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Performance Analysis of Innovative Propulsion Systems for Short-Haul Ferries

Antipollution regulations for marine applications have become increasingly stringent in recent years, with the International Maritime Organization (IMO) setting ambitious limitations for the coming years: a 70–80% reduction in greenhouse gases (GHGs) by 2040 and approximately net-zero by 2050. To meet these targets, a lot of research has been focused on developing both more efficient engines, powered by sustainable fuels, and electrified propulsion systems, especially for short-range marine applications. These systems combine internal combustion engines and electric motors to optimize the overall efficiency, improving both energy consumption (EC) and polluting emissions. In this study, three different propulsion system architectures are compared, which could be installed on a ferry traveling along a mission profile, typical of a line operating within the Venice Lagoon, in Italy. The comparison between an application with only a hydrogen combustion engine, an application with a hybrid propulsion system, and a fully electric application clearly highlights advantages and limitations in terms of consumption, weight, and, consequently, transportable payload. In fact, since the ferry's total mass remains constant, the choice of the type of propulsion system has a significant impact on both energy expenditure and transportable mass, i.e., on the maximum number of passengers that can be transported. [DOI: 10.1115/1.4069732]

1 Introduction

Short-haul ferries play a crucial role in facilitating regional and local transport across waterways, connecting islands, coastal communities, and mainland ports [1–8]. However, due to the continued reliance on traditional marine fuels like diesel, these

vessels are significant contributors to greenhouse gas (GHG) emissions (reaching up to 150 gCO_{2,eq}/km per passenger [9]) and other pollutant emissions, such as nitrogen oxides (NO_x) and particulate matter (PM), exposing on-board passengers and environmentally sensitive areas to pollutants [10–12]. In this context, the International Maritime Organization (IMO) [10], which is the agency responsible for regulating shipping, has been at the forefront of driving decarbonization and reducing the associated pollutant emissions of the sector (which is responsible for up to 24% of NO₂ emissions in the coastal area and up to 14% of PM_{2.5}) [11]. The

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introduction of stricter regulations from both the European Union (EU) and IMO is accelerating the need for such transformations [13,14]. In 2023, the IMO revised its previously presented plan to reduce GHG emissions from international shipping by at least 50% by 2050, compared to 2008 levels, targeting an ambitious 70–80% reduction by 2030 with almost net zero emissions in 2050 [13]. This initiative is in accordance with the EU's "Fit for 55" package, which aims for a 55% reduction of GHG emissions by 2030 and includes measures to reduce emissions from maritime transport, such as the inclusion of shipping in the EU Emissions Trading System and the promotion of alternative fuels [13,15]. As the global push for sustainability intensifies, there is an urgent need for the maritime sector, including short-haul ferries, to transition to cleaner and more efficient powertrain technologies. The shift toward alternative fuels such as hydrogen, ammonia, biofuels [5,16–21], and the development of hybrid or electric propulsion systems [3,22–25] are becoming essential for reducing the carbon footprint of the maritime sector, especially in short-distance travels, where alternative energy sources can be effectively utilized. Battery electric and hydrogen-fueled powertrains represent two of the most promising technologies for decarbonizing short-haul ferries. Battery electric ferries (BEFs) are well-suited for short, frequent routes where the energy demands are relatively low, and the energy efficiency of pure battery powertrain coupled with the zero tailpipe emissions can be enhanced [18,22–25]. However, the limitation of BEFs lies in their energy storage capacity density, which can restrict their range and payload [26]. Charging times can also be a bottleneck, requiring careful planning to minimize downtime between trips. Hybrid propulsion concepts allow to optimize performance, as suggested by Miretti et al. [8], who investigated the potential of hybrid diesel ferries in the Venetian context. However, as diesel combustion still generates pollutant and GHG emissions [27,28], hydrogen-fueled ferries (HFFs) offer a solution with zero GHG tailpipe emissions, being the hydrogen molecule carbon-free, and minimal NO_x emissions when burned [29]. Moreover, the higher energy density [30] allows for longer ranges (and higher payload capacity) and quicker refueling times compared to BEFs (high recharge rate could affect battery's health) [31,32]. Recently, sustainable hydrogen-based powertrains have been developed leveraging on fuel cell (FC) technologies and hydrogen internal combustion engines (H_2 ICEs) [33–39]. FCs convert hydrogen directly into electricity through an electrochemical process, with water vapor as the only by-product [40–42], making them an ideal option for zero-emission HFFs. The main limitation for a complete market protrusion of FCs lies in their high cost, primarily due to the expensive materials required, such as platinum for the catalysts, which makes them less economically viable for widespread adoption, and limited lifespan, with performance degradation over time, which can reduce their efficiency and increase maintenance costs [43]. On the other hand, H_2 ICEs burn hydrogen as in conventional engines achieving higher efficiencies (still lower than FCs) [33,44,45], and retrofitting conventional engines to hydrogen offers the advantage of cost-effective powertrain solutions, reducing emissions by utilizing existing engine infrastructures, allowing for a smoother transition to cleaner energy without the need for entirely new vehicle designs. Despite hydrogen combustion process generates NO_x emissions, proper combustion control techniques have been recently developed to limit them [44], allowing to achieve $0.05 \text{ g}_{\text{NO}_x}/\text{kWh}$ when integrated in hybrid H_2 ICEs (H- H_2 ICEs) [39].

