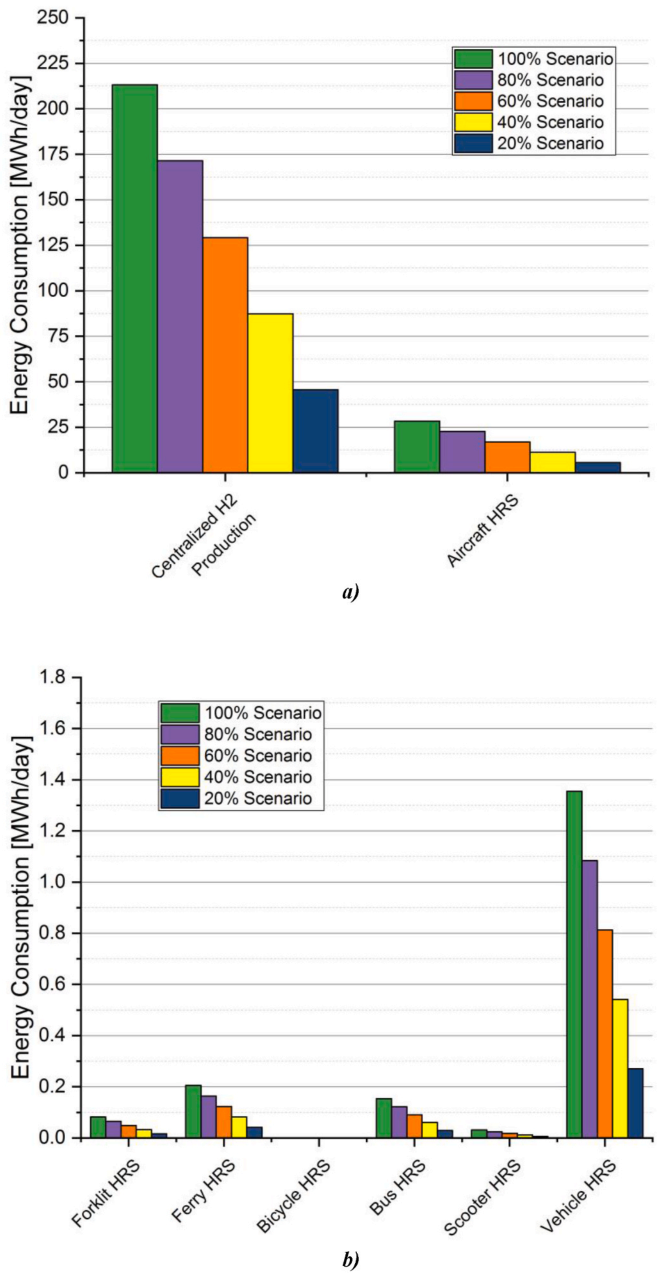


Fig. 10. Hydrogen Infrastructures, Daily Energy Expenditure: for Hydrogen Centralized Production (a) and Liquefaction System, and for the other facilities (b).

