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Novel short-term national strategies to promote the use of renewable hydrogen in road transport: A life cycle assessment of passenger car fleets partially fuelled with hydrogen

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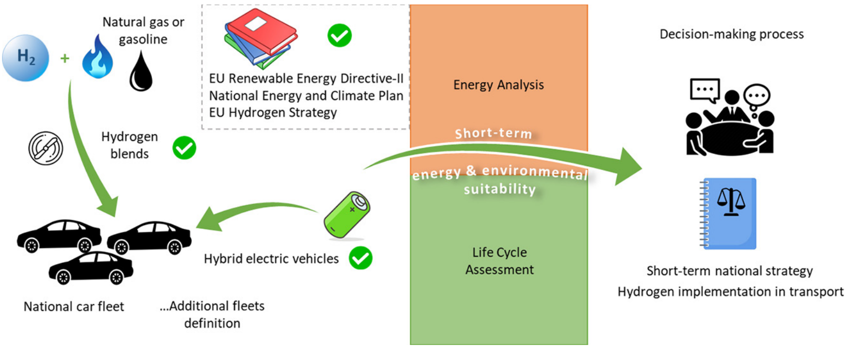
HIGHLIGHTS

- Novel car fleet strategies under limited green hydrogen availability are defined.
- 8 fleets partly fuelled with hydrogen are designed according to national targets for 2025.
- Fleets' energy and environmental suitability is assessed through Life Cycle Assessment.
- Fleet strategies involving hydrogen blends and hybrid electric vehicles are preferable.
- Implementation of blends could facilitate hydrogen penetration in road transport.

GRAPHICAL ABSTRACT



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ABSTRACT

This work presents an energy analysis combined with a comparative environmental life cycle assessment (LCA) of eight different passenger car fleets that use renewable hydrogen and a conventional fuel (natural gas or gasoline) under the same total energy input and the same hydrogen-to-mixture energy ratio. The fleets under comparison involve vehicles that use the two fuels separately or in a mixture. Using Italy as an illustrative country, this research work aims to help policy-makers implement well-supported strategies to promote the use of hydrogen in road transport in the short term. The proposed strategies achieve a carbon footprint reduction between 7 % and 35 % with respect to their conventional fleet benchmark. Within the current context, the results suggest the energy and environmental suitability of using hydrogen blends as short-term solutions, involving vehicles that require minor modifications with respect to current compressed natural gas vehicles and gasoline vehicles, while paving the way for pure hydrogen mobility.

1. Introduction

1.1. Contextualisation of the study

Awareness of responsibility for anthropogenic climate change has grown worldwide, and environmental issues are gaining centrality in the public debate. Policy and scientific actors worldwide recognise, with ever greater strength, the urgency for actions to avoid a climate catastrophe in

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Abbreviations: LCA, Life Cycle Assessment; NECP, National Energy and Climate Plan.

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the years to come. In 2015, near 200 countries negotiated the Paris agreement, the first universal and legally binding covenant on the global climate, aiming to limit global warming to well below +2 °C compared to the pre-industrial era (UNFCCC, 2015). Furthermore, the Intergovernmental Panel on Climate Change (IPCC, 2018) underlines the urgency to act drastically by 2030 to limit global warming below +1.5 °C. The Glasgow Climate Pact, which came out of the 26th United Nations Climate Change conference (UNFCCC, 2021), confirms the need to pursue efforts to maintain global warming below the 1.5 °C increase. In this context, Europe has set a carbon-neutrality target by 2050 (European Commission, 2019), with more and more ambitious intermediate goals for 2030, in a process of constant upward revision.

The main cause of these environmental issues lies in the massive use of fossil fuels for energy purposes. In 2018, the world primary energy demand amounted to 14,282 million tonnes of oil equivalent (Mtoe), of which 81 % was met by fossil fuels (IEA, 2020). The transport sector is particularly energy demanding and relies almost entirely on fossil fuels, thus releasing a considerable amount of greenhouse gas (GHG) emissions. In Europe, the transport sector represents above 30 % of energy consumption in final uses (287 Mtoe in 2018) (Eurostat, 2020) and is annually responsible for >1 Gt of equivalent CO_2 (CO_2 eq), corresponding to around 25 % of the total European GHG emissions (EEA, 2018a, 2019). Road transport, for both freight and passengers, is by far the dominant transport mode, constituting >70 % of the sectoral energy consumption and emissions (EEA, 2018a, 2018b, 2019; Eurostat, 2020). The greatest energy consumption is associated with passenger transport, in which the predominant vehicle category is constituted by light-duty vehicles and passenger cars (EIA, 2019), which in Europe make up 83 % of inland passenger transport (Eurostat, 2020).

Hence, the implementation of decarbonisation solutions for passenger cars is pivotal. In this sense, hydrogen arises as a promising solution (Bicer and Dincer, 2018; IEA, 2019) since its use phase does not involve direct carbon emissions; nevertheless, in compliance with environmental criteria, its production should rely on renewable sources (Dincer, 2012). In recent years, the European Union (EU) has paved the way to the energy transition (i) with the new renewable energy directive 2018/2001 (RED-II) (European Union, 2018), (ii) by requiring that member states draw up national energy and climate plans (NECPs) to meet EU targets by 2030 (European Commission, 2018), and (iii) by assigning a strategic role to hydrogen produced from renewables. The latter is evinced by the European strategy for hydrogen (European Commission, 2020) and the development of various hydrogen national strategies (BMWi, 2020; MiSE, 2020; MITERD, 2020), some of which are still under definition.

The RED-II and NECPs define, for the different countries, the target trajectories and the share of renewable energy to be achieved in the various energy uses, including transport. Many European countries such as Italy plan to fill a relatively small part of this renewable quota through the introduction of renewable hydrogen in transport, mainly by introducing fuel cell electric vehicles (FCEV) in their fleets (MiSE, 2019, 2020; MITERD, 2020). Although this represents a starting point for the development of a hydrogen economy relevant to the transport sector, a large-scale deployment of FCEVs seems to be still a long way off. Core barriers involve (i) the need to start massive production of renewable hydrogen from scratch and, therefore, a limited green hydrogen availability in the short term; (ii) the lack of a hydrogen distribution grid/infrastructure and, in particular, refuelling points; and (iii) current limitations of a technical, economic or social nature at the vehicle level. Therefore, innovative strategies that circumvent these barriers while favouring the use of hydrogen in the short term should be explored.

1.2. Motivation and novelty

On a national scale, in the short term, passenger car fleets would be fuelled only partially with hydrogen, as only relatively small amounts of renewable hydrogen would be available. On the other hand, it should be noted that the use of hydrogen in pure form is not the only option and several studies have shown the possibility to inject it into the natural gas (NG) network to a certain extent (Altfeld and Pinchbeck, 2013; European Commission, 2009; IEA, 2019; Kippers et al., 2011) or use it in mixture, for vehicular applications, with other fuels such as NG (Çeper, 2012; Genovese et al., 2011; Yan et al., 2017), gasoline (Akif Ceviz et al., 2012; Niu et al., 2016; Yu et al., 2017) or diesel (Vavra et al., 2019). It is therefore conceivable to propose different options of passenger car fleets that use both hydrogen and traditional fuels in diverse ways. However, to ensure an effective action, it is necessary to assess and compare the alternatives in terms of their energy and environmental performance. In order to conduct a comprehensive and sound comparison of the performance of different fleets involving hydrogen, a life-cycle approach is required. For this purpose, Life Cycle Assessment (LCA) is a consolidated methodology, as it allows analysts to compare different systems performing the same function and identify environmental hotspots (ISO, 2006a, 2006b).

In the automotive sector, well-to-wheels (WTW) analyses are most frequently conducted, including their subsets known as well-to-tank (WTT) and tank-to-wheels (TTW) depending on the definition of the system boundaries (Orsi et al., 2016; Torchio and Santarelli, 2010; Yazdanie et al., 2014). However, WTW analyses typically consider only some (fuel-related) life-cycle stages (i.e., fuel production, distribution up to the vehicle tank, and fuel use), while a vehicle LCA typically considers the WTW stages as well as the manufacturing, maintenance and end-of-life stages of the vehicle itself, thereby extending the system's boundaries (JEC, 2014; Ricardo E&E, 2020).

In a previous study, Candelaresi et al. (2021a) investigated the life-cycle environmental performance of different passenger car options fuelled with pure hydrogen or hydrogen blends (H_2-NG and H_2-gasoline), taking into account the life-cycle stages of vehicle production and maintenance in addition to the fuel-related ones. Renewable hydrogen produced through wind power electrolysis (WPE) was considered in the study. This previous work showed that: (i) vehicles fuelled with pure hydrogen are excellent decarbonisation solutions; (ii) for pure renewable hydrogen vehicles, according to current technology levels, vehicle infrastructure is the main source of environmental burdens; and (iii) vehicles with internal combustion engine (ICE) that use hydrogen mixed with fossil fuels (gasoline and NG) present an improved life-cycle environmental performance compared to traditional vehicles, arising as suitable short-term options temporarily circumventing major hydrogen storage and distribution issues.