This paper explores the development of new powertrain solutions for short-haul ferries in the Venetian context, considering an H_2 ICE, an H- H_2 ICE, and a BEF aiming to pave the way for more sustainable ferry operations. The results not only consider the energy efficiency of the different configurations, but analyze the effect of the powertrain (and energy storage) sizing on the effective payload capability of the different layouts. Furthermore, a sensitivity analysis has been conducted on the potential for battery/hydrogen recharge at half mission. Finally, a shot lifecycle assessment (LCA) of the GHG emissions of the different layouts is presented.

2 Materials and Methods

The historic city of Venice is characterized by its unique only water-based transport system [46]. Each year, Venice draws 25–30 million visitors, the majority of whom are day-trippers, resulting in an average of 130,000 people daily (residents and visitors combined) [46]. Being Venice a completely car-free city, transportation is performed either by foot or by private, hired, or public boats, making the Venetian panorama a unique and representative case study for the development of low-impact ferries. Line 1 of the *Vaporetto* (the typical public transport ferry of Venice) represents a suitable case study [46,47]. To properly model the dynamic behavior of the ferries, the potential of SIMULINK and SIMSCAPE by MATLAB have been exploited. In particular, for propeller modeling, a dedicated SIMSCAPE block has been adopted, while for ferry and powertrain modeling, previously developed SIMULINK blocks have been integrated [48].

Operative Path. As previously stated, for the sizing of the ferries, Line 1 of the Azienda del Consorzio Trasporti Veneziano (ACTV) waterbus routes has been adopted as a reference, since it represents the most typical and popular Venetian route [49], ensuring that the ferry design aligns with the operational demands and passenger capacity requirements of one of the most frequented and well-known routes in Venice.

Figure 1 presents the trace of ACTV Line 1 inside Venice (a) and the corresponding speed trace (b). As visible in the first part of the speed trace, the maximum speed is limited to below 13 km/h, and the stops are more frequent, being the *Vaporetto* in the *Canal Grande* (the main canal of the city), while in the last part of the route (after min 45), the *Vaporetto* operates in the Venetian Lagoon, with fewer stops and higher peak speeds (almost equal to 20 km/h). To consider a more feasible operative path, the speed trace of Fig. 1(b) has been coupled with the backward speed profile to cover a total duty of 9 h.

Ferry Modeling. Ferry and powertrains models have been developed using MATLAB SIMULINK and SIMSCAPE, adopting a hybrid approach to capture the complexities of integrating multiple energy sources and propulsion technologies. By leveraging SIMULINK's dynamic simulation capabilities and SIMSCAPE's physical modeling environment, the models are able to accurately represent the

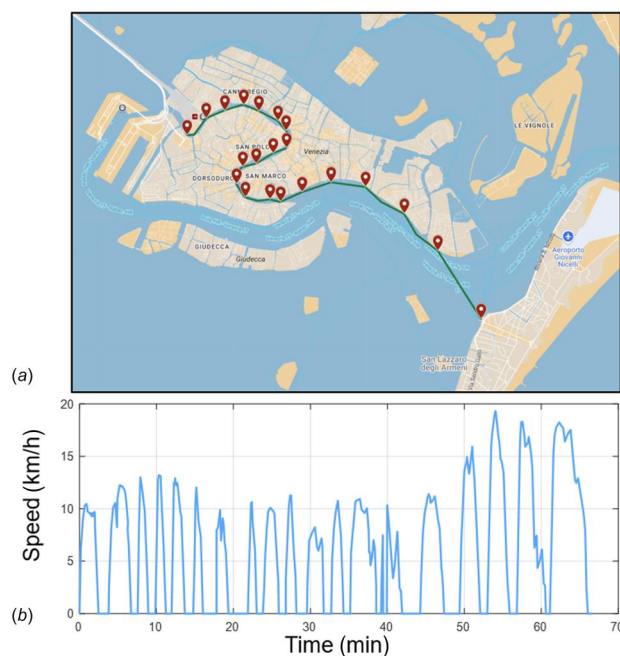


Fig. 1 ACTV Line 1: (a) path visualization and (b) speed trace [50,51]

