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Towards the decarbonization of maritime public transport in Venice: an LCA-based environmental impact assessment

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ACTV	Azienda del Consorzio Trasporti Veneziano
AP	Acidification Potential
AVM S.p.A.	Azienda Veneziana della Mobilità
CO_2	Carbon Dioxide
CtG	Cradle-to-Grave
ECA	Emission Control Area
ECMS	Equivalent Consumption Minimization Strategy
EF	Environmental Footprint
EMS	Energy Management System
EoL	End-of-Life
EP	Eutrophication Potential
ESS	Energy Storage System
EU	European Union
FAME	Fatty Methyl Acid Ester
Fr_h	Froude Number
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	Hydrocarbons
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil

ICE	Internal Combustion Engine
IGDT	Information Gap Decision Theory
IMO	International Maritime Organization
IWP	Inland Waterway Vessels
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFP	Lithium Iron Phosphate
LLCA	Live-Life Cycle Assessment
LPG	Liquified Petroleum Gas
NO_x	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
pkm	Passenger per kilometre
PM2.5	Particulate Matter 2.5 µm
PM10	Particulate Matter 10 µm
PN	Particle Number
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaics
SoC	State of Charge
SO_x	Sulfur Oxides
TtW	Tank-to-Wake
WHO	World Health Organization
WtT	Well-to-Tank
WtW	Well-to-Wake

Abstract

This thesis aims to analyse the environmental impacts arising from the decarbonization of the fleet of AVM S.p.A. - ACTV, the public transport operator in the historic centre of Venice. The current fleet, comprising around 150 vessels, is largely equipped with internal combustion (diesel) engines. This configuration contributes significantly to the city's air pollution, problems exacerbated by the so-called 'canyon effect' of Venice's canals, which hinders the dispersion of local pollutants. The main objective is to compare the current environmental impacts of the baseline scenario with those of a hybrid (diesel-electric) propulsion model using a Life Cycle Assessment (LCA), focusing the analysis specifically on the propulsion system. To do this, the study will address the retrofit strategy, namely the replacement of the propulsion system in vessels already in use. According to this approach, the processes related to the hull's life cycle are not taken into account in the LCA model, thereby enabling a comparative analysis of the propulsion systems. Furthermore, retrofitting represents an optimal strategy for mitigating emissions, as it ensures the reuse and extension of the life cycle of hulls that are still operational, thereby avoiding the emissions associated with building entirely new fleets.

1. Introduction

1.1 The global situation

Globally, the transport sector is one of the main sources of pollution, accounting for approximately 23% of total greenhouse gas (GHG) and carbon dioxide (CO_2) emissions (Chakraborty et al., 2013; Colombo et al., 2023; Saldarini et al., 2023). Although road transport remains the dominant contributor to transport-related GHGs, accounting for approximately two-thirds of the sector's climate impact in the European Union (EU) and 73% worldwide (Chakraborty et al., 2013), maritime transport still exerts a considerable environmental burden, using roughly 300 million tonnes of fossil fuel annually despite its relative efficiency in terms of freight and passenger capacity (Saldarini et al., 2023; Seithe et al., 2020; B. Zincir et al., 2023).

Maritime transport currently accounts for 80% to 90% of international trade, as well as a significant share of passenger transport, making it a vital resource for the global economy (B. Zincir et al., 2023). Between 1970 and 2019, global seaborne trade volume grew by 425%, with the global shipping fleet continuing to expand and currently encompassing nearly 100,000 vessels of 100 gross tonnes or more (B. A. Zincir & Arslanoglu, 2024). Despite its economic importance, the sector accounts for 2.1% to 3.5% of global GHG emissions. Indeed, if the shipping industry were a country, it would rank sixth in terms of total CO_2 emissions (Perčić, Vladimir, et al., 2020; B. Zincir et al., 2023). In addition, this sector emits significant amounts of other climate-changing and harmful air pollutants, contributing globally to 14.74% of nitrogen oxide (NO_x) emissions, 9.84% of sulphur oxide (SO_x) emissions, and between 3.5% and 6.7% of atmospheric particulate matter (PM10 and PM2.5) (B. Zincir et al., 2023). According to projections, the rapid increase in commercial demand will lead to a 50% to 250% increase in shipping emissions by 2050 compared to 2008 levels, potentially accounting for 17% or more of global GHG emissions (Amat Ventayol et al., 2025; Mukherjee et al., 2020; Perčić, Vladimir, et al., 2020; Seithe et al., 2020; H. Wang et al., 2020; B. Zincir et al., 2023)

Another critical factor is the location of emissions: almost 70% of them are released within 400 km of the coast, causing serious damage to port cities and densely populated coastal areas (Miretti, Nicolotti, et al., 2025; Seithe et al., 2020). In Europe, it is estimated that emissions from ships contribute on average to 8% of the primary PM2.5, 16.5% of NO_x, and 11% of SO_x to which the population is exposed (Miretti, Nicolotti, et al., 2025; Perčić, Vladimir, et al., 2020; Seithe et al., 2020).

This exposure poses a serious threat to public health, as it can lead to chronic and acute diseases such as asthma, heart attacks, strokes, and lung cancer in exposed individuals. The World Health Organisation (WHO) estimates that air pollution, to which maritime transport contributes substantially, causes approximately 4.2 million premature deaths globally each year (Chakraborty et al., 2013; B. Zincir et al., 2023). In addition to harming human health, the deterioration of air and water quality compromises local flora and fauna, as well as urban architectural heritage, as evidenced by the decay of historic buildings in Venice (Saldarini et al., 2023).

1.2 The Venetian context

In this complex scenario, the city of Venice and its lagoon represent a unique case study on a global scale: analysing and addressing the critical issues related to the sustainability of Venetian public maritime transport can serve as a springboard for the development of exemplary models of sustainable maritime transport, which can be replicated in other parts of the world and potentially applied to major trade routes as well (Guarnieri, Bovo, et al., 2018; Guarnieri, Morandin, et al., 2018; Morandin et al., 2015).

Built on an archipelago of 117 interconnected islands, Venice represents the largest car-free urban area in Europe (Pecorari et al., 2013). Due to its unparalleled uniqueness and the extreme fragility of the city and its ecosystem, Venice and its Lagoon were designated as a UNESCO World Heritage Site in 1987 (Bucci et al., 2016; Padolecchia et al., 2023). The urban layout is intersected by a complex network of 177 canals, which constitute the only infrastructure for passenger mobility and transport logistics (Colombo et al., 2023; Morandin et al., 2015; Pecorari et al., 2013). This unique paradigm results in highly intensive waterborne traffic, with an estimated fleet of approximately 33.500 vessels operating within the city's historic centre (Bucci et al., 2016; Morandin et al., 2015; Padolecchia et al., 2023; Pecorari et al., 2013).

The environmental vulnerability of Venice is aggravated by a convergence of geographical, urban and logistical factors (Bucci et al., 2016; Pecorari et al., 2020). Firstly, the city is located at the eastern end of the Po Valley, a basin characterised by some of the worst air quality in Europe, resulting in background pollution that is already critical in itself (Pecorari et al., 2020). Added to these macro-regional conditions are the intrinsic characteristics of the city's historic centre, where the entire urban transport system operates exclusively on waterways (Pecorari et al., 2020).

The impact of local maritime traffic, consisting mainly of small and medium-sized vessels, has a profound effect on air quality, causing significant emissions of nanoparticles such as PM10 and NO_x, which systematically exceed legal limits (Colombo et al., 2023; Miretti, Nicolotti, et al., 2025; Pecorari et al., 2020). The urban morphology represents a further critical factor: the Venetian canals, the so-called 'rii', are in fact very narrow waterways surrounded by relatively tall buildings (see ***Figure 1***) (Bucci et al., 2016), a configuration that triggers the so-called 'canyon effect' (Pecorari et al., 2020). This microclimatic condition prevents natural air circulation and hinders the dispersion of exhaust gases, creating dangerous pollution hotspots (Bucci et al., 2016; Pecorari et al., 2020). Consequently, pollutants such as NO_x, PM2.5 and PM10 tend to stagnate in the same areas for several days, exposing residents and tourists to atmospheric concentrations harmful to public health (Pecorari et al., 2020; Saldarini et al., 2023).

Figure 1-*Satellite view of Venice's historic centre. The image highlights the intricate layout of the city's waterways, formed by numerous intertwining canals. The Grand Canal, easily recognisable by its greater width and distinctive inverted 'S' shape, is the city's main waterway and the hub of both public and private transport (ESA, 2011).*

A prime example is the Grand Canal and the network of adjacent canals (see ***Figure 1***). Due to the high density of buildings and heavy maritime traffic, harmful emission peaks are recorded in this area. In some heavily trafficked urban canals, annual NO_x concentrations exceeding 100 µg/m³ have been documented, a level twice the average 45 µg/m³ recorded in the rest of the city, with summer peaks reaching 265 µg/m³ (Pecorari et al., 2020).

In addition to health impacts, air pollution from diesel exhaust fumes poses a direct threat to Venice's historical and architectural heritage, particularly the stone facades of the palaces overlooking the Grand Canal (Guarnieri, Morandin, et al., 2018; Morandin et al., 2015). Carbonaceous particles and polluting compounds chemically attack the marble and Istrian stone, triggering progressive processes of degradation, corrosion and blackening (Guarnieri, Morandin, et al., 2018; Morandin et al., 2015; Saldarini et al., 2023) (see ***Figure 2***).

Figure 2-*The effects of local pollutants on Flogini's palace and the facade of Ca' d'Oro, in the Grand Canal. The latter shows the original white-stone aspect of historical buildings (Morandin et al., 2015)*

Finally, in addition to air pollution, there is also noise pollution, caused by the vibrations of diesel engines, and mechanical damage resulting from so-called 'moto ondoso' (Guarnieri et al., 2024; Guarnieri, Morandin, et al., 2018; Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025; Padolecchia et al., 2023). Indeed, the abnormal waves created by moving hulls systematically erode the foundations of buildings, roads and the delicate natural embankments of the lagoon, compromising their condition and stability (Bucci et al., 2016; Padolecchia et al., 2023).

1.3 Normative context

The transition towards sustainable shipping, which is currently governed by numerous international, European and local regulations, aims to reduce climate-changing emissions by gradually phasing out the current widespread use of traditional fossil fuels, such as heavy fuel oil (HFO) and marine diesel, in favour of technologies with a lower environmental impact (Qazi et al., 2023; B. Zincir et al., 2023; B. A. Zincir & Arslanoglu, 2024).

At a global level, the International Maritime Organisation (IMO) is gradually adopting stricter regulations through Annex VI of the MARPOL 73/78 protocol (American Bureau of Shipping, 2020; IMO, 2022; B. Zincir et al., 2023; B. A. Zincir & Arslanoglu, 2024). The IMO's strategic objective is to reduce GHG emissions in the maritime transport sector by at least 50% by 2050 compared to 2008 levels, introducing efficiency requirements for fleets and promoting the transition to electrification and the adoption of low-carbon fuels such as hydrogen, ammonia, methanol and biofuels (B. Zincir et al., 2023; B. A. Zincir & Arslanoglu, 2024).

In this regard, starting in 2020, the IMO has lowered the global sulphur limit allowed in marine fuels, imposing thresholds between 0.10% and 0.50% within specific Emission Control Areas (ECAs) (American Bureau of Shipping, 2020; B. Zincir et al., 2023; B. A. Zincir & Arslanoglu, 2024). ECAs are specific maritime zones designated by the IMO where much stricter emissions regulations apply than global standards (American Bureau of Shipping, 2020; Perčić, Vladimir, et al., 2020; Seithe et al., 2020; B. Zincir et al., 2023). The purpose of ECAs is to mitigate local air pollution by requiring ships in transit to use smoke abatement technologies or alternative fuels rather than traditional fossil ones (B. Zincir et al., 2023). Indeed, in the ECAs, the IMO standards defined as 'Tier' I, II and III are applied for engines installed on inland waterway vessels (IWP), with Tier III representing the strictest limit applicable (American Bureau of Shipping, 2020; International Maritime Organization, n.d.).

At the same time, at European level, the standards for propulsion systems in IWP have been revised by Regulation (EU) 2016/1628 on non-road mobile machinery (NRMM) (International Council on Clean Transportation, 2016; Marine & Offshore Bureau Veritas, n.d.). This Regulation introduced Stage V, considered the most restrictive standard worldwide, representing a significant step forward compared to the previous Stage IIIA, introduced by Directives 97/68/EC and 2004/26/EC (International Council on Clean Transportation, 2016; Marine & Offshore Bureau Veritas, n.d.). Indeed, whilst Stage IIIA was limited to regulating the total mass of NO_x and PM pollutants, Stage V not only imposes even stricter limits on NO_x but also introduces rigorous particle number (PN) limits, set at $1 \times 10^{12}/$ kWh ("Emission Standards-EU: Nonroad Engines," n.d.; International Council on Clean Transportation, 2016).

In this context, the Venice Lagoon stands out as a unique case study, as it is subject to local, European, and international regulations (Bucci et al., 2016; Guarnieri et al., 2024). Local public transport vessels must, in fact, comply with both the European Stage V requirements and the regulations of the Venice Port Authority (Municipality of Venice et al., 2024; Pellizzari, 2023). The latter stipulates the use of fuels containing less than 0.10% sulphur by mass for all vessels in transit, at mooring or at anchor, thereby aligning local requirements with the strictest international standards (Municipality of Venice et al., 2024; Pellizzari, 2023).

Given these regulatory frameworks and constantly evolving standards, ACTV, the public transport operator in Venice, is undergoing a complex transition. Although the fleet still largely consists of vessels with traditional diesel propulsion systems compliant with Stage IIIA, the company is implementing a strategic renewal plan focused on hybrid-electric propulsion (Bucci et al., 2016; Guarnieri, Morandin, et al., 2018; Pecorari et al., 2020). ACTV has now completed the construction of two hybrid vessels and is testing the first hybrid repowering of a traditional vaporetto; furthermore, the company's prospects include designing an additional 20 hybrid vaporetti (ACTV-Annual Financial Report, 2024).

This solution optimises the operating point, genset, of the thermal generators, facilitating compliance with Stage V parameters and ensuring full alignment with the most stringent local, European, and international standards (ACTV-Annual Financial Report, 2024; Miretti et al., 2022).

1.4 Objectives

Recent scientific literature has extensively documented the urgent need for an ecological transition in the maritime sector, a process that necessarily requires the gradual phasing out of highly polluting conventional fossil fuels (Amat Ventayol et al., 2025; Cucinotta et al., 2024; Perčić, Vladimir, et al., 2020).

Focusing on this issue in the specific context of the Venice Lagoon, and with reference to local public water transport, several studies have proposed detailed models to estimate the current operational emissions of ACTV water buses (Pecorari et al., 2013, 2020). At the same time, research has explored possible alternative solutions, demonstrating the technical feasibility and potential ecological benefits of hybridising and electrifying the fleet operating in Venice (Guarnieri et al., 2024; Miretti, Nicolotti, et al., 2025; Morandin et al., 2015).

In parallel, the Life Cycle Assessment (LCA) methodology has been applied in various studies to evaluate the sustainability of emerging technologies in the deep-sea shipping sector (Cucinotta et al., 2024; B. Zincir et al., 2023; B. A. Zincir & Arslanoglu, 2024).

However, an analysis of the state-of-the-art reveals a significant research gap, as no differential analysis has yet quantified the actual environmental benefits associated with retrofitting traditional ACTV water buses with a series-hybrid system (Miretti, Nicolotti, et al., 2025).

This thesis aims to fill this gap: the LCA methodology will be used to quantify the environmental benefits of replacing the current diesel propulsion systems with hybrid systems in the ACTV fleet. Consequently, the main research question guiding this thesis is:

To what extent can replacing traditional diesel propulsion powertrains with series-hybrid systems, implemented through retrofitting, contribute to the decarbonization of local public transport in the historic centre of Venice?

To comprehensively address the main question, the research is further divided into two specific sub-questions:

1) What are the primary environmental trade-offs identified across the life cycle of the propulsion systems?
2) What are the net benefits in terms of the decrease in emissions of NO_x, PM, and HC pollutants?

To achieve these objectives, the study is structured into specific methodological phases, as detailed in Methodology 3. Chapter 2 presents the operational context, detailing navigation in Venice alongside the characteristics of the ACTV fleet. In Chapter 4, the methodology is applied. It begins with a scoping review, presented in Section 4.1, to provide a comprehensive overview of existing knowledge and identify the optimal methodological framework for the LCA. Section 4.2 then presents the LCA. The analysis is conducted in accordance with the ISO 14040 and 14044 standards, using the OpenLCA software (Amat Ventayol et al., 2025; Cucinotta et al., 2024) and includes four steps: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation of results. The LCI is developed relying on primary data provided by ACTV and supplemented with secondary data from sector-specific literature. This is followed by the Life Cycle Impact Assessment (LCIA), and finally, a sensitivity analysis is performed to simulate alternative scenarios allowing for the modelling of critical parameters, further minimizing the overall environmental footprint. The results obtained in Chapter 4 are then comprehensively discussed in Chapter 5. Finally, Chapter 6 includes concluding remarks and suggestions for overcoming the limitations of the present study.

2 Case study

2.1 Navigation in Venice

In a historically and environmentally sensitive area such as the Venice Lagoon and its urban centre, the impact of local maritime traffic is particularly severe (Guarnieri, Morandin, et al., 2018; Pecorari et al., 2020). Local public transport, water taxis, and commercial and recreational vessels are almost entirely powered by obsolete internal combustion engines (ICEs) (Bucci et al., 2016; Guarnieri et al., 2024; Guarnieri, Morandin, et al., 2018; Saldarini et al., 2023). This results in a drastic and systematic exceedance of legal limits for atmospheric emissions, particularly for NO_x and PM10 (Bucci et al., 2016; Colombo et al., 2023; Guarnieri et al., 2024; Guarnieri, Morandin, et al., 2018; Miretti, Nicolotti, et al., 2025). In this context, the local public transport fleet, largely managed by Azienda Veneziana della Mobilità (AVM S.p.A.) through Azienda del Consorzio Trasporti Veneziano (ACTV), uses vessels such as the traditional 'vaporetti' (see ***Figure 3***), whose conventional marine engines present several opportunities to reduce emissions and comply with the most recent and rigorous sustainability standards (ACTV-Annual Financial Report, 2024; Bertagna et al., 2022; Bucci et al., 2016; Guarnieri, Morandin, et al., 2018; Padolecchia et al., 2023).

Figure 3-*Traditional Vaporetto (InVenice Today, 2026)*

Indeed, the current emission rate of these vessels is further exacerbated by the hydrodynamics of navigation in the shallow waters of the Venetian canals (Bucci et al., 2016; Guarnieri, Morandin, et al., 2018). Passenger and commercial vessels often operate in a 'stop-and-go' pattern. This dynamic is particularly pronounced along the Grand Canal, where there is an average of one stop every 4 minutes: at each restart, the hulls must overcome significant resistance triggered by the so-called 'squat effect'

(Guarnieri, Morandin, et al., 2018; Morandin et al., 2015). When a dislocating hull, such as that of ACTV's vaporetti, moves through shallow water, the mass of water displaced by the bow is forced to channel not only to the sides but also into the narrow space between the keel and the seabed. In accordance with Bernoulli's Principle, the restriction of the flow area forces the fluid to accelerate to maintain a constant flow rate, generating a pressure drop beneath the hull (Kazerooni & Seif, 2014; Scarpa et al., 2019). This drop causes suction of the hull toward the seabed, which results in an increase in draught and a change in the vessel's trim, typically causing a hydrodynamic depression of the stern (Kazerooni & Seif, 2014; Scarpa et al., 2019).

The fundamental parameter governing this dynamic is the depth-related Froude number (Fr_h) $Fr_h = \frac{v}{\sqrt{gh}}$ (where v is the boat's speed, g is the gravitational acceleration, and h is the depth of the channel) (Bucci et al., 2016; Scarpa et al., 2019). When the vessel accelerates and Fr_h approaches the critical value of 1, a condition in which the vessel's speed equals the speed of wave propagation along the seabed, hydrodynamic resistance increases exponentially (Bucci et al., 2016). In this regime, the energy delivered by the engine no longer translates into an increase in speed, but is dissipated to overcome water friction, generating wave motion (Bucci et al., 2016; Scarpa et al., 2019).

Consequently, to overcome both the initial inertia of the heavy hull of a typical vaporetto and the water resistance generated by the squat effect, operators are forced to run the engine at full power as soon as the vaporetto sets off, in order to reach cruising speed in the shortest possible time (Guarnieri, Bovo, et al., 2018; Guarnieri, Morandin, et al., 2018; Morandin et al., 2015; Pecorari et al., 2020). Moreover, due to the frequent stops and the short distances between them, operators must maintain peak engine loads also to achieve effective deceleration before docking (Guarnieri, Morandin, et al., 2018; Morandin et al., 2015; Pecorari et al., 2013).

This mechanism significantly clashes with the thermodynamic characteristics of ICEs. Marine diesel engines are in fact designed to minimise emissions and maximise efficiency at a constant speed (Miretti, Nicolotti, et al., 2025; Morandin et al., 2015). During the sudden accelerations imposed by stop-and-go operation, the air-fuel ratio in the cylinders does not have time to stabilise, resulting in incomplete combustion (Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025; Morandin et al., 2015). By operating outside the ranges of maximum thermodynamic efficiency, the engines expel massive quantities of PM and unburned gases, generating huge peaks in NO_x emissions (Guarnieri, Morandin, et al., 2018; Morandin et al., 2015; Pecorari et al., 2020).

