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E-TANDEM

HYBRID TANDEM CATALYTIC CONVERSION PROCESS TOWARDS HIGHER OXYGENATE EFUELS

E-TANDEM - Deliverable report

D5.6 Report on integral source-to propeller LCA

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Project summary

E-TANDEM has enabled the efficient and direct production of a new higher-oxygenate, diesel-like e-fuel for the marine and heavy-duty transport sectors. This oxygenated fuel has been produced directly from water and CO_2 as the sole carbon source, with renewable electricity as the sole energy input, through a once-through hybrid catalytic conversion process integrating three key branches of catalysis: (1) high-pressure electrocatalysis for syngas production coupled with tandem catalytic e-syngas conversion, (2) thermocatalysis using solid catalysts, and (3) chemocatalysis employing molecular complexes. The project successfully demonstrated this novel e-fuel production route at bench scale in a continuously operating mini-plant and assessed its capability to operate under fluctuating renewable energy inputs.

Summary

This deliverable presents the development and application of an integral source-to-propeller life cycle assessment (LCA) framework for the evaluation of Higher Oxygenate E-Fuels (HOEF) within the E-TANDEM project, where boundary of the LCA is limited exclusively to the fuel life cycle. The assessment was designed to quantify and compare the environmental performance of the HOEF production concept against relevant benchmark fuel pathways for maritime transport, including marine gas oil (MGO), heavy fuel oil (HFO), paraffinic biomass-to-liquid (BtL) fuel and e-methanol.

The applied methodology integrates upstream fuel production processes and onboard fuel use within a consistent well-to-wake framework. Special emphasis was placed on the incorporation of mass and energy balances developed in the project for the HOEF production concept, enabling a process-specific assessment of the new fuel pathway. The framework was applied to a set of representative maritime case studies covering short-sea, coastal and long-haul shipping conditions, including a ferry, two fishing vessels, a bulk carrier and a cruise ship. The analysis considered both greenhouse gas emissions and local air-pollution-related impacts through selected life cycle indicators. The results provide a comparative environmental positioning of HOEF pathways in relation to conventional fossil and synthetic state-of-the-art alternatives. Across the analysed case studies, HOEF blends with marine gas oil demonstrated the potential to reduce greenhouse gas emissions as well as selected impacts related to acidification, particulate matter formation and eutrophication, with performance depending on the blending ratio, vessel operational profile and upstream electricity supply conditions. The results also confirmed the relevance of a full life cycle perspective for the robust evaluation of e-fuels in maritime applications.

The deliverable contributes directly to the project Result R5.2 by establishing the environmental positioning of the E-TANDEM fuel concept in the context of marine transport and by providing the analytical basis for a decision support system (DSS) for fuel selection under different vessel and operating conditions.

Contents

Abbreviations

Abbreviation	Explanation
AFP	Aerosol Formation Potential
AP	Acidification Potential
BtL	Biomass-to-liquid
CII	Carbon Intensity Indicator
co-SOEC	High-temperature solid oxide co-electrolysis
DE	Germany
DME	Dimethyl Ether
DSS	Decision Support System
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EP	Eutrophication Potential
EU	European Union
EU ETS	European Union Emissions Trading System
FR	France
FT	Fischer-Tropsch
GHG	Greenhouse gases
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HOEF	Higher Oxygenate E-Fuels
HR	Croatia
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MGO	Marine Gas Oil
NO	Norway
PL	Poland
PM	Particulate Matter
PtX	Power-to-X
RE	Renewable Electricity
TTW	Tank-to-wake
USA	United States
WTT	Well-to-tank
WTW	Well-to-wake

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1 Introduction

1.1 Maritime decarbonisation challenges and regulatory context

The maritime sector's reliance on fossil fuels significantly contributes to environmental pollution. Ships primarily use Heavy Fuel Oil (HFO) or Marine Gas Oil (MGO) for propulsion, the combustion of which results in various emissions, such as sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM) and greenhouse gases (GHGs) [1]. PM, SOx, and NOx emissions pose significant risks to human health, contributing to respiratory diseases and other health complications. In addition, NOx and SOx emissions adversely affect terrestrial and aquatic ecosystems by causing eutrophication and acidification. While these pollutants are primarily classified as local emissions with direct effects on population and the environment in the vicinity of shipping operations, the increasing concentration of GHGs poses a global environmental challenge [2]. Over the past several decades, the extensive use of fossil fuels has led to a significant rise in atmospheric concentrations of GHGs, intensifying global warming and contributing to climate change. The shipping sector is estimated to account for approximately 3% of total global carbon dioxide (CO_2) emissions, a share that may increase with the continued expansion of international trade [3]. International climate agreements, including the Paris Agreement (2015) and the Glasgow Climate Pact (2021), have therefore established targets to limit global temperature increase to well below 2°C above pre-industrial levels, with efforts to constrain it to 1.5°C [4,5].

Achieving this requires substantial reductions in GHG emissions across all economic sectors, including the maritime industry. As the specialised United Nations agency responsible for regulating international shipping, the International Maritime Organisation (IMO) plays a central role to reduce emissions from maritime sector. Historically, IMO regulation initially focused on addressing local air pollutants through the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, introducing limits on sulphur content in marine fuels and establishing Emission Control Areas (ECAs), where stricter standards for SOx and NOx emissions apply, primarily addressing air quality impacts in coastal regions. MARPOL Annex VI also introduces tiered limits for NOx emissions from marine engines, including Tier I and Tier II standards, which define progressively stricter emission limits expressed in g/kWh depending on the engine installation year [6]. Over time, regulatory attention has shifted toward GHG emissions and long-term decarbonization objectives. The IMO introduced technical and operational energy efficiency measures, including the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), aiming to progressively reduce carbon intensity across the fleet. This trajectory was reinforced by the 2023 Revised IMO GHG Strategy, which sets indicative targets for reducing total GHG emissions and promotes the uptake of zero and near-zero emission energy sources [7]. Achieving these objectives requires the combined implementation of technical, operational and market-based measures within the shipping sector [8]. At the regional level, the European Union (EU) complements the global framework through the extension of the EU Emissions Trading System (EU ETS) to maritime transport and the adoption of the FuelEU Maritime regulation. While the EU ETS introduces a carbon pricing mechanism for shipping emissions, FuelEU Maritime establishes binding limits on lifecycle GHG intensity of energy used by ships operating within EU waters, thereby promoting the uptake of low and zero-carbon fuels [9,10].

Collectively, these international and regional policy instruments shift compliance from solely operational efficiency improvements toward the lifecycle GHG performance of marine fuels [11]. As a result, fuel selection becomes a central technical and strategic decision for shipowners, particularly in the context of emerging alternative fuels. This transition requires robust and transparent assessment methodologies, such as Life Cycle Assessment (LCA), capable of evaluating environmental impacts across the entire fuel value chain [12,13].

1.2 Role of electrofuels in maritime transport

A range of alternative fuels has been proposed for maritime decarbonisation, including Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), methanol, Dimethyl Ether (DME), biofuels, hydrogen (H_2), ammonia (NH_3) and electricity-based fuels [14] . These options differ significantly in their potential to reduce GHG emissions [15]. Figure 1 illustrates the relative lifecycle GHG emission intensity of various marine fuel pathways.

Several low-carbon marine fuels offer partial emission reductions relative to conventional marine fuels. LNG and LPG enable compliance with sulphur emission limits and can reduce CO_2 emissions by approximately 10-20% due to their lower carbon content. However, their overall climate benefits remain constrained by continued fossil carbon dependence and, in the case of LNG, methane slip [16,17] Similarly, methanol and DME exhibit low local pollutant emissions, including near-zero SOx and reduced PM formation. Nevertheless, both fuels are characterised by lower energy density compared to conventional marine fuels, and their lifecycle GHG performance strongly depends on upstream production pathways [17–19].

In contrast, biofuels are commonly regarded as carbon-neutral fuel options due to the biogenic origin of carbon. Biofuels can achieve substantial lifecycle GHG reduction, with reported emission reduction up to 80% compared to conventional marine fuels. However, their overall climate performance remains highly dependent on feedstock type, land-use effect and agricultural inputs, while operational challenges such as storage stability and blend limitations may constrain their widespread deployment [20,21].

H_2 and NH_3 are considered zero-carbon fuels at the point of use, since they do not emit CO_2 during combustion [22]. Nevertheless, their lifecycle climate performance is highly dependent on the carbon intensity of upstream H_2 production, with fossil-based (grey or brown) pathways potentially resulting in high lifecycle GHG emissions [23]. H_2 and NH_3 produced from low-carbon or renewable pathways can significantly reduce lifecycle GHG emissions and are therefore widely considered for maritime decarbonisation [24]. Challenges related to low volumetric energy density for H_2, toxicity for NH_3, storage conditions and infrastructure availability remain key barriers to large-scale maritime deployment [25].

Among the alternative fuels, electrofuels (e-fuels) are increasingly considered as potential long-term solutions for maritime decarbonisation due to their potential to significantly reduce GHG emissions [26]. They are produced through Power-to-X (PtX) pathways, where electricity is used in water electrolysis to generate e-H_2, which serves as a key intermediate for further fuel synthesis [27]. Depending on the targeted fuel, e-H_2 can be combined with captured CO_2 or nitrogen (N_2) extracted from air to produce fuels such as e-methanol, e-diesel, e-LNG and e-NH_3 [28]. However, emissions from fuel combustion alone are not sufficient to assess the environmental performance of these fuels. While tank-to-wake (TTW) emissions may be very low or even zero, significant upstream emissions can occur in the well-to-tank (WTT) phase, which includes feedstock extraction, e-H_2 production, fuel synthesis, conditioning, storage, transport and bunkering prior to its use onboard. The magnitude of WTT emissions primarily depends on the carbon intensity of electricity used for electrolysis and the source of carbon feedstocks used during fuel synthesis [29,30]. Consequently, evaluating fuel sustainability requires a well-to-wake (WTW) perspective that integrates both WTT and TTW stages, and LCA is therefore commonly applied to quantify emissions across the entire fuel production and utilisation chain [31].