Table 1 Characteristics of hull and propeller

Parameter	Value
Gross tonnage (M_{ship})	23.9 ton [52]
Wet surface (A_{wet})	83.3 m ² [51]
Length (L_{ship})	21.8 m [52]
Propeller diameter (d_{prop})	0.4 m [53]
Propeller inertia (J_{prop})	1 kg m ² [53]

interactions between different powertrain components, enabling the possibility of energy efficiency optimization. Following the Venetian ferries database, the typical characteristics of the Vaporetto which operates in ACTV Line 1 have been selected (i.e., ferry weight, propulsion power, dimensions, etc.) [51–53]. Table 1 summarizes the main characteristics (common among all the models) of the hull and the propeller.

The thrust of the propeller (T_{prop}) has been calculated by means of the *propeller* block of SIMSCAPE, allowing to calculate the speed of the ferry (v_{ship}) as in Eq. (1), where the ship drag (D_{ship}) can be easily derived following Eq. (2), where c_d represents the drag coefficient and $\rho_{\text{H}_2\text{O}}$ the water density

$$v_{\text{ship}} = \sqrt{\frac{T_{\text{prop}} - D_{\text{ship}}}{M_{\text{ship}}}} \quad (1)$$

$$D_{\text{ship}} = \frac{1}{2} \rho_{\text{H}_2\text{O}} c_d v_{\text{ship}}^2 A_{\text{wet}} \quad (2)$$

However, to calculate T_{prop} , even the rotational speed of the propeller (ω_{prop}) has to be known. Following a torque-balance approach as in Eq. (3), ω_{prop} can be calculated, where R_{prop} represents the resistance torque of the propeller (calculated by the propeller block in SIMSCAPE) and Trq_{prop} the torque provided to the propeller from the powertrain

$$\omega_{\text{prop}} = \sqrt{\frac{\text{Trq}_{\text{prop}} - R_{\text{prop}}}{J_{\text{prop}}}} \quad (3)$$

To follow the target speed trace, starting from the requested speed (Fig. 1(b)), a *driver model* has been developed to convert the target speed into a powertrain torque request ($\text{Trq}_{\text{pwt,req}}$) by means of a proportional integral controller that compares the target and actual speeds). This request is saturated between the maximum torque curve (as a function of engine/motor speed) allowing to calculate the Trq_{prop} , as discussed in Ref. [54] for a different application. Finally, T_{prop} is calculated by means of the SIMSCAPE propeller block, resulting in T_{prop} . Figure 2 represents a schematic of the followed approach.

As the performance of the ship is influenced by M_{ship} , in this analysis it has been assumed that M_{ship} is maintained constant among the different layouts, ensuring consistency in the hypothesis of a fixed A_{wet} . However, it is important to consider that each powertrain will have a different weight, affecting the effective available passenger payload. In fact, given the fixed M_{ship} , a heavier

powertrain will reduce the amount of weight allocated to passengers and cargo, while a lighter system could maximize the payload capacity.

Powertrain Models. The powertrain models utilized in this work have been derived from previous research following a map-based approach and machine learning techniques for rule-based energy management for the H-H₂ICE [48]. The layout of the powertrains is reproduced in Fig. 3 where the torque produced by the powertrains is sent to the propeller via a fixed gear ratio (GR) transmission (the transmission is even capable of inverting the direction of rotation). The different powertrain configurations studied are a battery electric one, and two hydrogen-based powertrains: the first one is a traditional layout (thermal engine with fixed gear ratio reduction) fueled with hydrogen, and the second one is a series hybrid plug-in version (the propulsion is fully electric, with an electric motor directly coupled with the propeller via a constant gear ratio; the motor can be powered either by the battery or from the electrical power produced by the thermal hydrogen engine coupled with a generator, which can also recharge the battery) as reported in Fig. 3 [48].