2.1.1 The ACTV Nautical Fleet

The ACTV naval fleet consists of approximately 150 vessels, strategically divided into various categories to meet specific operational demands for navigation within the lagoon and Venice's canals (Colombo et al., 2023; Miretti, Nicolotti, et al., 2025; Nicolotti et al., 2024; Pecorari et al., 2013). The core of the fleet comprises about 70 traditional vaporetti (***Figure 3***), primarily deployed for passenger transport along the Canal Grande, complemented by roughly 60 motorboats, designated for the city's circular routes (Guarnieri, Bovo, et al., 2018; Mazzarino & Rubini, 2019; Pecorari et al., 2013, 2020). Connections to the islands and outer lagoon routes are operated by 20 'motobattelli foranei', larger vessels that can exceed 30 meters in length and accommodate over 320 passengers (Mazzarino & Rubini, 2019; Miretti, Nicolotti, et al., 2025; Pecorari et al., 2020). Finally, the fleet comprises 10 motor ships that can handle large passenger flows and 8 ferry boats dedicated to the combined transport of vehicles and passengers (Colombo et al., 2023; Pecorari et al., 2013, 2020).

The waterborne public transport network managed by ACTV is an extensive and highly capillary system, comprising 27 lines that cover a total distance of approximately 230 km (***Figure 4***) (Miretti, Nicolotti, et al., 2025; Pecorari et al., 2020). Annually, the service accounts for over 535.000 hours of navigation, transporting around 145 million passengers (Miretti, Nicolotti, et al., 2025; Pecorari et al., 2020). Operationally, the transport infrastructure is divided into three main categories: internal routes, operating strictly within the historic centre of Venice, which experience the highest passenger footfall and frequency (Colombo et al., 2023; Pecorari et al., 2013, 2020); circular and connecting routes, linking the city with the closest and most populated islands (Pecorari et al., 2020); lagoon routes, which are characterized by longer travel distances, navigating through the open waters of the lagoon to reach external areas (Mazzarino & Rubini, 2019; Miretti, Nicolotti, et al., 2025; Nicolotti et al., 2024; Pecorari et al., 2020).

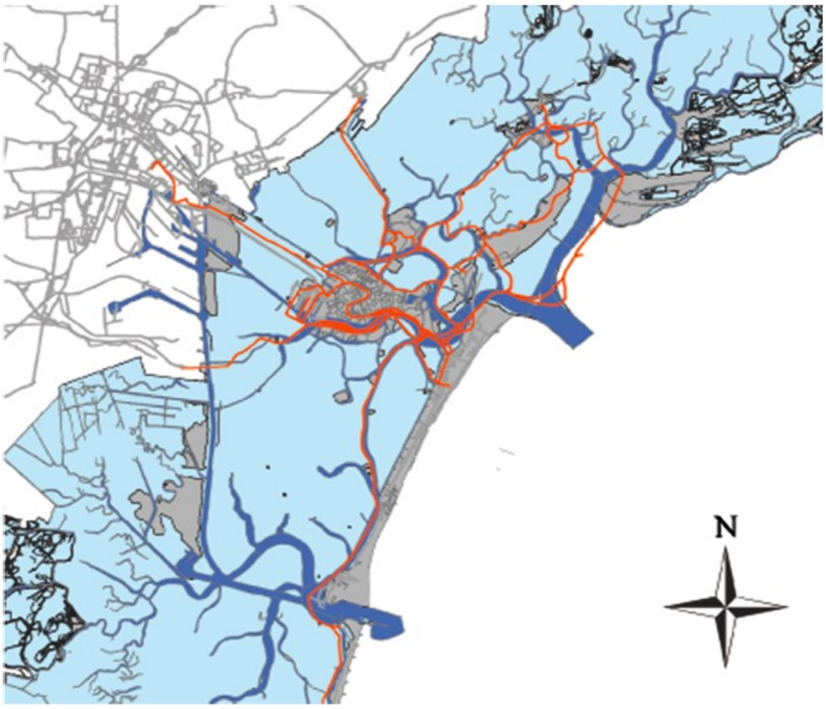

Figure 4*-Navigation routes within the Venice Lagoon (Pecorari et al., 2013).*

2.2 State of the art of the technology

Considering the complex dynamics outlined above, it is clear that simply upgrading and optimising diesel engines (see ***Figure 5***) is insufficient to mitigate the emissions produced (B. Zincir et al., 2023). Safeguarding the city and the lagoon requires directing investment towards the electrification of maritime vessels, to ensure navigation that minimises chemical air pollution and noise impacts (Bucci et al., 2016; Colombo et al., 2023). In this context, the main local public companies, including ACTV and Gruppo Veritas, which is responsible for urban waste management, are launching significant investments in the development of hybrid-powered fleets (Bucci et al., 2016; Guarnieri et al., 2024; Guarnieri, Morandin, et al., 2018; Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025).

From a system architecture perspective, hybrid propulsion can be divided into two distinct configurations (Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025; B. Zincir et al., 2023):

1) Parallel hybrid: In this configuration, the ICE and the electric motor are mechanically connected to the same propeller shaft (Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025; B. Zincir et al., 2023). This architecture allows the torques of the two propulsion units to be combined, or the electric motor to be used as a generator while the ICE is running (Padolecchia et al., 2023). As a mechanical link is maintained between the diesel engine's rotational speed and the propulsion speed, the scope for continuously optimising the ICE's operating point is limited (Miretti, Novello, et al., 2025).

2) Series hybrid (***Figure 5***): In this solution, the ICE is completely decoupled from the propeller shaft and acts exclusively as a generator to power the electric motors or recharge the battery pack, known as the Energy Storage System (ESS) (Miretti, Novello, et al., 2025; B. Zincir et al., 2023).

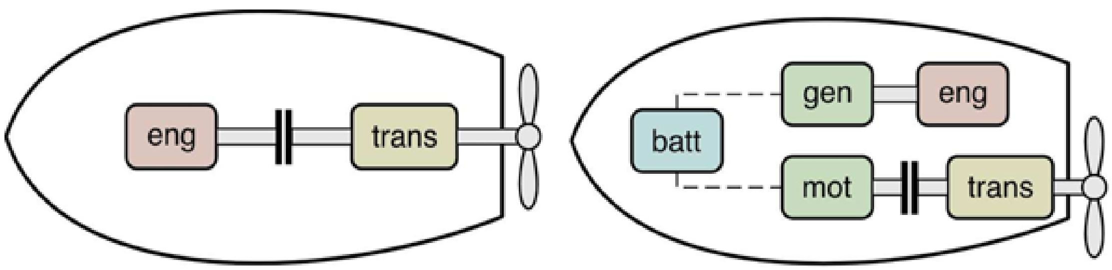

Figure 5*-Traditional diesel (on the left) and series-hybrid (on the right) architectures (Miretti et al., 2022)*

For displacement-hulled vessels and for the typical operating profiles of Venetian vaporetti, with highly variable speeds, the series architecture appears to be the most suitable (Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025). It offers several strategic advantages, including load levelling (Miretti, Novello, et al., 2025): by decoupling the motor from the propeller shaft, it can maintain a constant, high-efficiency rotational speed (Miretti, Novello, et al., 2025). This occurs because the battery pack acts as a 'leveller', absorbing energy fluctuations, recharging when propulsion demand is low, and releasing energy during transient absorption peaks, for example when a strong acceleration occurs (Miretti, Novello, et al., 2025). This mechanism allows for a drastic reduction in fuel consumption and emission peaks, as well as improved operational stability in stop-and-go conditions, keeping the engine at its optimal rotational speed and maximising efficiency (Miretti, Novello, et al., 2025).

The efficiency of hybrid propulsion, however, depends entirely on the Energy Management System (EMS), the algorithm that determines the power split at any given moment, namely the distribution of the required power between the powertrain and the ESS (Guarnieri et al., 2024; Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025).

EMSs are divided into two categories: Rule-Based and Optimization-Based (Guarnieri et al., 2024; B. Zincir et al., 2023). The former relies on deterministic logic, based on predefined efficiency maps that operate according to static thresholds, such as the battery's State of Charge (SoC) or the torque demand (Guarnieri et al., 2024; B. Zincir et al., 2023). Optimisation-Based EMSs, on the other hand, represent more advanced and promising approaches (Guarnieri et al., 2024; B. Zincir et al., 2023). Among these are the so-called Equivalent Consumption Minimisation Strategies (ECMS), which allow for the calibration of the optimal trade-off between fuel consumption, NO_x emissions, and unburned hydrocarbons (HC) (Guarnieri et al., 2024; Miretti, Nicolotti, et al., 2025; Miretti, Novello, et al., 2025).

Furthermore, some recent studies suggest that integrating algorithms based on Information Gap Decision Theory (IGDT) can be particularly effective in minimising emissions while ensuring service reliability (Vahabzad et al., 2020). IGDT, in fact, enables the management of uncertainties inherent in the operational profile, such as variations in passenger load or weather and sea conditions, minimising emissions and operating costs while ensuring maximum robustness of the operational service (Vahabzad et al., 2020).

To accelerate the transition to hybrid propulsion systems, one of the most proactive and strategic measures to adopt in Venice is retrofitting (Guarnieri, Morandin, et al., 2018). This practice involves keeping existing hulls in use, which often have a lifespan of more than 40 years, by replacing only the diesel propulsion system with a hybrid system, thereby eliminating the industrial impact of producing new vessels with high emissions (Miretti, Nicolotti, et al., 2025). Moreover, to maximise the lifespan of battery packs and limit degradation caused by continuous and sudden accelerations, typical of 'stop and go' navigation profiles, the most advanced ESS designs include supercapacitors (Guarnieri, Morandin, et al., 2018; Padolecchia et al., 2023; B. Zincir et al., 2023). These, whilst storing little overall energy, can discharge in a matter of seconds, providing the strong initial burst of power, known as peak shaving, necessary to overcome the initial resistance of the water that the vaporetti face at every departure, thereby significantly extending the life of the batteries (Guarnieri, Morandin, et al., 2018; Guellard et al., 2013; Padolecchia et al., 2023; B. A. Zincir & Arslanoglu, 2024). Additionally, retrofitting serves as an essential strategy for fleet operators to comply with increasingly stringent maritime emissions standards (Miretti, Nicolotti, et al., 2025).

However, this process presents complex engineering challenges that must be carefully managed. Indeed, ESS require substantially greater volume and weight compared to conventional diesel systems to store an equivalent amount of energy (Guarnieri, Morandin, et al., 2018; Miretti, Novello, et al., 2025). Furthermore, in traditional vaporetti, where onboard space is highly constrained and vessel draught is restricted, retrofitting may pose hydrodynamic and stability issues, meaning it may not always be a universally applicable solution, especially when a reduction in the number of passengers is needed to compensate for the load (Colombo et al., 2023; Padolecchia et al., 2023).

Despite these technical challenges, the strategic importance of retrofitting cannot be overstated (Miretti, Nicolotti, et al., 2025). From a life cycle perspective, it perfectly embodies the principles of the circular economy by extending the life of existing, functional physical assets and drastically cutting emissions associated with shipbuilding (Cucinotta et al., 2024; Seithe et al., 2020).

3 Methodology

3.1 Literature review

The initial phase of the research was dedicated to reviewing the existing scientific literature to establish the state-of-the-art in the application of LCA in the maritime sector and to ensure comparability with other studies. To achieve this, a Scoping Review was conducted. This method is an evidence synthesis approach utilized to determine the extent, range, or coverage of the available literature on a given topic. Consequently, this type of analysis is particularly effective for comprehensively mapping existing knowledge and providing an overview of the literature (Munn et al., 2018).

The literature search was conducted utilizing the Scopus database, following the methodological approaches proposed by Cucinotta et al., 2024, and Mondello et al., 2023. The database queries were structured using various combinations of keywords from three different fields. The first family pertains to the methodology (“Life Cycle Assessment”, “Life Cycle Analysis”, “LCA”), the second concerns the naval sector (“Ship”, “Naval”, “Maritime”, “Vessel”), and the third addresses the propulsion systems (“Propulsion”, “Engine”, “Motor”, “Fuel”). ***Figure 6*** shows the adopted combinations.

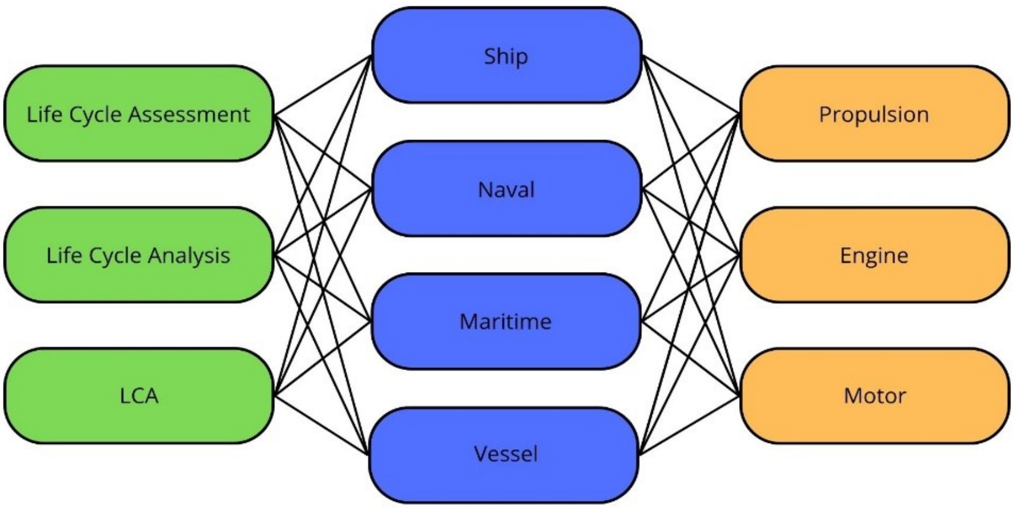

Figure 6*-Combination of keywords used to conduct the review*

To conduct the review, strict eligibility criteria were applied to ensure the relevance and currency of the results: only peer-reviewed journal articles published in English between 2017 and 2026 were included, thereby guaranteeing the inclusion of the most up-to-date research. Following a screening of titles and abstracts, the full texts of the retrieved papers were evaluated to select studies relevant to the review. After selection, a bibliometric analysis was conducted. This included a keyword co-occurrence analysis using the VOSviewer software to evaluate emerging research trends, along with an assessment of the publications' geographical, temporal, and subject-area distributions. Furthermore, this review methodology facilitates the identification of key methodological requirements, ensuring comparability with previous studies regarding the choice of the functional unit (FU), the definition of system boundaries, and the selection of the LCIA method (see **Table 1**).

3.2 Life Cycle Assessment

LCA is a standardised method regulated at international level by ISO 14040 and 14044 standards, ensuring reliable results that are comparable with other studies in the sector (ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022). This methodology allows the impact of a product or process to be examined throughout its entire life cycle. Environmental performance is quantified by analysing energy and material flows at every stage: from raw material extraction to the End-of-Life (EoL), through the manufacturing and the use phase (ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022).

Unlike traditional monitoring, which is often limited to measuring direct emissions during the use phase, the holistic approach of LCA enables the identification of environmental hotspots throughout the entire life cycle (Guinée et al., 2011). This includes upstream emissions, linked to the material and energy flows of industrial processes, as well as the potential for reuse and recycling in the EoL phase (Guinée et al., 2011; National Academies of Sciences Engineering & Medicine, 2022).

Furthermore, this methodology can assess a wide range of impact categories, highlighting the overall footprint of the product or process under investigation (Guinée et al., 2011; National Academies of Sciences Engineering & Medicine, 2022).

LCA involves four fundamental phases (ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022) (***Figure** 7*):

1) Goal and Scope definition.
2) Life Cycle Inventory (LCI).
3) Life Cycle Impact Assessment (LCIA).
4) Interpretation of results.

The Goal and Scope definition represents the first fundamental step of the LCA methodology (ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022). This phase establishes the rationale for the study and defines the system boundaries, explicitly stating which life cycle stages are included in the analysis (Cucinotta et al., 2024; ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022; B. A. Zincir & Arslanoglu, 2024). Furthermore, it introduces the functional unit (FU), which serves as the quantified reference of the study. Defining the FU is crucial for ensuring that the stages under evaluation are functionally equivalent, thereby guaranteeing a comparable, objective, and methodologically sound analysis (Amat Ventayol et al., 2025; B. A. Zincir & Arslanoglu, 2024).

The LCI constitutes the operational quantification phase. It involves the rigorous collection and compilation of data regarding all material and energy flows, both inputs and outputs, crossing the defined boundaries (Amat Ventayol et al., 2025; Cucinotta et al., 2024; ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022; B. A. Zincir & Arslanoglu, 2024).

Subsequently, the LCIA translates raw data from the LCI into results through standardized impact assessment methods. All input and output flows are classified and characterized into specific impact categories, such as Global Warming Potential (GWP), Terrestrial Acidification, and Human Toxicity (Amat Ventayol et al., 2025; Cucinotta et al., 2024; ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022; B. A. Zincir & Arslanoglu, 2024).
After this phase, a Scenario Analysis can be performed to examine how different conditions or strategic decisions affect the final impacts. This process is crucial for verifying the robustness of the results, as well as for formulating alternative hypotheses and evaluating how variations can influence the overall systems (Guinée et al., 2011).

Finally, the Interpretation phase of the procedure synthesizes and critically evaluates the findings from the previous stages in relation to the defined objectives. During this final step, it is possible to identify critical environmental hotspots, draw robust conclusions, and formulate strategic recommendations to support decision-making processes regarding the analysed systems (ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022; B. A. Zincir & Arslanoglu, 2024).

LCA serves as a useful decision-making and environmental assessment tool, identifying gaps and opportunities to reduce environmental impacts within the product or processes' life cycle (Guinée et al., 2011; ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022; National Academies of Sciences Engineering & Medicine, 2022).

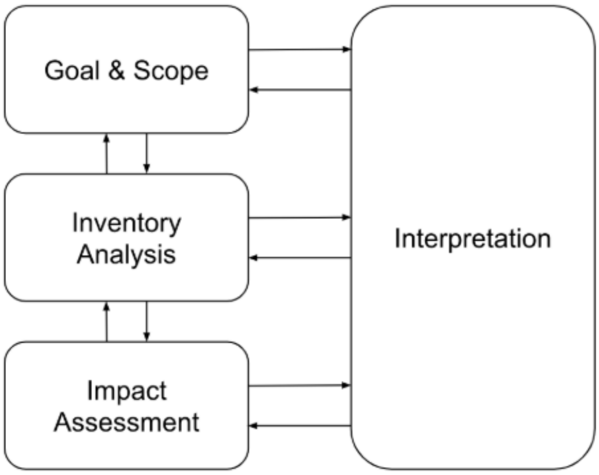

Figure 7*-LCA framework according to ISO 14040 (ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022).*

4 Results

4.1 Literature Review

To conduct the review, all possible keyword combinations were searched using the logical operator "AND", and the eligibility criteria reported in Section 3.1 were applied. The entire screening process is documented in the PRISMA flow diagram (***Figure 8***).

The initial search yielded a total of 630 records, of which 350 were duplicates and therefore excluded. Additionally, 123 studies were removed because they fell outside the scope of the present analysis. The remaining 157 articles were screened, and 103 were excluded based on their titles and abstracts, as the Life Cycle Assessment methodology was not applied. The full text was available for 49 out of the 54 remaining papers. 23 papers were then excluded because they focused on fuel types and did not provide a broader evaluation of the powertrain architecture and performance, falling outside the defined scope of the present analysis.