Considering this background and the limited availability of hydrogen on a national scale, this work aims to give insight into environmentally-preferred passenger car fleets partially fuelled with hydrogen. Ultimately, the goal of this study is to provide policy actors with well-supported information in order to accelerate the resource-efficient implementation of renewable hydrogen in road transport. The main novelty lies in the proposal of innovative national strategies to promote the use of hydrogen in road passenger transport in the short term. The suitability of the proposals is evaluated by performing a comparative LCA of passenger car fleets that use hydrogen and traditional fuels either separately (in different vehicles) or in a mixture (in the same vehicle). In order to enable a fair comparison, fleet alternatives are defined under the same energy input. In addition, within the framework of the study, life-cycle inventories for two new vehicle types not available in the literature (hybrid electric vehicles, HEV, that burn hydrogen blends in their ICE) are developed.

2. Material and methods

This study addresses the definition and identification of passenger car fleets partially fuelled with hydrogen that could be both energy and environmentally convenient in the short term, under the constraint of a limited fixed amount of hydrogen available on a national scale. While Italy was taken as a reference country for some assumptions (Section 2.2), the proposed methodological approach could be applied to a large number of countries in a similar situation. Likewise, while –in accordance with previous work (Candelaresi et al., 2021a)– hydrogen from WPE was considered in this study, the analysis could be extended to other renewable hydrogen options with low environmental impacts. Nine types of vehicles were considered, which in turn were combined in eight different fleets. Four fleets are fuelled by hydrogen and NG, whereas the remaining ones by hydrogen and gasoline, with an energy equivalent amount. The fleets under analysis can use the two fuels separately or as a mixture inside the same vehicle. Other options such as diesel internal combustion engine vehicles or battery electric vehicles are out of the scope of this study. Furthermore, this study should be understood within the expected context of coexistence of complementary solutions for sustainable mobility such as hydrogen vehicles and battery electric vehicles (Staffell et al., 2019; Valente et al., 2021).

2.1. Technical background

Regarding blends, the Italian transmission system operator Snam has already experimented with the injection of hydrogen into some sections of its NG grids at different volumetric percentages, demonstrating that it is possible to transport H_2 up to $10\%_{vol}$ blended with NG in the existing infrastructure (SNAM, 2020). In fact, other studies have demonstrated the technical feasibility of blending hydrogen in the NG grid in higher amounts (IEA, 2019; Melaina et al., 2013), with minor technical concerns when the hydrogen content is $<20\%_{vol}$ (European Commission, 2009; Kippers et al., 2011; Kouchachvili and Entchev, 2018).

Regarding final uses, the Italian companies Fiat and Iveco have already experimented with the use of H_2-NG mixtures in ICEs, demonstrating the possibility of using mixtures with $20\%_{vol}$ or even up to $30\%_{vol}$ of H_2 (Il Sole 24 Ore, 2012; IVECO, 2010a, 2010b; NGV Journal, 2011). Moreover, there are several studies in the scientific literature dealing with H_2-NG or H_2-gasoline mixtures, at different proportions, to fuel ICEs (Anstrom and Collier, 2016; Genovese and Villante, 2013; Pana et al., 2007; Shi et al., 2017). Generally, the results show that –after optimising the engine parameters– the addition of hydrogen improves the combustion characteristics, increasing engine efficiency and reducing fuel consumption and emissions (Luo et al., 2020).

Fig. 1 shows the vehicles considered in the present study for the definition of fleets. Detailed information of the single vehicles is given in previous studies (Candelaresi et al., 2021a; Valente et al., 2020). As regards pure hydrogen-fuelled solutions, only FCEVs were considered.

On the other hand, vehicles equipped with ICE powertrain include: compressed natural gas (CNG) vehicle, gasoline vehicle, hythane vehicle, and dual-fuel hydrogen-gasoline vehicle. Hythane® is a commercial name for a gaseous mixture of $20\%_{vol}$ H_2 and $80\%_{vol}$ NG; for a fair comparison, the hydrogen-gasoline mixture was considered with an energy ratio of the mixture equal to that of hythane (i.e., H_2 provides 7.3 % of the mixture energy). HEVs of the full-hybrid, series/parallel type were also considered. These comprehend HEVs fuelled with compressed natural gas (HEV CNG) or gasoline (HEV Gasoline). In addition, for the first time, two novel HEVs were considered in the present study: an HEV fuelled with hythane (HEV Hythane), and an HEV fuelled with a hydrogen-gasoline mixture (HEV H_2-Gasoline).

An average European passenger car with a rated vehicle power of 80 kW was considered as reference, taking into account the different powertrain technologies to model each of the different vehicle options. The reference car is a sedan type, 5-door, belonging to segment C (small family cars/compact cars). Further details on the bill of materials for car manufacturing and use can be found in Candelaresi et al. (2021a).

By using the above-mentioned vehicle options, the fleets subject to comparison were defined as follows: fleet F1 involving CNG vehicles and FCEVs; F2 involving Hythane; F3 with HEV CNG and FCEVs; F4 with HEV Hythane; F5 with Gasoline vehicles and FCEVs; F6 with H_2-Gasoline vehicles; F7 with HEV Gasoline and FCEVs; and F8 with HEV H_2-Gasoline. Hence, fleets from F1 to F4 are fuelled by NG and hydrogen, while fleets from F5 to F8 by gasoline and hydrogen. The number of vehicles in each fleet is not defined here because it derives from the energy analysis as an intermediate result (Section 3.1).

2.2. Energy analysis and national contextualisation

In order to maximise the penetration of hydrogen-related vehicles in national fleets, it is necessary to promote fleets that use the available fuels with high efficiency. The aim of this energy analysis is to explore, given a fixed amount of fuel, which fleets can travel higher distances. In countries with a high number of passenger cars, even the achievement of a small hydrogen penetration (e.g., 1 % of the national fleet) could be a challenging short-term target. For instance, Italy is the second country in the European Union with the largest number of passenger cars, 646 per thousand inhabitants (Eurostat, 2020); according to the Italian Automobile Club (ACI, 2021), there were 39,717,874 cars in circulation on the Italian roads in 2020. Some constraints were set to carry out the energy analysis, mainly regarding the quantity of the two fuels available in each fleet in a year, fuel consumption and annual driving performance of each vehicle. The driving performance, namely the average distance travelled by one vehicle in a year, was assumed to be 15,000 km.

For comparative purposes, each fleet was fed with the same amount of total energy input, supplied in the form of two fuels. In particular, the amount of hydrogen available was set the same for all fleets, while the remaining part of the energy is supplied with CNG or gasoline. The amount of available hydrogen was assumed on the basis of NECPs and national hydrogen strategies, while the analysis is scalable to different hydrogen amounts. The amount of fossil fuel was subsequently calculated by considering an energy share of H_2 and fossil fuel of 7.3 % and 92.7 % of the available energy, respectively. This is the energy share fixed by hythane, and it was assumed to be the same in every case in order to put all fleets under the same conditions.

Regarding the hydrogen amount, the RED-II and the Italian NECP set the objectives to be achieved for Italy as a share of renewable energy sources in the final gross energy consumption of transport (RES-T) at 22 % by 2030 and 14.4 % by 2025 (European Union, 2018; MiSE, 2019). However, as part of the “Fit for 55” package proposed in July 2021 by the European Commission (2021), the RED-II is undergoing a review process and these objectives could become more ambitious in the coming years. According to the NECP (MiSE, 2019), the preliminary guidelines for the Italian national hydrogen strategy (MiSE, 2020) and the more recent national recovery and resilience plan (NRRP) (Italian Council of Ministers, 2021), Italy plans to reach one percentage point of the RES-T target by 2030 through the use of green hydrogen. The NECP also suggests that a part of this hydrogen might be blended in the NG network or converted into renewable synthetic methane (0.8 percentage points of the RES-T target) while the remaining hydrogen might be used “as is” (i.e., in pure form) for direct use in cars, buses and trains (0.2 percentage points). As a 1 % hydrogen-related target is set for 2030, a 0.5 % short-term target was assumed for 2025.

According to the statistics of the Italian energy services operator (GSE), the national energy consumption in the transport sector amounted to 39,830 ktoe in 2019, with 83.2 % of this value coming from road transport (GSE, 2021). The energy consumption foreseen by the NECP and the GSE report for the Italian transport in 2025 is 28,851 ktoe, which corresponds to the denominator considered for the calculation of the targets according to the RED-II procedure. Taking into account the hydrogen-specific 0.5 % target for 2025 and the calculation procedure shown in Fig. 2, a hydrogen availability above 5 kt was estimated for Italian passenger cars in 2025. This is aligned with the national goals and the short-term perspective of the study, considering the need to start massive production of renewable hydrogen from scratch.

According to the previously defined energy ratio (7.3 %), the amounts of CNG (168 kt) or gasoline (183.8 kt) available for each fleet in 2025, as well as the total energy (8.65 PJ), were derived. This means that, in energy terms for the year 2025, each fleet uses 8.65 PJ of energy: 0.63 PJ of hydrogen and 8.02 PJ of fossil fuel (NG or gasoline).

Finally, operational parameters for each vehicle, namely fuel consumption and tailpipe emissions, were based on Candelaresi et al. (2021a), where data from manufacturer declarations and technical datasheets are used along with scientific literature and databases such as GREET and Ecoscore (Timmermans et al., 2006; Vrije Universiteit Brussel, 2006).