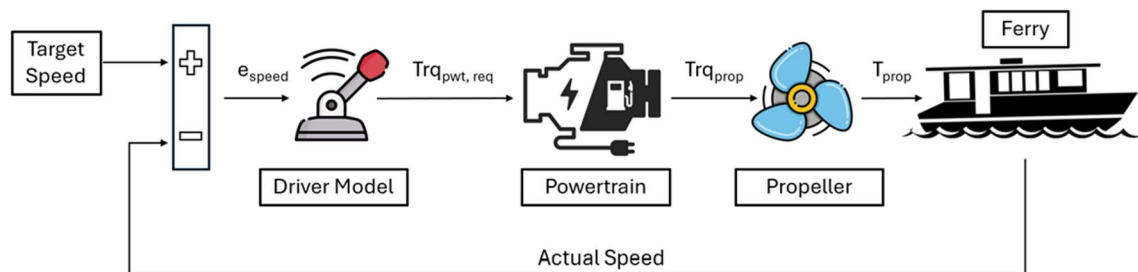
Lithium-ion batteries have been considered with different sizes as discussed in Sec. 3, while the characteristics of the hydrogen engine, which is in common between the H₂ICE version and the H-H₂ICE one, are summarized in Table 2 [39,44,48].

Considering ACTV Line 1 and typical characteristics of the Vaporetto of Venice, all the powertrains have been designed with a peak propulsive power of 100 kW [48,52].

Conducted Simulations. The simulations performed in this study were designed to investigate energy consumption (EC), pollutant tailpipe emissions (for HFFs), and optimal sizing under the typical ACTV Line 1 route. The speed trace has been concatenated with its flipped version to cover a total duration of 9 h considered as the typical duty duration. In the first place, the ECs (and HFFs NO_x emissions) have been quantified for the three configurations, allowing to properly design the size of the battery and the tanks' capacity. Then, smaller tanks/battery sizes have been considered to assess the potential for half-day recharge/refueling, allowing for smaller energy reservoirs and higher payload capacity.

3 Results and Discussion

Gear Ratio Optimization. The first activity has been focused on the quantification of the different concepts ECs under different GRs (i.e., 3, 2, and 1.5), the purpose being to optimize the GR themselves. As already mentioned, the available propulsive power of each layout has been set equal to 100 kW. While the hydrogen tanks have not been kept into account in this first phase (this aspect does not affect the results, as the analysis has been conducted under the hypothesis of fixed total weight), batteries sizes equal to 150 kWh and 70 kWh have been considered for the BEF and the H-H₂ICE, respectively. As a matter of fact, as the state of charge (SOC) affects the discharge efficiency, and thus the EC [48,55], the sizes of the batteries have to be considered. Figure 4 summarizes the results of the EC and engine-out NO_x (EO_{NOx}) emissions of the different powertrain

**Fig. 2 Visualization of torque determination procedure**

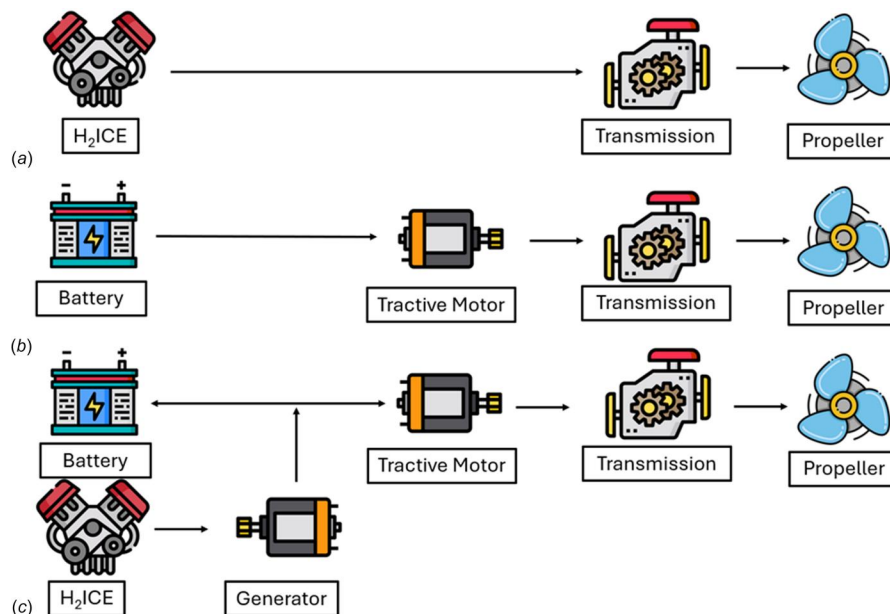


Fig. 3 Powertrain layouts: (a) H₂ICE, (b) battery electric, and (c) H-H₂ICE

Table 2 Hydrogen engine characteristics [39]