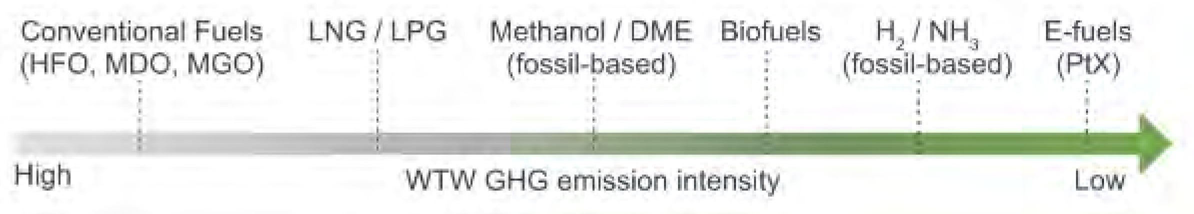

Figure 1. Relative WTW GHG emission intensity of selected marine fuels.

1.3 The HOEF concept within E-TANDEM project

The proposed production pathway of E-TANDEM Higher Oxygenate E-Fuels (HOEF) converts CO_2, water and renewable electricity into liquid oxygenated fuels through an integrated catalytic process. Figure 2 illustrates the conceptual production pathway of HOEF. Renewable electricity drives high-temperature solid oxide co-electrolysis (co-SOEC) of CO_2 and steam to produce an e-syngas mixture composed of H_2 and carbon monoxide (CO). This intermediate stream subsequently undergoes tandem catalytic conversion, integrating Fischer-Tropsch (FT) synthesis and reductive hydroformylation, enabling the formation of higher oxygenates. The process enables the formation of higher aliphatic alcohols, which can further undergo catalytic dehydration to produce higher aliphatic ethers. Within the project, two fuel realizations are considered: HOEF I, consisting of mixtures of higher aliphatic alcohols (C_5-C_{13}) and HOEF II, consisting of higher ethers (C_{10}-C_{22}) derived from these alcohol intermediates.

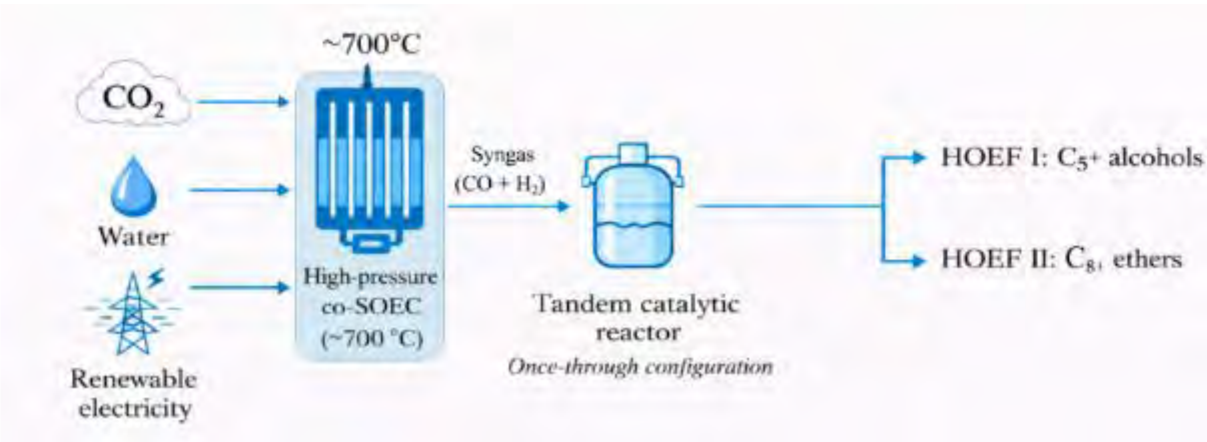

Figure 2. Conceptual process scheme for the production of two HOEF realizations

The detailed process configuration and operational parameters of the HOEF production pathway are developed within Task 4.3 of the E-TANDEM project, where mass and energy balances of the integrated production concept are established.

It should be noted that the higher oxygenate e-fuel (HOEF), as referred to in this report, includes exclusively the fraction of higher alcohols or their corresponding ether derivatives obtained through the tandem e-syngas conversion process developed within the E-TANDEM project, based on the results achieved at laboratory scale. Additional non-oxygenated hydrocarbons, which are also formed as by-products of the process and could potentially be upgraded (e.g. via hydro-isomerisation) and blended into the final fuel, thereby reducing the required share of fossil MGO, are not included within the definition of HOEF for the analyses presented in this report.

1.4 Objectives and scope of Deliverable D5.6

Deliverable D5.6 develops and applies an integrated LCA framework to evaluate the environmental performance of HOEF in maritime applications. The approach uses a unified source-to-propeller (well-to-wake) system boundary, combining upstream fuel production and onboard use to enable consistent comparison of marine fuel pathways.

The framework is applied to representative case studies, including a cruise ship, bulk carrier, ro-ro passenger ship, and two fishing vessels (purse seiner and trawler). Fuels assessed include Marine Gas Oil (MGO) as the reference, biomass-to-liquid (BtL) FT diesel, e-methanol, and multiple HOEF blends with marine gas oil (HOEF I: 30% and 50%; HOEF II: 10% and 20%). Both well-to-tank (WTT) and tank-to-wake (TTW) stages are covered, including main and auxiliary engines to capture total onboard energy demand.

Environmental performance is evaluated using key indicators: Global Warming Potential (GWP), Acidification Potential (AP), Aerosol Formation Potential (AFP), and Eutrophication Potential (EP). The results support positioning HOEF against conventional and alternative fuels (R5.2) and provide a basis for a Decision Support System (DSS) to guide fuel selection across vessel types and operations.

1.5 Structure of the report

The report is structured as follows. Chapter 2 defines the LCA goal and scope, including system boundaries, functional units, case studies, fuel pathways, impact categories, and key assumptions. Chapter 3 describes the life cycle inventory modelling, covering fuel production (WTT), mass and energy balances, and ship energy use and emissions (TTW). Chapter 4 outlines the case studies and vessel operational profiles. Chapter 5 presents LCA results across fuels and vessel types, while Chapter 6 assesses their robustness through sensitivity analysis. Chapter 7 interprets the results, highlighting the performance of HOEF across contexts, and Chapter 8 introduces a DSS for fuel selection. Chapter 9 discusses broader implications and trade-offs, and Chapter 10 concludes with key findings and recommendations.

2 Goal and scope definition

2.1 Goal of the life cycle assessment

The goal of this LCA is to evaluate and compare the environmental performance of different marine fuel pathways used in representative ship operations considered within the E-TANDEM project. The assessment is applied to several representative maritime case studies, including a cruise ship, a bulk carrier, a ro-ro passenger ship and two fishing vessels (a purse seiner and a trawler), reflecting different operational segments of the maritime sector. The analysed fuel pathways include MGO as a reference fossil fuel, HFO, BtL FT-diesel, e-methanol and several HOEF blending scenarios, enabling a comparative evaluation of conventional and alternative marine fuels.

The assessment follows the methodological framework defined by the ISO 14040 and ISO 14044 standards for LCA [12,13]. The objective is to quantify environmental impacts associated with ship operation rather than solely evaluating the properties or energy content of the fuels themselves. This approach enables a consistent comparison of fuel pathways under realistic ship operational conditions.

To capture the full environmental implications of marine fuel use, the analysis adopts a WTW system boundary, which includes both upstream (WTT), such as fuel production, transport and fuel supply processes, and emissions generated during fuel combustion onboard the vessel (TTW). This approach is consistent with the LCA framework recommended by the IMO for evaluating the GHG intensity of marine fuels [32].

The results of the analysis provide a quantitative basis for comparing the environmental performance of conventional and alternative marine fuels and support the environmental positioning of the HOEF concept within different maritime operational scenarios.

2.2 Integral source-to-propeller system boundary

The LCA adopts an integral source-to-propeller system boundary (Figure 3), ensuring that both upstream fuel production processes and onboard fuel utilisations are consistently integrated within the analysis. This approach enables a comprehensive evaluation of environmental impacts associated with marine fuels by capturing emissions and resource use across the entire energy supply chain. The system boundary follows the WTW framework, which consists of two main components: the WTT phase and TTW phase.

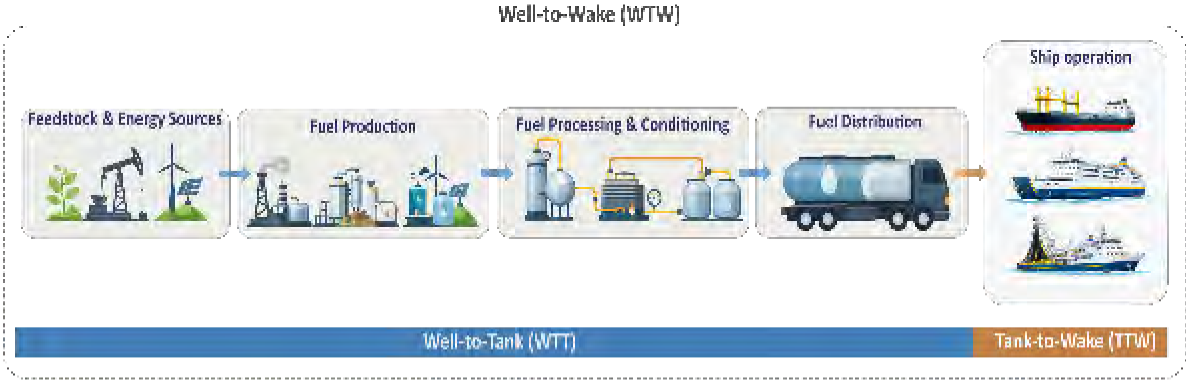

Figure 3. Source-to-propeller system boundary applied in the WTW LCA of marine fuel pathways

The WTT phase includes all processes associated with the production and supply of marine fuels. Depending on the fuel pathway, this stage covers feedstock extraction or capture, production of energy carriers such as e-H_2, fuel synthesis processes (e.g. FT synthesis or methanol synthesis), conditioning and upgrading of the fuel, as well as transport, distribution and bunkering prior to use onboard the vessel.