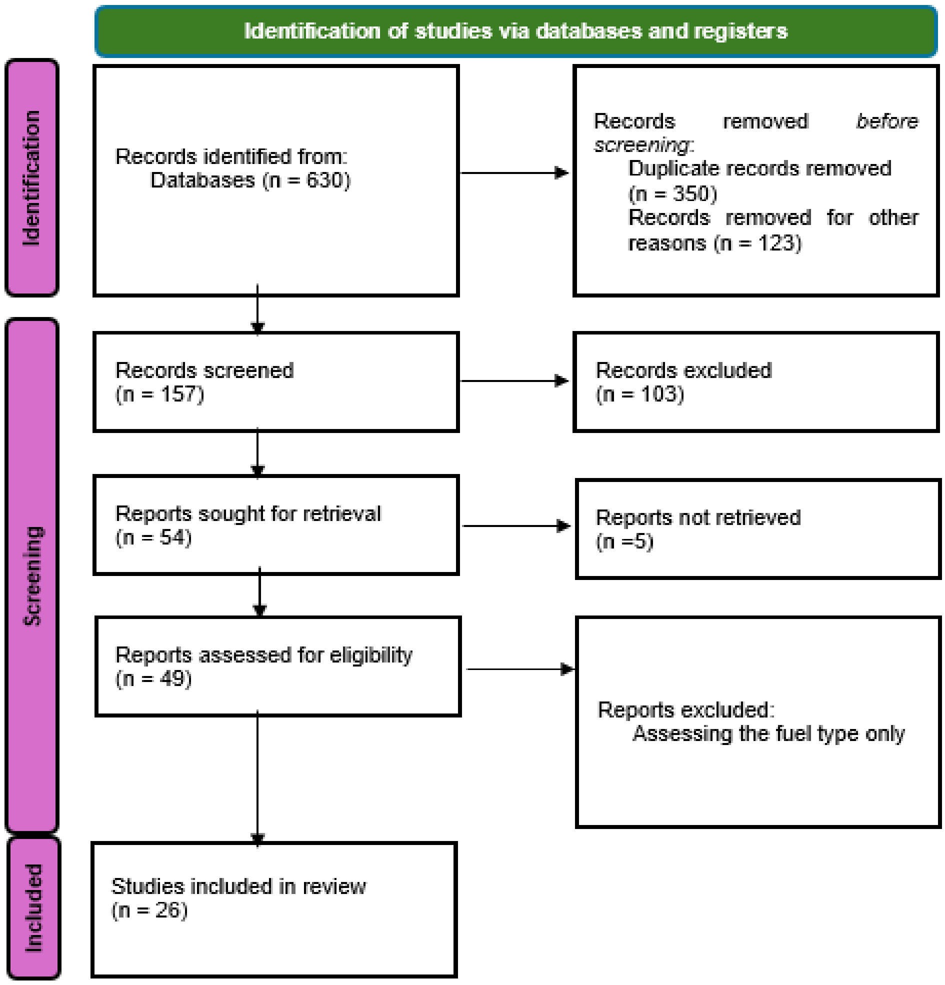

Figure 8-*PRISMA Flow Diagram used for the identification of the studies used to conduct this review*

A preliminary bibliometric analysis of the retrieved research papers provides insightful trends regarding the evolution and focus of the research field. To delve deeper into the structure of the selected literature, the papers were entered into the VOSviewer software, which provided a keyword co-occurrence analysis. As illustrated in ***Figure 9***, the network reveals a highly interconnected structure organized around four primary clusters. The orange cluster, partially overlapping with the purple one, represents the methodological core of the literature, linking "LCA" and "Life Cycle Assessment" to the green and yellow clusters. The former highlights the transition toward low-carbon technologies, featuring nodes such as "Battery", "Carbon Credit", and "Decarbonization", as well as methods for assessing the economic impact of the transition, represented by "LCCA". The latter cluster represents "Marine Fuels", the sector targeted in this analysis.

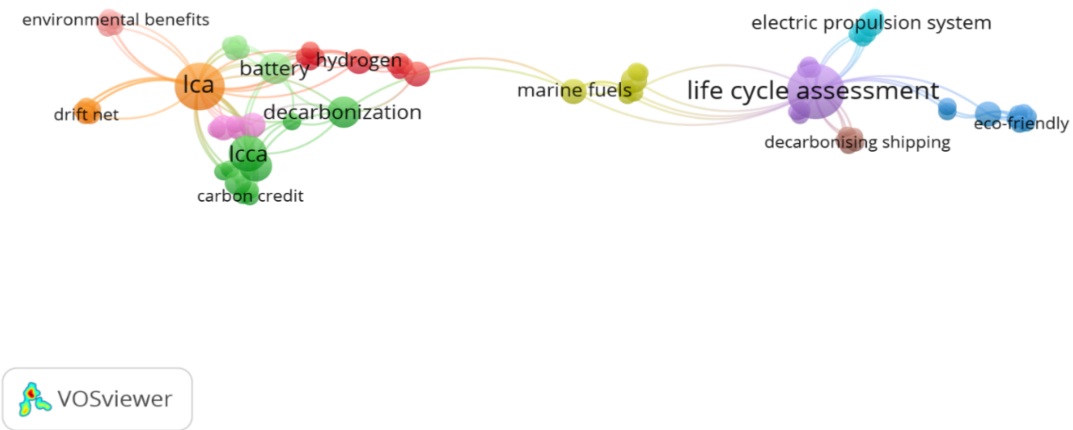

Figure 9*-VOSviewer keyword co-occurrence network analysis*

The temporal distribution of publications, illustrated in ***Figure 10***, highlights growing academic interest in the subject, especially after 2020, with peaks in 2022 and 2025. This upward trend underscores the growing urgency within the maritime sector to comply with stringent international regulations regarding powertrain technologies and their footprint (IMO, 2022). Furthermore, the sustained publication rate reflects the increasing need for rigorous LCA applications to evaluate the true impacts of alternative propulsion systems (Nomak & Çiçek, 2026).

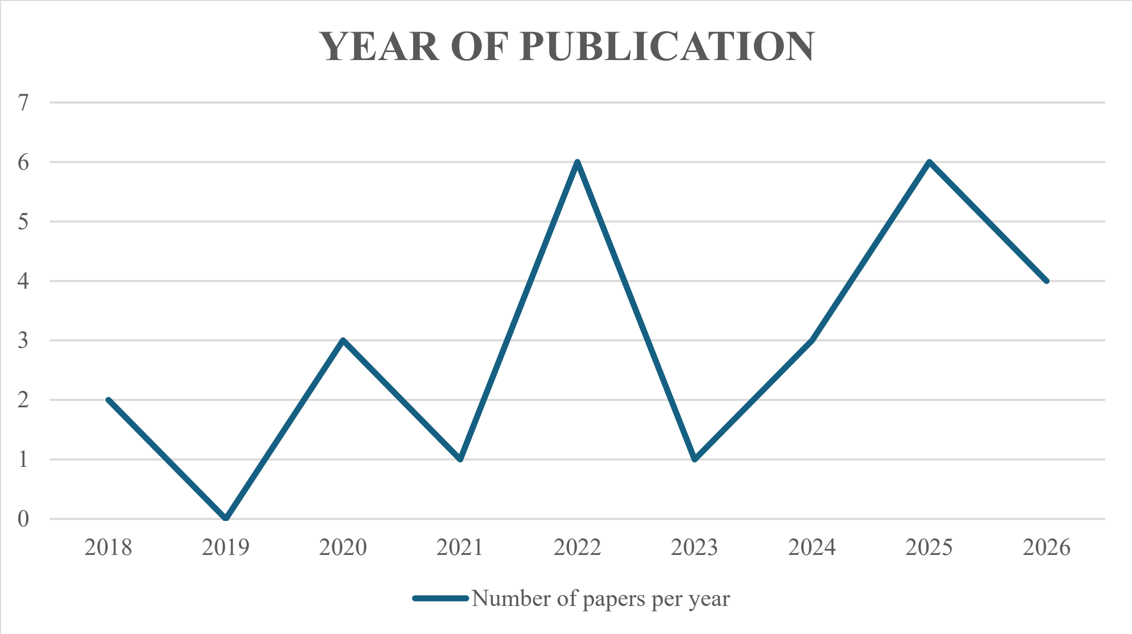

Figure 10-*Temporal distribution of the selected research papers*

From a disciplinary perspective (***Figure 11***), the selected literature exhibits a distinctly multidisciplinary character, driven primarily by three key subject areas: Environmental Sciences (34%), Engineering (25%), and Energy (20%). These main domains are complemented by subjects such as Business Management and Accounting (3%), Social Sciences (3%), Chemistry (3%), and Earth and Planetary Sciences (3%). This distribution confirms that while the transition towards more sustainable maritime mobility remains dominated by scientific and technical research, it is increasingly being explored from economic and social standpoints. Consequently, this underscores the complexity of the challenge, which requires holistic integration across different disciplines.

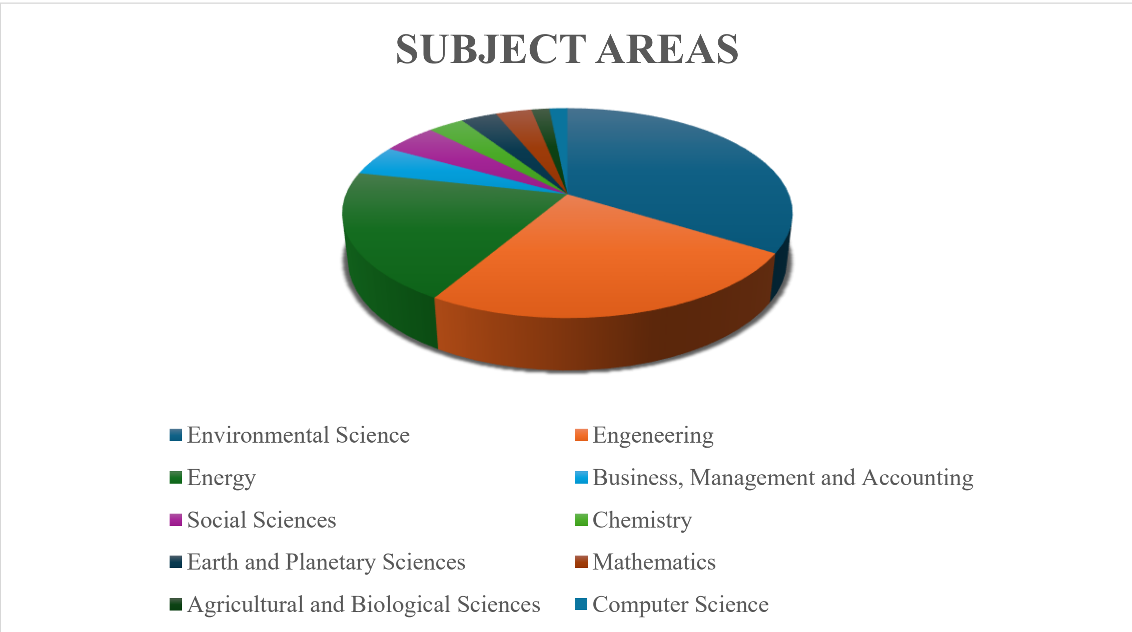

Figure 11-*Disciplinary domains of the selected research papers*

Geographically (***Figures 12*** and ***13***), the papers are affiliated with institutions spread all over the world. However, the most represented country is South Korea, followed by the United Kingdom, China, and Croatia. The dominance of Asian countries aligns with their substantial shipbuilding capacity and battery manufacturing (Laurence & Bai, 2025; Park, 2026). Conversely, the substantial scientific output from the United Kingdom and the United States of America is primarily driven by the extensive application of the LCA methodology in naval engineering studies, coupled with ambitious decarbonization targets for the marine sector (Bilski, 2025; Jeong et al., 2018, 2020; Maydison et al., 2025; Park et al., 2022; Y. Wang et al., 2024). Furthermore, the prominence of Mediterranean countries such as Italy, Spain, and Croatia highlights their intensive academic focus on short-sea shipping, vessel electrification, and coastal ecosystem protection (Ceballos-Santos et al., 2023; D'Amico et al., 2026; Koričan et al., 2022; Perčić, Ančić, et al., 2020; Perčić et al., 2024; Villanueva-Rey et al., 2018).

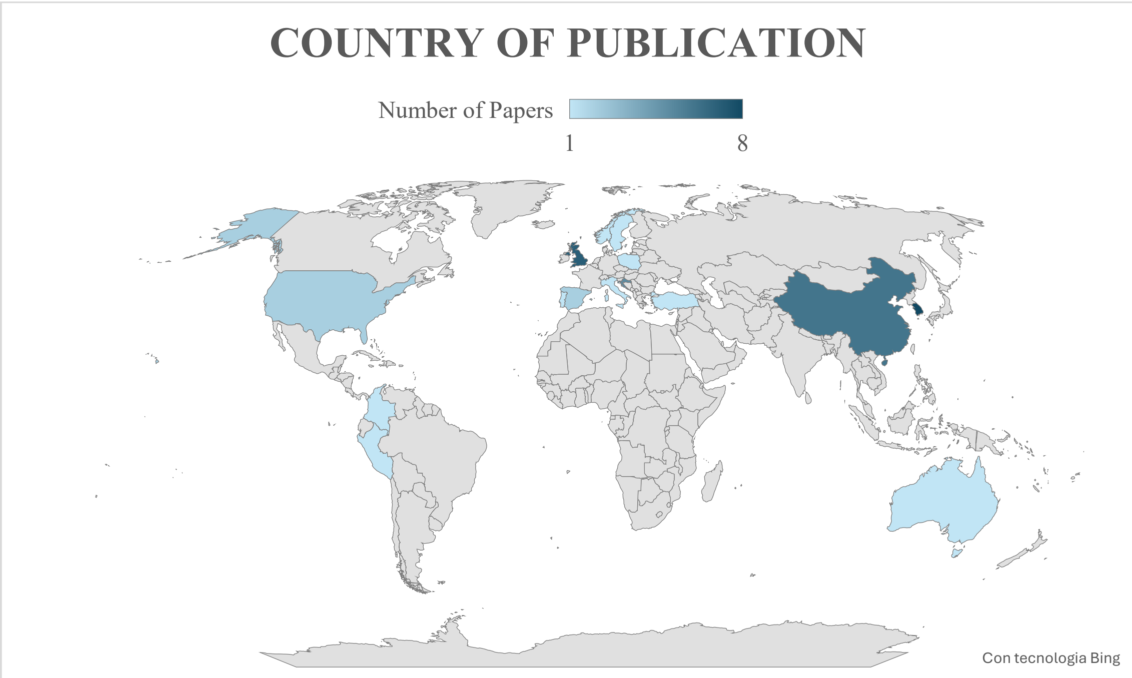

Figure 12*-Geographical distribution of the selected research papers*

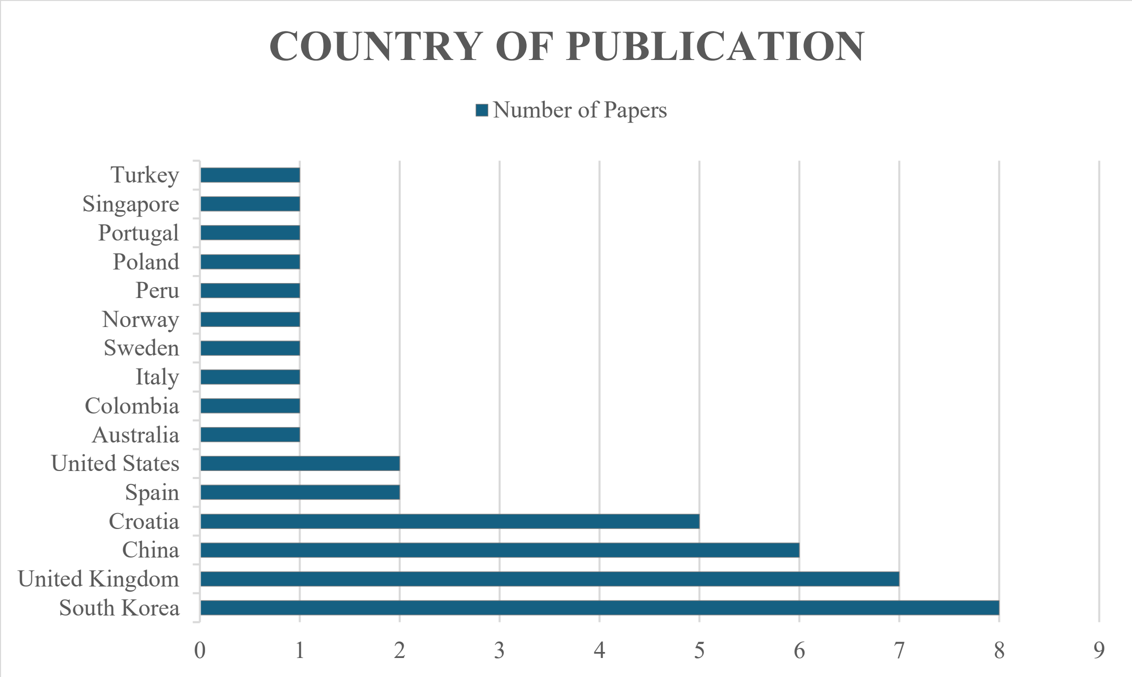

***Figure 13**-Geographical distribution of the selected research papers*

The Scoping Review approach proved to be highly appropriate for exploring a field such as the life-cycle analysis of marine propulsion systems. **Table 1** illustrates the details of the LCAs conducted in the selected research papers, highlighting the software and database used, the FU, the system boundaries, the impact assessment method, and the type of propulsion system evaluated:

Authors	Software and Database	Functional Unit	System Boundaries	Impact Assessment Method	Propulsion systems assessed
Bilski, 2025	Unspecified	Unspecified	Unspecified	GHG emissions, primary energy consumption, potential impact on aquatic ecosystems	Full-electric, hydrogen only and hybrid in the yachting sector
Borja-Marrugo et al., 2025	SimaPro v9.3 with Ecoinvent v3.8	Total navigable distance in km	Cradle-to-Gate (CtG)	CML 2000	Conventional, hybrid and full-electric

Ceballos-Santos et al., 2023	SimaPro v9.3 with Ecoinvent v3.5 and Agribalyse v3.0	1 kg of landed fish by Cantabrian fleet in year 2019	‘Cradle-to-port’, raw material extraction, construction, use and maintenance	EF v3.0	Fishing vessels
D’Amico et al., 2026	Ecoinvent database, software unspecified	Three-phase induction motor	Well-to-Wake (WtW) for the fuel life cycle; electricity production; motor operating phase	Environmental Product Declaration of the Swedish Environmental Council	Control algorithms applied to motor’s operational phase
Douglas et al., 2025	GREET	Unspecified	WtW	GWP 100-AR5	ICEs and electric motors
Gopujkar & Worm, 2024	GREET v2020	A ferry trip from Mackinaw City to Mackinac Island and back	WtW	Calculation of CO_2, NO_x and SO_2 emissions	ICE-powered and electric ferries
Hüllein et al., 2026	SimaPro v10.1.0.2 with Ecoinvent v3.9.1	Provision of energy for one fishing day	CtG	ReCiPe 2016 midpoint (H)	Battery and Fuel cell in a coastal fishing vessel
Jeong et al., 2018	GaBi and in-house program	Unspecified	WtW	CML 2016, ReCiPe, TRACI, CML 2010	Traditional diesel and hybrid in a ferry and optimal engine configuration in a tug vessel

Jeong et al., 2020	Sphera GaBi v2019	Unspecified	Production, transport and use	GWP, Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Creation Potential (POCP)	Diesel-mechanical and fully battery-powered vessels
Jeong et al., 2022	GaBi v2020	Unspecified	CtG	GWP, AP, EP, POCP	Diesel and battery-electric propulsions
Kanchiralla et al., 2022	Ecoinvent v3.7.1	One round trip from Gothenburg to Kiel and back with the case study ship	CtG	GWP20, GWP100-AR6, EF v3.0	ICEs, fuel cells and carbon capture technologies
S. Kim et al., 2022	Sphera GaBi v2021	1 kWh	Well-to-Tank (WtT) and Tank-to-Wake (TtW)	CML 2001 (GWP, AP, EP, POCP)	Diesel and hybrid powered fishing boats
J. K. Kim et al., 2025	Undefined	kg CO_2eq/kg for Construction; g CO_2eq/MJ for Operation; kg CO_2eq/kg for Scrapping	Construction, Operation and Scrapping	GWP	Liquefied Petroleum Gas (LPG) generator engine motor; LPG main engine direct propulsion; battery electric propulsion

Koričan et al., 2022	GREET v2021	Undefined	Manufacturing, Well-to-Pump, Pump-to-Wake	Carbon Footprint	Diesel-powered fishing vessels
Laurence & Bai, 2025	OpenLCA with Ecoinvent v3.8	Total distance traveled during the entire ship's lifetime	CtG	CML-IA	Diesel-powered and full-electric vessels
Maydison et al., 2025	GREET v2023	Fulfillment of the operational scenario function of the designed ship	TtW (only operational phases)	GWP20-AR6	Diesel-battery hybrid electric propulsion systems for fast patrol boats
Nomak & Çiçek, 2026	Excel using process data from peer-reviewed literature	Provision of auxiliary propulsion and hotel electrical services over 20 years or 20,000 nm (~37,000 km)	Propulsion and onboard energy-system differences	GWP100	Renewable-electric propulsion systems in sailing yachts
Park et al., 2022	GaBi, RETSreen and Matlab/Simulink	kg CO_2eq/kg, kg SO_2eq/kg, kg Phosphate eq/kg, kg Ethene eq/kg	WtW	CML 2001 (GWP, AP, EP, POCP)	Solar-electric propulsion compared to diesel and plug-in battery
Park, 2026	Matlab/Simulink	kg CO_2eq/kg and kg CO_2eq/kWh	WtW	GWP	Conventional diesel main engine, diesel-electric, full-electric supplied by shore electricity and solar-electric

Perčić, Ančić, et al., 2020	GREET v2018	Unspecified	WtW	Carbon Footprint (GWP)	Diesel-powered and battery-powered with and without photovoltaic (PV) cells (for one type of ship)
Perčić et al., 2021	GREET v2020	Unspecified	WtW	Carbon Footprint (GWP)	Diesel-powered and battery-powered with and without PV cells (for three types of ships)
Perčić et al., 2022	GREET v2020	Amount of emissions over the ship's lifetime (20 years)	WtW	CO_2, NO_x, SO_x	Diesel engine and full-electric in short-sea navigation ro-ro passenger ships
Perčić et al., 2024	GREET v2022	1 kWh of energy consumed	CtG	CO_2, CH_4, N_2O, NO_x, SO_x, PM	Full electrification of two types of fishing vessels with different types of lithium batteries
Villanueva-Rey et al., 2018	SimaPRO v8.2	1 metric ton of landed pilchard at a Galician port	CtG	ILCD, IPCC 2013, ReCiPe midpoint (H)	Fishing vessels

H. Wang et al., 2020	GaBi and ShipLCA (in-house software)	Unclear	Construction, Operation and Scrapping	CML (GWP, AP, EP, POCP)	5 different ICE configurations
Y. Wang et al., 2024	OpenLCA with ELCD v3.2 and Ecoinvent v3.7.1	Lifecycle impact of the propulsive power required for 1 km distance traveled under nominal loading and average hotel loads, presented in kg or g emission-eq/ km	Manufacturing, WtT, TtW and EoL	CML 2001 (GWP, AP, EP, POCP)	Hybrid PV-electricity-diesel and hydrogen fuel cells in an inland waterway vessel

A more detailed analysis of the 26 papers identified for the Scoping Review indicates that employing the LCA methodology to evaluate alternative powertrains is essential to overcome the limitations of measuring only operational emissions (Jeong et al., 2020, 2022; Villanueva-Rey et al., 2018). This approach provides a holistic analysis that encompasses both upstream and downstream impacts (Douglas et al., 2025; Perčić et al., 2022; H. Wang et al., 2020). Indeed, from a methodological standpoint, the reviewed papers predominantly adopt a Cradle to Grave (CtG), or Well to Wake (WtW), approach, aiming to avoid misinterpretations by evaluating the entire life cycle of the considered systems (Ceballos-Santos et al., 2023; D'Amico et al., 2026; Douglas et al., 2025; Jeong et al., 2018; Laurence & Bai, 2025; Villanueva-Rey et al., 2018). Moreover, LCA facilitates a multi-criteria evaluation, enabling the simultaneous calculation of multiple environmental impact categories (D'Amico et al., 2026; Hüllein et al., 2026; Jeong et al., 2018; Kanchiralla et al., 2022).