Parameter	Value
Engine architecture	3.0 l, V6
Compression ratio	12.85
Injection system	Double port fuel
Boost system	Single-stage variable turbine
Exhaust gas recirculation system	High pressure
Peak efficiency	42%

configurations as a function of the GR. As it is possible to see, the BEF allows to minimize the EC, being the most efficient layout, while the H₂ICE is the least efficient owing to lower conversion efficiency. Finally, the H-H₂ICE is a tradeoff solution, being the EC in between the BEF's and the H₂ICE's ones. The optimal GR changes, being the final drive coupled with the transmission either electric or mechanical. As a matter of fact, a lower GR allows to reduce the speed of the ICE (and to increase the load for a fixed power request), leading to a higher engine efficiency. Conversely,

for the electric motor, the lower the speed, the lower the efficiency. As regards NO_x emission, the EO_{NO_x} are reported in Fig. 4(b). Extremely low NO_x emissions are reached and, in particular, the H-H₂ICE presents higher NO_x emissions, as the energy management system targets higher power values [48]. Furthermore, EO_{NO_x} of H-H₂ICE increase as GR reduces, as for lower GR the EC is higher; therefore higher energy has to be provided from the thermal engine. Finally, for the H₂ICE, EO_{NO_x} are almost constant.

“Come & Go” Analysis. In the second part, the optimizations of battery size and energy reservoirs have been performed, considering a Come & Go (C&G) scenario (energy reservoirs are sized to allow the entire mission to be carried out without any refilling/recharge). For the present analysis, only the results with the optimized GR have been considered.

Focusing on the hydrogen tanks, the quantification of the needed hydrogen mass for the H₂ICE (H_{2,H₂ICE}) is straightforward (as the consumption of the engine is not affected by the filling level of the tanks, and the weight of the ferry has been considered always constant) as described in Eq. (4), where LHV_{H₂} is the lower heating value of hydrogen and a_g represents the autonomy gain (that quantifies the desired extra energy in the reservoir)

$$H_{2,H_2ICE} = \frac{EC_{H_2ICE}}{LHV_{H_2}} \cdot a_g \quad (4)$$

For the BEF, batteries size determination is less straightforward, as the final EC is affected by the final SOC, which is in turn affected by the battery size. An iterative study has been conducted to identify the proper size of the battery for the BEF. An a_g equal to 15% has been considered, resulting in an optimized size of the battery of 105 kWh (considering a GR equal to 3), which corresponds to an EC 6% higher than the 150 kWh baseline case (however, a smaller battery will have positive effects on the maximum allowable payload, as will be discussed).

The same happens for the H-H₂ICE hydrogen tanks size, which is indirectly affected by the size of the battery. As a matter of fact, one of the inputs of the H-H₂ICE hybrid energy management strategy is battery SOC [48]. To simplify the analysis, the H-H₂ICE battery size has been kept equal to 70 kWh and an a_g of 15% has been considered as well, this time on the hydrogen mass (being the configuration plug-in, it is more convenient to store the extra-energy in a lower-

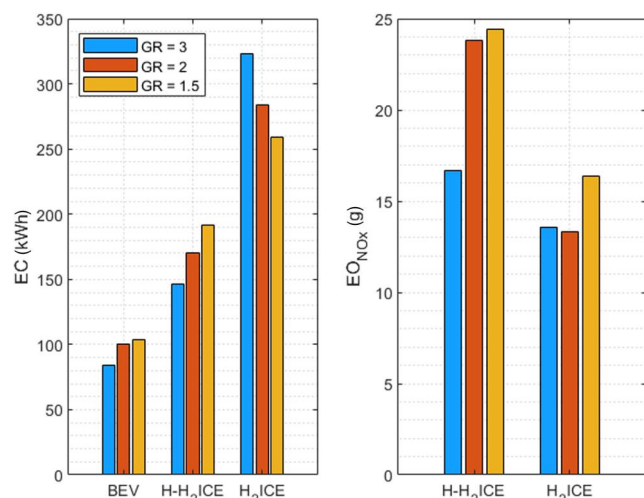


Fig. 4 EC (a) and EO_{NO_x} (b) as a function of GR

Table 3 C&G results

	BEF	H-H ₂ ICE	H ₂ ICE
EC (kWh)	89	146	260
Tail _{NO_x} (g)	—	1.6	1.6
Battery size (kWh)	105	70	—
Battery weight (kg)	840	560	—
H ₂ mass (kg)	—	3.7	8.9
W _s (kg)	840	606 @350 bar 625 @700 bar	111 @350 bar 158 @700 bar

efficient way but prioritizing the gravimetric density, as probably such energy will not be used frequently).