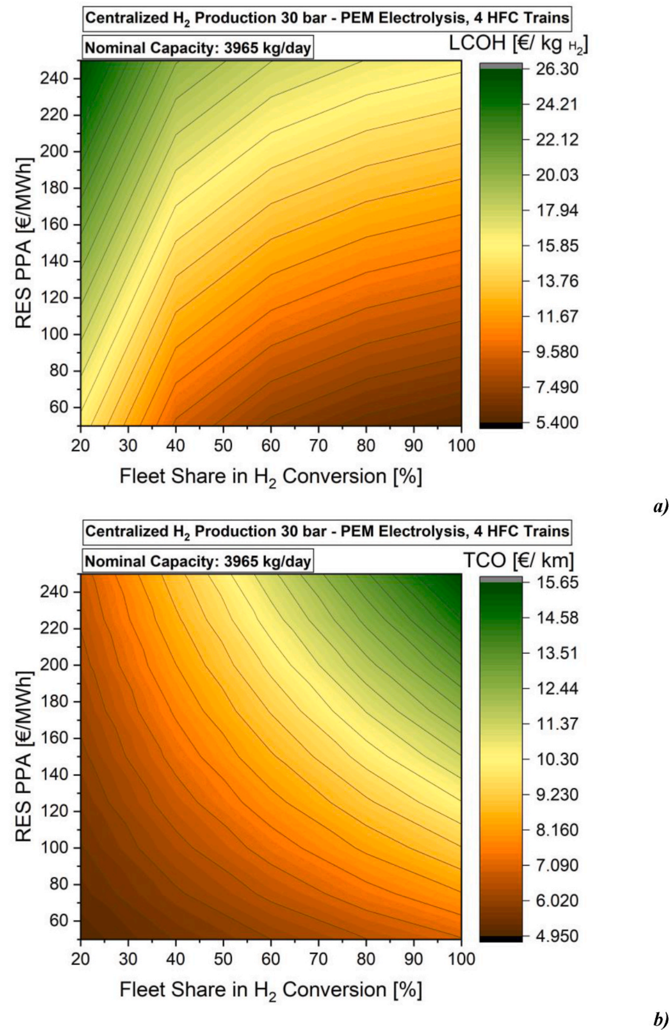


Fig. 11. Centralized H_2 Production Center: LCOH levels (a) and TCO levels (b).

material handling vehicles, such as forklifts. In order to control and oversee the facility operation, an operator is assumed to be present on-site. For all 100 forklifts, the LCOH varies from 6.15 €/kg with a RES PPA price of 50 €/MWh to 8.45 €/kg with a higher RES PPA price of 250 €/MWh, as Fig. 12a depicts. The value of the LCOH quickly rises to up to 12 €/kg under various scenarios, such as when the fleet contribution in hydrogen conversion is less than 50 %, and even more, up to 17 €/kg under the worst circumstances. Similar performance is obtained by the HRS for city buses, having similar equipment, but with different sizes. The economic performance is shown in Fig. 12d: compared to forklift HRS, the LCOH levels have similar trends, but with different minimum and maximum values. This facility presents a maximum value of 13 €/kg in the worst case, and a minimum value of 5.2 €/kg in the most optimistic case, e.g. RES PPA of 50 €/MWh and 100 % of fleet conversion.

Since the end-user demands a pressure level of 30 bar, the bicycle refueling infrastructure lacks equipment for refueling. The bicycle storage system simply uses a two-stage pressure reduction process to obtain the necessary pressure level while the carried trailers have a pressure level of 250 bar. Therefore, the CAPEX involved consists of the hydrogen storage system, which has a daily capacity of 4.55 kg, and the refueling terminal, for which an OPEX is also incurred for routine maintenance. Due to the minimal number of components present and the consequently low power consumption, it is feasible to have a very low LCOH under these boundary circumstances. As a result, the energy purchase cost has little impact. Therefore, the cost of purchasing hydrogen is then controlled by the boundary conditions of the production facility and whose economic performances are shown in Fig. 10a–b, and it is the key factor affecting the LCOH. If the facility provides between 60 % and 100 % of the fleet of bicycles and with low RES PPA costs, lower than 160 €/MWh, the LCOH of HRS for bicycles assumes values between roughly 4–6 €/kg, while it has values greater than 8 €/kg if it supplies less than 40 % of the fleet.

Concerning the remaining facilities, Fig. 13a shows the HRS economic performance for FCESs, with a refueling infrastructure at 350 bar. The minimum achievable LCOH is about 8.3 €/kg, while the maximum value is about 28.3 €/kg. This HRS turned out to be the most critical one, mainly due to the high hydrogen cost for such vehicles. Competitive levels of LCOH are obtained for the FCEV HRS, shown in Fig. 13b, with LCOH values close to 5 €/kg in the most optimistic scenario. The HRS for FCEAs, with an on-site liquefaction system and a refueling infrastructure at 20 K, showed good performance for fleet share conversion of more than 60 %, as described in Fig. 13c.