When integrated with Life Cycle Cost Assessment (LCCA), LCA establishes a comprehensive decision-making framework that supports shipowners, shipbuilders, and policymakers in making strategic, long-term oriented decisions (D'Amico et al., 2026; Jeong et al., 2018; Perčić et al., 2021, 2022; Villanueva-Rey et al., 2018). Furthermore, traditional LCA models can be further refined through the Live-Life Cycle Assessment (LLCA) framework (Park, 2026; Park et al., 2022). By coupling LCA software with advanced dynamic simulators like MATLAB/Simulink, and direct empirical measurements, LLCA calculates impacts based on high-resolution, real-time kinematic profiles, delivering highly accurate insights (Park, 2026; Park et al., 2022).

4.1.1 Hybrid technology

The selected literature extensively analyses and compares various technological pathways for the implementation of alternative maritime powertrains (Bilski, 2025; Perčić et al., 2022, 2024) and identifies the hybrid diesel-electric architecture as one of the most effective transitional strategies for marine decarbonization (Koričan et al., 2022; Maydison et al., 2025; Park, 2026).

Furthermore, some papers verified the efficiency of the hybrid infrastructure in retrofitting scenarios, proving that replacing or assisting traditional diesel systems with electric drives effectively lowers the carbon footprint and operational costs on already existing and operating vessels (Koričan et al., 2022; H. Wang et al., 2020). This is consistent with several LCA models, which demonstrate that optimizing engine configuration, such as substituting massive conventional engines with a group of medium-sized generator sets, significantly abates costs and emissions while improving operational efficiency (Jeong et al., 2018; H. Wang et al., 2020).

However, hybrid systems can incur significant weight and spatial penalties, necessitating high-level EMS to optimize power distribution and minimize transmission losses (Laurence & Bai, 2025; Maydison et al., 2025; Nomak & Çiçek, 2026). Moreover, although hybrid architectures effectively mitigate operational environmental impacts and reduce GWP, they are often associated with natural resource depletion, as well as high risks of human toxicity and ecotoxicity (Hüllein et al., 2026; Perčić et al., 2021).

Indeed, several research papers highlight that adopting diesel-electric propulsion does not inherently guarantee pollution abatement (Borja-Marrugo et al., 2025; Hüllein et al., 2026; Park, 2026). Many sources underscore the critical ‘Burden-shifting’ phenomenon that may be caused by batteries: while downstream emissions are reduced to zero, impacts are drastically offset by high upstream emissions (Borja-Marrugo et al., 2025; Hüllein et al., 2026; Y. Wang et al., 2024). For instance, burden-shifting is evident in the manufacturing phase of lithium-ion batteries (Laurence & Bai, 2025), where the extraction and processing of critical raw materials often introduce severe upstream impacts, particularly concerning Material resources and Ozone Depletion Potential, Human and Marine Toxicity Potentials (Hüllein et al., 2026; Laurence & Bai, 2025).

Nonetheless, the reviewed literature indicates broad consensus that adopting a diesel-electric architecture can still achieve lower overall environmental impacts than conventional diesel infrastructure. Hybrid systems can, in fact, decouple power generation from propulsion, allowing for effective peak shaving (S. Kim et al., 2022; Park et al., 2022; Perčić et al., 2022). This mechanism absorbs load fluctuations, enabling the ICE to operate consistently within its maximum thermodynamic efficiency curve, while the ESS provides extra bursts of power or stores energy (Park et al., 2022; Perčić, Ančić, et al., 2020; Perčić et al., 2022). Consequently, hybrid powertrains drastically reduce fuel consumption and the localized emissions of NO_x, SO_x, and PM compared to diesel systems (Jeong et al., 2018; S. Kim et al., 2022; Maydison et al., 2025). When combined with smart control algorithms, such as the ECMS, fuel consumption and GHG emissions can be further reduced by approximately 10% (S. Kim et al., 2022).

4.2 Life Cycle Assessment

4.2.1 Goal & Scope Definition

In accordance with the ISO 14040 and 14044 standards, the primary goal of this LCA is to comprehensively evaluate and compare the environmental performance resulting from the substitution of diesel engines with hybrid systems in ACTV's traditional vaporetti (see ***Figure 3***) (Guinée et al., 2011; ISO. Environmental Management-Life Cycle Assessment-Requirements and Guidelines, 2022). Specifically, this study assesses the environmental benefits and potential trade-offs of retrofitting a traditional diesel-powered vaporetto with a series-hybrid system, assuming the original hull remains unaltered.

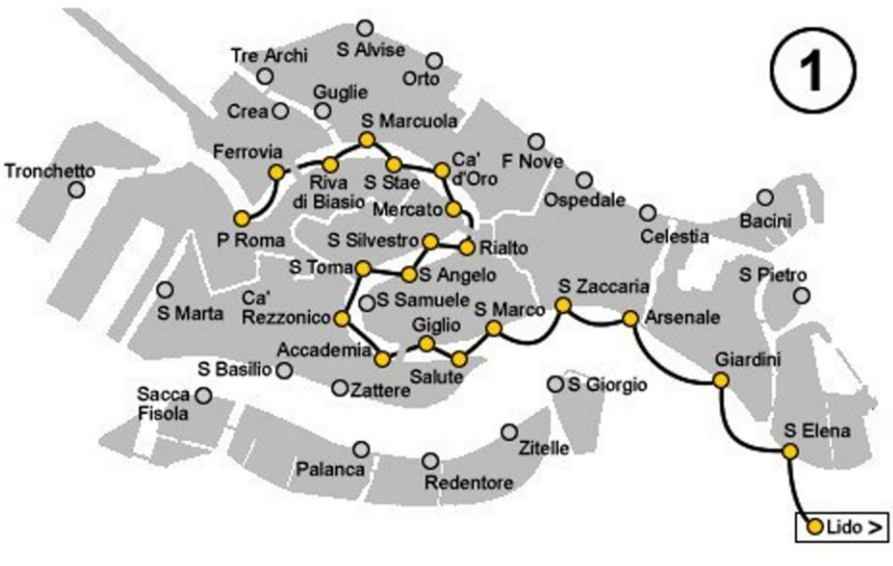

***Figure 14**-Route of Line 1 (Misul et al., 2021)*

In this LCA analysis, the traditional vaporetto operating on Line 1, which connects Piazzale Roma to Lido (see ***Figure 14***), was selected as the reference system. The vessel features a 24-meter-long hull, with a maximum beam of 4.22 meters. It has a structural displacement of approximately 37 tons and accommodates an average of 200 passengers per trip (Colombo et al., 2023; Guarnieri, Morandin, et al., 2018; Mazzarino & Rubini, 2019; Morandin et al., 2015). It is equipped with a

147-kW marine ICE, and the propulsion system consists of a single-propeller and single-rudder architecture (Colombo et al., 2023; Guarnieri, Morandin, et al., 2018; Morandin et al., 2015). Moreover, a dedicated reduction-reversing gear on the drive shaft enables the rapid thrust reversals essential during frequent docking manoeuvres, consistent with the 'stop-and-go' profile described in paragraph 2.1.1 (Guarnieri, Bovo, et al., 2018; Guarnieri, Morandin, et al., 2018).

Operationally, a Line 1 vaporetto remains in service for an average of 16 hours per day. It navigates at an average speed of 7 km/h, and each one-way trip between Piazzale Roma and the Lido takes approximately one hour (Colombo et al., 2023; Guarnieri, Morandin, et al., 2018; Morandin et al., 2015).

The LCA is intended to evaluate the environmental performance and identify the main categories of environmental impact using the software OpenLCA and the EcoInvent v3.10 database.

The intended audience for this study includes the R&D department of AVM-ACTV S.p.A., local policymakers, and the broader scientific community involved in the decarbonization of the maritime sector. The results are intended to provide a robust quantitative foundation to support strategic decision-making for the sustainable future upgrading of the local naval fleet.

4.2.1.1 Functional Unit

To conduct an accurate and consistent comparison of environmental performances, it is necessary to define a FU based on the system's primary function. Since the environmental impact of ACTV's vessels is directly linked to its role as a public transport operator, the FU must reflect its main purpose, namely the transport of passengers in the historic centre and on the islands of Venice.

As evidenced by the literature review and the results reported in ***Table 1***, various metrics can be used for the Functional Unit in maritime LCA. However, most papers focused on fishing vessels, ferries, tugboats, and yachts, rather than passenger transport. Hence, the choice of the FU followed what is commonly adopted in LCA studies focusing on the impact of public transport, such as the metric passengers per kilometre (Antczak & Porta, 2026; Chester & Horvath, 2012; van Lier & Macharis, 2014).

Therefore, the FU for this study is defined as:

"One passenger transported for one kilometre (1 pkm)."

4.2.1.2 System Boundaries

As the analysis focuses exclusively on comparing the traditional vaporetti's propulsion systems with hybrid ones, the system boundaries have been defined using a 'Well-to-Wake' approach, covering both upstream and downstream flows for the powertrain (see ***Figure 15***). This allows for an extended assessment of the manufacturing phase, as well as the entire operational phase of the engines, including routine maintenance, extending through to EoL scenarios.

Flows related to everything other than the propulsion systems, such as the manufacture and distribution of the hull, are excluded from the analysis. This means that only the changes in impact generated by the technological replacement are assessed in this study.

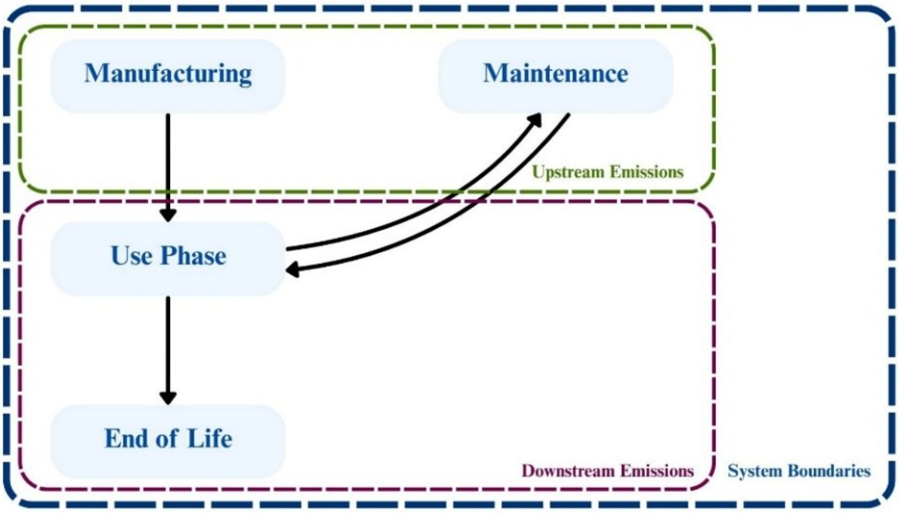

Figure 15*-Scheme representing System Boundaries, Upstream and Downstream Emissions*

4.2.2 Life Cycle Inventory

Most of the material and energy flows used to compile the LCI for both the traditional powertrain and the series-hybrid alternative were obtained directly from primary data provided by ACTV. Specifically, inventory data for manufacturing, maintenance, and EoL were derived from company records. Data for the use phase were obtained from Guarnieri, Bovo, et al., 2018; Pecorari et al., 2013, 2020; Vermeire, 2026.

All inventory data were subsequently scaled to the FU of 1pkm. The scaling was based on the assumption that Line 1 accommodates an average of 200 passengers per trip, operates for approximately 16 hours per day, navigates at an average speed of 7 km/h, and completes a one-way trip in roughly one hour (Colombo et al., 2023; Guarnieri, Morandin, et al., 2018; Mazzarino & Rubini, 2019; Morandin et al., 2015). Whenever annual data were available, inputs and outputs were converted to the FU, assuming 5000 operating hours per year.

The lifespan of the propulsion systems was also included in the calculations. The conventional propulsion system was assumed to operate for 15 years and undergo 3 scheduled maintenance interventions, one every 5 years. The hybrid propulsion system was assumed to have a lifespan of 7.5 years, resulting in its replacement once over the 15-years reference period.

The complete LCI is reported in Appendix A – LCI

4.2.3 Life Cycle Impact Assessment

LCIA was performed by applying the Environmental Footprint (EF) v3.0 impact method, recommended by the European Commission's Joint Research Centre (Fazio et al., 2018) to ensure method standardisation and maximum comparability with the relevant literature (Ceballos-Santos et al., 2023; Kanchiralla et al., 2022; B. A. Zincir & Arslanoglu, 2024).

Although the method can calculate results for 27 indicators, this analysis focuses on the 16 main impacts:

- Acidification (mol H^+-Eq)
- Climate change (kg CO_2-Eq)
- Ecotoxicity: freshwater (CTUe)
- Energy resources: non-renewable (MJ, net calorific value)
- Eutrophication: freshwater (kg P-Eq)
- Eutrophication: marine (kg N-Eq)
- Eutrophication: terrestrial (kg N-Eq)
- Human toxicity: carcinogenic (CTUh)
- Human toxicity: non-carcinogenic (CTUh)
- Ionising radiation: human health (kBq U235-Eq)
- Land use (dimensionless)
- Material resources: metals/minerals (kg Sb-Eq)
- Ozone depletion (kg CFC-11-Eq)
- Particulate matter formation (disease incidence)
- Photochemical oxidant formation: human health (kg NMVOC-Eq)
- Water use (m^3 world Eq deprived)

The remaining 11 impact categories were excluded from the analysis, as they represent midpoint indicators, subcategories of broader indicators already considered.

***Table 2** illustrates the results of the LCIA for the baseline scenarios, namely the traditional diesel and the hybrid systems for the 16 categories listed above:*

Impact categories	Unit	Diesel transport	Hybrid Transport
Acidification	*mol H^+-Eq*	3.05159e-4	2.84543e-4
Climate change	*g CO_2-Eq*	10.3807	5.79773
Ecotoxicity: freshwater	*CTUe*	0.377662	0.908714
Energy resources: non-renewable	*MJ*	1.05153	0.595995
Eutrophication: freshwater	*g P-Eq*	0.00103405	0.00715455
Eutrophication: marine	*g N-Eq*	0.133158	0.102942
Eutrophication: terrestrial	*g N-Eq*	1.45251	1.15576
Human toxicity: carcinogenic	*CTUh*	3.10194e-12	9.93450e-12
Human toxicity: non-carcinogenic	*CTUh*	2.71504e-10	6.80650e-10
Ionizing radiation: human health	*kBq U235-Eq*	3.39794e-4	5.90667e-4
Land use	*dimensionless*	0.0556580	0.0597417
Material resources: metals/minerals	*g Sb-Eq*	1.66219e-5	1.23286e-3
Ozone depletion	*g CFC-11-Eq*	1.79160e-6	1.03533e-6
Particulate matter formation	*disease incidence*	2.18674e-9	1.93254e-9
Photochemical oxidant formation: human health	*g NMVOC-Eq*	0.478262	0.341418
Water use	*m^3 world Eq deprived*	0.00144926	0.00268437

The hybrid architecture demonstrates substantial environmental superiority across impact categories strictly related to fossil fuel combustion, such as GWP, represented by the 'Climate change' indicator, non-renewable energy consumption, PM formation, and acidification. Conversely, the traditional system's impacts are significantly lower in the material resource depletion and freshwater eutrophication categories, highlighting the environmental burden caused by the manufacturing phase of electric systems.

4.2.4 Interpretation

The analysis of the results confirms that in the baseline scenario with a traditional diesel powertrain (***Figure 16***), environmental impacts are almost entirely concentrated in the operational phase, which dominates the impact profile, accounting for nearly 100% of the contribution across almost all categories. This result is attributable to emissions from the combustion of fossil diesel during use, since, as the architecture consists exclusively of an ICE, the manufacturing, maintenance, and EoL footprints are almost entirely negligible.

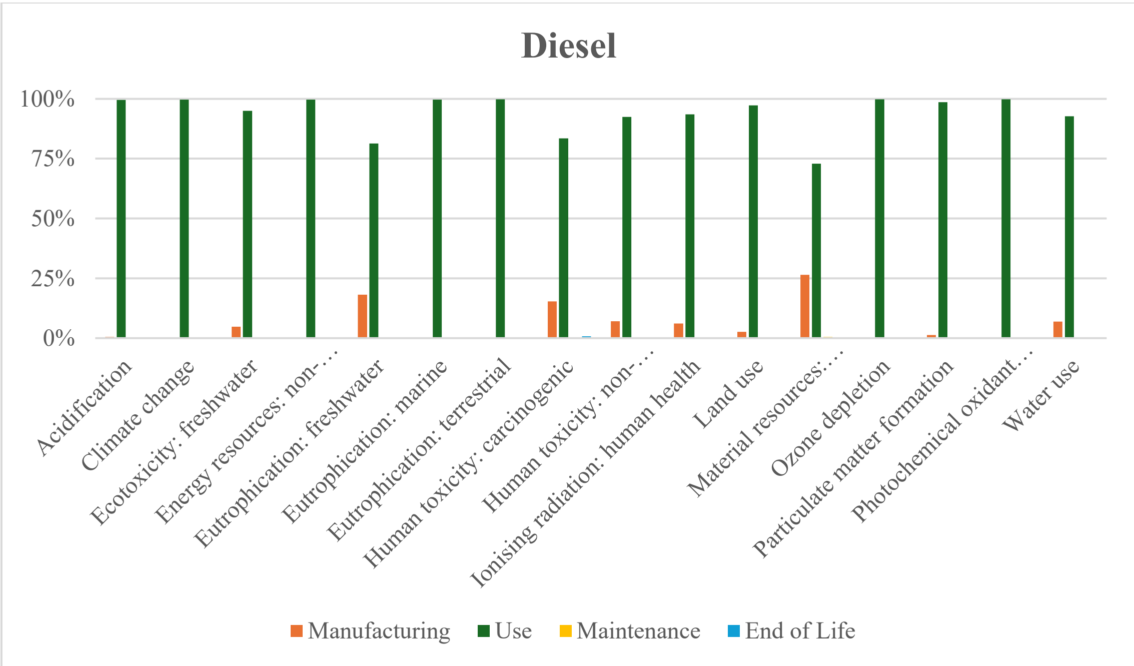

Figure 16*-Hotspot analysis on diesel system's lifecycle*

Conversely, the life-cycle chart for the hybrid system (***Figure 17***) shows that emissions from a diesel-electric powertrain are concentrated mainly in the manufacturing phase, due to electrical components such as batteries, inverters, and the motor, and in the use phase, as diesel combustion still occurs, albeit to a lesser extent than in the traditional system. The EoL phase also has a relatively low impact in this case, although it is not negligible due to its effects on human toxicity, which stems largely from the pyrometallurgical process used to dispose of the non-ferrous materials contained in the battery.