As regards NO_x emissions, suitable tailpipe NO_x (Tail_{NO_x}) have been obtained, considering a 90% efficiency, as reported for selective catalyst reduction system [56], allowing to produce less than 2 g_{NO_x}/day/ferry.

Table 3 presents the results, which confirm the trend presented in Sec. 2 and highlight the differences between energy storage efficiencies. Considering reference specific weights equal to 8 kg/kWh [57] for the battery, 12.5 kg/kg_{H₂} and 17.8 kg/kg_{H₂} for hydrogen tanks, at 350 bar and 700 bar, respectively [58,59] (lower storage pressure solutions are more convenient from a gravimetric point of view, but are bulkier), it is evident that HFFs are less affected by the weight of the storage (W_s) than BEFs. This aspect has an impact on the maximum number of passengers, which decrease, with respect to the lighter solution (H₂ICE), by nine people for the BEF and by six for the H-H₂ICE.

In-Mission Recharge/Refuel Analysis. This section investigates the potential, feasibility, and impact on powertrain design of considering recharging/refueling halfway through the mission. For all the three configurations, a complete recharge of the energy reservoirs mid-mission has been evaluated (feasibility study on the actual recharge capabilities as a function of the available power supply infrastructure will be discussed later), allowing to reduce the size of the energy reservoirs with respect to the C&G scenario (with an ag equal to 15%).

The results of the in-mission scenario are reported in Table 4. Once again, lowering the battery size has an effect on the total consumption, which increases due to the lower discharge efficiency of the battery: the EC of the BEF increases by 4.5% with respect to the 105 kWh battery case. The same happens for the H-H₂ICE, where the EC increases due to both lower discharge efficiency and higher hydrogen consumption (4.7% higher). Finally, halving the H₂ICE hydrogen tanks size shows only positive effect, as W_s decreases by 37–38%.

The reduction of W_s also has a positive impact, in all the cases considered, on the passenger load. In fact, only four passengers are lost for the BEF (with respect to the baseline H₂ICE for the full route, which is the lighter configuration) and two passengers for the H-H₂ICE.

The last step of the in-mission analysis regards the evaluation of the time spent to recharge/refuel. For the recharge processes of the battery packs, recharge power supplies of 100 kW (r₁₀₀) and 22 kW (r₂₂) have been considered (with a recharge efficiency equal to 90%) [54].

Table 4 In-mission results

	BEF	H-H ₂ ICE	H ₂ ICE
Total EC (kWh)	93	153	260
Tail _{NO_x} (g)	—	1.7	1.6
Battery size (kWh)	55	35	—
Battery weight (kg)	440	280	—
H ₂ mass (kg)	—	1.8	5.6
W _s (kg)	440	303 @350 bar 313 @700 bar	70 @350 bar 98 @700 bar

Table 5 Recharge time

	Recharge type	Refuel time (min)	Recharge time (min)	Total time (min)
BEF	r ₂₂	—	281	281
	r ₁₀₀	—	62	62
	r ₂₂ s-350	0.5	162	~162
	r ₂₂ hf-350	0.25	162	~162
H-H ₂ ICE	r ₂₂ s-700	0.5	162	~162
	r ₁₀₀ s-350	0.5	35	~35
	r ₁₀₀ hf-350	0.25	35	~35
	r ₁₀₀ s-700	0.5	35	~35
	s-350	1.5	—	1.5
H ₂ ICE	hf-350	0.8	—	0.8
	s-700	1.5	—	1.5

As regards hydrogen refueling, *standard* (s) 3.6 kg_{H₂}/min for a peak *high flow* (hf) of 7.2 kg_{H₂}/min (for 350 bar only) have been considered [31,60]. Table 5 reports the results of these processes, considering in-series procedure for the H-H₂ICE (meaning that the battery and the tanks are not recharged in parallel).