Table 1 presents fuel economy (i.e., the reciprocal of fuel consumption), energy consumption and tailpipe emissions for each of the nine vehicles

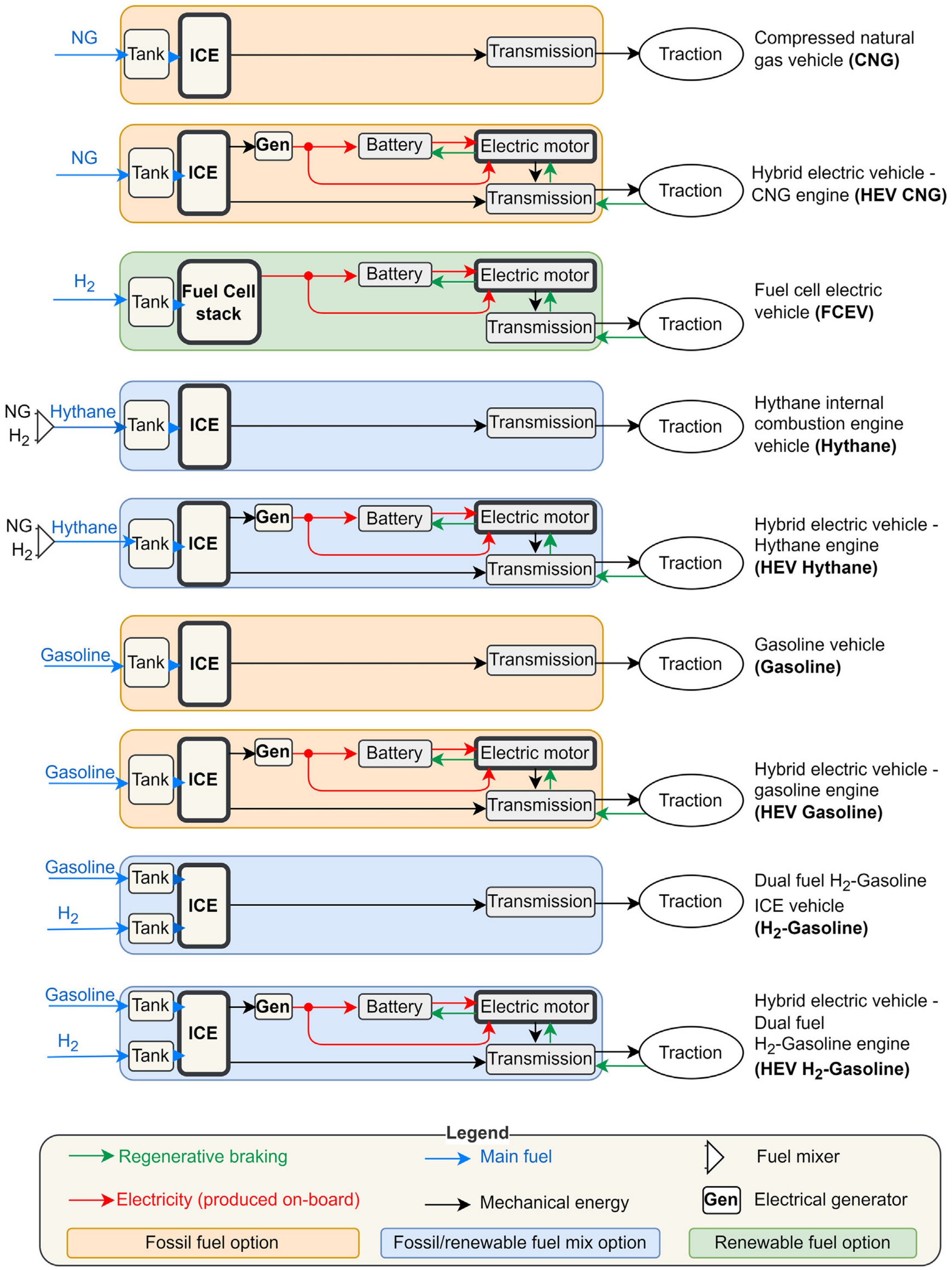


Fig. 1. Vehicle concepts involved in fleet composition.

involved in fleets composition. For the sake of completeness, water emissions were included (as they could be relevant for other purposes, including the implementation of future progress in characterisation factors for water emissions) even though they do not currently affect the LCA results of this study. Values for fuel consumption refer to NEDC (New European Driving Cycle) under a combined cycle (urban/extra-urban route). The main considerations behind the energy analysis of fleets are summarised in Fig. 3.

Altogether, Table 1 and Figs. 2 and 3 present the key assumptions made for the study at the level of both national hydrogen availability (Fig. 2) and technical features of vehicles (Table 1) and fleets (Fig. 3).

2.3. LCA framework

In order to investigate the environmental suitability of the fleets under comparison, the LCA methodology (ISO, 2006a, 2006b) was applied first to each vehicle system and then to each fleet (once vehicles were arranged into fleets by means of the energy analysis results). Fig. 4a shows the system boundaries considered for each vehicle, involving both the fuel life cycle and the vehicle one (Ricardo E&E, 2020). The former includes the (WTW) stages of production, distribution and use of the fuel, including one or two fuels depending on the type of vehicle (whether it uses a mixture or not).

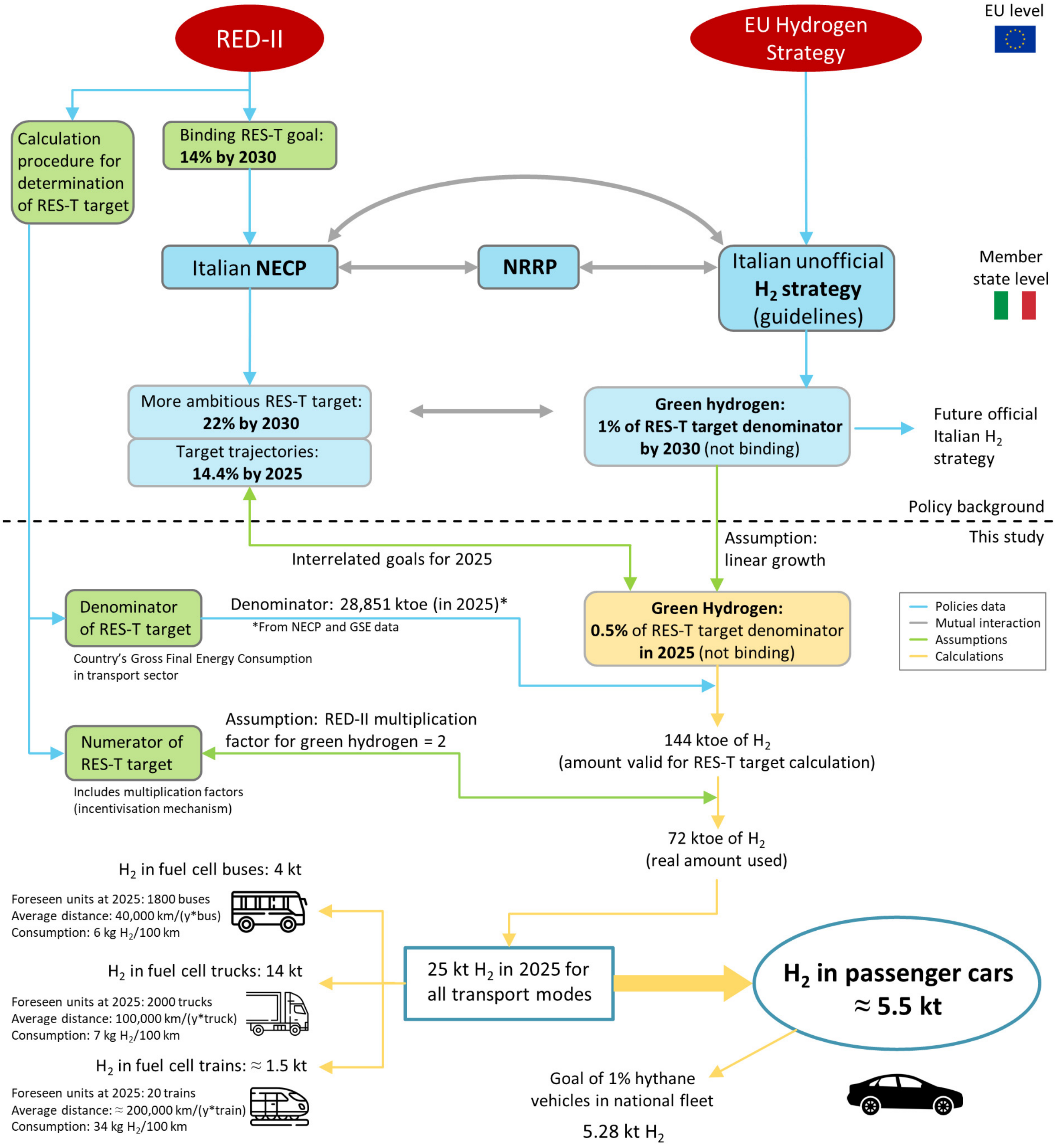


Fig. 2. Calculation procedure for the target use of hydrogen in Italian passenger cars in 2025.