The TTW phase represents the utilisation of the fuel during operation. It includes fuel combustion in the ship propulsion system and the conversion of chemical energy contained in the fuel into mechanical energy delivered to the propeller. The analysis considers the energy demand associated with representative operational profiles of the investigated vessels. In addition to the main propulsion engine, auxiliary engines are also included in the TTW phase, as they contribute to the total onboard energy demand by supplying electrical power required for navigation systems, onboard equipment and hotel loads, and therefore represent an essential component of the overall energy balance of the vessel

By integrating both WTT and TTW stages, the source-to-propeller system boundary provides a consistent framework for comparing the environmental performance of different marine fuel pathways across the analysed ship operations.

2.3 Functional units and reference flows

In LCA, the functional unit defines the quantified performance of a product system and provides the reference to which all inputs and outputs are related. In the context of maritime transport, the functional unit represents the transport service delivered by a vessel under defined operational conditions. Depending on the vessel type and operational characteristics, the functional unit may be defined either as a representative operational mission, such as a return trip or fishing operation, or as a transport work metric, such as tonne-nautical mile or passenger-nautical mile. This reflects differences in vessel operation and ensures that each case study is described in a way that best represents its operational characteristics. Fuel pathways are compared within the same operational task to ensure a consistent and fair comparison. For each case study, the functional unit therefore defines the transport service that must be delivered, while the corresponding reference flow represents the amount of fuel required to fulfil this task and serves as the basis for LCA calculations. An overview of the functional units adopted for each case study is provided in Table 1.

Table 1. Overview of functional units for the analysed vessel types

Case study	Functional unit	Type of functional unit
Ferry	One return trip	Operational mission
Trawler	One fishing cycle	Operational mission
Purse seiner	One fishing cycle	Operational mission
Bulk carrier	Transport of 1 tonne over 1 nautical mile	Transport work
Cruise ship	Transport of 1 passenger over 1 nautical mile	Transport work

For the ferry case study, the functional unit is defined as one return trip, representing the transport service delivered by the vessel during a typical operational mission [33]. The return trip includes all operational phases of the voyage, such as manoeuvring in port and cruising between two ports. This functional unit provides a consistent basis for estimating propulsion energy demand and fuel consumption associated with the ferry operation.

The functional unit for the fishing vessels is defined as one complete fishing cycle, representing a typical operational sequence of the vessel during a single fishing activity. A fishing cycle in the case of trawler consists of multiple operational phases, including cruising, net setting, trawling, net hauling and searching for fish and vessel repositioning, followed by a second trawling and net hauling phase, and finally cruising back [34]. In the case of purse seiner, the fishing cycle consists of cruising to the fishing location, followed by searching for fish, net setting, hauling and catch loading operations. These phases may be repeated multiple times within a single fishing trip depending on catch success, after which the vessel returns to the port [35]. This functional unit captures the full operational variability of fishing activities, thereby providing a representative basis for estimating energy demand and fuel consumption associated with commercial fishing operations.

The functional unit for the bulk carrier case study is defined as the transport of one tonne of cargo over one nautical mile (ton-nm). This reflects the operational characteristics of bulk carriers, which operate on long-distance routes under steady operating conditions and without distinct operational phases. Unlike ferries and fishing vessels, where the functional unit is based on a representative operational mission, a transport-based functional unit is adopted, enabling a consistent comparison of energy demand and environmental impacts across different operating conditions.

For the cruise ship case study, the functional unit is defined as the transport of one passenger over one nautical mile (pax-nm), representing the transport service delivered during a cruise voyage. This functional unit is directly linked to the operational profile of cruise ship, which is characterised by a combination of sea-going and port (hoteling) phases. As a result, the energy demand underlying the functional unit includes both propulsion-related consumption during sea-going and significant auxiliary loads associated with onboard services, particularly during port stays [36].

2.4 Case study framework and operational scenarios

Five representative vessel types were selected to cover the main operational segments of maritime transport: a ferry, a bulk carrier, a cruise ship and two fishing vessels (a trawler and a purse seiner). These vessels represent different operational patterns and energy demand profiles. The selection enables the assessment of HOEF blends with marine gas oil applicability across cargo transport, passenger services and fishing activities, which together represent a significant share of maritime operations.

From an operational perspective, the selected vessels cover two main shipping regimes: short-sea shipping and coastal operations, as well as deep-sea shipping. Short-sea shipping refers to maritime transport over relatively short distances, typically characterised by frequent port calls and defined routes, and is represented by the ferry [37]. Coastal operations are represented by a trawler and a purse seiner. In contrast, deep-sea shipping involves long-distance voyages and continuous operation over extended periods, which is typical for vessels such as bulk carriers and cruise ships [38]. Considering these distinct operational profiles is important when evaluating the potential of HOEF blends with marine gas oil, as fuel consumption patterns and engine loads vary significantly between vessel types. In addition to operational regimes, the case study framework also considers different regulatory operating conditions related to air emission control. In particular, the analysis distinguishes between vessel operation inside ECA and outside ECA regions. Within ECA zones, stricter limits on SOx, NOx and PM apply according to the requirements of IMO MARPOL Annex VI [39].

2.5 Compared fuel pathways

This section defines the set of marine fuel pathways considered in the comparative assessment. The selected fuels represent both the conventional fuel currently used in maritime transport, represented by MGO, and several alternative options (BtL, e-methanol, HOEF blends) that are being investigated as potential solutions for reducing emissions in the sector.

MGO is used as the reference fossil fuel in the comparative assessment. To evaluate the environmental impacts associated with its use in maritime transport, the analysis considers the complete fuel pathway within a WTW framework which consists of WTT and TTW stages. The WTT stage includes all processes required to supply the fuel for ship operation, starting from crude oil extraction, followed by crude oil transport, refinery processing and fuel distribution prior to bunkering. As a petroleum-derived middle-distillate fuel, MGO is produced through conventional refining of crude oil and subsequently delivered for marine use. The TTW stage represents the operational use of the fuel onboard the vessel and includes the combustion of MGO in the ship's main and auxiliary engines [40].

BtL is a synthetic paraffinic diesel fuel produced from biomass via thermochemical conversion. The WTT stage for BtL starts with biomass provision, including collection and transport of the biomass feedstock to the conversion facility. It then comprises biomass pre-treatment and gasification, followed by syngas cleaning and conditioning to obtain a syngas suitable for FT conversion. The resulting hydrocarbon mixture is subsequently upgraded and fractioned to produce a paraffinic diesel fuel. Finally, storage, transport and bunkering of the final fuel are included prior to its onboard use. The TTW stage comprises of the combustion of BtL fuel in the ship propulsion system [41].

E-methanol is a synthetic methanol produced from e-H_2 and captured CO_2 through catalytic methanol synthesis. The WTT stage for e-methanol begins with electricity supply used for e-H2 production via water electrolysis. Water supply and conditioning are included as part of the electrolysis process. CO_2 is provided through capture and purification processes and subsequently compressed and transported to the synthesis facility. H_2 and CO_2 are then converted into e-methanol through catalytic methanol synthesis. The crude methanol product undergoes purification and distillation to obtain fuel-grade e-methanol. Finally, storage, transport and bunkering of the produced fuels are included prior to its onboard use. The TTW stage covers the combustion of e-methanol in the marine propulsion system [27].

HOEF fuels are considered in blends with MGO, which pathway is already described in this chapter. The investigated fuel mixtures include HOEF I blends containing 30% and 50% HOEF I and HOEF II blends containing 10% and 20% HOEF II, with remaining fraction consisting of MGO. The WTT stage therefore includes both the upstream production of HOEF and MGO, fuel blending, storage, transport and bunkering before onboard use. In the WTT phase, HOEF is produced from captured CO_2, water and renewable electricity through an electrochemical and catalytic conversion pathway. Renewable electricity is used to drive high temperature co-SOEC, producing syngas that is subsequently converted into oxygenated fuels through tandem catalytic processes. The TTW phase represents the combustion of HOEF blends with marine gas oil in the marine propulsion system, where fuel is converted into mechanical energy for vessel propulsion and associated exhaust emissions are generated. The WTW system boundary for HOEF blends with marine gas oil is shown in Figure 4.