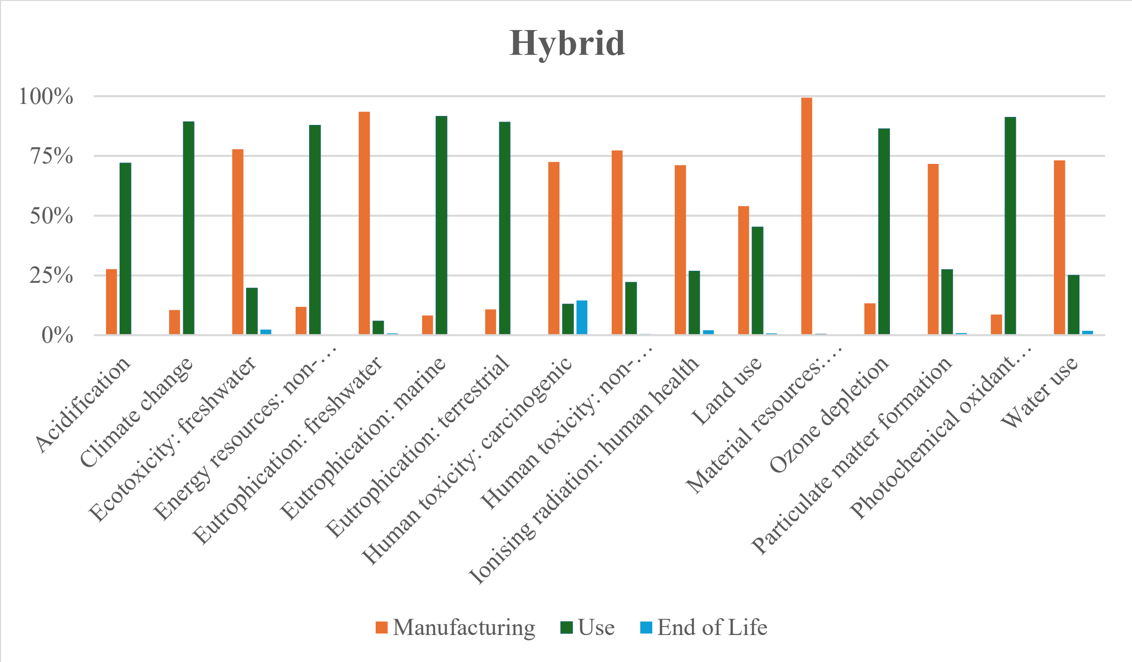

Figure 17*-Hotspot analysis on hybrid system's lifecycle*

The results presented in the previous section demonstrate the potential to improve the operational phase associated with diesel consumption in both architectures, as well as the opportunity to mitigate the impacts related to the electrical components of the hybrid system. Consequently, two alternative scenarios have been designed to address these issues:

1) The substitution of conventional diesel with biodiesel;
2) The implementation of a second-life strategy for the battery pack.

The first proposed scenario involves using biodiesel, specifically Fatty Acid Methyl Ester (FAME), instead of conventional marine diesel. FAME is synthesized via the transesterification of renewable, biogenic lipid sources, such as palm, soybean, and rapeseed oils, and is usually derived from residual waste streams (CIMAC WG7, 2024; Mohd Noor et al., 2018). During this chemical process, triglycerides in oils and fats react with an alcohol, typically methanol, in the presence of an alkaline catalyst, such as sodium or potassium hydroxide, yielding FAME alongside glycerol as a primary byproduct (CIMAC WG7, 2024; Mohd Noor et al., 2018).

From an environmental perspective, FAME contributes significantly to marine decarbonisation strategies. The inherent oxygen content within the FAME molecular structure, approximately 10%, enhances combustion efficiency, improving its emission profile (Mohd Noor et al., 2018). Furthermore, FAME is highly versatile and functions as a ‘drop-in’ fuel, as its use does not require any preliminary modification to traditional marine engines (CIMAC WG7, 2024; Oloruntobi et al., 2025; Sagin et al., 2024). In addition, it can be used as a 100% substitute (B100) or blended in various volumetric ratios with conventional diesel (CIMAC WG7, 2024; Mohd Noor et al., 2018; Mukherjee et al., 2020).

The second proposed scenario investigates extending the operational lifespan of the vessel's battery packs by repurposing them for secondary applications after they are retired from the vaporetti. In the maritime sector, batteries are conventionally dismissed once their nominal capacity decreases by 20% to 30% (Nazim & Madurai Elavarasan, 2026). However, at this threshold, the modules retain substantial residual capacity and material value, making them highly suitable for stationary ESS (Nazim & Madurai Elavarasan, 2026). Such applications demand significant storage capacity but are characterized by less intensive discharge rates and less frequent cycling, which aligns perfectly with the performance limits of second-life batteries (Mandrile et al., 2023).

These stationary systems can be deployed in both on-grid and off-grid configurations across the domestic, industrial, or commercial sectors (Mandrile et al., 2023). Specifically, they can provide grid-support functions such as renewable firming, mitigating the sudden fluctuations and intermittency typical of renewable sources, as well as load levelling and peak shaving, which stabilize grid demand and curtail peak power absorption (Mandrile et al., 2023). This approach effectively extends the battery's functional lifespan by 50 to 65% (Lehmusto & Santasalo-Aarnio, 2022), supporting circular economy principles by curbing demand for virgin raw materials and delaying EoL disposal (Nazim & Madurai Elavarasan, 2026).

To analyse these alternative scenarios, the model was built using secondary data sourced from the relevant literature. Specifically, the operational emission factors associated with biofuel combustion were adopted from the findings of Zincir & Arslanoglu, 2024. The mass of FAME was then calculated based on energy density equivalence to conventional marine diesel to ensure consistency with the FU (CIMAC WG7, 2024).
Furthermore, within the alternative hybrid architecture scenario, the decommissioned battery packs allocated for second-life use were modelled applying the 'avoided burden', or system expansion, approach (Accardo et al., 2023; Chain, 2023). Methodologically, the repurposed batteries are accounted for as a co-product output at the EoL phase (Chain, 2023; Farrapo et al., 2023). This approach helps resolve multifunctionality issues, allowing for the transparent quantification of the net environmental benefits derived from circular economy practices (Schrijvers et al., 2021).
Specifically, batteries are assumed to be used onboard the vaporetti until they reach 80% of their nominal capacity. To align with this assumption, a functional equivalent factor of 0.8 was introduced (Accardo et al., 2023; Schrijvers et al., 2021). This prevents overestimating the environmental benefits while still assigning an environmental credit for the lifespan expansion, as it avoids the primary production of a new equivalent ESS. In the computational model, this was

implemented by subtracting the environmental impacts of primary ESS manufacturing from the system's inventory, while accounting for the additional burdens required for the repurposing phase. The inventories of the Scenario Analysis are reported in Appendix B – Scenario Analysis.

Table 3. *Results of the Scenario Analysis:*

Impact categories	**Unit**	**Second-life battery**	**Biodiesel traditional**	**Biodiesel hybrid**
Acidification	*mol H^+-Eq*	2.65477e-4	1.66960e-3	9.13635e-4
Climate change	*g CO_2-Eq*	5.67832	5.73432	3.47086
Ecotoxicity: freshwater	*CTUe*	0.807027	1.95215	1.69596
Energy resources: non-renewable	*MJ*	0.581631	0.311248	0.225856
Eutrophication: freshwater	*g P-Eq*	0.00635016	0.0104325	0.0118538
Eutrophication: marine	*g N-Eq*	0.101122	1.14314	0.580004
Eutrophication: terrestrial	*g N-Eq*	1.11197	8.82125	4.53428
Human toxicity: carcinogenic	*CTUh*	8.82605e-12	3.22058e-11	2.44864e-11
Human toxicity: non-carcinogenic	*CTUh*	5.97298e-10	2.00320e-9	1.52095e-9
Ionizing radiation: human health	*kBq U235-Eq*	5.30295e-4	1.00008e-3	9.20810e-4
Land use	*dimensionless*	0.0528408	3.89742	1.98062
Material resources: metals/minerals	*g Sb-Eq*	1.11215e-3	1.60627e-4	1.30486e-3
Ozone depletion	*g CFC-11-Eq*	1.01802e-6	1.13826e-6	7.08660e-7
Particulate matter formation	*disease incidence*	1.79382e-9	1.01020e-8	5.58347e-9
Photochemical oxidant formation: human health	*g NMVOC-Eq*	0.336045	1.75817	0.908502
Water use	*m^3 world Eq deprived*	0.00234009	0.0306355	0.0172775

The results obtained are mixed. Using biofuel within the hybrid system leads to a significant reduction in impacts across all indicators, with the sole exceptions of material resource depletion and freshwater eutrophication. As for the battery's second-life scenario, it performs similarly to biodiesel in the traditional system in terms of GWP, resulting in an impact approximately 1.6 times greater than that of the biofuel hybrid, and in terms of ozone depletion. However, in the remaining categories, the second-life strategy ensures excellent mitigation, often outperforming even the hybrid biodiesel scenario, particularly regarding eutrophication, human toxicity, and water and land use. Conversely, a greater impact is observed solely in relation to the consumption of non-renewable energy resources.

Specifically, in the scenario involving the adoption of FAME biofuel within the traditional architecture (***Figure 18***), the environmental impacts are almost entirely driven by the operational phase. This alternative was designed to reduce GHG emissions during vessel operation. However, while implementing biodiesel in conventional powertrains reduces CO_2 eq. by approximately 45% and mitigates impacts related to ozone depletion and non-renewable energy consumption, it simultaneously exacerbates environmental burdens across all other analysed categories.

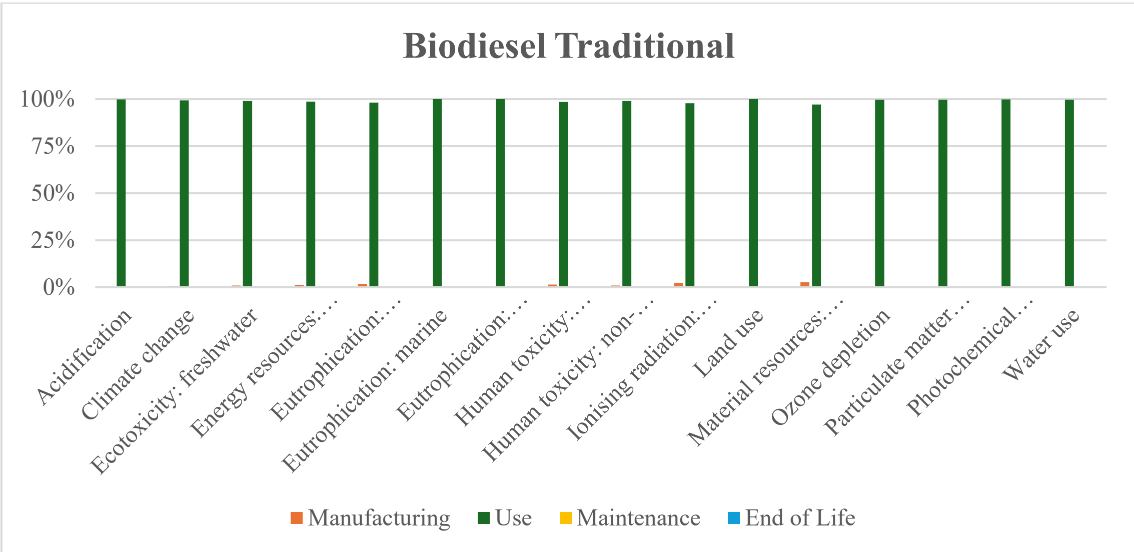

Figure 18*-Hotspot analysis on the use of biofuel on diesel systems*

Conversely, in the hybrid model, biodiesel shows a more balanced distribution of its environmental burdens, particularly between the manufacturing and use phases (***Figure 19***), although it still yields higher overall impacts across all categories except climate change, ozone depletion, and non-renewable energy consumption.

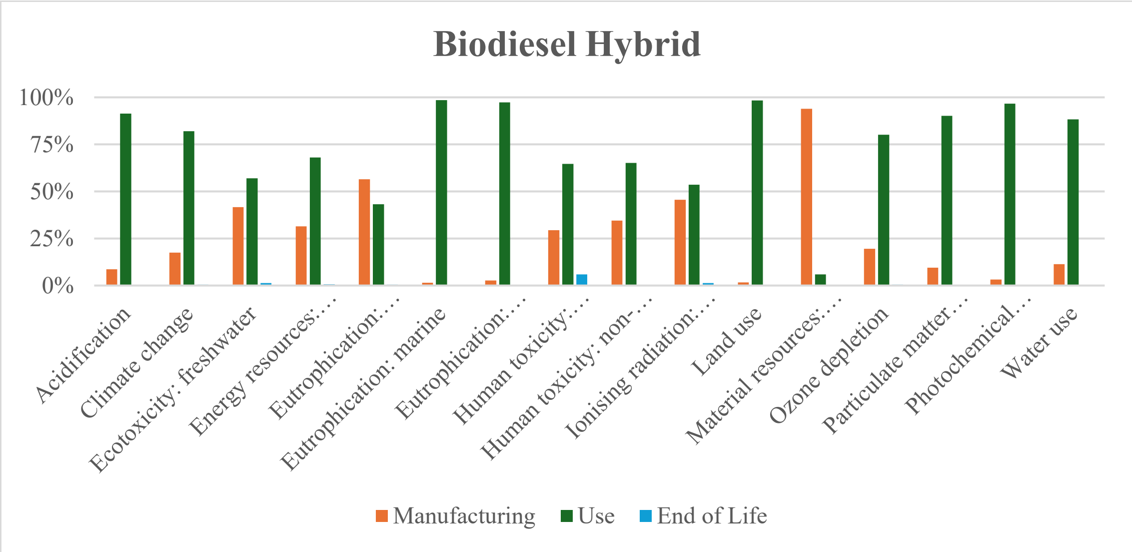

Figure 19-*Hotspot analysis on the use of biofuel on hybrid systems*

The second proposed scenario explores extending the lifespan of the battery packs by repurposing them for alternative applications once decommissioned from the vaporetti (***Figure 20***). The results are noteworthy because, under the avoided burden approach, the EoL phase yields environmental credits, shown as negative percentages in the graph. It is crucial to clarify that these represent avoided impacts from offsetting the primary production of the battery, rather than physical negative emissions.

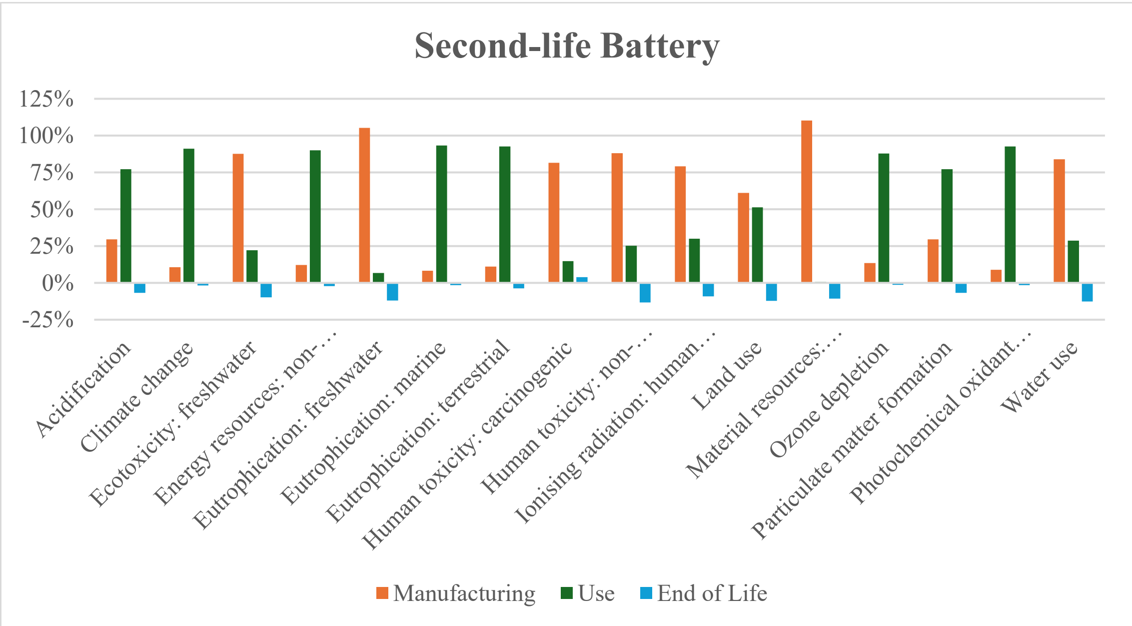

Figure 20-*Hotspot analysis on the battery's second life scenario*

5 Discussion

This chapter analyses environmental shifts across the selected impact categories, compares the findings with the current sector-specific literature, and critically evaluates the alternative scenarios chosen to mitigate the environmental burden of conventional diesel and hybrid architectures.

The results of the analysis are summarized in ***Figure 21***, which shows, for each impact category, the percentual impact, normalized to the highest score. In this histogram, the maximum value for each indicator is set to 100%, and the results of the other variants are displayed relative to it. The multi-criteria analysis reveals that replacing the traditional powertrain with a hybrid system is particularly effective at mitigating several impact categories, including acidification, climate change, marine and terrestrial eutrophication, and photochemical oxidant formation. However, the hybrid configuration, due to its electronic components, has a much greater impact on the use of mineral resources, as well as on freshwater ecotoxicity and eutrophication, human toxicity, and ionising radiation.

Although the FAME biodiesel usage scenario allows for a reduction in CO_2 eq. emissions of approximately 45% for the conventional architecture and 67% for the hybrid one, the adoption of this fuel shows significant anomalies across both powertrain options. The impacts are particularly evident in acidification, freshwater, marine and terrestrial ecotoxicity, eutrophication, human toxicity, land use, and photochemical oxidant formation.

Regarding the second-life battery scenario, its emission profile closely mirrors that of the baseline hybrid system across all evaluated categories. However, it achieves a reduction in overall impacts due to the environmental credits generated by avoiding the burden of producing a second equivalent ESS.

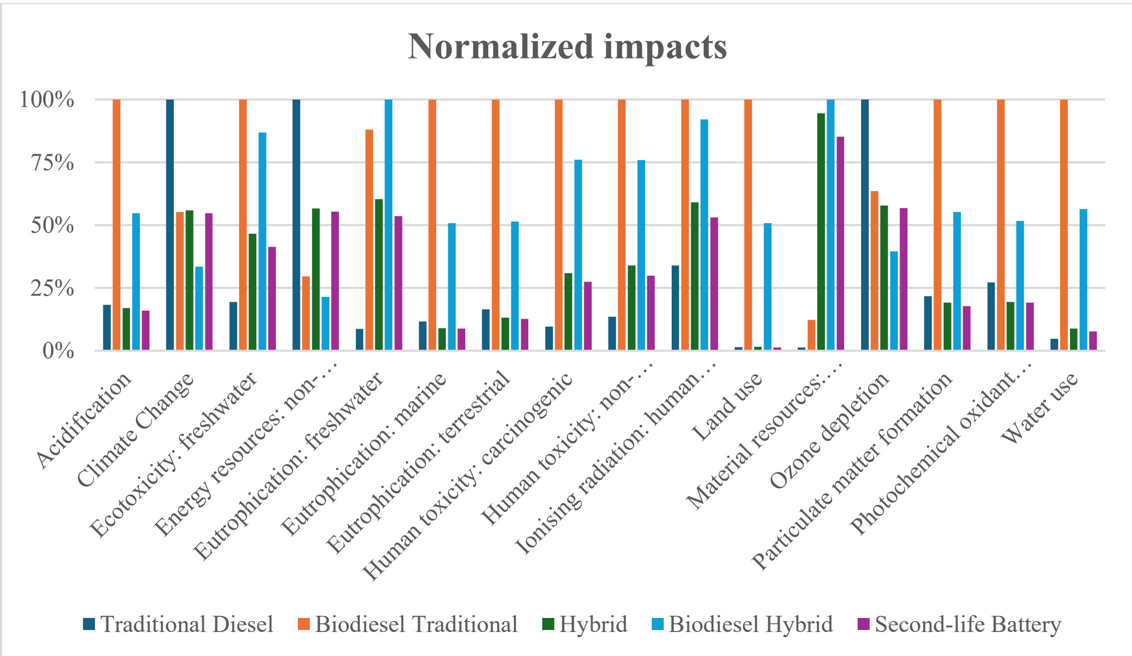

Figure 21*-Relative contributions of the analysed scenarios*

5.1 Analysis of the Impacts

5.1.1 Climate Change and Non-Renewable Energy Resources

In the Climate Change category (***Figure 22***), the emissions balance for traditional diesel systems stands at 10.38 g CO_2-eq per passenger per km travelled. The introduction of the hybrid powertrain leads to a significant reduction in emissions, which falls to 5.80 g CO_2-eq/pkm, representing a reduction of approximately 45%. This result is corroborated by the study by Miretti et al., 2025, which highlights the reduction potential of the series hybrid architecture at between 30% and 50%. These reduction peaks reach their highest point when biodiesel is used in the hybrid architecture, falling to 3.47 g CO_2 eq/pkm, leading to an emissions cut of approximately 66%. The extent of this reduction, as confirmed by the studies conducted by Perčić, Ančić, et al., 2020; Perčić, Vladimir, et al., 2020, is due to the non-fossil origin of the CO_2. In this case, from an LCA perspective, the amount of CO_2 emitted is considered zero since, being of biogenic origin, it is assumed to be absorbed directly from the atmosphere. CO_2 emissions resulting from the combustion of biodiesel are therefore calculated as a 'closed loop' and are thus carbon neutral. Conversely, the use of fossil-derived CO_2, which involves an extraction process, causes a net increase in GHG in the atmosphere.

A comparable trend is observed in the consumption of non-renewable energy (***Figure 22***), where every impact mirrors the profiles identified in the climate change category across all analysed solutions. The conventional diesel architecture exhibits the highest burdens, due to fossil fuel combustion, while the hybrid systems reduce this consumption thanks to optimized engine management and peak shaving (Guarnieri et al., 2024; Skjong et al., 2016). Conversely, the use of FAME biodiesel yields the most substantial mitigation due to its renewable and biogenic production process, which confines its fossil energy footprint exclusively to the upstream supply chain operations (Koričan et al., 2022; Oloruntobi et al., 2025).