Table 1
Fuel economy and tailpipe emissions for the vehicles involved in fleets composition based on (Candelaresi et al., 2021a).

Vehicle	Fuel economy [km/kg]	Energy consumption [a] [MJ/km]	CO_2 [g/km]	CO [mg/km]	HC [b] [mg/km]	NO_x [mg/km]	H_2O [c] [g/km]
FCEV	131.58	0.912	–	–	–	–	67.9
CNG	29.240	1.631	94	48.25	29.4	16.8	76.8
HEV CNG	44.303	1.077	66.888	32.33	20.1	4.9	50.7
Hythane	34.382	1.451	75.670	27.79	19.4	26.9	71.3
HEV Hythane	52.094	0.958	53.845	18.62	13.3	7.9	47.0
Gasoline	26.667	1.635	105.4	292.54	41.2	20.5	53.2
HEV Gasoline	40.404	1.079	75	196	28.2	6.0	35.1
H_2-Gasoline	31.352	1.459	87.146	102.27	25.8	33.7	52.0
HEV H_2-Gasoline	47.503	0.963	62.011	68.52	17.6	9.9	34.3

[a] Lower heating values of the fuels involved: 120 MJ/kg for hydrogen; 47.7 MJ/kg for CNG; 43.6 MJ/kg for gasoline; 49.9 MJ/kg for hythane; and 45.7 MJ/kg for H_2-Gasoline.
[b] HC: unburned hydrocarbons.
[c] Stoichiometric values; gasoline was considered as iso-octane.

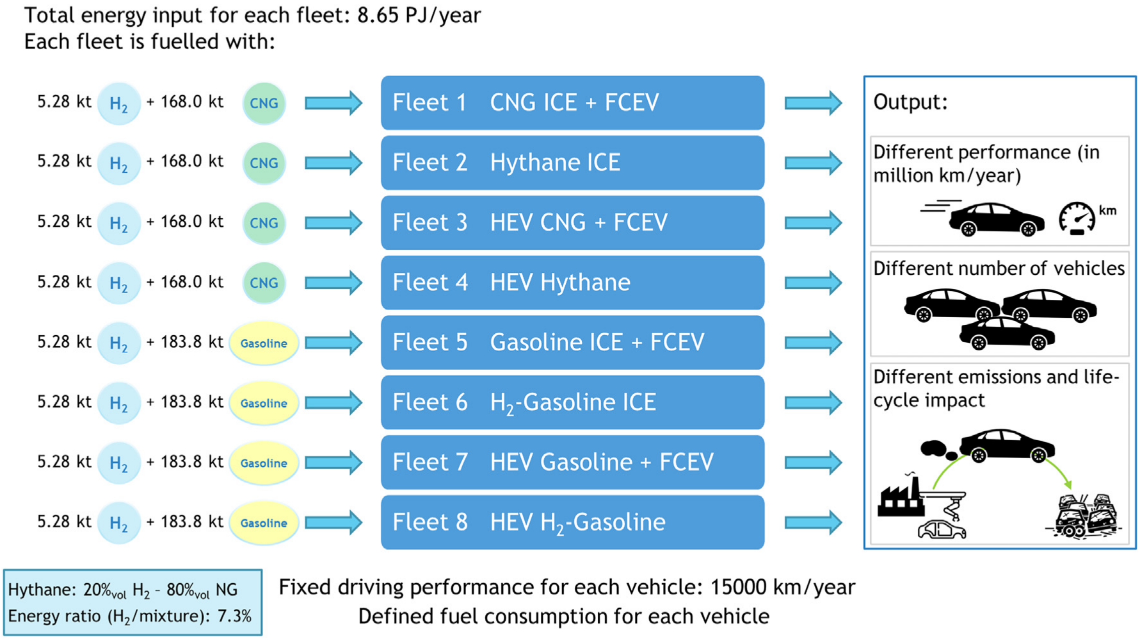


Fig. 3. Main assumptions for the energy analysis of fleets.

"Fuel 1" refers to CNG or gasoline, while "Fuel 2" stands for hydrogen. The vehicle life-cycle involves here the stages of vehicle manufacturing, operation and maintenance. Vehicle end-of-life was not included due to the acknowledged need for robust inventory data on this stage (Funazaki et al., 2003; Karagoz et al., 2020). The fuel and vehicle life cycles converge on the vehicle operation phase.

Fig. 4b instead shows the system boundaries applied for a fleet system. Fleets were formed using different vehicles (in number and/or type). Inside a fleet, vehicles were homogeneously grouped by technology. In this regard, "Vehicle A" always refers to a type of vehicle that uses fossil fuel, pure or mixed with hydrogen, while "Vehicle B" (when present) always refers to FCEVs. The functional unit (FU) of the study was defined as 1 km travelled by each fleet.

The life-cycle environmental performance of each system was characterised in terms of global warming impact potential (GWP), acidification impact potential (AP) and cumulative non-renewable energy demand (CED) using the methods IPCC (2013), CML (Guinée et al., 2001) and VDI (2012), respectively. The selection of these indicators was based on their specific relevance to hydrogen energy systems (Valente et al., 2017a).

2.4. Data acquisition

Concerning fuels, harmonised life-cycle indicators based on previous studies were used for hydrogen produced via WPE: carbon, acidification and non-renewable energy footprints (Valente et al., 2017b, 2018, 2019) were adapted to the hydrogen pressure of 700 bar to comply with FCEV and H_2-Gasoline vehicle specifications (Candelaresi et al., 2021a; Valente et al., 2020). Hydrogen distribution from the production site to the refuelling point (100 km) by a tanker truck was considered (Sergeant et al., 2009). Regarding CNG and gasoline production and distribution, background data from the ecoinvent database (Frischknecht et al., 2007) were used. Regarding hythane, it was assumed that hydrogen is injected into the NG grid (blending) and distributed (100 km) via pipeline to the refuelling point (Candelaresi et al., 2021a; Sergeant et al., 2009).

For most of the vehicle types involved in fleets composition, inventory data for their manufacturing were directly retrieved from previous studies (Candelaresi et al., 2021a; Valente et al., 2020). On the other hand, those vehicles not previously considered are presented in Table 2. In particular, the inventories for the HEV Hythane and HEV H_2-Gasoline options constitute a novelty of this work. The technical feasibility of these options was not deemed a problem as they represent a combination of well-known technologies: internal combustion engines with soft modifications to run with hydrogen blends and common hybridisation by integration of an electrical propulsion system. However, the willingness to invest in these two innovative vehicle technologies to put them on the market will depend mainly on car manufacturers and policies.

In addition, for the sake of completeness and traceability, the inventories for the Gasoline and HEV Gasoline options are also presented. The procedure and sources for the collection of the main inventory data for the stages of production, operation and maintenance of individual vehicles have been extensively covered in Candelaresi et al. (2021a) and are based on well-established life cycle databases such as ecoinvent (Frischknecht et al., 2007) and GREET (Wang et al., 2007), industry specifications, manufacturer statements, reports, and scientific literature.

For the options Gasoline and HEV Gasoline, data from technical datasheets released by manufacturers, as well as from literature and databases, were retrieved. On the other hand, for commercially unavailable vehicles (HEV Hythane and HEV H_2-Gasoline), data collection was based on specific literature combined with technical specifications regarding current HEVs. In particular, the ICE versions of Hythane and H_2-Gasoline vehicles from Candelaresi et al. (2021a) were adapted to HEVs through the different sizing of the thermal and electrical subsystems that make up the vehicle powertrain. The overall rated power considered for individual HEVs is 80 kW (the same as all the other vehicles), which –for the degree of hybridisation and the assumptions made in Candelaresi et al. (2021a)– is obtained through a 58.4 kW ICE and a 48.6 kW electric motor. In addition, HEVs present a 1.8 kWh Li-ion battery and a power control unit for smart management of electrical flows. HEVs and ICE vehicles were considered to involve the same glider, therefore the main differences in vehicle manufacturing are linked to powertrain configurations (additional components such as tanks, batteries, power control unit, etc.).

The HEV Hythane option is equipped with a 100-l CNG-II tank (metal liner hoop-wrapped with glass fibre and epoxy resin), in which about 15 kg of hythane can be stored at 200 bar. It also involves a gaseous fuel distribution system and an exhaust gas system in which the amounts of platinum group metals (PGMs) in the catalytic converter are adjusted according to the emission characteristics of the vehicle.