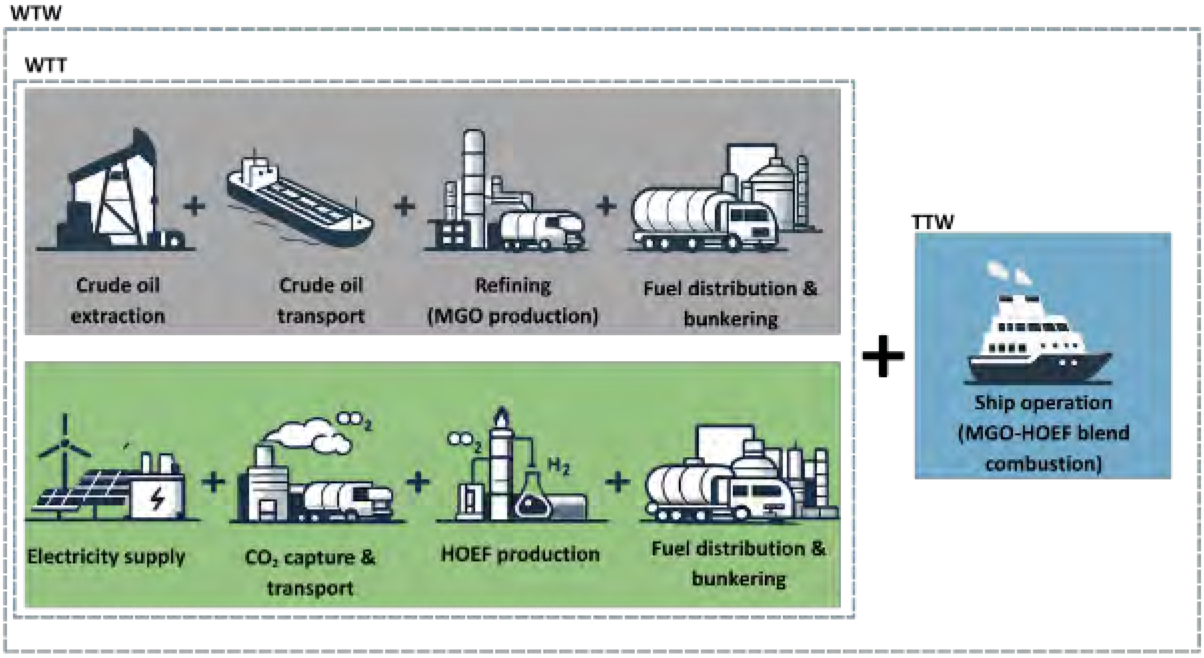

Figure 4. WTW system boundary for MGO-HOEF blends.

HFO is used as a conventional residual fuel representing heavy fuel oils commonly used in maritime transport, particularly in operations outside ECA. The WTT stage includes all processes required to supply the fuel for ship operation, starting from crude oil extraction, followed by crude oil transport, refinery processing and fuel distribution prior to bunkering. As a residual fuel, HFO is obtained from the heavier fractions of crude oil remaining after the separation of lighter products during refining and is subsequently blended to meet fuel specifications. The TTW stage represents the operational use of the fuel onboard the vessel and includes the combustion of HFO in the ship's main and auxiliary engines [42].

The associated emissions depend on the fuel consumption required to provide the defined transport service for each vessel case study. The comparison assumes that the vessel provides the same transport service in all fuel scenarios. Therefore, the operational and propulsion energy demand remain constant, while fuel consumption varies according to the lower heating values of the analysed fuels. This approach ensures that the comparison between fuel pathways is based on an equivalent transport service.

2.6 Life cycle impact categories and indicators

To capture environmental effects of the considered application cases, four impact categories are considered: Global Warming Potential (GWP), Acidification Potential (AP), Atmospheric Fine Particle Formation Potential (AFP) and Eutrophication Potential (EP). These indicators allow for the evaluation of both global climate impacts and local air pollution associated with maritime fuel use [36].

The GWP indicator quantifies the contribution of GHG emissions to climate change. In the context of maritime transport, the most relevant GHGs include CO_2, methane (CH_4) and nitrous oxide (N_2O), which are emitted during fuel production and combustion. GWP is calculated using 100-year time horizon (GWP100) and expressed in terms of kg CO_2 equivalents (CO_2-eq), enabling the aggregation of different GHGs into a single climate change indicator [43]. The AP indicator reflects the potential of emitted

pollutants to cause acidification of terrestrial and aquatic ecosystems, and is expressed in kg SO_2-eq [44]. The AFP indicator captures the formation of fine PM ($PM_{2.5}$) in the atmosphere, which is associated with adverse impacts on human health and air quality. PM emitted directly from marine engines, as well as secondary particles formed from gaseous precursors such as SOx and NOx, contribute to this impact category that is expressed in kg $PM_{2.5}$-eq [45]. Finally, the EP indicator represents the potential of nutrient emissions to cause excessive nutrient enrichment in aquatic and terrestrial ecosystems. NOx emitted from ship exhaust gasses can be deposited onto water and soil, contributing to increased nutrient loads and the disruption of ecosystem balance. The EP indicator is expressed in kg PO_4^{3-} -eq [46].
The impact categories, indicators, main contributing emissions and corresponding units used in the LCA are summarised in Table *2*.

Table 2. Environmental impact categories and corresponding indicators used in the LCA.

Impact category	Indicator	Main contributing emissions	Unit
Climate change	Global Warming Potential (GWP100)	CO_2, CH_4, N_2O	kg CO_2-eq
Acidification	Acidification Potential (AP)	SOx, NOx	kg SO_2-eq
Fine particulate formation	Atmospheric Fine Particle Formation Potential (AFP)	PM_{10}, SOx, NOx	kg $PM_{2.5}$-eq
Eutrophication	Eutrophication Potential (EP)	NOx	kg PO_4^{3-} -eq

2.7 Key assumptions and limitations

The following key assumptions and limitations are considered in the analysis to ensure transparency and consistency of the applied methodology:

- A marine diesel engine operating on HOEF-MGO blends has the same overall efficiency as when operating on pure MGO. No efficiency penalty or improvement due to blending is considered. This simplification enables a direct comparison of fuel pathways under identical operational conditions.
- HOEF and e-methanol are assumed to be produced using electricity exclusively from renewable energy sources and CO_2 obtained from DAC. Variation in the electricity mix or CO_2 source would directly affect the WTT emissions and overall life-cycle results.
- The analysis focuses exclusively on environmental impacts and does not include economic assessment such as fuel production costs, infrastructure investments or retrofit expenses.
- The operational profiles applied for each vessel type are based on representative and simplified operating conditions. In real applications, ship operating is influenced by a range of factors, including weather conditions, sea state, cargo load variations, routing decisions and operational constraints. These factors may lead to variations in engine load, fuel consumption and resulting emissions, which are not explicitly captured in the present analysis.

3 Life cycle inventory modelling

3.1 General LCA methodology

The environmental assessment performed in this study follows the LCA framework defined by ISO 14040 and ISO 14044 standards. While Chapter 2 defines the goal and scope of the assessment, the present chapter describes the modelling approach used to quantify environmental impacts associated with HOEF blends with marine gas oil use in the analysed ship operations. The applied methodology integrates both WTT and TTW components within a WTW framework. In this modelling approach, the WTT stage represents upstream processes associated with fuel production and supply, while TTW stage describes the operational use of fuels onboard the vessel.
The WTT component of the analysis includes feedstock extraction or capture, fuel synthesis processes and fuel supply prior to bunkering. These processes are modelled using life cycle inventory datasets representing the respective fuel production pathways.
The TTW component represents the operational phase of the vessel and includes emissions generated during fuel combustion in the main propulsion engine and auxiliary engines. In this study, the TTW modelling is based on vessel operational energy demand determined for each case study. Fuel consumption is calculated using case-specific energy demand models, which account for engine power, load factors and vessel operational characteristics. The resulting fuel consumption values are then used to estimate the emissions associated with ship operation.

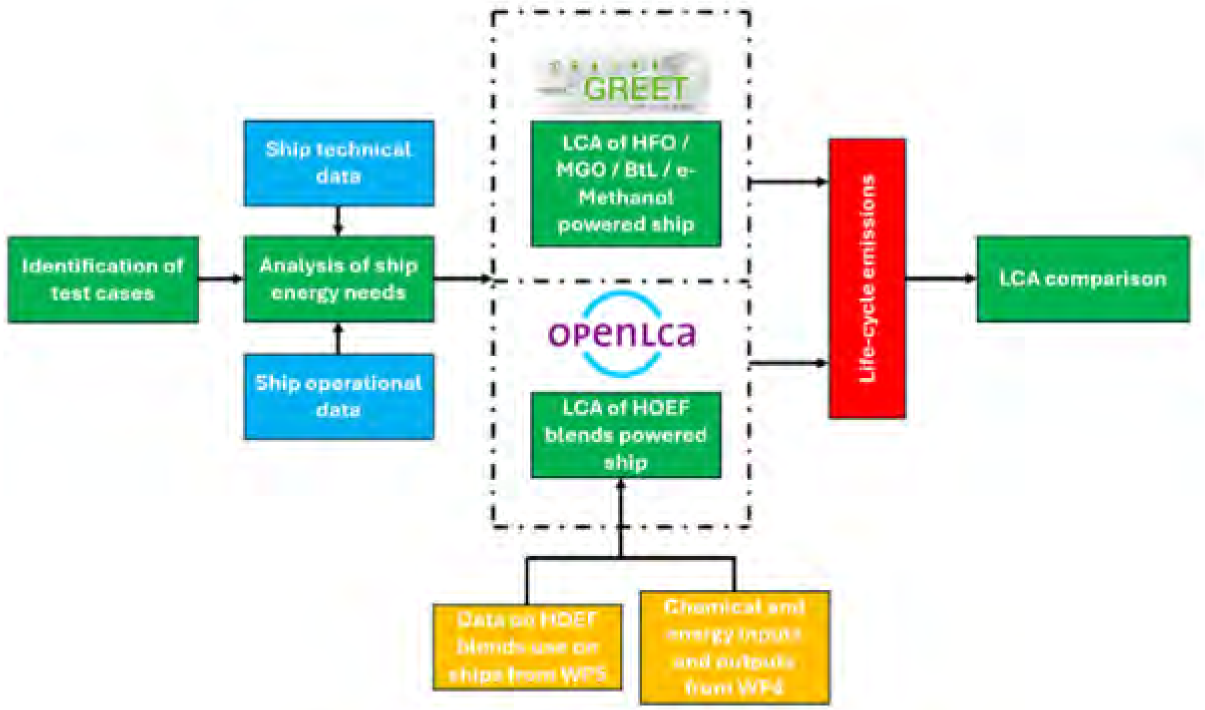

Figure 5. General LCA methodology used in report.