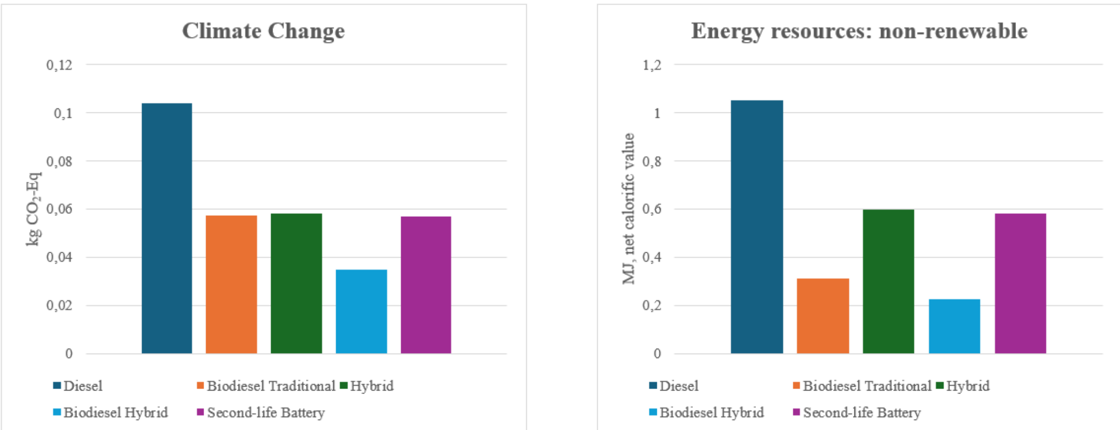

Figure 22-*Contribution to climate change and consumption of non-renewable energy resources*

5.1.2 Acidification

In the Acidification category (***Figure 23***), FAME biodiesel in conventional ICE systems exhibits the most significant impact, increasing by approximately 550%, rising from 0.00031 mol H^+-eq/pkm for conventional diesel to 0.00167 mol H^+-eq/pkm. This can be attributed to the oxygenated molecular structure of FAME, which promotes more complete combustion of CO and HC, reducing GHG emissions by significantly raising the temperatures at which the process occurs. However, this thermal peak also favours massive formation of NO_x, the primary precursors of acidification (Amat Ventayol et al., 2025; Antczak & Porta, 2026; B. A. Zincir & Arslanoglu, 2024).

Conversely, the hybrid scenario effectively mitigates this category, achieving an impact of 0.00028 mol H^+-eq/pkm. This reduction is consistent with emissions estimates from the WATERBUS model developed by Pecorari et al., 2013, 2020, which indicates that hybridisation reduces the concentration of acidifying NO_x gases by approximately 27%, while also decreasing PM emissions by approximately 19%, CO by 54% and HC by 43%.

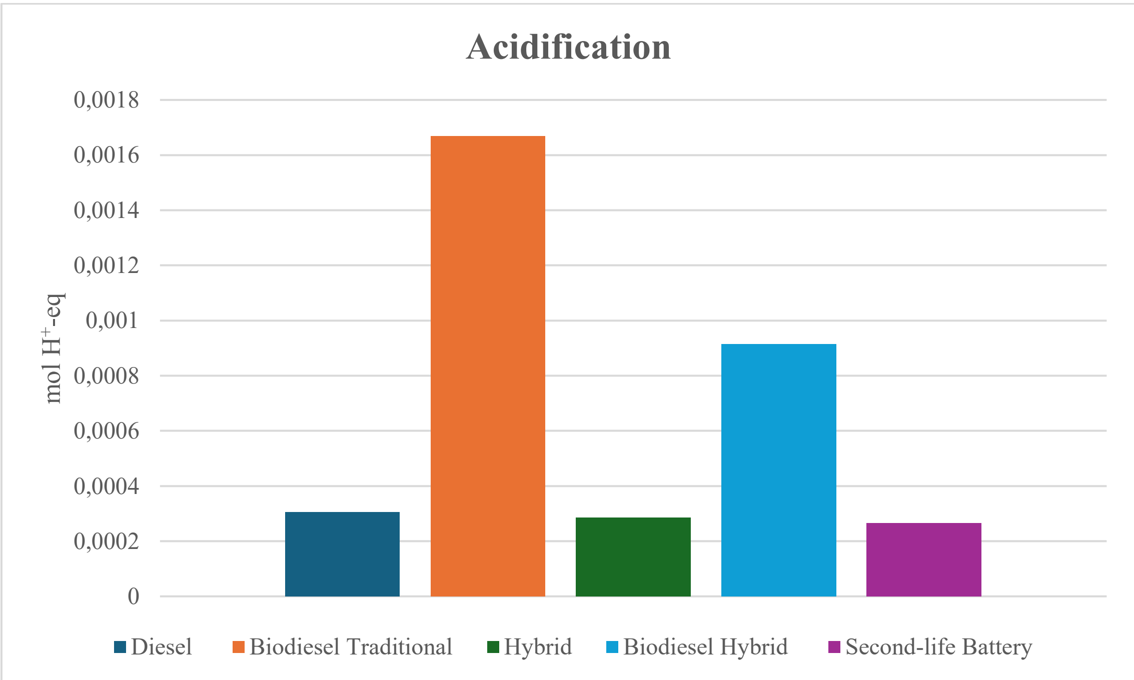

Figure 23*-Contribution to acidification*

5.1.3 Mineral Resources Depletion, Land Use, Water Use

As in the Acidification category, the impacts on Land and Water Use (***Figure 24***) are predominantly driven by the biodiesel scenarios. This outcome is directly linked to the upstream FAME supply chain, specifically the agricultural phase required for vegetable oil production, which can lead to highly intensive land and water use (Koričan et al., 2022; Oloruntobi et al., 2025).

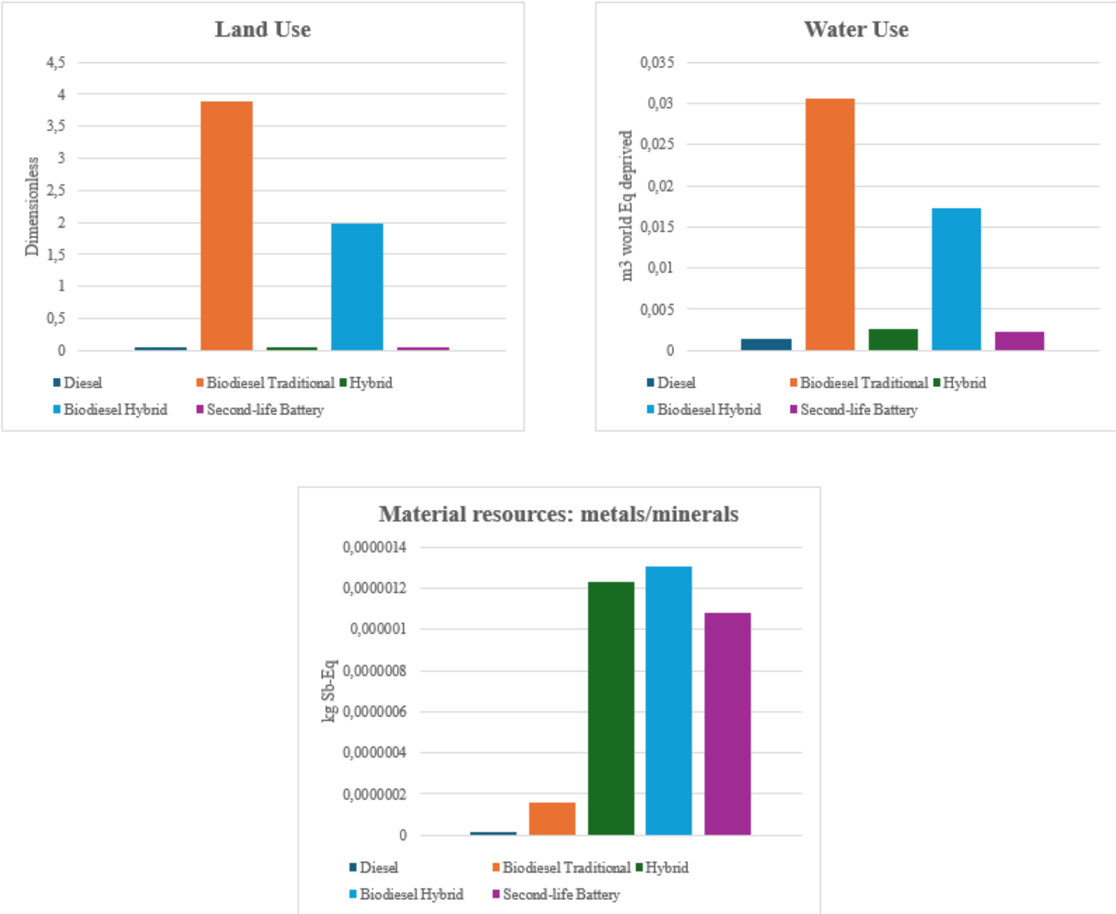

Figure 24-*Contribution to Land and Water Use, and to Material resources depletion*

The analysis of the results reveals a further critical issue, primarily linked to the fleet hybridisation process. In the Material Resource Use impact category (***Figure 24***), conventional diesel exhibits a minimal impact on mineral resources at 0.000017 g Sb-Eq/pkm. This is followed by the biodiesel scenario in the traditional architecture, which is approximately 10 times more impactful at 0.000161 g Sb-Eq/pkm. However, hybrid systems exert a significantly greater burden on this category, with the traditional hybrid configuration standing at 0.00123 g Sb-Eq/pkm, nearly 75 times the traditional diesel baseline.

The severe environmental impact of hybrid systems on mineral resources stems almost entirely from the manufacturing phase (***Figure 17***). This evidence unequivocally highlights the phenomenon of burden shifting, whereby the hybridisation of the fleet significantly limits downstream emissions arising from the system's use phase, but at the same time the impacts are transferred to the upstream phases, specifically the 'Well-to-Tank' phase, during the manufacturing process (Jeong et al., 2022; Perčić et al., 2024).

To visualize the spatial distribution of impacts, ***Figure 25*** presents a map of the physical flows generated by the hybrid system for the Resource Use impact category. The map was developed by exporting vector data from the OpenLCA software and reprocessing it in the QGIS geographic information system, utilising Google Satellite imagery. It highlights the global geographical distribution of impacts caused by hybrid systems, primarily due to the manufacturing of electrical components and batteries, which require critical materials such as lithium, copper, and graphite, as well as rare earth elements, extracted from localized mining regions, including Chile, Australia, the USA, Canada, and China (Antczak & Porta, 2026; Laurence & Bai, 2025; Nazim & Madurai Elavarasan, 2026).

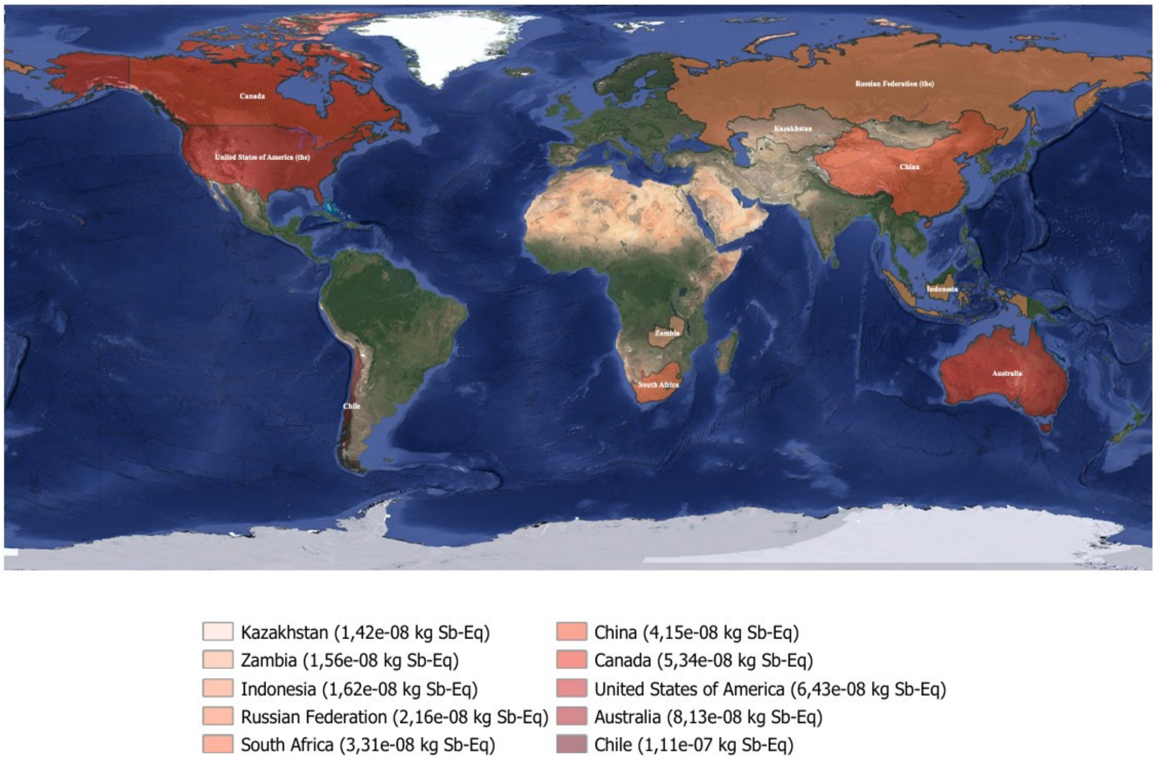

Figure 25*-Countries most impacted by material resource depletion caused by the hybrid system's lifecycle*

5.1.4 Eutrophication

Similar to Acidification Potential and Land and Water Use, both Marine and Terrestrial Eutrophication (***Figure 26***) are heavily impacted by the adoption of FAME biofuel. In these categories, FAME shows high upstream emissions linked to its production processes, as well as high NO_x emissions during its operational phase (Koričan et al., 2022).

Conversely, hybrid architectures mitigate these two categories by approximately 20% due to their reduced NO_x emissions during use (Jeong et al., 2022). However, hybrid systems have a significant impact on Freshwater Eutrophication (***Figure 26***). This outcome is mainly linked to the manufacturing of the systems' electrical components and batteries, which involve processes that release large amounts of Phosphorus-equivalent (P-eq.) substances (Hüllein et al., 2026).

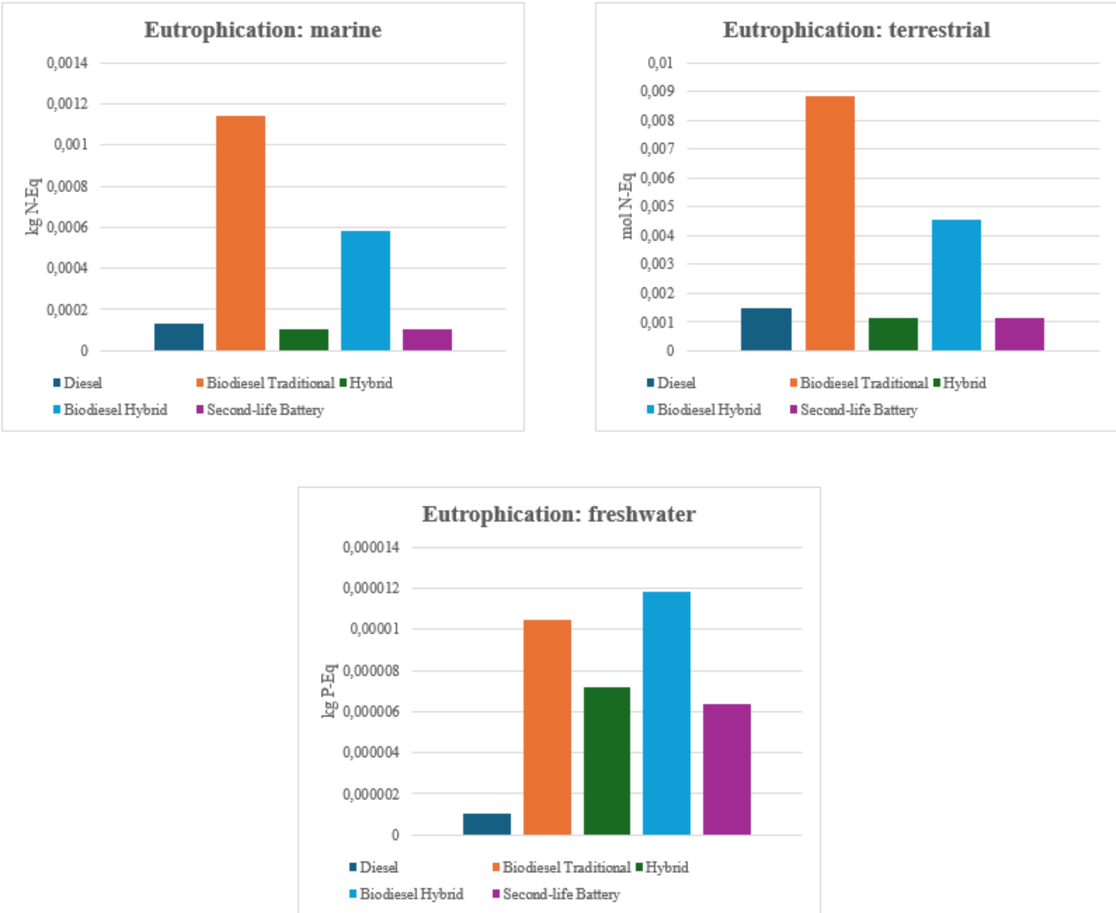

Figure 26*-Contribution to freshwater, marine and terrestrial eutrophication*

5.1.5 Toxicity and Impacts on Human Health

A similar trend is observed across toxicity-related impact categories, including Ecotoxicity and Human Toxicity, incorporating both carcinogenic and non-carcinogenic effects (***Figure 27***). In these categories, the conventional diesel configuration stands out as the least impactful architecture, whereas the hybrid system increases the environmental burden by approximately three times (Hüllein et al., 2026).

However, once again, FAME biofuel adoption yields the highest overall impacts (Koričan et al., 2022; B. Zincir et al., 2023; B. A. Zincir & Arslanoglu, 2024). Notably, when biodiesel is utilized within a hybrid architecture, impacts are reduced by about 25% compared to the "Biofuel Traditional" scenario. This mitigation is driven by the lower fuel consumption enabled by optimized energy management systems and the efficient operation of the ESS (Guarnieri et al., 2024; Hüllein et al., 2026; Koričan et al., 2022; Miretti, Nicolotti, et al., 2025; Skjong et al., 2016; B. A. Zincir & Arslanoglu, 2024).

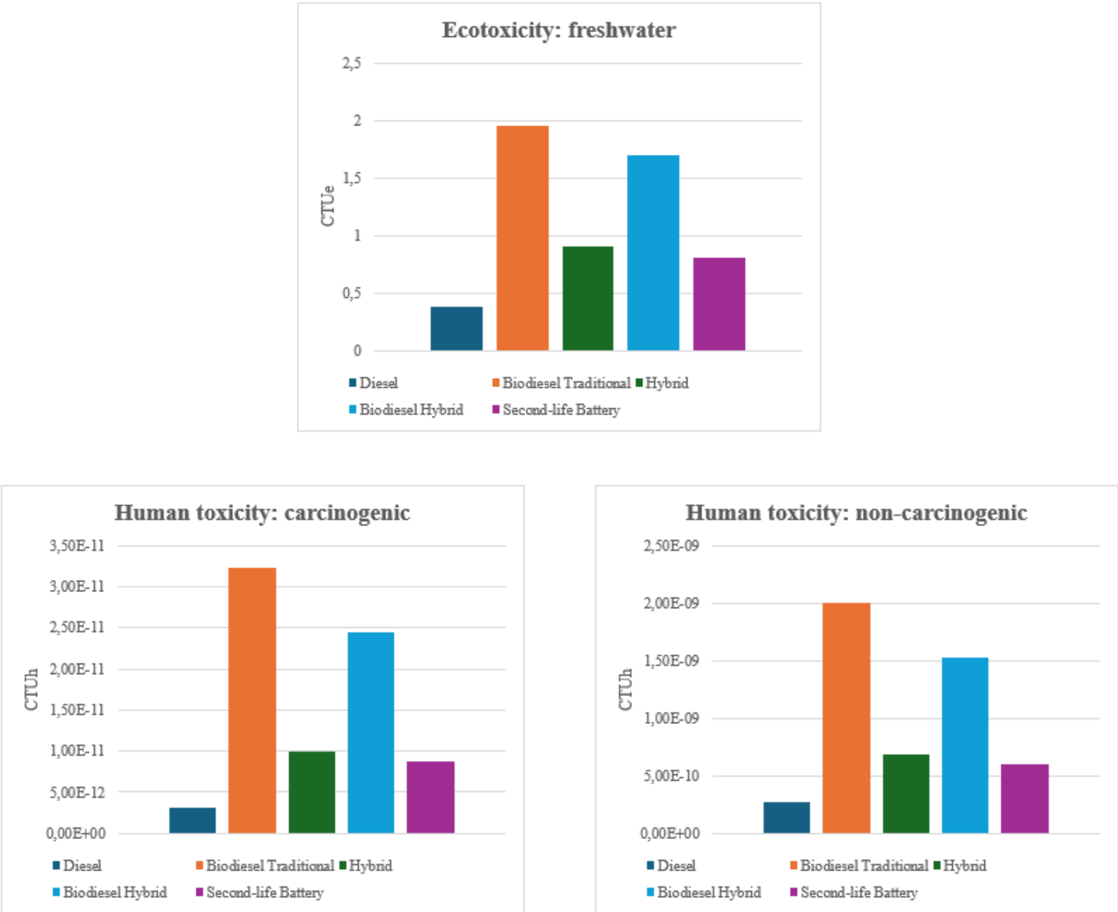

Figure 27*-Contribution to freshwater ecotoxicity and human toxicity*

Regarding the other impact categories assessing impacts on human health (***Figure 28***), the results are dominated by the biodiesel scenarios due to upstream emissions from its production process (B. A. Zincir & Arslanoglu, 2024).