Regarding the HEV H_2-Gasoline option, the differences in components (compared to HEV Gasoline) are closely linked to the presence of hydrogen. Being a dual-fuel vehicle, two separate tanks and fuel distribution systems

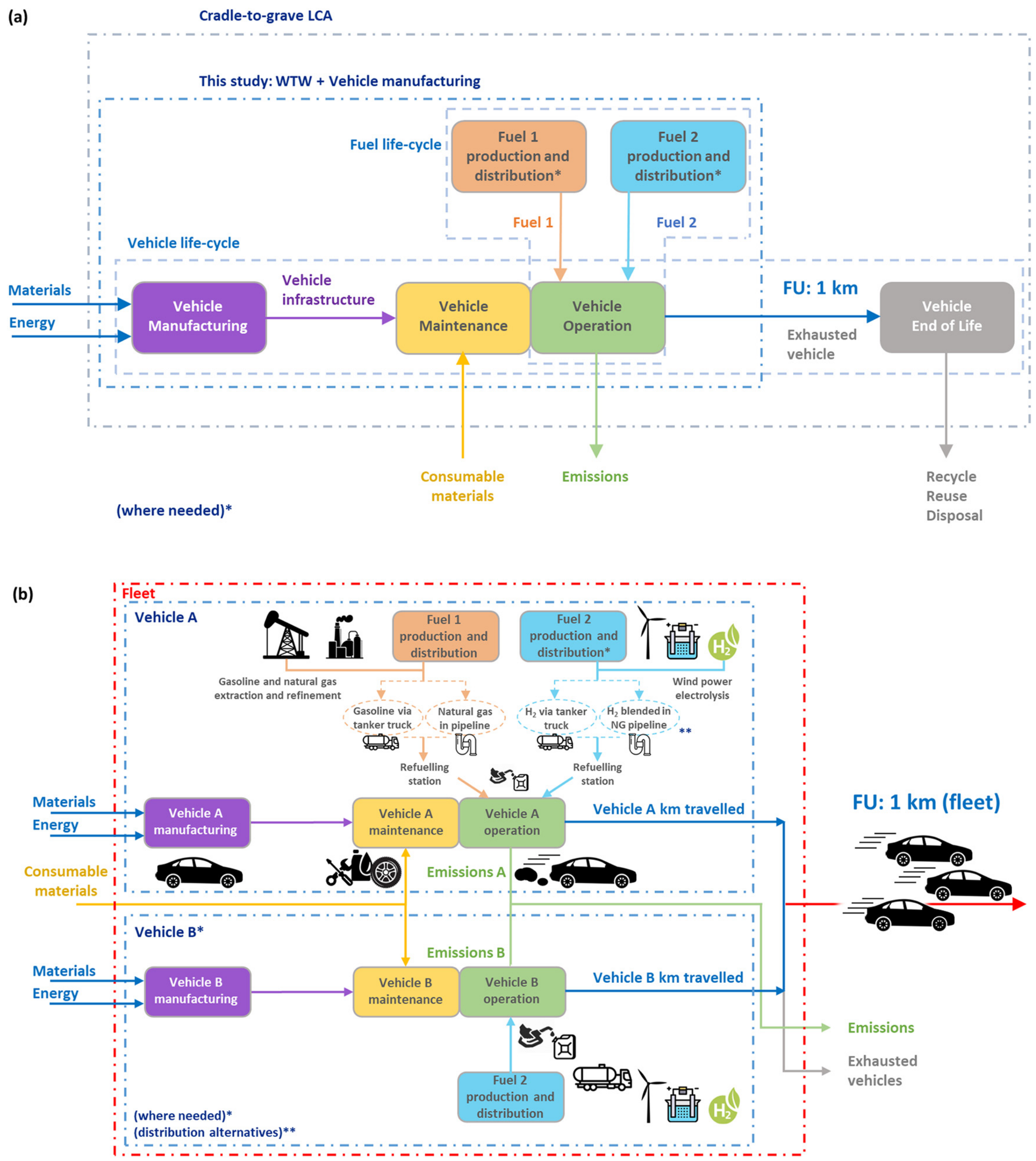


Fig. 4. System boundaries: (a) single vehicle, and (b) fleet.

are present on-board for each fuel: gasoline is stored in a common plastic tank paired with a traditional fuel distribution system, while pure hydrogen is stored in a composite cylinder at 700 bar (type-IV tank). The 25-l hydrogen tank (18.6 kg) can store about 1 kg H_2. The small amount of hydrogen required by the vehicle mitigates hydrogen storage issues. Dedicated hydrogen supply (refuel filler neck, valves, special pipes) and distribution (pressure reducer, systems to prevent backfire, manifold/rail, gaskets, etc.) systems are also present, besides minor ICE modifications such as hydrogen injectors (in addition to gasoline injectors) and reinforced valve seats. Due to combustion improvements with respect to conventional gasoline vehicles, a lower load of PGMs was considered in the catalytic converter. Further details on the inventories of individual subsystems and components can be found in Candelaresi et al. (2021a) and Valente et al. (2020).

Operational parameters regarding fuel consumption and tailpipe emissions are those presented in Table 1. The values for the new vehicle concepts (HEV Hythane and HEV H_2-Gasoline) were based on the H_2-blend vehicles in Candelaresi et al. (2021a), adapted to vehicle hybridisation. These, in turn, were based on specific literature about experimental tests and measures on ICEs according to the hydrogen percentage under examination for both NG (Genovese et al., 2011; Yan et al., 2017) and gasoline (Akif Ceviz et al., 2012; Conte and Boulouchos, 2008; Du et al., 2016, 2017; Shi et al., 2017) blends. The values considered for these two vehicle options correspond to a conservative approach and therefore present room for improvement through engine optimisation.

Values from Table 1 were used to derive the amounts of fuel consumption and tailpipe emissions throughout the entire vehicle life. Inventory data for vehicle operation and maintenance are presented in Table 3.

The wear of tyres, brakes and road due to abrasion phenomena was taken into consideration, as it leads to emissions of particulate matter during the vehicle useful life. These emissions were calculated proportionally to each vehicle weight.

The life-cycle models presented in Tables 2 and 3 were implemented in SimaPro 9.4 using the ecoinvent database as the data source for background processes. The environmental characterisation was carried out by taking into account the selected life-cycle indicators and impact assessment methods. The combination of the LCA results for the individual vehicles

Table 2
Main inventory data for vehicle production (values per one vehicle).

Item	Unit	HEV Hythane	HEV H_2-Gasoline	Gasoline	HEV Gasoline
Vehicle rated power	kW	80	80	80	80
Vehicle kerb weight	kg	1480	1425	1250	1400
Body and chassis	p	1	1	1	1
Fluids	p	1	1	1	1
ICE	kW	58.4	58.4	80	58.4
└Steel, low-alloyed	kg	36.80	37.86	50.41	36.80
└Aluminium	kg	30.22	31.28	41.40	30.22
└Polyphenylene sulphide	kg	18.02	20.14	24.68	18.02
└Lubricating oil	kg	6.37	6.37	8.73	6.37
Fuel system	p	1	1	1	1
└Copper	kg	3.94	3.94	–	–
└Polyvinylchloride	kg	0.92	0.92	–	–
└Reinforcing steel	kg	–	1.45	1.45	1.45
Gasoline tank	p	–	1	1	1
└High-density polyethylene, HDPE	kg	–	17.5	17.5	17.5
└Injection moulding	kg	–	17.5	17.5	17.5
Tank CNG-II	kg	80	–	–	–
└Steel, low-alloyed	kg	70	–	–	–
└Epoxy resin, liquid	kg	6	–	–	–
└Glass fibre	kg	4	–	–	–
Hydrogen tank (CNG-IV)	kg	–	18.60	–	–
└Aluminium	kg	–	1.42	–	–
└Carbon fibre	kg	–	3.96	–	–
└Epoxy resin, liquid	kg	–	5.93	–	–
└Glass fibre	kg	–	1.12	–	–
└High-density polyethylene, HDPE	kg	–	2.05	–	–
└Polyurethane, flexible foam	kg	–	0.93	–	–
└Steel, low-alloyed	kg	–	2.13	–	–
└Electricity	MJ	–	2.57	–	–
Exhaust system	p	1	1	1	1
└Reinforcing steel	kg	34.9	34.9	34.9	34.9
└Synthetic rubber	kg	1.45	1.45	1.45	1.45
└Talc	kg	1.4	1.4	1.4	1.4
└Steel, low-alloyed	kg	25.2	25.2	25.2	25.2
└Platinum	g	1.4	1.12	1.6	1.6
└Palladium	g	0.7	0.42	0.6	0.6
└Rhodium	g	0.64	0.48	0.3	0.3
└Cerium concentrate	kg	0.04	0.04	0.04	0.04
└Zirconium oxide	kg	0.14	0.14	0.14	0.14
└Aluminium oxide	kg	0.02	0.02	0.02	0.02
└Polyphenylene sulphide	kg	0.1	0.1	0.1	0.1
Li-ion battery	kWh	1.8	1.8	–	1.8
Electric motor	kW	48.6	48.6	–	48.6
Power control unit	kg	33.3	33.3	–	33.3
Gearbox	kg	80	80	80	80
Start system	p	1	1	1	1
Cooling system ICE	kg	29.1	29.1	29.1	29.1
Electronics for control units	kg	1.3	1.3	1.3	1.3
Tyres	p	4	4	4	4
Natural gas	MJ	1933	1933	1933	1933
Electricity	kWh	691	691	691	691

with the results of the energy analysis allows the evaluation of the environmental performance of each fleet.

3. Results and discussion

3.1. Energy analysis results

Table 4 presents the energy analysis results for each of the fleet systems under evaluation. According to the given energy input and vehicle fuel consumption, the annual kilometres travelled by each vehicle type (i.e., homogeneously grouped by technology) and the total annual kilometres travelled by each fleet were calculated. Additionally, taking into account the passenger transport function of a fleet by means of an occupancy rate of 1.6 for every vehicle (average number of passengers occupying a vehicle) (Archer et al., 2018; EEA, 2016), the total annual passenger-km (pkm) associated with each fleet were calculated.