Figure 5 presents the integrated methodological framework used in the report for conducting a source-to-propeller LCA of marine fuel pathways. The analysis begins with the identification of test cases and the collection of ship technical and operational data, which are used to model vessel energy demand and determine fuel consumption under representative operating conditions. These results are then linked to life cycle modelling, where the GREET model is applied to assess the environmental performance of conventional and established fuels analysed in the report, including HFO, MGO, BtL and e-methanol. In parallel, openLCA is used to model HOEF blend fuels, integrating detailed production data from WP4 and fuel usage data from WP5. Both modelling approaches quantify life-cycle emissions within a well-to-wake (WTW) framework, combining upstream fuel production and onboard combustion. The resulting emissions are subsequently used to perform a comparative LCA across different fuel pathways. This integrated approach ensures a consistent evaluation of environmental impacts and supports the positioning of HOEF fuels relative to conventional and alternative marine fuels within the study

3.2 Integration of T4.3 mass and energy balances

The modelling of the well-to-tank (WTT) phase for HOEF fuels is based on the integration of detailed mass and energy balances developed within Task 4.3 of the E-TANDEM project. These balances represent the core input for quantifying emissions associated with fuel production and therefore constitute a key innovation of the applied LCA framework. The HOEF production pathway, illustrated in Figure 11, describes a process in which renewable electricity, water and captured CO_2 are converted into liquid oxygenated fuels through a sequence of electrochemical and catalytic steps. The process begins with high-temperature co-electrolysis (co-SOEC), where CO_2 and steam are converted into synthesis gas (a mixture of H_2 and CO), which serves as a key intermediate for subsequent fuel synthesis. The mass and energy balances developed in Task 4.3 quantify all relevant input and output streams across these process stages, including electricity demand, water consumption, CO_2 feedstock, intermediate flows and final product yields. These data are subsequently translated into life cycle inventory inputs by linking each process flow with corresponding emission factors, thereby enabling the calculation of upstream emissions associated with fuel production. This approach ensures that key parameters, such as electricity carbon intensity and process efficiency, are explicitly reflected in the WTT results. Compared to conventional fuels, where standard database values can be applied, the HOEF modelling requires a process-based representation due to the novelty and complexity of the production pathway. By incorporating the T4.3 mass and energy balances, the model provides a high-resolution and transparent representation of HOEF production and ensures consistency within the overall source-to-propeller LCA framework.

3.3 Ship energy demand modelling

The HOEF production process was modelled at a demonstration scale of 1 MW. In order to evaluate the applicability of HOEF fuels across different maritime sectors, several reference vessels were analysed, including a ferry, cruise ship, bulk carrier, trawler and purse seiner. The annual energy demand of these vessels was used to assess the required fuel supply and to ensure consistency between fuel production and fuel consumption within the LCA framework.

The fuel consumption of the ferry was estimated based on the operational profile and the corresponding engine loads. The operational profile was divided into different navigation modes, each characterised by a specific engine load and operating time. For each operating mode, the actual engine power was calculated using the engine load factor according to:

$$P_{act} = LF \times P_{rated} \tag{1}$$

where P_{act} represents the actual engine power (kW), LF the load factor, and P_{rated} the rated engine power (kW).

The energy consumption for each operational segment was then calculated as:

$$EC_i = P_{act,i} \times t_i \tag{2}$$

where EC_i represents the energy consumption for operational segment i (kWh) and t_i the duration of that operating mode (h).

Both the main engine (ME) and auxiliary engines (AE) were considered in the calculation of the total energy demand. The total energy consumption of the vessel was therefore calculated as:

$$EC_{tot} = \sum EC_{ME,i} + \sum EC_{AE,i} \tag{3}$$

Finally, the fuel consumption was determined using the specific fuel consumption of the engines:

$$FC = EC_{tot} \times SFC \tag{4}$$

where FC represents the fuel consumption, EC_{tot} the total energy consumption, and SFC the specific fuel consumption of the engine.

The energy demand for both fishing vessels are determined based on a multi-year measurement campaign conducted by UZ. The vessel was equipped with fuel monitoring system, GPS and engine activity sensors, while the collected data were visualised through MAPON software [47]. Based on the collected measurements, Jadran Tri performs approximately 200 fishing cycles per year, with and average MGO consumption of 400 L per fishing cycle, while purse seiner Noa has average MGO consumption of 576 L per fishing cycle. The energy demand per fishing cycle was determined as:

$$EC = \frac{FC_{MGO} \times \rho_{MGO}}{SFC} \tag{5}$$

where EC represents the energy consumption per fishing cycle (kWh), FC_{MGO} the consumption of MGO per fishing cycle (m^3), ρ_{MGO} the density of MGO (kg/m^3) and SFC the specific fuel consumption of the engine (kg/kWh).

The ship energy demand for the bulk carrier case study is modelled assuming continuous sailing conditions, with the main engine providing propulsion power and the auxiliary engines covering onboard electricity demand. The route is divided into segments inside and outside ECA, allowing for the application of different fuels depending on regulatory conditions. The bulk carrier is represented by a steady-state operational profile, where changes in energy demand are primarily associated with vessel speed. The main engine power demand is estimated from the installed main engine power, assuming an average engine load of 75% Maximum Continuous Rating (MCR), and adjusted according to vessel speed as follows:

$$P_{ME,ave} = (P_{ME} \cdot 0.75) \cdot \left(\frac{v}{v_d}\right)^3 \tag{6}$$

where $P_{ME,ave}$ is the average main engine power demand (kW), v is the operating vessel speed (kn) and v_d is the design speed of the vessel (kn).

The total onboard power (P_{tot}) demand is calculated as the sum of the main engine and auxiliary engine power:

$$P_{tot} = P_{ME,ave} + P_{AE} \tag{7}$$

The energy consumption per nautical mile (EC_{nm}) is then determined as:

$$EC_{nm} = \frac{P_{tot}}{v}\,[kWh/nm] \tag{8}$$

Fuel consumption is calculated based on the obtained power demand and the specific fuel consumption of the main and auxiliary engines, considering different values for each engine type:

$$FC_{ME} = \frac{P_{ME,ave} \cdot SFC_{ME}}{1000} \tag{9}$$

$$FC_{AE} = \frac{P_{AE} \cdot SFC_{AE}}{1000} \tag{10}$$

$$FC = \frac{FC_{ME} + FC_{AE}}{v}\,[kg/nm] \tag{11}$$

The total fuel consumption is subsequently distributed according to the operational region, distinguishing between fuel consumed outside ECA (FC_{out}) and within ECA (FC_{in}). Fuel consumed outside ECA is assigned to HFO, while fuel consumed in ECA is assigned to MGO-HOEF blends. This allocation is expressed as:

$$FC_{out} = (1 - f_{ECA}) \cdot FC_{HFO} \tag{12}$$

$$FC_{in} = f_{ECA} \cdot FC_{blend} \tag{13}$$

where f_{ECA} represents the ECA share of operation within ECA.

The total fuel consumption is then given as:

$$FC_{total} = FC_{out} + FC_{in} \tag{14}$$

The energy demand for cruise ship case study is modelled using a two-segment operational profile, distinguishing between the sea-going phase and the port (hoteling) phase. This approach reflects the specific operating characteristics of cruise ships, for which onboard energy demand is not determined only by propulsion, but also by substantial auxiliary loads associated with hoteling services. During the sea-going phase, both the main engines and auxiliary engines are considered. The main engine power demand during sea-going is estimated as:

$$P_{ME,sea} = (P_{ME} \cdot 0.8) \cdot \left(\frac{v_{sea}}{v_d}\right)^3 \tag{15}$$

The auxiliary engine power demand during sea-going is assumed as an average value, typically corresponding to 50-70% of the installed auxiliary power, reflecting the high onboard energy demand of cruise ship. The total engine power demand during sea-going is then:

$$P_{tot,sea} = P_{ME,sea} + P_{AE,sea} \tag{16}$$

And the corresponding energy consumption during sea-going is:

$$E_{sea} = P_{tot,sea} \cdot t_{sea} \tag{17}$$

During the port phase, the main engine is assumed to be inactive, resulting in negligible propulsion-related energy demand. In this phase, the total energy demand is covered by the auxiliary engines, operating at an average load corresponding to the onboard hoteling demand. As a result, the energy consumption during port stay is calculated as:

$$E_{port} = P_{AE,port} \cdot t_{port} \tag{18}$$

The total energy demand per cruise is obtained as:

$$E_{tot,cruise} = E_{sea} + E_{port} \tag{19}$$

Fuel consumption is then determined using a specific fuel consumption of the main and auxiliary engines. For the sea-going and port phases, fuel consumption is calculated as:

$$FC_{ME,sea} = \frac{P_{ME,sea} \cdot SFC_{ME} \cdot t_{sea}}{1000} \quad (20)$$

$$FC_{AE,sea} = \frac{P_{AE,sea} \cdot SFC_{AE} \cdot t_{sea}}{1000} \quad (21)$$

$$FC_{port} = \frac{P_{AE,port} \cdot SFC_{AE} \cdot t_{port}}{1000} \quad (22)$$

The total fuel consumption per cruise mission is therefore:

$$FC_{tot} = FC_{ME,sea} + FC_{AE,sea} + FC_{port} \quad (23)$$

3.4 Emission modelling and data sources

Emissions are quantified by applying fuel-specific emission factors, which express the amount of pollutants released per unit of fuel consumed. These factors are defined for key emission species, CO_2, CH_4, N_2O, NO_X, SO_X and PM. The selection of emission factors is based on established literature sources, standard emission guidelines and life cycle inventory databases, ensuring methodological consistency across all analysed fuel pathways.