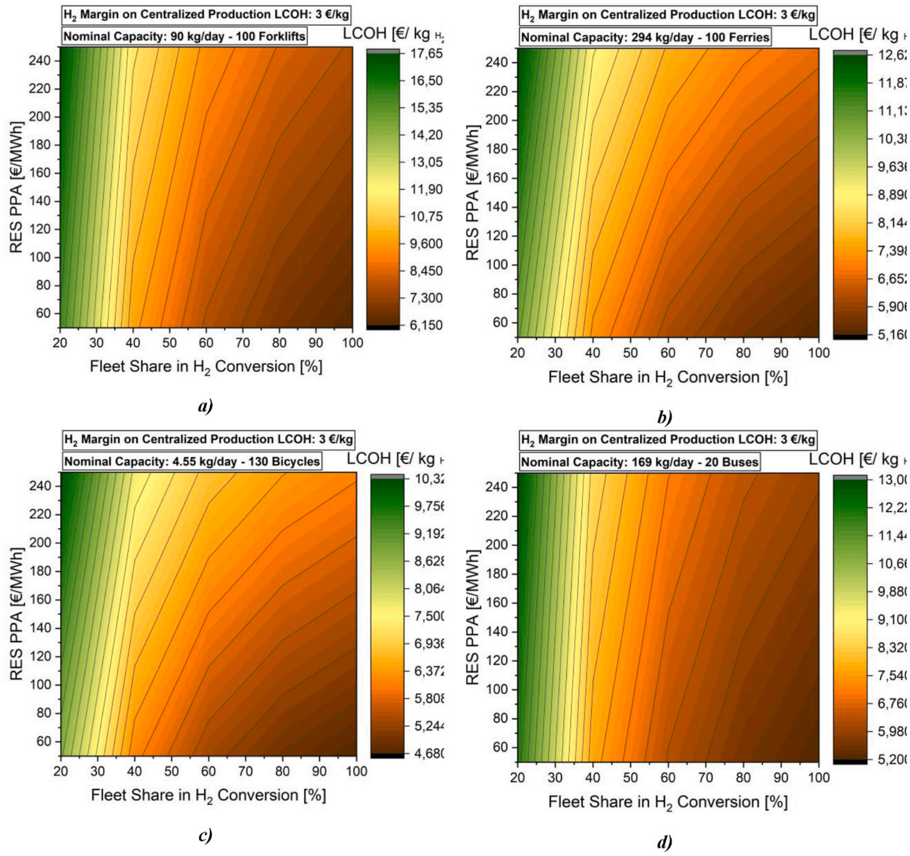


Fig. 12. LCOH levels for the Forklift HRS (a), Ferry HRS (b), Bicycle HRS (b), and Bus HRS (d).

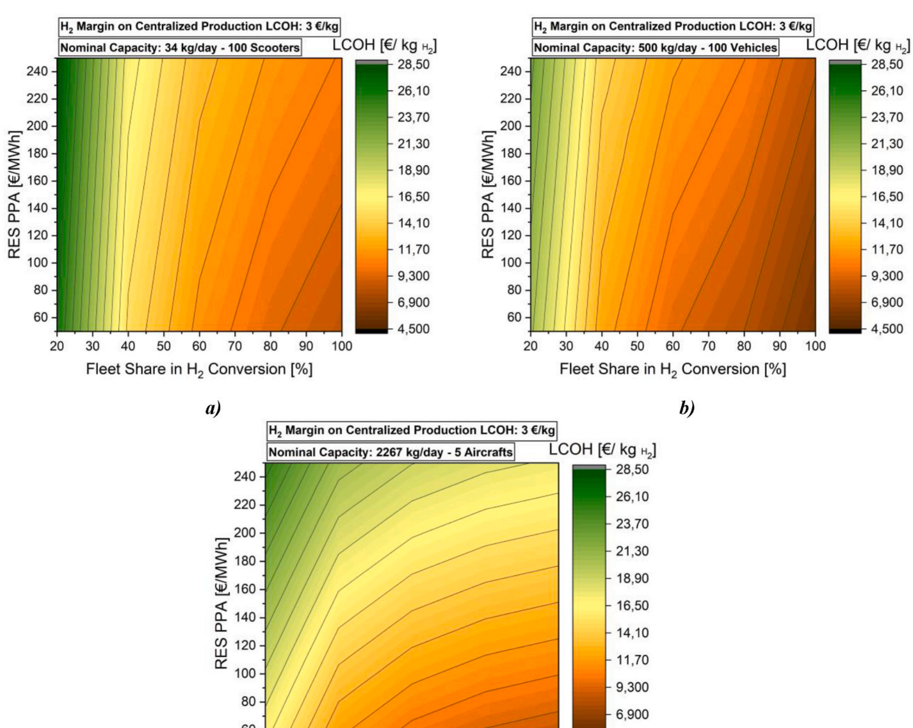


Fig. 13. LCOH levels for the Scooter HRS (a), Vehicle HRS (b), and Aircraft HRS (c).