Since the amount of energy entering the systems is the same, the fleets that exhibit the highest number in terms of total km or pkm are those that achieve the best energy performance. In this sense, Table 4 results show that the fleets that use blends outperform those with separate use of the two fuels (e.g., F2 vs F1 or F4 vs F3), and that HEV fleets behave better than those with simple ICEs (e.g., F3 vs F1, F4 vs F2 or F3 vs F2). The same is true for fleets involving the use of gasoline, where a gradual improvement was observed when switching from F5 to F8. This is due to an enhanced fuel economy of vehicles that use blends with respect to the separate use of fuels, and of HEVs compared to ICE vehicles. Thus, the fleets with the best performance were found to be F4 (involving only HEV Hythane) and F8 (involving only HEV H_2-gasoline). As another finding, fleets that involve the use of NG perform slightly better than their gasoline counterparts (e.g., F2 vs F6 or F3 vs F7). The worst strategies, among the analysed ones, would refer to the simple combination of FCEVs and existing gasoline or CNG cars (F5 and F1). In this sense, under specific circumstances hampering the use of hydrogen mixtures, HEVs (instead of conventional cars) are recommended to be deployed along with FCEVs.

Table 5 presents the results in terms of the number of vehicles that make up each fleet, penetration impact on the Italian fleet, and average fleet fuel economy, expressed as fleet efficiency. Taking into account the total kilometres travelled by each vehicle type and the fixed annual driving performance of each single vehicle (15,000 km), the number of vehicles within each fleet was calculated. Considering the total number of passenger cars circulating on Italian roads (presented in Section 2.2), national fleet penetration for both the total number of vehicles in a fleet and only hydrogen-related vehicles were estimated. Fleet average efficiency was calculated as the inverse of the weighted average obtained by vehicle number in a fleet and vehicle specific energy consumption.

Results in Table 5 are aligned with those in Table 4. In this case, the greater the total number of vehicles that can be fuelled with the same energy input, the better the energy performance of the fleet. The same observations made for Table 4 regarding the fleets ranking are applicable. This trend is explained by the fleet average efficiency, with the favourable effect of a large number of medium-efficient vehicles exceeding that of high efficiency in a limited number of vehicles. The use of hydrogen-mixture vehicles leads to homogeneous fleets with a relatively high average efficiency. Since HEVs enjoy a more favourable fuel economy than their non-hybrid counterparts, the best performance was found for the combined use of hydrogen mixtures and HEVs (F4 and F8).

The amount of hydrogen taken into consideration would power only 0.12 % of the national fleet if used in FCEVs. However, the same amount of hydrogen used in hythane vehicles would result in a penetration of 1 % of the national fleet, and 1.52 % if the mixture is used to fuel HEVs. This is due to the fact that each mixture-vehicle uses less hydrogen than an FCEV, as well as to higher average fleet efficiency. According to the Italian Automobile Club (ACI, 2021), the total number of CNG cars in circulation on Italian roads in 2020 amounted to 978,832 vehicles. Having 5.28 kt of renewable hydrogen annually available, it would be possible to convert 40.6 % of the Italian CNG cars into hythane cars or 61.5 % into HEV hythane cars. Therefore, by moderately increasing the assumed amount of renewable hydrogen available at the national level, the full Italian CNG car fleet could move to the use of mixtures containing hydrogen.

In order to sensibly understand the suitability of the proposed strategies, an environmental perspective is also needed. Contrary to the case in which hydrogen is used in FCEVs, the use of the same amount of hydrogen in vehicles fuelled with a mixture involves tailpipe exhaust emissions. Nevertheless, a fair environmental comparison between the fleets cannot be limited to tailpipe emissions, but a thorough LCA study is required. In this regard, for the subsequent LCA study, the results of the energy analysis were referred to one km travelled by each fleet (FU) and the fleets were represented as entities with a certain consumption of each of the fuels and a certain distance share associated with each type of vehicle (Table 6). As in Fig. 4, "Fuel 1" refers to NG, hythane or gasoline depending on the fleet; "Fuel 2" corresponds to pure hydrogen; "Vehicle A" refers to a vehicle that uses fossil fuel, pure or mixed with hydrogen; and "Vehicle B" corresponds to an FCEV.

Table 3
Main inventory data for vehicle operation and maintenance (values per total kilometres travelled by one vehicle during its useful life).

Item	Unit	HEV Hythane	HEV H_2-Gasoline	Gasoline	HEV Gasoline	Ref. for inventory
Operational inputs						
Vehicle infrastructure	p	1	1	1	1	Table 2
Hydrogen fuel	t	0.187	0.176	–	–	a
Natural gas	GJ	284	–	–	–	b
Gasoline (unleaded)	t	–	6.14	11.25	7.43	b
Maintenance inputs						
Lubricating oil	kg	34.6	34.6	34.6	34.6	b, c
Ethylene glycol	kg	12.9	12.9	12.9	12.9	b, c
Decarbonised water	kg	8.58	8.58	8.58	8.58	b, c
Tyres	p	12	12	12	12	c, d
Li-ion battery	kWh	1.8	1.8	–	1.8	e, f
Emissions						
Carbon dioxide	t	17.2	18.6	31.6	22.5	Table 1
Carbon monoxide	kg	5.96	20.6	87.8	58.8	Table 1
Hydrocarbons, unspecified	kg	4.24	5.28	12.4	8.46	Table 1
Nitrogen oxides	kg	2.52	2.96	6.15	1.8	Table 1
Brake wear emissions	g	436	380	334	374	b
Road wear emissions	kg	4.79	4.19	3.67	4.11	b
Tyre wear emissions	kg	28.05	24.50	21.49	24.07	b
Kilometres travelled	km	320,000	300,000	300,000	300,000	g

a: Valente et al. (2020); b: Frischknecht et al. (2007); c: Wang et al. (2007); d: Bras and Cobert (2011); e: Ellingsen et al. (2014); f: Majeau-Bettez et al. (2011); g: Candelaresi et al. (2021a).

Table 4
Fleets' energy performance expressed as annual km travelled and annual passenger-km (pkm).

Fleet	Vehicles A	Vehicles B	Total km fleet	Vehicles A	Vehicles B	Total pkm fleet
	[million km/year]	[million km/year]	[million km/year]	[million pkm/year]	[million pkm/year]	[million pkm/year]
F1: CNG + FCEV	4912.29	694.58	5606.87	7859.67	1111.33	8970.99
F2: Hythane	5957.68	–	5957.68	9532.29	–	9532.29
F3: HEV CNG + FCEV	7442.86	694.58	8137.45	11,908.58	1111.33	13,019.91
F4: HEV Hythane	9026.79	–	9026.79	14,442.86	–	14,442.86
F5: Gasoline + FCEV	4901.29	694.58	5595.88	7842.07	1111.33	8953.40
F6: H_2-Gasoline	5927.92	–	5927.92	9484.67	–	9484.67
F7: HEV Gasoline + FCEV	7426.20	694.58	8120.78	11,881.93	1111.33	12,993.25
F8: HEV H_2-Gasoline	8981.70	–	8981.70	14,370.72	–	14,370.72

3.2. Environmental results

Fig. 5 shows the carbon footprint per km travelled by each fleet, including its breakdown according to the main life-cycle stages and the type of vehicle. In agreement with the energy analysis results in Section 3.1, the most favourable profile was found for the fleet of HEVs fuelled with hythane (F4).

For comparative purposes, in Fig. 5 the results are also benchmarked against two conventional fleets (B1 and B2) composed solely of either CNG or gasoline vehicles under the same assumptions used to define the other fleets (total input energy of 8.65 PJ). In this regard, the conventional CNG and gasoline fleets involve 353,373 and 352,582 cars, respectively. The comparison with conventional fleets allows evaluating the impact reduction achieved when applying the proposed fleet strategies.

The carbon footprint reduction was found to range from 7 % to 35 % when comparing either F1-F4 with the conventional CNG or F5-F8 with the conventional gasoline fleet. The fleets showing an impact reduction >30 % compared to their conventional benchmark are F4 (HEV Hythane) and F8 (HEV H_2-Gasoline).

Regarding the carbon footprint breakdown, the emissions of the operational phase (TTW) from type-A vehicles (which burn fossil fuel solely or in mixture) were found to play the leading role, clearly ahead of vehicle manufacturing and fuel production.

Regarding FCEVs, while their fuel-use emissions are null, the role of vehicle manufacturing becomes more relevant. It should be noted that, in this regard, the infrastructure impact has to be read in light of the number of vehicles of each type.

The impact of renewable hydrogen, including production from WPE and distribution, was found to be negligible compared to the total fleet impact. This is true both in the case of pure hydrogen distributed via road (e.g., Vehicle B WTT in Fig. 5) and in the case of hydrogen

Table 5
Number of vehicles, fleets composition and national fleet penetration.