The results underscore that r₂₂ is not sufficient to completely recharge the batteries, even for the H-H₂ICE, where the battery is 37% smaller than the one of the BEF. However, while for the BEF the r₂₂ scenario is unfeasible, for the H-H₂ICE it is possible to consider a 1 h recharge (equal to almost 20 kWh), which will allow to complete the second part of the mission with an increase of the EC of the second half of the mission with respect to the first one by about 4%. Conversely, r₁₀₀ represents a high-sufficient power to recharge even the BEF in almost 1 h. Conversely, for hydrogen, the time spent for the refueling process is always negligible (<2 min) for both HFFs.

In conclusion, the in-mission scenario shows negligible variations in the accomplishment of the mission of the H₂ICE, as the EC in unaltered and the refuel time is negligible. Conversely, for both H-H₂ICE and BEF, the recharge time is significant (35–62 min), with a 100 kW recharge infrastructure needed and an EC increase of 4.7% and 4.5%, respectively, while in the meantime allowing to more than halve the number of passengers unloadable due to W_s.

Final Lifecycle Assessment. The previous paragraphs allowed to quantify the different powertrains' ECs and energy reservoirs sizes. In this last part, a final LCA of the overall GHG emissions is performed (starting from the hypothesis of retrofitting existing *Vaporetti*, therefore neglecting emissions related to hull manufacturing as well as to seats/interiors). Hydrogen production impact has been kept into account, considering the results of Incer-Valverde et al. [61]; the Italian energy mix and its forecasted evolution have been considered for the impact of electric energy production [13,62–68] and component manufacturing impacts (i.e., battery, thermal engine, electric motor, and tanks) have been derived from Refs. [69–74].

Furthermore, Tail_{NO_x} and NO_x emissions associated with components' manufacturing processes, electricity generation, and hydrogen production have been considered as well [48]. The analysis has been conducted starting from 2025, and considering a time horizon of 25 years, with 320 operative days/yr for 9 h/day.

Figure 5 reports the results of the LCA for BEF and HFFs, considering three different hydrogen colors: gray (from methane steam reforming), blue (from methane steam reforming coupled with carbon capture techniques), and green (from renewable-powered water electrolysis). Among the three subplots, the trends of the emissions of BEFs are constant, as they are only influenced by the electricity generation energy mix, considered variable during the years, but are not affected by the hydrogen color. It is evident that considering the recharge for BEF is favorable only in the first years (as the manufacturing of the powertrain presents lower emissions). In the long term (after 10 years), the lower efficiency of the smaller battery results in higher overall emissions with respect to the

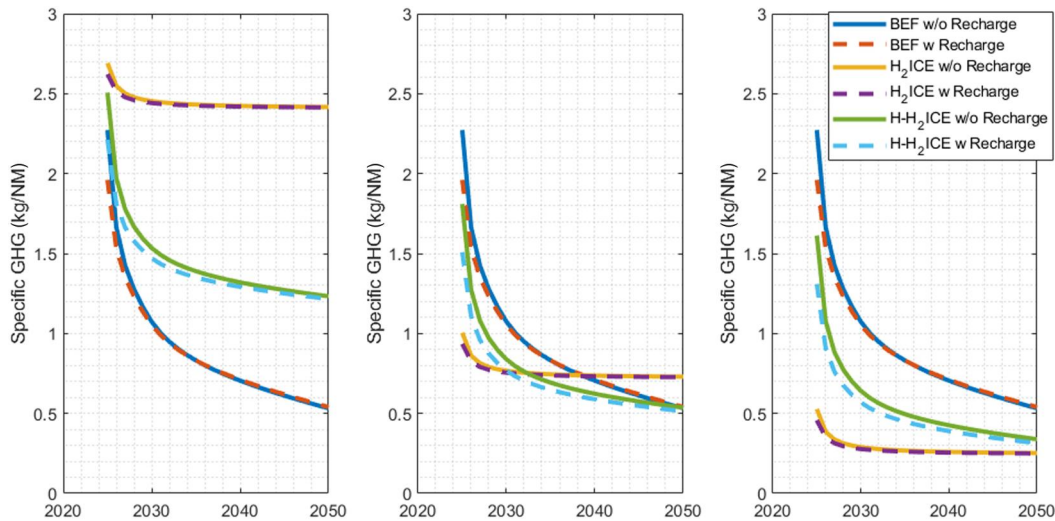


Fig. 5 Lifecycle specific GHG emissions considering gray H₂ (a), blue H₂ (b), and green H₂ (c)