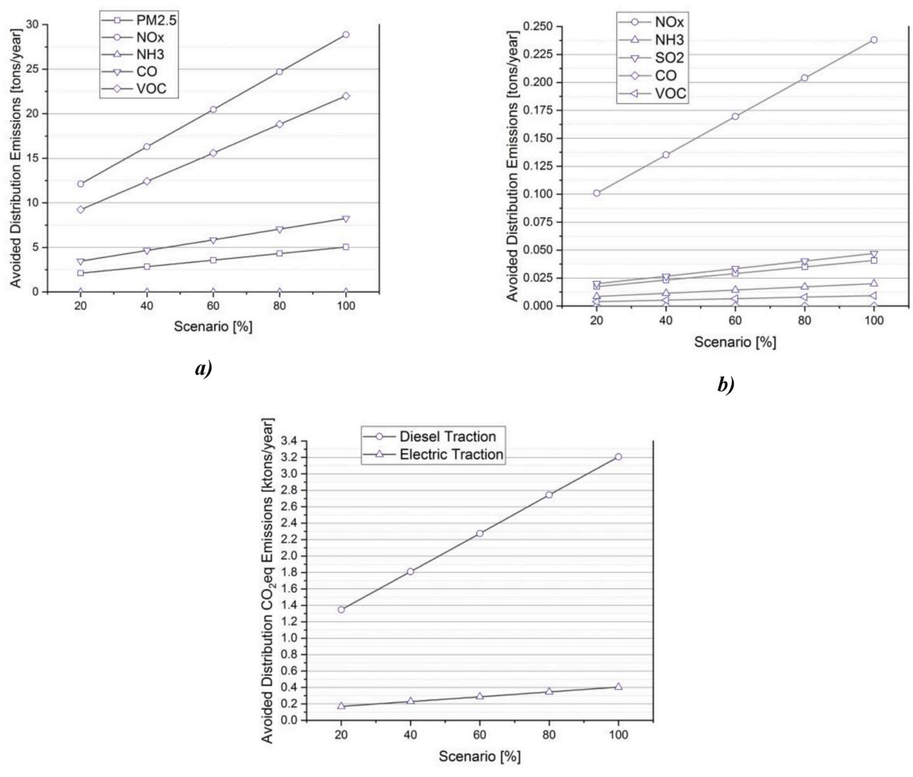
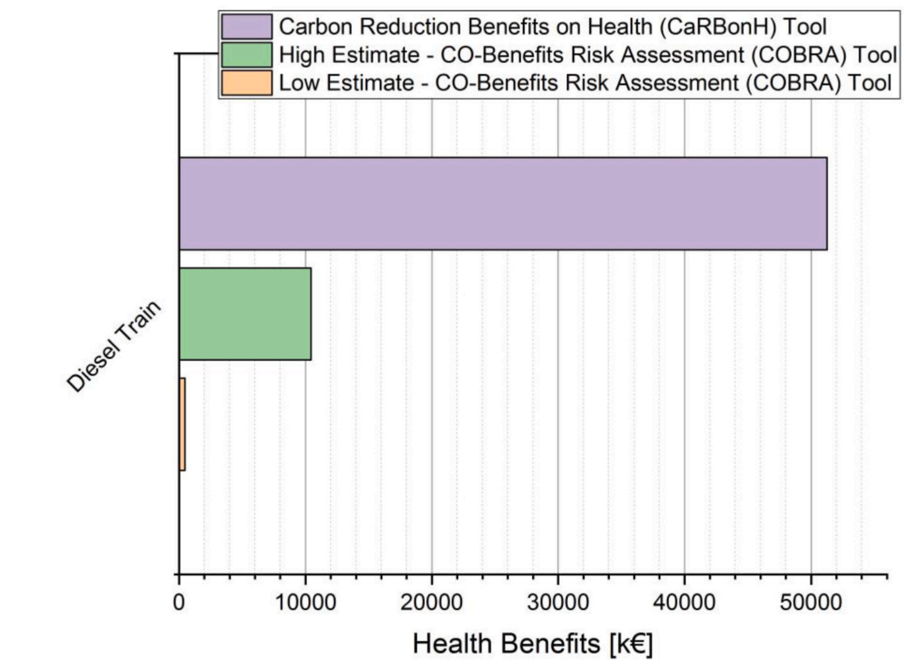