The modelling framework integrates emission data within LCA tools used in the project. The GREET model is applied for conventional and established fuels, providing consistent emission factors for combustion processes, while openLCA is used for modelling HOEF blends with marine gas oil, where emission factors are adapted to reflect their specific chemical composition and combustion characteristics. This dual approach ensures that both conventional and novel fuels are represented with an appropriate level of detail within the TTW phase. By combining project-specific fuel consumption data with emission factors sourced from GREET, openLCA and supporting databases, the TTW modelling provides a consistent and transparent representation of onboard emissions within the overall well-to-wake LCA framework.

4 Case study definition

4.1 Ferry case study-Mljet

The ferry Mljet (Figure 6) is considered as a representative vessel on a short-distance coastal passenger route in the Adriatic Sea. The vessel operates on the Split-Supetar route in the Adriatic Sea (Figure 7), which represents a typical ferry service characterised by relatively short voyage distance and frequent departures throughout the year. Both the main propulsion engines and auxiliary engines are considered in the analysis to capture the total onboard energy demand during vessel operation.

Figure 6. Ferry Mljet.

Figure 7. Geographical context and operational route of the ferry Mljet case study.

The main technical and operational characteristics of the ferry Mljet are summarised in Table 3 and Table 4.

Table 3. Technical characteristics of the ferry Mljet.

Ship name	Mljet
Length between perpendiculars, L_{pp} (m)	89.1
Breadth, B (m)	17.5
Draught, T (m)	2.4
Main engine(s) power, P_{ME} (kW)	1,764

Auxiliary engine(s) power, P_{AE} (kW)	840
Design speed, v_d (kn)	12.3
Passenger capacity	616
Vehicle capacity	145

Table 4. Operational characteristics of the ferry Mljet.

Route	**Split – Supetar**
Return trip duration, t (min)	100
Route length, l (nm)	17.72
Average speed, v_{ave} (kn)	10.62
Annual number of return trips, N_A	1,095

4.2 Trawler case study-Jadran Tri

Trawlers represent an important segment of small-scale commercial fishing operations, characterised by energy-intensive and highly variable operational profiles driven by fishing activities [48]. The fishing trawler Jadran Tri (Figure 8) is considered as a representative vessel operating in the Adriatic Sea.

Figure 8. Trawler Jadran Tri.

The main technical characteristics of the trawler Jadran Tri are summarised in Table 5.

Table 5. Technical characteristics of the trawler Jadran Tri.

Ship name	**Jadran Tri**
Length overall, (m)	22.1
Breadth (m)	5.65
Draught (m)	1.99
Gross tonnage, GT	65
Main engine power, P_{ME} (kW)	223
Auxiliary engine power, P_{AE} (kW)	35

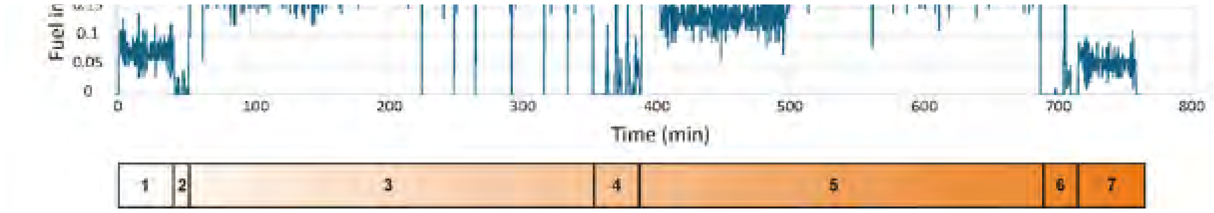

Figure 9, including cruising, net deployment, trawling, net hauling, as well as intermediate searching for fish and repositioning periods [35].

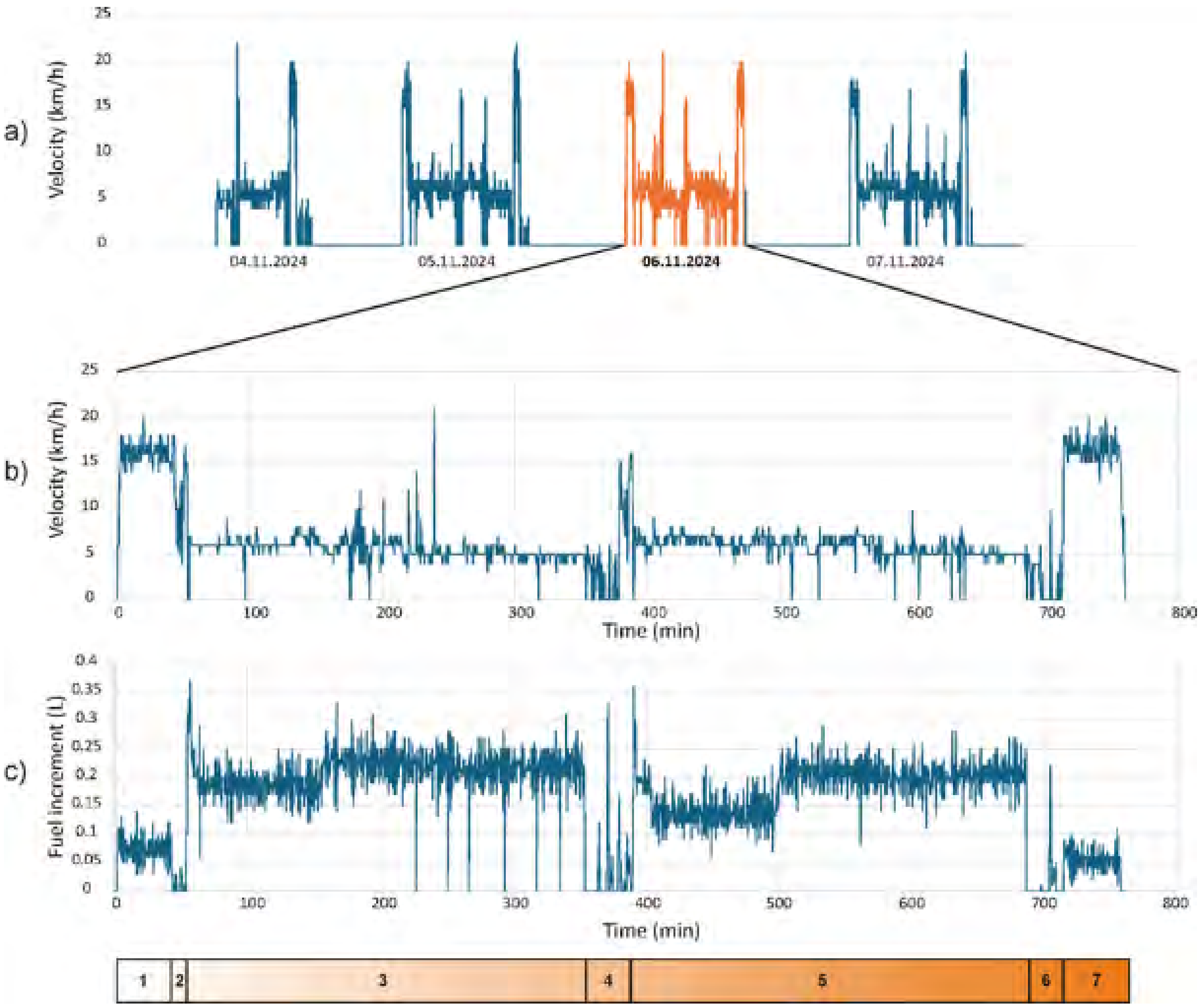

Figure 9. Typical operating phases in daily operation for Jadran Tri trawler (1-cruising, 2-setting the net, 3-trawling, 4-net hauling, searching for fish and setting the net, 5-trawling, 6-net hauling, 7-cruising).

Both the main propulsion engine and auxiliary engines are considered in the analysis to capture the total onboard energy demand. The vessel's operational profile is represented by a typical fishing cycle, reflecting variations in speed and operating conditions across different phases, while the energy demand is determined based on the measured fuel consumption of MGO per cycle. The functional unit is defined as one fishing cycle, representing a complete fishing operation [35].

4.3 Purse seiner case study-Noa

Unlike trawlers, purse seiners do not tow fishing gear through the water, but instead encircle fish schools using a net, resulting in different energy demand patterns and operational dynamics [34]. The fishing vessel Noa (Figure 10) is a representative purse seiner operating in the Adriatic Sea.

Figure 10. Purse seiner Noa.

The main technical characteristics of the purse seiner Noa are summarised in Table 6.

Table 6. Technical characteristics of the purse seiner Noa.

Ship name	Noa
Length overall, (m)	27.40
Breadth (m)	7.00
Gross tonnage, GT	142
Main engine power, P_{ME} (kW)	370
Auxiliary engine power, P_{AE} (kW)	1x130
	1x70
	1x30

The operational profile of the purse seiner is defined by a sequence of activities that differ significantly from trawling operations as shown in Figure 11. A typical fishing cycle includes port preparation, transit to the fishing grounds, searching for fish, net setting, pursing and hauling, catch handling, return transit and unloading in the port. The operational profile of purse seiners shows a distinct variation in energy demand across individual phases. High propulsion demand is observed during transit phases, but also remains significant during net setting, while auxiliary and deck demand dominates during pursing, hauling, net setting and handling operations. The operational profile reflects a mixed energy demand structure, where both propulsion and auxiliary loads vary depending on the specific activity.