Nevertheless, an interesting trade-off emerges when analysing hybrid systems: while hybridization provides a 30% reduction in Photochemical Oxidant Formation and a 12% reduction in Particulate Matter Formation, thanks to lower operational emissions of HC, PM, and NO_x (Hüllein et al., 2026; Miretti, Nicolotti, et al., 2025; Nicolotti et al., 2024), it exhibits a 175% increase in Ionising Radiation compared to the conventional diesel powertrain. This severe environmental burden is driven by the energy-intensive manufacturing phase of electric motors, inverters, and battery packs, which may result in emissions of U235-eq substances (Hüllein et al., 2026). Notably, adopting a second-life scenario for the battery would mitigate this burden by 12% compared to the baseline hybrid, offsetting the manufacturing process of a second ESS (Nazim & Madurai Elavarasan, 2026; Romare & Dahllöf, 2017).

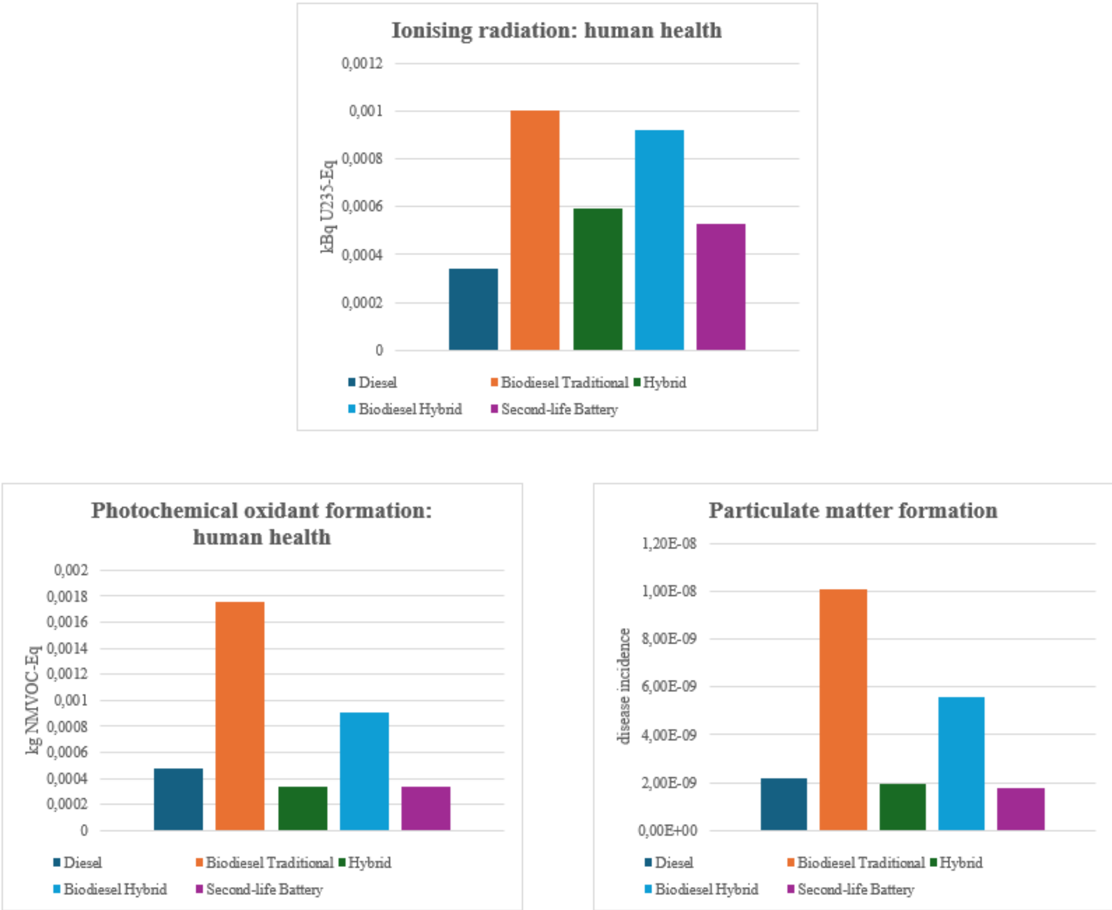

Figure 28*-Impacts on human health (ionizing radiation, PM and photochemical oxidant formation)*

5.1.6 Ozone Depletion

An analysis of Ozone Depletion potential reveals that the conventional diesel architecture emerges as the most impactful scenario (***Figure 29***) (Laurence & Bai, 2025). This high environmental burden is primarily driven by the fossil fuel supply chain, specifically crude oil extraction and petroleum refining, as well as the final operational combustion of diesel (Hüllein et al., 2026; Laurence & Bai, 2025). Consequently, transitioning away from purely fossil-based propulsion provides substantial environmental benefits in this category, achieving impact mitigations ranging from 37% to 43% (Borja-Marrugo et al., 2025). The most remarkable performance, however, is observed in the 'Biodiesel Hybrid' scenario, which delivers a 60% reduction in ozone depletion impacts relative to the diesel baseline (Hüllein et al., 2026; Laurence & Bai, 2025).

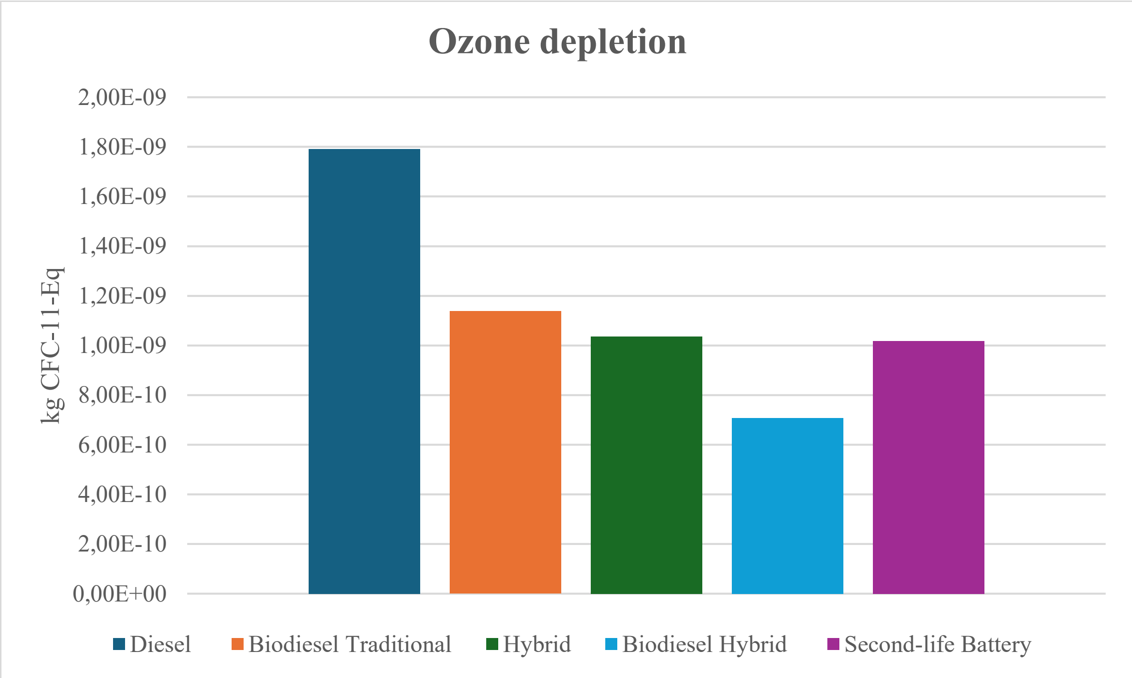

Figure 29*-Contribution to ozone depletion*

5.2 Limitations

While this study provides a comprehensive Life Cycle Assessment of the traditional diesel systems and the hybrid alternative for Venetian vaporetti, with two proposed scenarios, some inevitable methodological and practical limitations must be acknowledged.

A preliminary limitation stems from reliance on secondary data from the Ecoinvent v3.10 database for background processes and flows. Although Ecoinvent is widely accepted in the scientific community, it relies on global or regional averages that may not perfectly represent the specific supply chain of the marine components analysed in this study.

Moreover, due to data acquisition constraints with the transport company during the research timeframe, the maintenance phase of the hybrid systems was excluded from the System Boundaries. Although omitting these activities precludes a fully exhaustive evaluation, preliminary assessments indicate that maintenance constitutes a marginal fraction of the total environmental footprint. To justify this assumption, ***Figure 30*** illustrates the contribution of maintenance activities within the traditional diesel lifecycle.

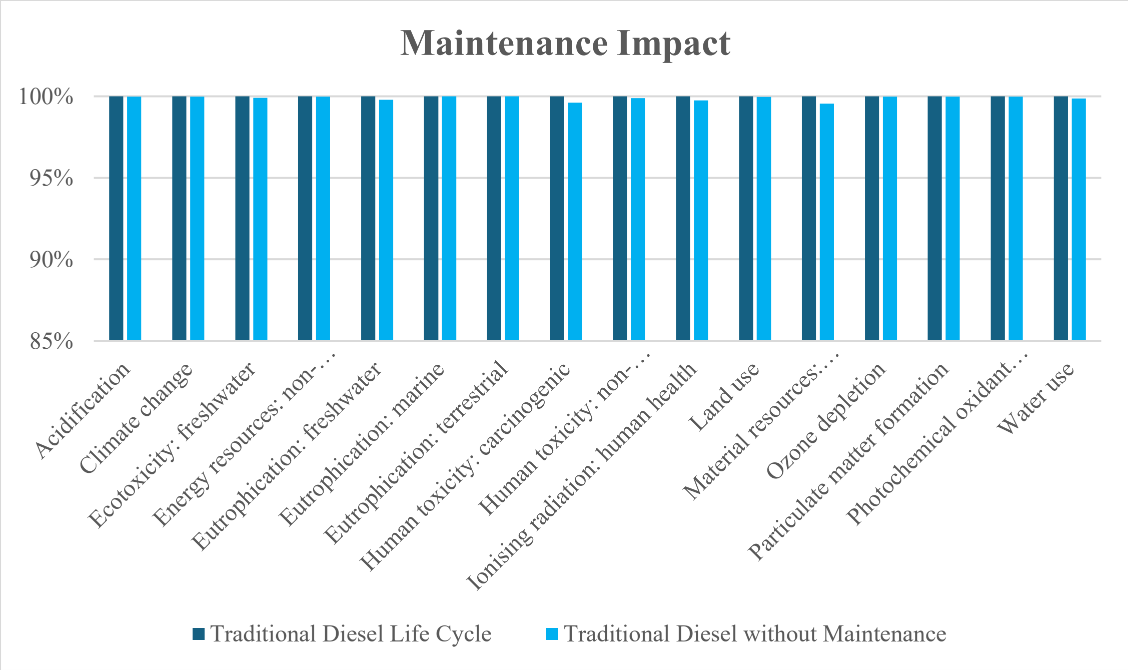

Figure 30-*Impacts of the Maintenance phase*

Furthermore, the software and the underlying background databases pose additional limitations. While the current study evaluated FAME biodiesel, the assessment of other promising alternative fuels was precluded. Specifically, the available databases lack comprehensive inventory flows for the complete supply chains of other fuels, and constructing these complex models from primary or secondary data was beyond the temporal constraints of this study. Notably, expanding the scenario analysis to include Hydrotreated Vegetable Oil (HVO) would have been of great interest, as it holds the potential for even greater mitigation (Oloruntobi et al., 2025). Although HVO shares a similar composition with FAME, it is produced through a catalytic hydrocracking process, in which triglycerides are treated at high temperatures and pressures in the presence of hydrogen (Mukherjee et al., 2020; Oloruntobi et al., 2025). This process completely deoxygenates HVO's chemical structure, avoiding, as a result, the typical combustion trade-offs associated with FAME, and leading to a substantial reduction in both PM and NO_x emissions, the same emissions that penalize FAME's environmental profile during the operational phase (Mohd Noor et al., 2018; Oloruntobi et al., 2025).

6 Conclusions

The imperative to decarbonize maritime transport poses a critical challenge for the city of Venice, where waterborne mobility must balance global climate goals and regulations with the preservation of a fragile ecosystem and historical heritage. To this end, this study evaluated the environmental performance of the propulsion systems of a typical vaporetto operating on the Line 1 route over a 15-year lifespan. Applying a WtW LCA methodology encompassing 16 impact categories, the study compared the baseline diesel configuration with a hybrid infrastructure, and two alternative scenarios: the use of FAME biofuel and the implementation of a second-life management strategy for the hybrid system's battery packs.

The findings indicate that no single technological pathway offers a "zero-impact" solution, but rather, each introduces specific environmental trade-offs. The transition from a conventional diesel propulsion system to a series-hybrid architecture yields a substantial reduction in GWP, cutting CO_2 eq emissions by approximately 45%. This electrification also significantly mitigates non-renewable energy resources exploitation, ozone depletion, and PM formation.

However, the analysis highlighted the burden shifting phenomenon: while the hybrid system effectively minimizes downstream emissions, it shifts the environmental load upstream to the manufacturing phase. This is evidenced by marked increases in freshwater ecotoxicity and eutrophication, and, most notably, in material resources depletion, which surged by a factor of 70 in the electrified scenarios compared to the traditional diesel baseline.

To mitigate the severe resource depletion caused by the hybrid alternative, the extension of the battery's lifespan proved to be a highly effective strategy. The modelled "hybrid second life" scenario proved that repurposing degraded batteries for second-life activities generates a significant environmental credit. This approach reduces overall impacts, effectively offsetting the manufacturing burden and aligning with the circular economy principles.

Furthermore, the substitution of conventional marine diesel with biogenic FAME, in both traditional and hybrid architectures, emerged as the most effective immediate measure to abate GWP, non-renewable energy consumption, and ozone depletion. Nevertheless, the LCA revealed a critical operational trade-off, mainly due to FAME combustion. As highlighted in the discussion section, the presence of oxygen atoms within the chemical structure of FAME leads to a detrimental surge in NO_x, which directly exacerbates high impacts. The use phase of biofuels indeed results in high impacts in terms of acidification potential, ecotoxicity, human toxicity, eutrophication, land and water use, PM and photochemical oxidant formation.

Based on the findings of this research, several strategic recommendations can inform ACTV's decision-making. Primarily, it is of paramount importance to continue researching low-carbon alternatives and to pair them with strategies that simultaneously reduce upstream emissions. For instance, the present analysis demonstrates that while FAME biodiesel effectively lowers GWP, its severe impact on EP and toxicity categories renders it a suboptimal strategy for the Venice Lagoon's ecosystem. However, the literature highlights that alternative fuels can be integrated into existing diesel engines and generators without requiring preliminary modification, offering comparable climate benefits without the toxicity penalties associated with FAME (Oloruntobi et al., 2025).

Moreover, to actualize the environmental benefits of the hybrid architecture and reduce its upstream emissions, ACTV should establish strategic partnerships with companies specializing in second-life management and repurposing of Lithium Iron Phosphate (LFP) batteries.

Future research must address the current study's limitations, and the LCA should be refined by incorporating primary data on the hybrid's maintenance phase to achieve a broader, more comprehensive evaluation. Additionally, this study focused exclusively on environmental indicators. However, a comprehensive cost analysis is necessary to evaluate the economic feasibility and the cost advantages and disadvantages of the proposed transitions. The exclusion of a comprehensive LCCA prevents the evaluation of the payback period and the carbon abatement costs of the proposed solutions. Sustainable decision-making for authorities like ACTV requires a holistic approach that balances environmental benefits with economic viability. Hence, further research should integrate the environmental assessment with an economic and social evaluation to provide stakeholders with a complete multi-criteria analysis.

Ultimately, this research underscores that future maritime policies must look beyond simple tailpipe emissions and adopt a holistic life-cycle perspective to successfully integrate GHG reductions while actively preventing global resource depletion and ecological degradation.

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Appendix A – LCI

Inputs/Outputs - Diesel transport-Manufacturing

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
marine engine	C:Manufacturing/28:...	6.33333E...	Item(s)		none		market...			

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
Diesel transport-...		**1.00000**	**p*km**		**none**					

Figure A.1*-LCI for the manufacturing phase of the diesel system*

Inputs/Outputs - Diesel transport-Use Phase

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
diesel	C:Manufacturing/19:...	0.02000	kg		none		market...			

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
Diesel transport-...		**1.00000**	**p*km**		**none**					
Carbon dioxide, fos...	../Emission to air/hig...	0.08400	kg		none					
Carbon monoxide, ...	../Emission to air/hig...	0.13485	g		none					
Hydrocarbons, alip...	../Emission to air/hig...	0.03620	g		none					
Nitrogen oxides	../Emission to air/hig...	0.30960	g		none					
Particulate Matter, ...	../Emission to air/hig...	0.01885	g		none					

Figure A.2*-LCI for the use phase of the diesel system*

Inputs/Outputs - Diesel transport-Maintenance

Inputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided ...	Provider	Data quali...	Location	Description
ethylene glycol	C:Manufacturing/20:M...	6.57143E-7	kg		none		market ...			
lubricating oil	C:Manufacturing/19:M...	1.08771E-6	kg		none		market ...			
propylene glycol, liqu...	C:Manufacturing/20:M...	6.57143E-7	kg		none		market ...			

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data quali...	Location	Description
Diesel transport-M...		**1.00000**	**p*km**		**none**					
spent antifreezer liquid	E:Water supply; sewera...	1.31429E-6	kg		none		market ...			
waste mineral oil	E:Water supply; sewera...	1.08771E-6	kg		none		market ...			

General information | Inputs/Outputs | Documentation | Parameters | Allocation | Social aspects | Direct impacts

Figure A.3*-LCI for the maintenance phase of the diesel system*

Inputs/Outputs - Diesel transport-End of Life

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
Diesel transport-E...		**1.00000**	**p*km**		**none**					
used internal comb...	E:Water supply; sewe...	6.33333E...	kg		none		market...			

Figure A.4*-LCI for the EoL phase of the diesel system*

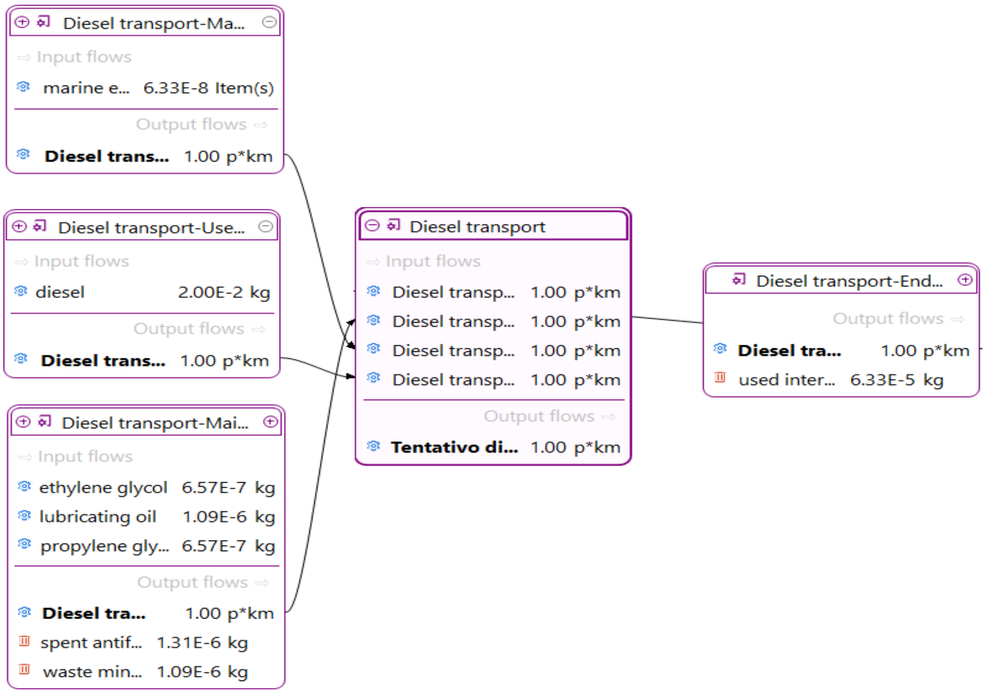


Figure A.5*-Product System of the diesel architecture*

Inputs/Outputs - Hybrid Manufacturing

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
battery, Li-ion, LFP, ...	C:Manufacturing/27:...	9.60000E...	kg		none		market...			
inverter, for electric ...	C:Manufacturing/27:...	7.20000E...	kg		none		market...			
marine electric mot...	A:Agriculture, forestr...	1.00000E...	Item(s)		none		market...			
marine engine	C:Manufacturing/28:...	8.00000E...	Item(s)		none		market...			