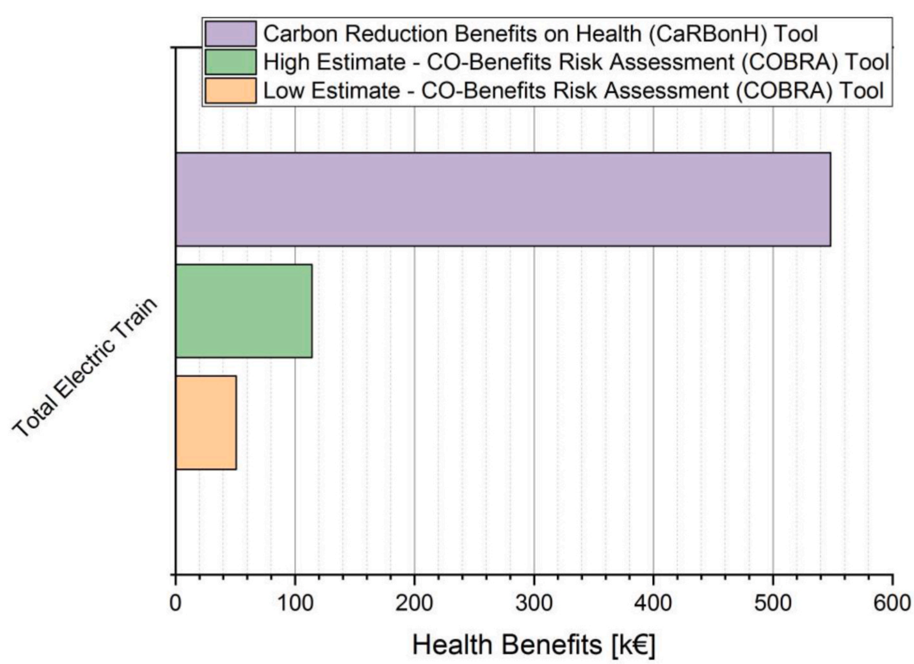
Fig. 14. Emission Reduction in Comparison to Hydrogen Transport via Diesel Train (a), Total Electric Train (b), and their related carbon dioxide equivalent emissions (c).

Focusing on the innovative concept of the hydrogen transport system by rail, which, to the authors' best knowledge, has never been extensively studied in the scientific literature, a comparative study of hydrogen transport via diesel trains and total electric trains has been performed, in terms of emission reductions. As presented in Fig. 14a, diesel trains show remarkable emissions, especially in terms of NO_x, with a maximum value of about 29 tons per year. In comparison, total electric trains, shown in Fig. 14b, have lower emissions but are still higher than FCHTs powered by green hydrogen, with a maximum emission of 0.385 tons of NO_x per year. Fig. 14c displays the overall comparison, in terms of carbon dioxide equivalent emissions: 3.2 ktons/year vs 0.4 ktons/year respectively emitted by diesel trains and total electric trains.

As described in Section 2.5, Fig. 15 shows the health benefit estimate of hydrogen transport via FCHTs compared to diesel trains (Fig. 15a) and total electric trains (Fig. 15b). The health benefits were accumulated for the life of the system, 15 years, and each year has an effect that is calculated in the next 20 years. For diesel trains, the health benefits



a)



b)

Fig. 15. Health benefits, in comparison to diesel trains (a) and electric trains (b).

ranged from 4.6 to 10 million euros, calculated with the tool COBRA, and the total health benefits were 51 million euros when equivalent CO_2 emissions were included, calculated with the tool CaRBonH. In comparison, FCHTs enable health benefits of 0.05–0.114 million euros compared to total electric trains, excluding equivalent CO_2 emissions, and 0.548 million euros when they are included.