scenario without recharging. Clearly, this effect is not present for the H₂ICE, where the recharge has only positive effects (the consumption is unaltered). For the H-H₂ICE, the energy management strategy avoids to reach low values of the SOC [48], enhancing efficiency; therefore, this inversion of the trend is not present (at least in the considered horizon). Commenting on the effect of the hydrogen production method, in the gray scenario (Fig. 5(a)), the lower efficiency of the H₂ICE results in maximum emissions. Despite being close to the BEF's ones in the manufacturing year, the gap widens, reaching almost five times the BEF's values in 2050 (for H-H₂ICE the situation improves, but the final emissions are still three times higher than BEFs). The blue scenario (Fig. 5(b)) shows that HFFs are the best option: in the first five years, H₂ICE presents the lowest emissions, then H-H₂ICE recovers its higher manufacturing impact, becoming the powertrain with the lowest emissions (slightly lower than BEFs in 2050). It is worth noting that H₂ICE in the first years is the best solution and the worst in the last years. This is due to the lower efficiency of the powertrain with respect to BEFs and H-H₂ICEs, which succeed in reducing their higher initial manufacturing emissions thanks to the decarbonization of the grid. Finally, the green scenario (Fig. 5(c)) underlines that the lower powertrain complexity of the H₂ICE, coupled with extremely low hydrogen production emissions, is enough to minimize the emissions despite the lower efficiency.

4 Conclusion

In this paper, three different powertrain configurations for Vaporetti have been assessed in the Venetian panorama, even considering the potential for recharge mid-mission, in a 25-years horizon. At first, the final transmission GRs have been optimized. The results underscore that the BEF is the one with the lower EC, followed by the H-H₂ICE, and finally by the H₂ICE. As regards NO_x emissions, minimum levels have been reached (lower than 1.6 g_{NOx}/day). Then, an optimization procedure on the battery size of the BEF has been conducted. The BEF presents the heaviest powertrain, which results in lower payload capability (up to nine passengers less than the lighter powertrain). The potential for recharge mid-mission allows to limit the payload loss for BEF to only four passengers. However, the smaller battery results in higher consumption. Furthermore, the infrastructure plays a key role in recharging process, as only the H-H₂ICE can complete the mission if low-power supply is present (22 kW).

Finally, a LCA procedure has been conducted considering three different hydrogen production methods. The results underscore that the recharging process is detrimental in the long terms for BEFs, as the emissions' share due to utilization more than offsets the ones from manufacturing. Overall, BEFs are the best solution only when

gray hydrogen is adopted; with blue hydrogen, the results of H-H₂ICEs and BEFs are almost equal, while, with green hydrogen, H₂ICEs are always the most environmentally friendly solution.

It is evident that other aspects have to be carefully evaluated, as the ownership costs to fully understand the best configuration in the long-term. However, from the results here presented, rechargeable H-H₂ICEs fueled with either blue or green hydrogen seem to be the best compromise between payload capabilities, energy efficiency, and overall greenhouse gas emissions.

Future developments of this work should include evaluations and comparisons regarding tradeoffs among the three configurations in terms of feasibility and scalability. Moreover, future battery chemistries' impact should be accounted for as well.

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Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

- a_g = autonomy gain
- A_{wet} = wet area
- ACTV = Azienda del Consorzio Trasporti Veneziano
- BEF = battery electric ferry
- c_d = drag coefficient
- C&G = Come & Go scenario
- d_{prop} = propeller diameter
- D_{ship} = ship drag
- EC = energy consumption
- EU = European Union
- EO_{NOx} = engine-out NO_x emissions
- FC = fuel cell
- GHG = greenhouse gas
- GR = gear ratio
- Hf = high-flow refuel flow rate
- HFF = hydrogen-fueled ferry
- H-H₂ICE = hybrid hydrogen internal combustion engine
- H₂ICE = hydrogen internal combustion engine
- IMO = International Maritime Organization
- J_{prop} = propeller moment of inertia

L_{ship} = ship length
 LCA = lifecycle assessment
 LHV = lower heating value
 M_{ship} = ship gross tonnage
 NO_x = nitrogen oxides
 PM = particulate matter
 r_{22} = recharge at 22 kW
 r_{100} = recharge at 100 kW
 R_{prop} = propeller torque
 s = standard refuel flow rate
 SOC = state of charge
 T_{prop} = propeller thrust
 $\text{Tail}_{\text{NO}_x}$ = tailpipe NO_x emissions
 Trq_{prop} = torque to propeller
 $\text{Trq}_{\text{pwt,req}}$ = powertrain requested torque
 v_{ship} = ship speed
 W_s = storage weight
 $\rho_{\text{H}_2\text{O}}$ = water density
 ω_{prop} = propeller angular speed

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