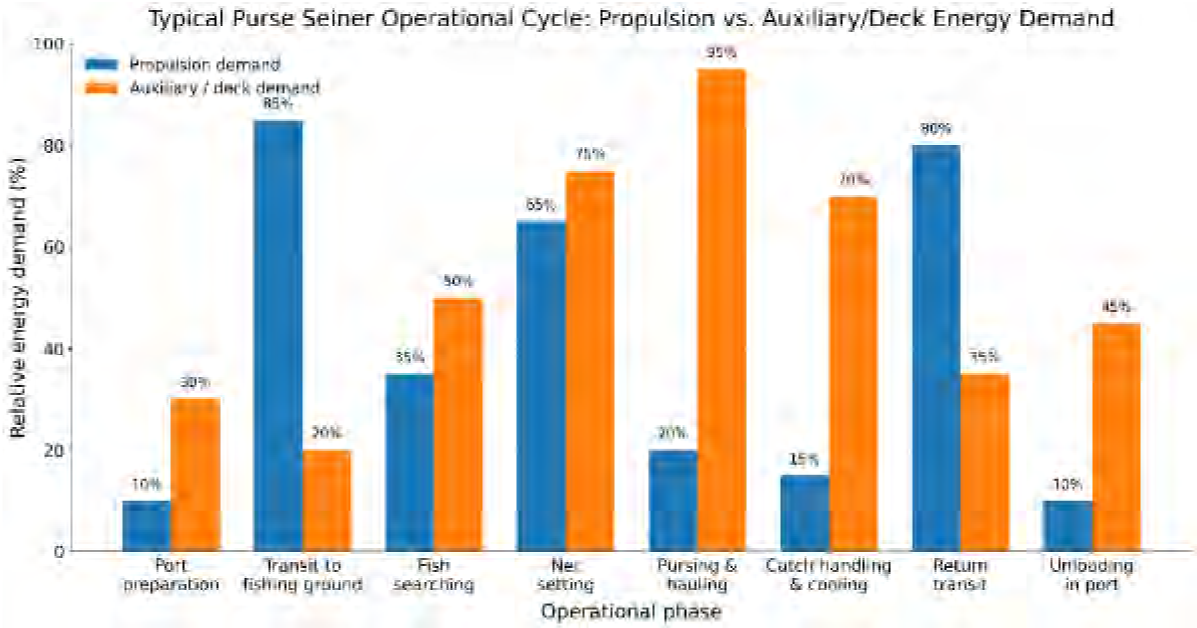

Figure 11. Typical operational phases and energy demand distribution of a purse seiner.

4.4 Bulk carrier case study-Stoja

The bulk carrier Stoja (Figure 12) is considered as a representative cargo vessel operating on international routes that include both global (non-ECA) and ECA segments. The analysed route (Figure 13) connects South American and Norther Europe ports, representing a typical deep-sea shipping operation with both transoceanic and ECA-regulated segments. Such operational conditions enable the assessment of fuel switching strategies, with HFO used outside ECA and alternative fuels applied within ECA.

Figure 12. Bulk carrier Stoja.

Figure 13. a) International shipping route of the bulk carrier Stoja, b) ECAs along the route.

The main technical characteristics of the bulk carrier Stoja are summarised in Table 7.

Table 7. Technical characteristics of the bulk carrier Stoja.

Ship name	**Stoja**
Length overall (m)	190
Breadth (m)	32
Draught (m)	6.7
Gross tonnage, GT	30,092
Main engine power, P_{ME} (kW)	8,600
Auxiliary engine power, P_{AE} (kW)	3x650
Deadweight, DWT (t)	51,888
Design speed (kn)	14

The operational profile of the bulk carrier is characterised by continuous operation without discrete operating phases, with propulsion demand dominating the total energy consumption and auxiliary systems providing a continuous onboard power supply. The functional unit is defined as transport work, expressed in tonne-nautical mile, providing a consistent basis for comparing different alternative fuel scenarios.

4.5 Cruise ship case study Norwegian Star

The cruise ship Norwegian Star (Figure 14) is considered as a representative cruise vessel operating on international cruise route in the Mediterranean and North Atlantic region. The analysed route (Figure 15) includes multiple port calls and island destinations, representing a typical cruise route with frequent stops and operation in near-coastal areas. The route partially overlaps with ECA, enabling the assessment of fuel switching strategies, with HFO considered for operation outside ECA and alternative fuels applied within ECA.

Figure 14. Cruise ship Norwegian Star

Figure 15. a) Representative cruise route of the Norwegian Star, b) ECA regions along the route.

The main technical characteristics of the cruise ship Norwegian Star are summarised in Table 8.

Table 8. Technical characteristics of the cruise ship Norwegian Star.

Ship *name*	Norwegian Star
Length overall (m)	294
Breadth (m)	32
Draught (m)	8.2
Gross tonnage, GT	91,740
Total engine power (kW)	4x14,700
Design speed (kn)	24.6

The analysis considers an ECA-based fuel switching scenario, where HFO is used outside ECA, while alternative fuels are applied within ECA and during port operations. The functional unit for the cruise ship case study is defined as passenger transport work, expressed in passenger-nautical mile (pax-nm), ensuring consistency with operational profile and enabling comparison between different fuel pathways.

5 Life cycle assessment results

5.1 Ferry case study

The LCA results for the ferry Mljet operating on the Split-Supetar route are presented in this section. The results are reported for the defined functional unit of one return trip and include both WTT and TTW emissions.

Figure 16 shows the WTW GHG emissions associated with the analysed fuel pathways. The conventional MGO pathway exhibits the highest WTW emissions among the considered options. The introduction of HOEF I blends leads to a substantial reduction in GHG emissions, approximately 36% for HOEF I_30 and 51% for HOEF I_50. HOEF II blends provide emission reduction of approximately 21% and 26% compared to MGO. The lowest overall WTW emissions are observed for BtL and e-methanol, primarily due to the negative contributions in the WTT phase.

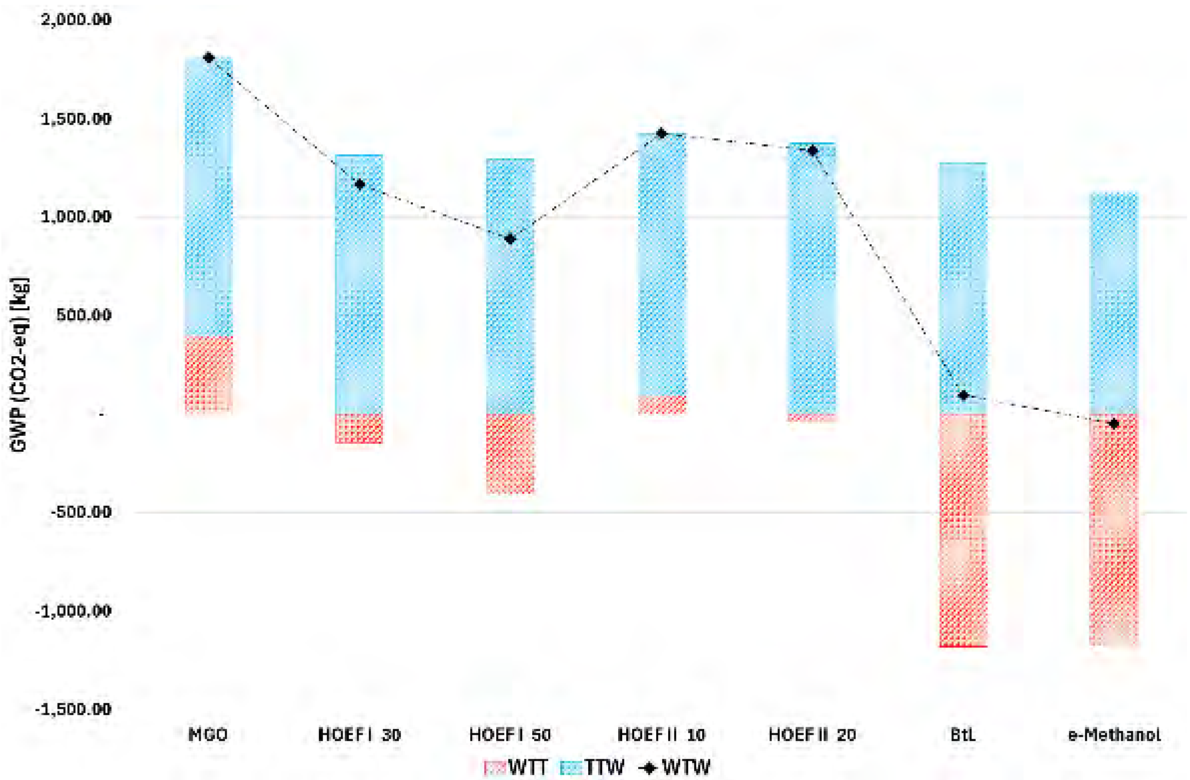

Figure 16. WTW GHG emissions (GWP, CO_2-eq) for the ferry case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

Figure 17 shows the WTW acidification potential for the analysed fuel pathways. The conventional MGO pathway exhibits the highest AP, followed by e-methanol and BtL. The inclusion of HOEF I blends results in the lowest acidification impacts, with reductions of 39% for HOEF I_30 and 42% for HOEF I_50, followed by HOEF II_10 and HOEF II_20 blends, achieving the reduction of 37% and 36%, respectively, compared to MGO pathway.