Fleet	Number of Vehicles A	Number of Vehicles B	Total vehicle number in fleet	National fleet penetration	Hydrogen-related vehicles national fleet penetration	Fleet average efficiency
	[cars]	[cars]	[cars]	[%]	[%]	[km/MJ]
F1: CNG + FCEV	327,486	46,305	373,791	0.941 %	0.12 %	0.648
F2: Hythane	397,178	–	397,178	1.000 %	1.00 %	0.689
F3: HEV CNG + FCEV	496,190	46,305	542,495	1.366 %	0.12 %	0.941
F4: HEV Hythane	601,785	–	601,785	1.515 %	1.52 %	1.044
F5: Gasoline + FCEV	326,752	46,305	373,057	0.939 %	0.12 %	0.647
F6: H_2-Gasoline	395,194	–	395,194	0.995 %	0.99 %	0.686
F7: HEV Gasoline + FCEV	495,080	46,305	541,385	1.363 %	0.12 %	0.939
F8: HEV H_2-Gasoline	598,779	–	598,779	1.508 %	1.51 %	1.039

Table 6

Consumption of fuels per km travelled by each fleet and distance travelled with each vehicle type.

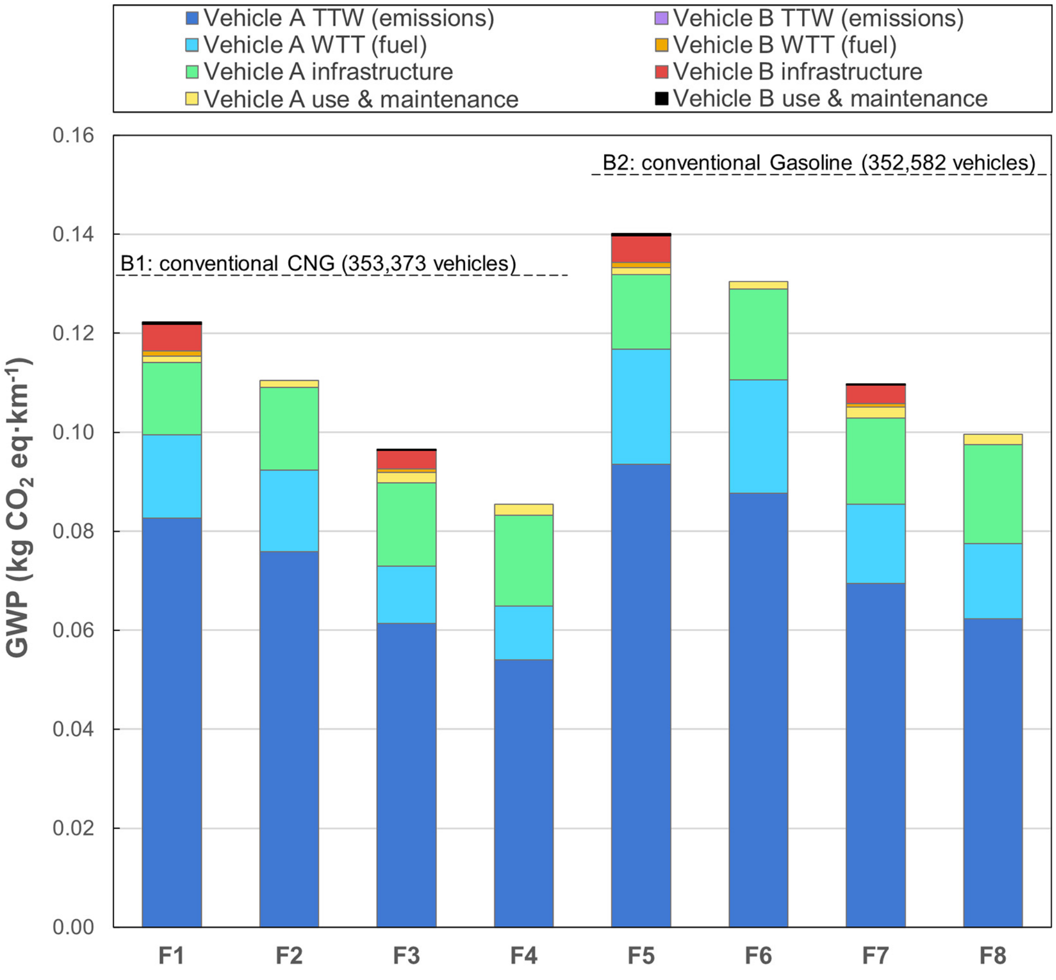
Fleet	Fuel 1 [g/FU]	Fuel 2 [mg/FU]	km Vehicles A [km/FU]	km Vehicles B [km/FU]
F1: CNG + FCEV	29.963[a]	941.5[d]	0.876	0.124
F2: Hythane	29.085[b]	–	1	–
F3: HEV CNG + FCEV	20.645[a]	648.7[d]	0.915	0.085
F4: HEV Hythane	19.196[b]	–	1	–
F5: Gasoline + FCEV	32.845[c]	943.3[d]	0.876	0.124
F6: H_2-Gasoline	31.006[c]	890.5[d]	1	–
F7: HEV Gasoline + FCEV	22.633[c]	650.0[d]	0.914	0.086
F8: HEV H_2-Gasoline	20.464[c]	587.7[d]	1	–

[a] Amount of CNG required per each km travelled by the fleet.
[b] Amount of hythane required per each km travelled by the fleet.
[c] Amount of gasoline per each km travelled by the fleet.
[d] Amount of hydrogen per each km travelled by the fleet.

distributed via pipeline and/or mixed with other fuels (a fraction of Vehicle A WTT in Fig. 5). Vehicle maintenance was also found to play a minor role.

Concerning fuel production, it should be noted that the NG/gasoline used in type-A vehicles was considered entirely of fossil origin. Some regions, such as Italy, aim for an increased use of biomethane, especially that produced from urban, agricultural or livestock waste, encouraging its injection into the gas grid (GSE, 2021). If significant amounts of biomethane were injected into the NG network, this could reduce the fuel-related impact and methane-hydrogen blends would increase their renewable content.

As the purpose of this work is to help policy actors make well-supported decisions, the total result deriving from each strategy was also considered. To that end, Fig. 6 shows the total carbon footprint of the proposed fleet strategies. However, it should be noted that each of the proposed fleets is composed of a different number of vehicles and involves a different number of kilometres, therefore the total carbon footprint must be interpreted accordingly. This means that some measures show a higher total carbon footprint but lead to travel more kilometres (or, in other words, to power more vehicles), whereas others show a lower impact but a poorer functional performance. Depending on whether the policy-maker prioritises only the carbon footprint, only the energy performance or both aspects, different fleet rankings are obtained. In the event that it is decided to prioritise both the carbon footprint and the energy performance, the best fleets



	F1	F2	F3	F4	F5	F6	F7	F8
Number of Vehicle A	CNG 327,486	Hythane 397,178	HEV CNG 496,190	HEV Hythane 601,785	Gasoline 326,752	H_2-Gasoline 395,194	HEV Gasoline 495,080	HEV H_2-Gasoline 598,779
Number of Vehicle B	FCEV 46,305	-	FCEV 46,305	-	FCEV 46,305	-	FCEV 46,305	-
Total vehicle number	373,791	397,178	542,495	601,785	373,057	395,194	541,385	598,779

Fig. 5. Breakdown of the carbon footprint of the proposed fleets per km travelled.

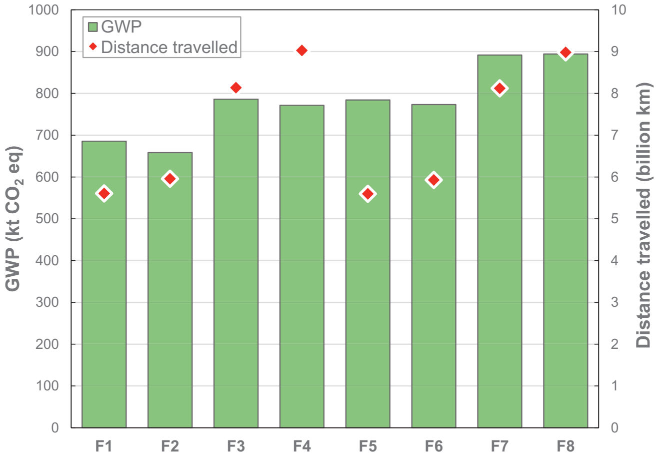
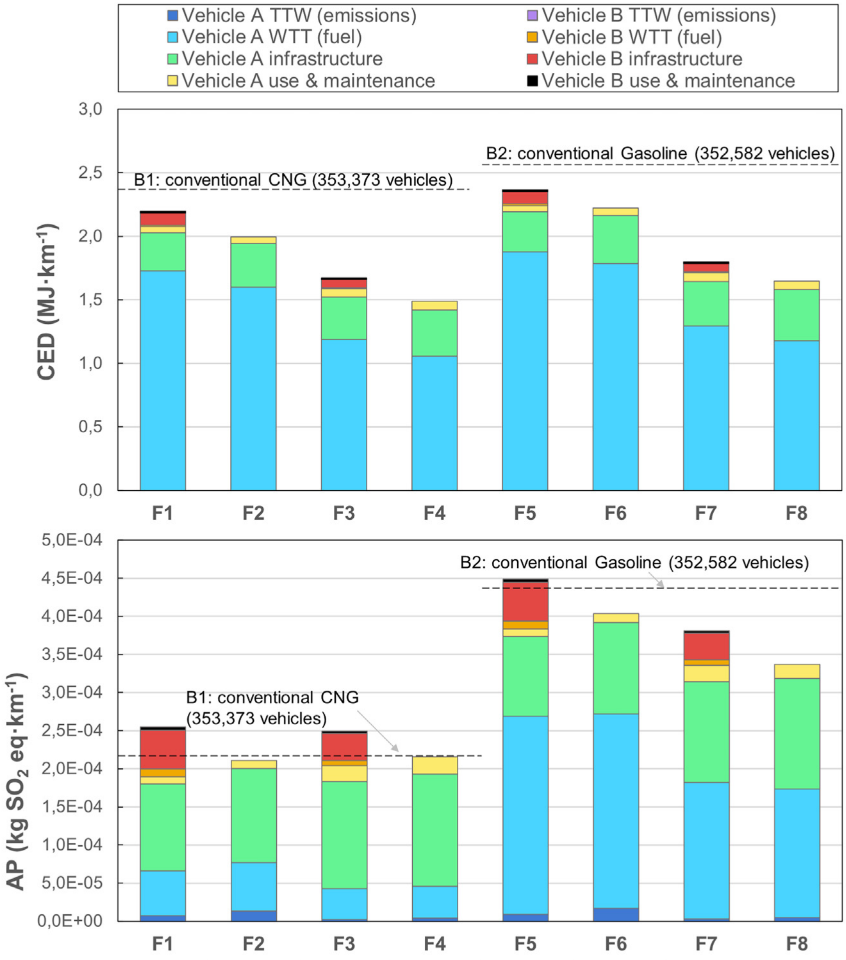