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
Hybrid Manufact...		**1.00000**	**p*km**		**none**					

Figure A.6*-LCI for the manufacturing phase of the hybrid system*

Inputs/Outputs - Hybrid Use

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
diesel	C:Manufacturing/19:...	0.01000	kg		none		market...			

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
Hybrid Use		**1.00000**	**p*km**		**none**					
Carbon dioxide, fos...	../Emission to air/hig...	0.04200	kg		none					
Carbon monoxide, ...	../Emission to air/hig...	0.09101	g		none					
Hydrocarbons, alip...	../Emission to air/hig...	0.03347	g		none					
Nitrogen oxides	../Emission to air/hig...	0.22660	g		none					
Particulate Matter, ...	../Emission to air/hig...	0.01292	g		none					

Figure A.7*-LCI for the use phase of the hybrid system*

Inputs/Outputs - Hybrid End of Life

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
Hybrid End of Life		**1.00000**	**p*km**		**none**					
used internal comb...	E:Water supply; sewe...	8.00000E...	kg		none		market...			
used Li-ion battery	E:Water supply; sewe...	9.60000E...	kg		none		market...			

Figure A.8*-LCI for the EoL phase of the hybrid system*

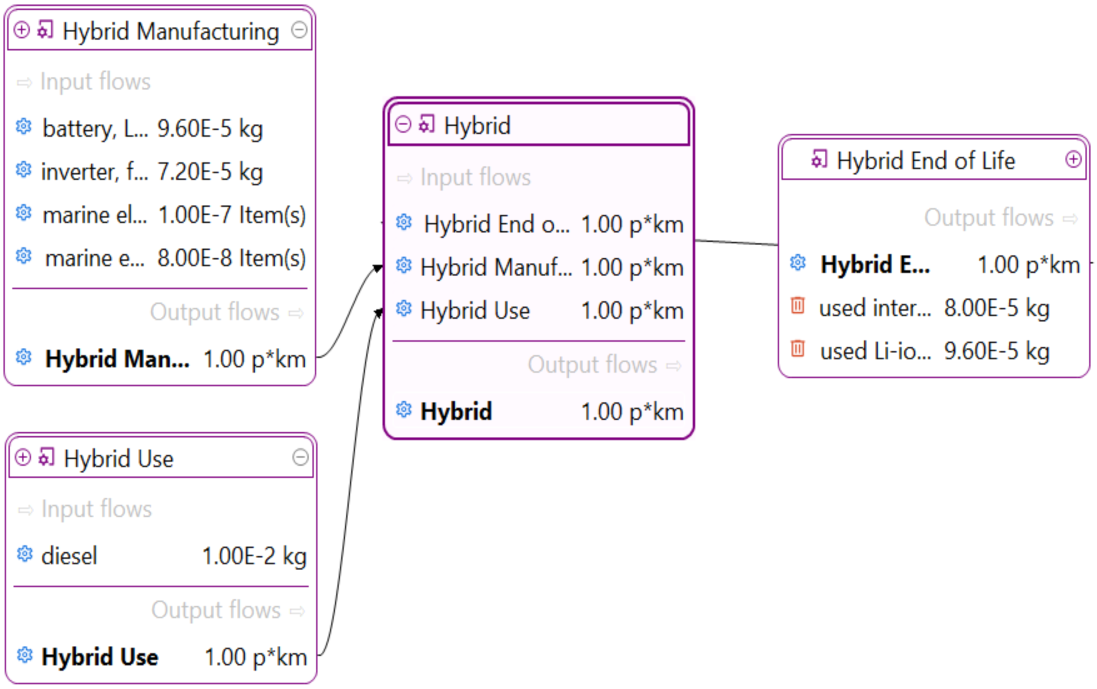


Figure A.9-*Product System of the hybrid architecture*

Appendix B – Scenario Analysis

Inputs/Outputs - Biodiesel Use Phase

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
fatty acid methyl es...	E:Water supply; sewe...	0.02239	kg		none		market...			

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
Biodiesel Use Pha...		**1.00000**	**p*km**		**none**					
Carbon dioxide, no...	../Emission to air/hig...	0.06605	kg		none					
Carbon monoxide, ...	../Emission to air/hig...	0.15673	g		none					
Hydrocarbons, alip...	../Emission to air/hig...	0.06695	g		none					
Methane, non-fossil	../Emission to air/hig...	0.00134	g		none					
Nitrogen oxides	../Emission to air/hig...	1.60760	g		none					
Particulate Matter, ...	../Emission to air/hig...	0.01590	g		none					
Particulate Matter, ...	../Emission to air/hig...	0.01769	g		none					

Figure B.1-*Use phase for the biodiesel scenario in traditional powertrains*

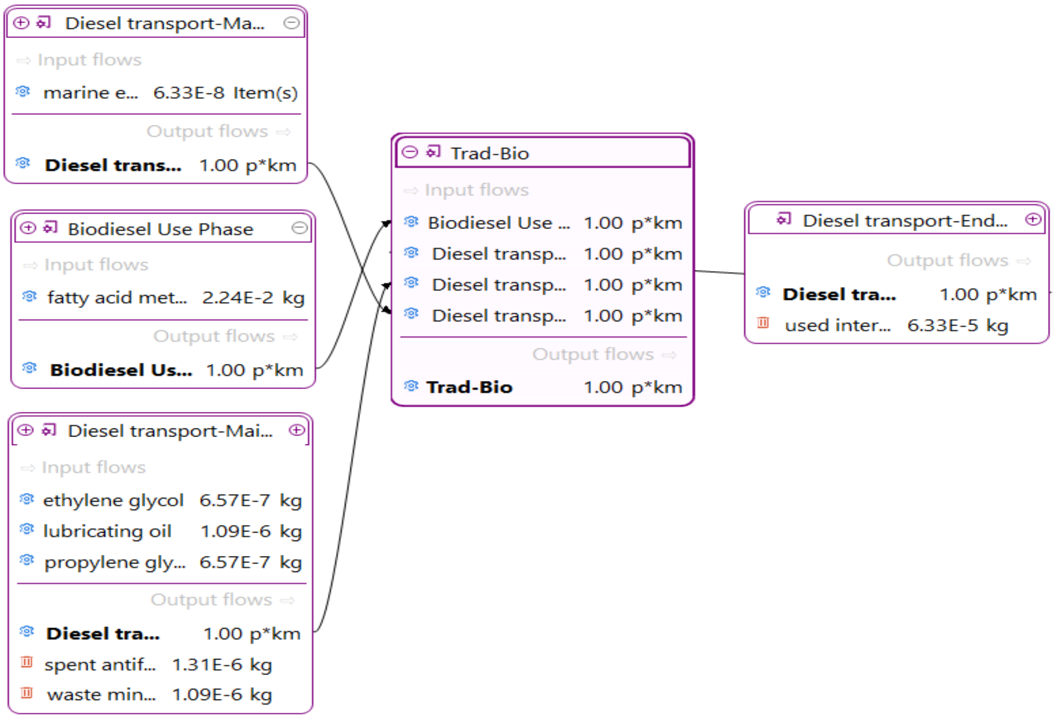


Figure B.2*-Product System of the biodiesel scenario in traditional powertrains*

Inputs/Outputs - BioHybrid Use Phase

Inputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
fatty acid methyl es...	E:Water supply; sewe...	0.01120	kg		none		market...			

Outputs

Flow	Category	Amount	Unit	Costs/Re...	Uncertain...	Avoided ...	Provider	Data qual...	Location	Descripti...
BioHybrid Use Ph...		**1.00000**	**p*km**		**none**					
Carbon dioxide, no...	../Emission to air/hig...	0.03302	kg		none					
Carbon monoxide, ...	../Emission to air/hig...	0.07837	g		none					
Hydrocarbons, alip...	../Emission to air/hig...	0.03347	g		none					
Methane, non-fossil	../Emission to air/hig...	0.00067	g		none					
Nitrogen oxides	../Emission to air/hig...	0.80380	g		none					
Particulate Matter, ...	../Emission to air/hig...	0.00795	g		none					
Particulate Matter, ...	../Emission to air/hig...	0.00884	g		none					

Figure B.3*-Use phase for the biodiesel scenario in hybrid systems*

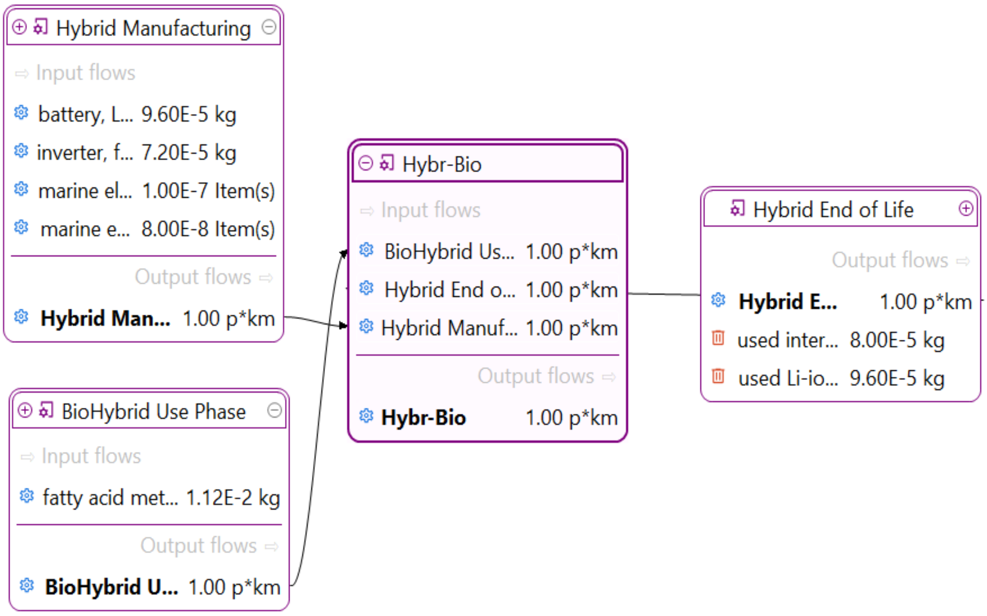
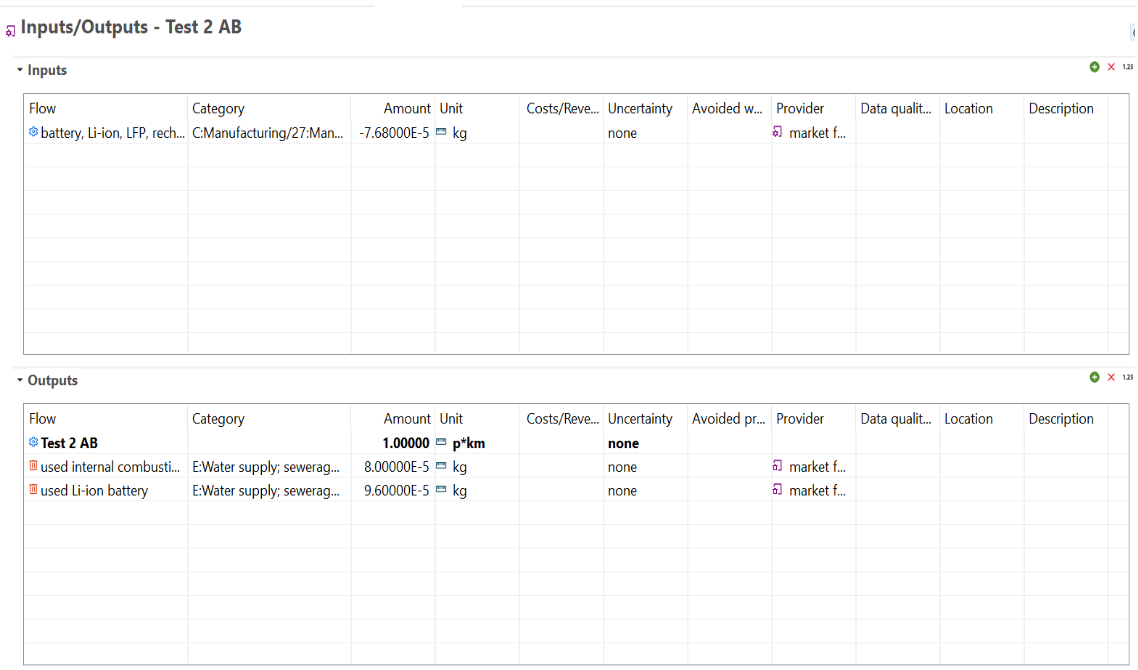


Figure B.4- *Product System of the biodiesel scenario in hybrid systems*



Inputs/Outputs - Test 2 AB

Inputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty	Avoided w...	Provider	Data qualit...	Location	Description
battery, Li-ion, LFP, rech...	C:Manufacturing/27:Man...	-7.68000E-5	kg		none		market f...			

Outputs

Flow	Category	Amount	Unit	Costs/Reve...	Uncertainty	Avoided pr...	Provider	Data qualit...	Location	Description
Test 2 AB		**1.00000**	**p*km**		**none**					
used internal combusti...	E:Water supply; sewerag...	8.00000E-5	kg		none		market f...			
used Li-ion battery	E:Water supply; sewerag...	9.60000E-5	kg		none		market f...			

Figure B.5-*EoL phase in the second-life scenario for batteries in hybrid systems*

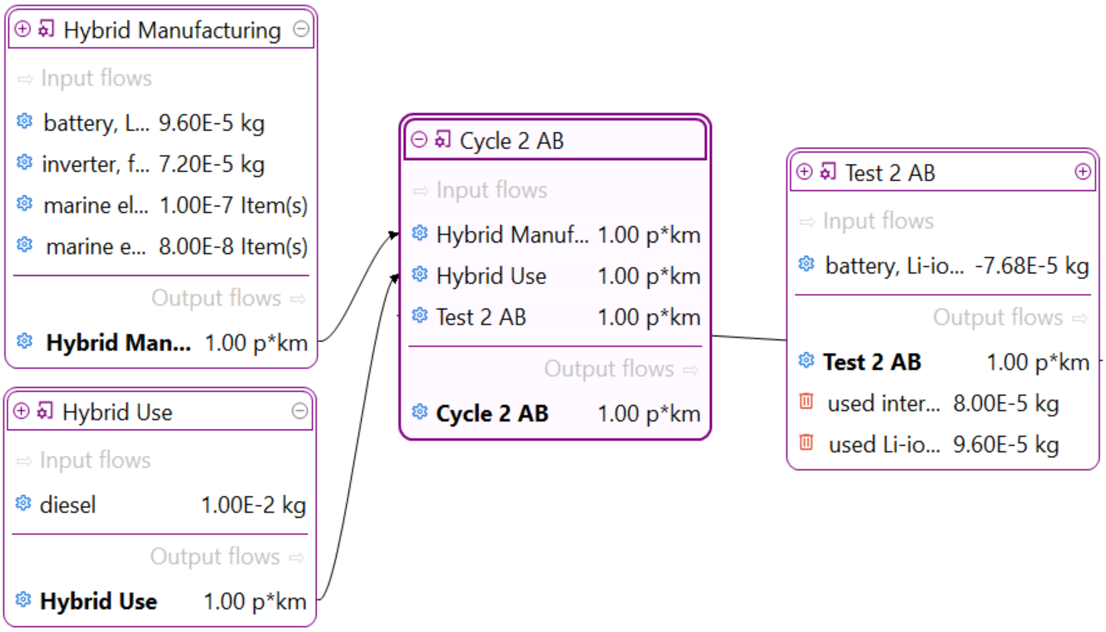


Figure B.6*-Product System of the second-life scenario for batteries in hybrid systems*

Appendix C – Additional results from the literature review

Full-Electric technology

The selected literature identifies full-electric propulsion, heavily reliant on battery ESSs, as one of the most mature options for short-range navigation, especially for short-sea transport, ferries, and inland river routes (Bilski, 2025; Perčić, Ančić, et al., 2020; Perčić et al., 2022, 2024). Regarding batteries, among the commercially available technologies, LFP and Lithium Nickel Manganese Cobalt Oxide (NMC 811) offer the best trade-off among energy density, lifespan, environmental impact, and economic viability, significantly outperforming lead-acid or nickel-metal hydride alternatives (Laurence & Bai, 2025; Perčić et al., 2022, 2024).

Despite the evident reduction in operational emissions, the reviewed literature consistently highlights that adopting electric propulsion does not inherently guarantee overall pollution abatement (Borja-Marrugo et al., 2025; Hüllein et al., 2026; Park, 2026). To accurately evaluate environmental performance, an LCA using a WtW approach emerges as one of the most effective methods (Jeong et al., 2022; Park, 2026). When the electricity used to charge ESSs is sourced from carbon-intensive, fossil-fuel-reliant grids, the overall life-cycle environmental impact of a full-electric vessel can paradoxically exceed that of a traditional one powered by a marine diesel engine (Borja-Marrugo et al., 2025; Gopujkar & Worm, 2024; Jeong et al., 2022). Some studies highlight this dynamic, demonstrating that, due to the fossil-heavy grids, direct-propulsion LPG engines produce a lower GHG impact than full-battery systems (J. K. Kim et al., 2025).

Nevertheless, when alternative propulsion systems are paired with low-carbon power grids, LCA studies confirm a remarkable reduction in GWP, mitigating overall GHG emissions by 80% to 85% (Nomak & Çiçek, 2026; H. Wang et al., 2020; Y. Wang et al., 2024).

Alternative Solutions

Concurrently, while evaluating alternative powertrains, some authors also focused on the performance of alternative fuels (Douglas et al., 2025; Kanchiralla et al., 2022). Among these, hydrogen-fed fuel cells emerge as one of the most promising solutions (Bilski, 2025). They provide extended autonomy with zero tailpipe emissions, yielding only water vapor as a byproduct of the electrochemical reaction, thereby completely eliminating operational GHG and local pollutant emissions (Bilski, 2025; Y. Wang et al., 2024). Moreover, compared to full-electric or hybrid systems, hydrogen offers substantially reduced charging time (Bilski, 2025).

However, the widespread adoption of this technology is currently hindered by the lack of adequate production and bunkering infrastructure (Bilski, 2025; Koričan et al., 2022). While hydrogen can be produced via electrolysis powered by renewable sources, most current supplies are generated through Steam Methane Reforming using natural gas (Y. Wang et al., 2024). Under this fossil-based production process, the overall life cycle emissions can exceed those of traditional marine diesel (Hüllein et al., 2026; Y. Wang et al., 2024).

Similarly, ammonia exhibits significant decarbonization potential because, as a carbon-free fuel, it does not produce CO_2 during combustion (Douglas et al., 2025; Hüllein et al., 2026; Kanchiralla et al., 2022). However, unlike traditional diesel engines, it generates substantial levels of N_2O, a powerful GHG with a GWP 273 times greater than that of CO_2 (Douglas et al., 2025; Kanchiralla et al., 2022). Mitigating these emissions requires advanced Selective Catalytic Reduction systems, and to completely abate operational emissions, ammonia must be utilized within Solid Oxide Fuel Cells, an electrochemical alternative to combustion that entirely avoids NO_x and N_2O outputs (Douglas et al., 2025; Koričan et al., 2022).

Nevertheless, much like hydrogen, ammonia production relies on energy-intensive processes that can generate significant upstream emissions (Douglas et al., 2025; Kanchiralla et al., 2022). Furthermore, at present, the adoption of these alternative fuels entails management and operational costs that are substantially higher than those of conventional diesel systems (Douglas et al., 2025; Koričan et al., 2022).

Moreover, technological feasibility is strictly dictated by vessel type. In the fishing sector, where strict weight and space limitations preclude the installation of bulky battery packs, alternative fuels such as

Liquefied Natural Gas and biodiesel blends, such as B20, represent the most viable transition options (J. K. Kim et al., 2025; Koričan et al., 2022). Conversely, for recreational vessels such as yachts and sailing boats, integrating full-electric systems with onboard renewable energy sources, such as photovoltaic panels, micro-wind turbines, or hydrokinetic generators, can satisfy up to 80% of energy demand, ensuring high autonomy without the need for external shore power, when adequate energy management strategies are employed (Nomak & Çiçek, 2026).

The undersigned Enrico Federici, student ID number 908461, enrolled at Ca' Foscari in the Joint International Master's Degree Programme in Sustainable Development, author of the final degree thesis "Towards the decarbonization of maritime public transport in Venice: an LCA-based environmental impact assessment", thesis supervisor Professor Roberto Pastres, aware of the penalties provided for in Article 76 of the Consolidated Act set out in Presidential Decree no. 445 of 28 December 2000, and of the loss of benefits provided for in Article 75 of the same Consolidated Act in the event of false or misleading statements, under his/her own responsibility pursuant to Articles 46 and 47 of Presidential Decree no. 445 of 28 December 2000,

DECLARES

that he **HAS** used generative artificial intelligence technologies to support various aspects of the research and writing of his final degree thesis, in particular:
For the revision and optimisation of texts to improve clarity and coherence, the following tools were used: DeepL, grammarly, ChatGPT 5.5 released in April 2026, and Gemini 3.1 Pro released in February 2026.

All chapters have been optimized using the AI tools mentioned. All AI-generated content was critically reviewed and adapted before being included in the thesis. The accuracy, quality, and reliability of content suggested by AI were verified against original academic literature and primary sources.

DECLARES FURTHER

that all material generated by AI has been carefully checked, reviewed and reworked by the author, who assumes full responsibility for the quality, accuracy and scientific integrity of the work.