6. Conclusions

As multimodal local transportation services are often required in Calabria, Southern Italy, near the Mediterranean Sea, a 3 E (energy, economic, and environmental) analysis of a virtual hydrogen valley has been proposed in this research. With the valley concept, hydrogen is produced centrally and distributed to different locations, each one with a specific mobility hub.

- FCEVs, with a refueling infrastructure at 700 bar;
- FCFs, with a refueling infrastructure at 350 bar;
- FCBs, with a refueling point at 30 bar via a pressure double-stage reduction system;
- FCEBs, with a refueling infrastructure at 350 bar;
- FCEFs, with a refueling infrastructure at 250 bar;
- FCESs, with a refueling infrastructure at 350 bar;
- FCEAs, with an on-site liquefaction system and a refueling infrastructure at 20 K.

The daily consumption of the infrastructure reaches 213 MW h/day, in the nominal scenario, useful for producing almost 4 ton/day. The economic parameters reach satisfying results: minimum values of about 5.4 €/kg of LCOH, with a PPA price of 50 €/MWh, and of approximately 10 €/km of TCO, with RES PPA price under 160 €/MWh, are achieved. Concerning the environmental aspects, the use of fuel cell trains for hydrogen transport enables health benefits of 0.548 million euros compared to total electric trains (including equivalent CO_2 emissions).

To the best of the authors' knowledge, no comprehensive study of the groundbreaking idea of a hydrogen transport system by rail exists in the scientific literature, and this article provided such an analysis, including energy, economic, and environmental aspects.

The performance of mobility technologies based on the hydrogen energy carrier, such as the management of small fleets of hydrogen fuel cell vehicles and hydrogen distribution, were analyzed by virtually simulating a hydrogen cluster, and economic analysis of hydrogen distribution and refueling infrastructures as an energy vector that benefits a variety of mobility uses was performed. Specifically, an examination of how the leveling cost of hydrogen fluctuates with changes in fleet size and the price of renewable energy acquired via power purchase agreements (PPAs) was presented.

The hydrogen valley showed competitive performance, both in economic and environmental terms, as well as in terms of efficiency and energy consumption, encouraging the idea of a "Hydrogen Valley" to highlight the potential of hydrogen use in the environmental transition process and to pique interest in mobility-related activities. The supplied methodology and preliminary results could be adopted by enterprises and government agencies that need expert expertise in hydrogen facility design, building, distribution, and environmental performance.

Authors contribution

All the authors equally contribute to the research activity, numerical simulations, and manuscript preparation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

APPENDIX A

Table A1
Centralized Facility Main Findings and Performance

Centralized Production	3965.44	kg/day
Days of Operation	320.00	day/year
PEM Electrolyzer		
Hours of operation	24.00	hours
Specific Energy Consumption	52.00	kWh/kg
Size	8.59	MW
Energy Efficiency	64.10	%
Storage Compressor		
Mass Flow	165.23	kg/hr
Suction Pressure	10.00	bar
Delivery Pressure	200.00	bar
Polytropic Index	1.61	–
Inlet Temperature	353.15	K
Specific Energy Consumption	3867.83	kJ/kg
Compressor Efficiency	80	%
Specific Energy Consumption	1.07	kWh/kg
Power	177.52	kW
Compressor Interstage Cooling	0.63	kWh/kg
Energy Consumption	6770.36	kWh
Refueling Compressor		
Mass Flow	108.00	kg/hr
Suction Pressure	50.00	bar
Delivery Pressure	350.00	bar
Polytropic Index	1.61	–
Inlet Temperature	353.15	K
Specific Energy Consumption	1997.81	kJ/kg
Compressor Efficiency	80	%
Specific Energy Consumption	0.55	kWh/kg

(*continued on next page*)

Table A1 (*continued*)