Fig. 6. Total carbon footprint of the different fleet strategies proposed, and total distance travelled.

would ideally be those with the lowest carbon footprint combined with the highest number of kilometres travelled.

Besides the carbon footprint, the non-renewable energy footprint and the acidification impact per km travelled by each fleet were assessed. Fig. 7 shows the breakdown by life-cycle stage and vehicle type for the CED and AP results of the proposed fleets, including their benchmarking against conventional fossil fleets. Regarding CED, the results show a strong correlation with the carbon footprint ones, leading to the same ranking of fleet strategies. It should be clarified that CED encloses the energy consumption cumulated over the life-cycle stages, whereas the energy analysis in Section 3.1 focuses on fuel consumption.

On the other hand, the AP results show different hotspots and ranking in comparison with the previous results. From the breakdown in Fig. 7, it can be observed that vehicle manufacturing plays a key role in terms of acidification, which is linked to the number and type of vehicles. Regarding single vehicles, the infrastructure contribution to AP is relatively low for vehicles equipped with ICEs, intermediate for HEVs, and very high for FCEVs (Candelaresi et al., 2021a). This trend is associated with vehicle-specific aspects such as (i) electrification-related components such as batteries, electric motors, power control units and fuel cell stacks, (ii) materials contained in the above-mentioned components, such as platinum in fuel



Number of Vehicle A	CNG 327,486	Hythane 397,178	HEV CNG 496,190	HEV Hythane 601,785	Gasoline 326,752	H_2-Gasoline 395,194	HEV Gasoline 495,080	HEV H_2-Gasoline 598,779
Number of Vehicle B	FCEV 46,305	-	FCEV 46,305	-	FCEV 46,305	-	FCEV 46,305	-
Total vehicle number	373,791	397,178	542,495	601,785	373,057	395,194	541,385	598,779

Fig. 7. Breakdown of the energy and acidification footprints of the proposed fleets per km travelled.

cells, and (iii) other vehicle components such as heavier car gliders or hydrogen tanks involving composite material. In HEVs and ICEs, especially CNG-fuelled ones, also the PGMs in the exhaust system show a certain AP incidence. For these reasons, in terms of acidification, there is a change in the ranking, with F2 performing slightly better than F4. The high contribution of infrastructure to AP in FCEVs leads the fleets F1 and F3 to a higher acidification impact than their CNG benchmark, while F2 and F4 remain slightly below the conventional CNG fleet. Finally, gasoline-related fleets show a higher acidification footprint than those related to NG, even though –apart from F5– they outperform their benchmark (conventional gasoline fleet).

3.3. Perspectives and final remarks

Overall, the results show that the use of hydrogen blends would be beneficial under different energy and environmental aspects to boost the hydrogen economy in the short term. While this result could be affected by important changes in technical aspects such as fuel consumption, lifespan, occupancy rate, weight and emission factors of each vehicle, the key findings in this work are deemed robust as the technical parameters considered in this paper are intended to give an average representation of each vehicle technology. In this regard, Candelaresi et al. (2021b, 2021c) carried out a sensitivity analysis to technical parameters, showing the functional dependencies of the LCA results as the technical parameters vary. For instance, fuel consumption was found to have a linear influence on the impact indicators. By considering a realistic range of variation between worst and best cases of technical parameters, and its effect on LCA results, it was possible to represent each average vehicle technology in a robust way. Finally, rather than the numerical impact value of each vehicle or fleet, the key finding to be highlighted refers to the possible relationship between the different fleet options and the strategic opportunities that may arise from it.

Besides, other technical, economic and social co-benefits may derive from the use of hydrogen blends. For instance, the increased use of hydrogen would result in a large number of people acquainted with hydrogen energy systems, thereby favouring social acceptance.

From a techno-economic point of view, the use of mixtures would allow the immediate use of the available green hydrogen, relying on existing infrastructure and vehicles with minor modifications and thus starting up a market without gaps in the supply chain. In line with European goals, this would allow an initial concentration of investments in the production of hydrogen from renewable or low-carbon sources. At a later time, when green hydrogen production have already been scaled up, major investments related to pure-hydrogen infrastructure and end uses could be attracted. Alternatively, the hydrogen content in the mixture could be increased over time.

Among the opportunities derived from using blends, countries with a large number of CNG refuelling points such as Italy could start up hydrogen deployment with minor infrastructure modifications. Alternatively to hydrogen blending in pipeline, pure renewable hydrogen could be transported (e.g., by road) from the production point and used separately and/or mixed with CNG at the filling station. Regarding on-board storage, hythane can be stored at pressures similar to those already used for CNG (200 bar) and in very similar tanks, already suitable or adapted for containing small amounts of hydrogen. Storage pressure could be slightly raised to recover the loss of volumetric energy density due to hydrogen addition or further extend the driving range. Similarly, the combustion engine requires minimal modifications compared to a CNG engine.

As regards H_2-gasoline vehicles, in the absence of a dedicated hydrogen pipeline, pure hydrogen should be transported to the refuelling station by road. Since the amount of pure hydrogen stored in the vehicle is small, tank volume and weight issues associated with pure hydrogen storage are mitigated. The ICE presents minor modifications with respect to the conventional one, and the driving range is similar to that of a conventional gasoline vehicle. A more distributed use of pure hydrogen would allow the creation of several hydrogen refuelling stations of small size, which could be expanded at a later time to allow also refuelling FCEVs. The increased number of users would allow these stations to be exploited with high utilisation factors, thus accelerating the return on investment. Furthermore, the increased number of small filling stations would enable an enhanced coverage of the national road network, hastening action on the main transport arteries and points of national/European strategic interest such as big cities, main highways and the Trans-European Transport Network (TEN-T) core.

4. Conclusions

This study explored –from an energy and life-cycle environmental perspective– eight innovative fleet strategies for the short-term implementation of hydrogen in road transport (passenger cars) at the national level. The proposed strategies achieve a carbon footprint reduction ranging between 7 % and 35 % with respect to their conventional fleet benchmark. It is concluded that strategies using hydrogen mixtures in homogeneous fleets are more suitable than those separately using hydrogen and fossil fuels in heterogeneous fleets. In particular, strategies based on blends of natural gas and hydrogen (hythane) generally outperform those based on gasoline-hydrogen mixtures. Moreover, fleets involving hybrid electric vehicles perform better than those involving internal combustion engines. Thus, the best results were generally found for the fleet strategy based on the use of hythane in hybrid electric vehicles (35 % reduction in carbon footprint with respect to its benchmark). Where this is not possible or under policy scenarios prioritising the separate use of hydrogen, it is advisable to encourage fleets involving both hybrid and fuel cell electric vehicles. The fleet strategies involving the use of hydrogen mixture and internal combustion engines could arise as a first step towards their hybrid versions as they would be preferred over those involving traditional vehicles alongside fuel cell electric vehicles. Overall, also taking into account potential technical, economic and social advantages, the use of hydrogen blends could facilitate the transition towards an environmentally sustainable transport while hastening the advent of the hydrogen economy.

CRediT authorship contribution statement

Daniele Candelaresi: Investigation, Data curation, Software, Formal analysis, Writing – original draft, Visualization. **Antonio Valente:** Methodology, Software, Writing – review & editing, Visualization. **Diego Iribarren:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Javier Dufour:** Resources, Supervision, Writing – review & editing. **Giuseppe Spazzafumo:** Conceptualization, Methodology, Supervision, Funding acquisition.

Data availability

No data was used for the research described in the article.

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.

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