Centralized Production	3965.44	kg/day
Power	59.93	kW
Compressor Interstage Cooling	0.44	kWh/kg
Energy Consumption	246.20	kWh

Table A2
Forklift HRS Main Findings and Performance

Forklift HRS	90.00	kg/day
Refueling Compressor		
Mass Flow	108	kg/hr
Suction Pressure	50	bar
Delivery Pressure	350	bar
Polytropic Index	1.609	–
Inlet Temperature	298	K
Specific Energy Consumption	1685.82	kJ/kg
Compressor Efficiency	80	%
Specific Energy Consumption	0.468	kWh/kg
Power	50.57	kW
Compressor Interstage Cooling	0.439	kWh/kg
Energy Consumption	81.738	kWh

Table A3
Ferry HRS Main Findings and Performance

Ferry HRS	293.74	kg/day
Refueling Compressor		
Mass Flow	108.00	kg/hr
Suction Pressure	50.00	bar
Delivery Pressure	250.00	bar
Polytropic Index	1.61	–
Inlet Temperature	298.00	K
Specific Energy Consumption	1299.06	kJ/kg
Compressor Efficiency	80	%
Specific Energy Consumption	0.36	kWh/kg
Power	38.97	kW
Compressor Interstage Cooling	0.34	kWh/kg
Energy Consumption	205.14	kWh

Table A4
Scooter HRS Main Findings and Performance

Scooter HRS	33.93	kg/day
Refueling Compressor		
Mass Flow	30.00	kg/hr
Suction Pressure	50.00	bar
Delivery Pressure	350.00	bar
Polytropic Index	1.61	–
Inlet Temperature	298.00	K
Specific Energy Consumption	1685.82	kJ/kg
Compressor Efficiency	80	%
Specific Energy Consumption	0.47	kWh/kg
Power	14.05	kW
Compressor Interstage Cooling	0.44	kWh/kg
Energy Consumption	30.81	kWh

Table A5
Bus HRS Main Findings and Performance

Bus HRS	168.56	kg/day
Refueling Compressor		
Mass Flow	216.00	kg/hr
Suction Pressure	50.00	bar
Delivery Pressure	350.00	bar
Polytropic Index	1.61	–
Inlet Temperature	298.00	K
Specific Energy Consumption	1685.82	kJ/kg
Compressor Efficiency	80	%
Specific Energy Consumption	0.47	kWh/kg
Power	101.15	kW
Compressor Interstage Cooling	0.44	kWh/kg
Energy Consumption	153.07	kWh

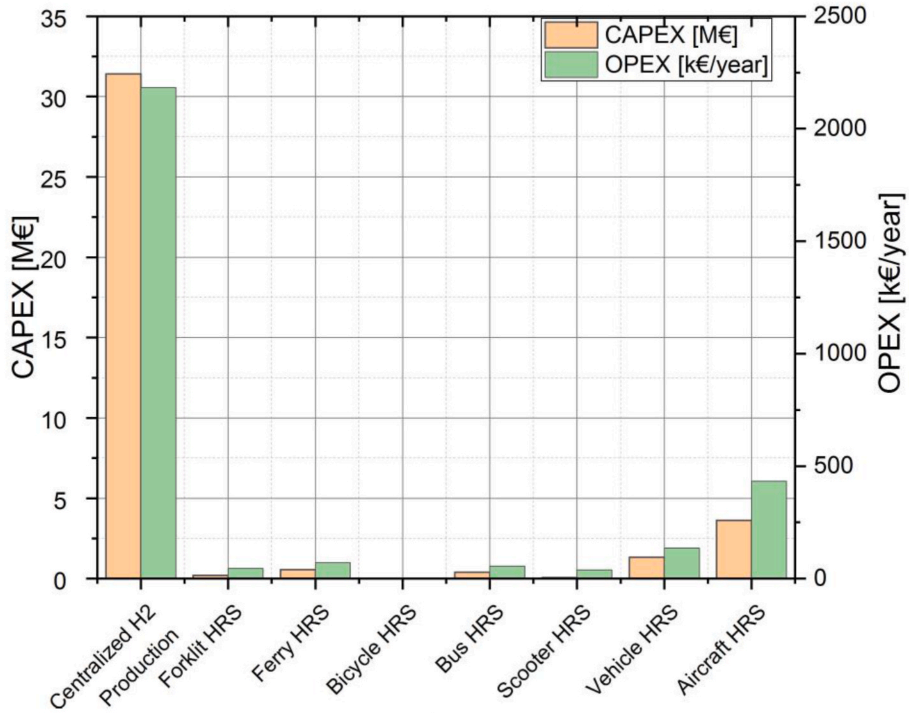
Table A6
Vehicle HRS Main Findings and Performance

Vehicle HRS	500.00	kg/day
Refueling Compressor		
Mass Flow	108.00	kg/hr
Suction Pressure	50.00	bar
Delivery Pressure	700.00	bar
Polytropic Index	1.61	–
Inlet Temperature	298.00	K
Specific Energy Consumption	2656.08	kJ/kg
Compressor Efficiency	80	%
Specific Energy Consumption	0.74	kWh/kg
Power	79.68	kW
Compressor Interstage Cooling	0.57	kWh/kg
Energy Consumption	654.60	kWh
H_2 Chiller		
Mass Flow	108.00	kg/hr
Specific Energy Consumption	1.40	kWh/kg
Energy Consumption	700.00	kWh
Cooling Load	40.22	kW

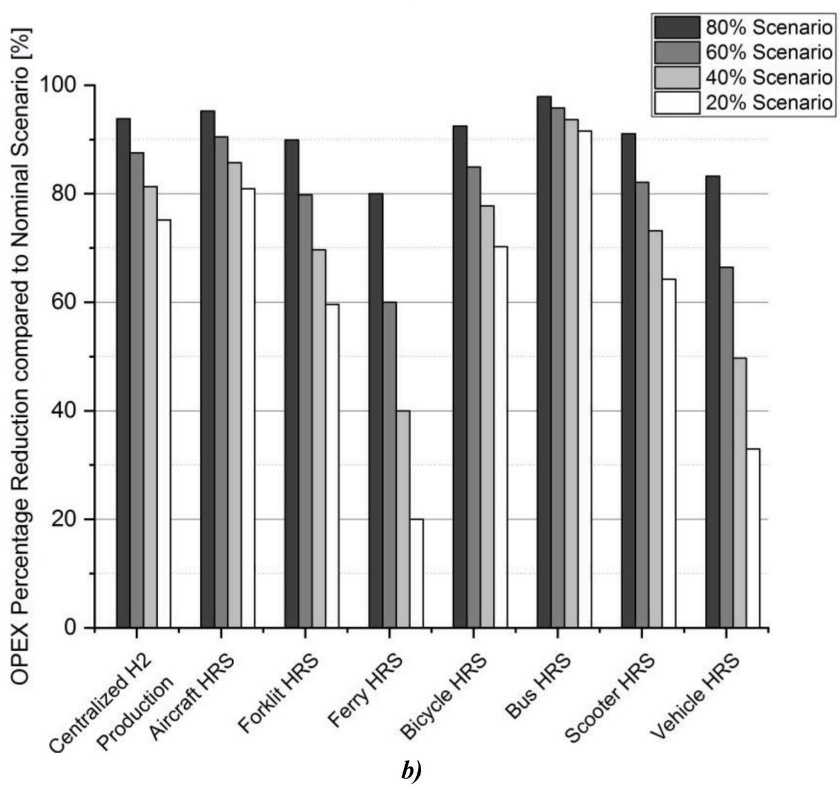
Table A7
Aircraft HRS Main Findings and Performance.

Aircraft HRS	2266.67	kg/day
Liquefaction System		
Mass Flow	94.44	kg/hr
Specific Energy Consumption	12.00	kWh/kg
Power	1133.33	kW
Energy Consumption	27200.00	kWh
H_2 Refueling		
Mass Flow	94.44	kg/hr
Specific Energy Consumption	0.50	kWh/kg
Energy Consumption	1133.33	kWh
Power	47.22	kW

Appendix B



a)



b)

Fig. B1. CAPEX and OPEX for the several facilities (a), and OPEX reduction as a function of the fleet size (b).

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