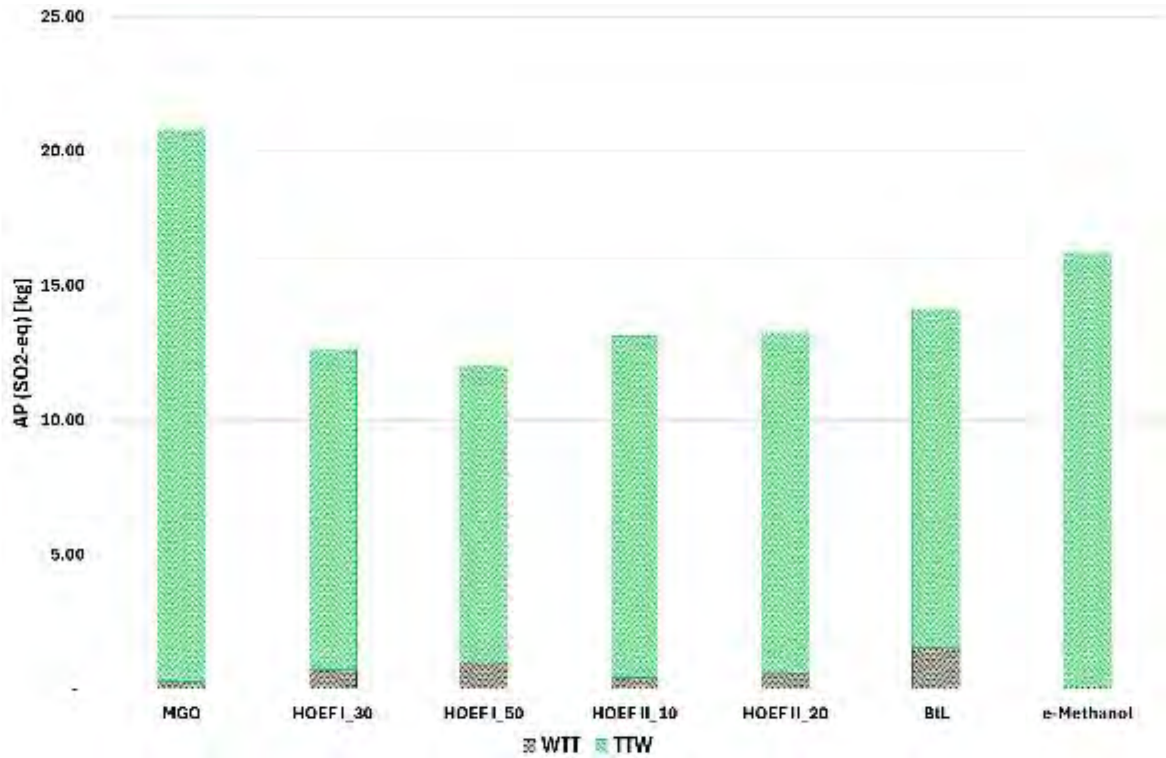

Figure 17. WTW acidification potential (AP, SO_2-eq) for the ferry case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

Figure 18 shows the WTW APF associated with the analysed fuel pathways. The highest APF values are observed for MGO and e-methanol, followed by BtL. Among the considered options, HOEF I_50 exhibits the lowest AFP, followed by HOEF I_30, corresponding to reduction of 29% and 25%, respectively, compared to MGO. The HOEF II blends also demonstrate reduced impacts, with HOEF II_10 and HOEF II_20 showing reductions of approximately 22% and 21%, respectively, relative to MGO pathway.

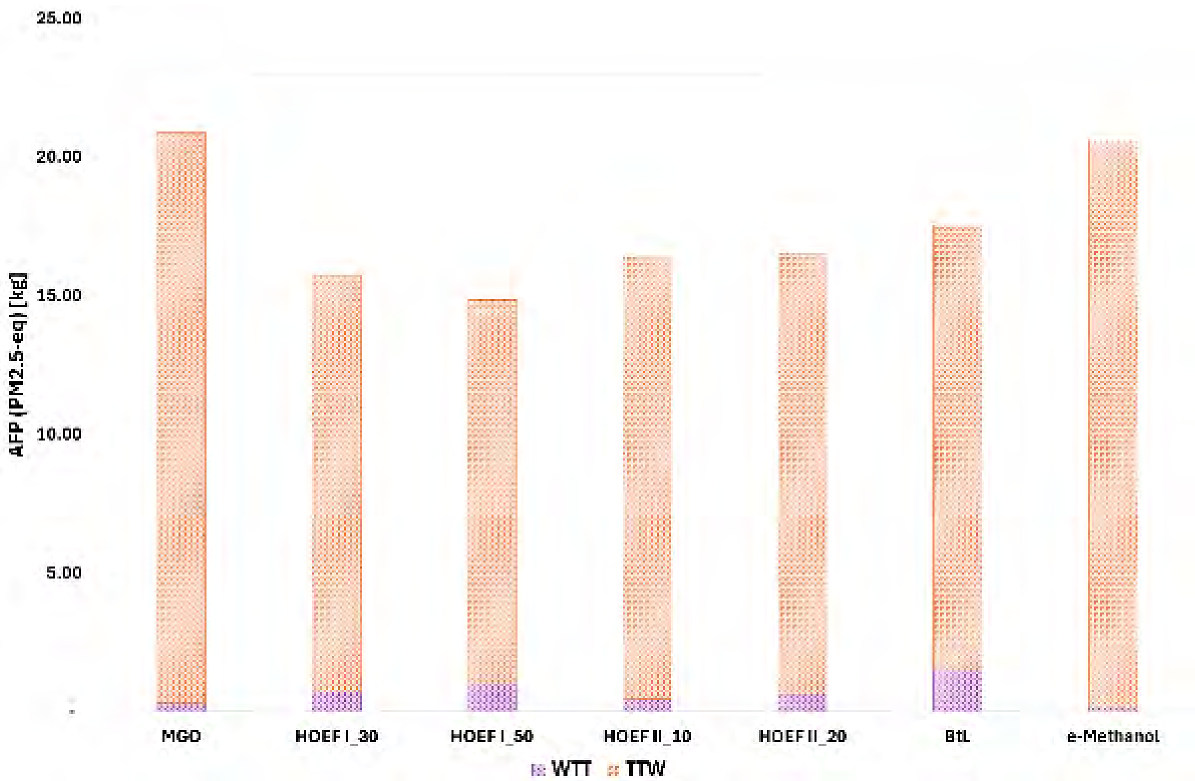

Figure 18. WTW particulate matter formation (AFP, $PM_{2.5}$-eq) for the ferry case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

Figure 19 shows the WTW EP associated with the analysed fuel pathways. E-methanol exhibits the highest EP impact, followed by BtL and MGO. HOEF I blends show the lowest EP, followed by MGO. HOEF II blends demonstrate slightly larger impact compared to MGO. Additional analysis of NOx emissions at the engine level supports these findings, showing that HOEF I blends achieve the lowest NOx emissions and fall below the IMO Tier II limit, while MGO and HOEF II blends remain closer to or above this threshold (see **Error! Reference source not found.**).

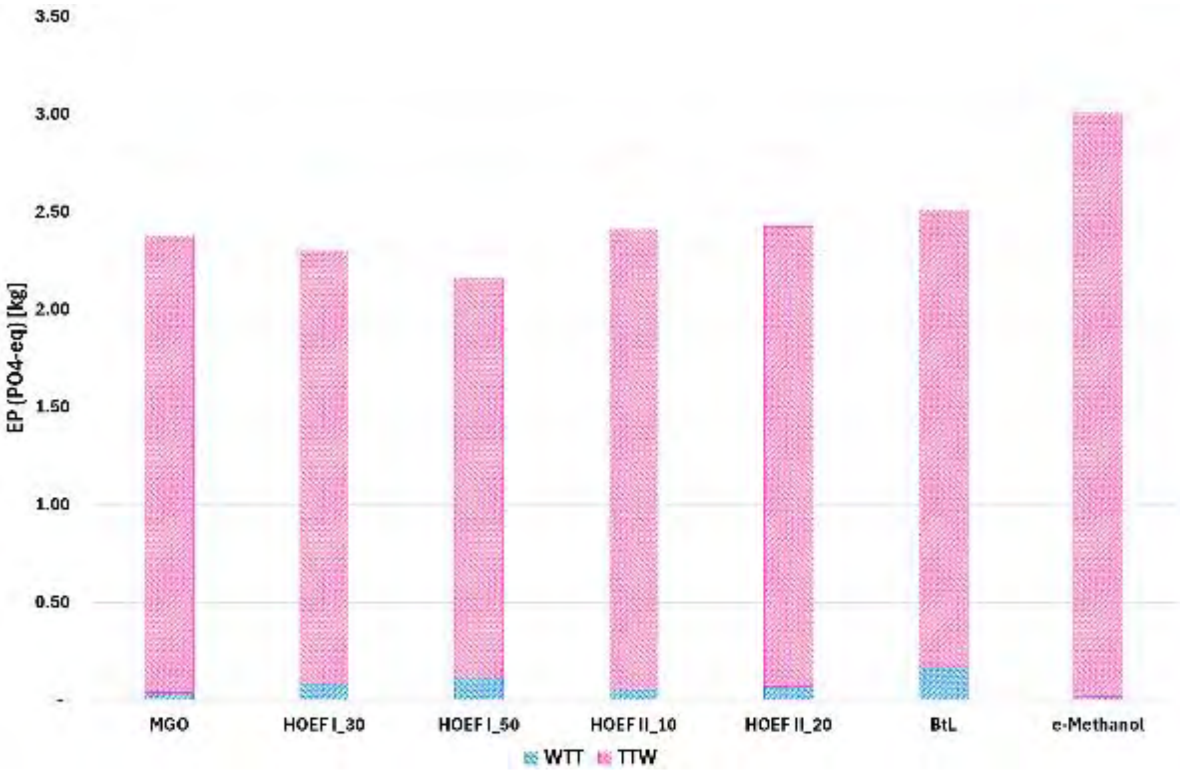

Figure 19. WTW eutrophication potential (EP, PO_4^{3-}-eq) for the ferry case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

For most of the analysed impact categories, including AP, AFP and EP, the TTW phase represents the dominant contribution to the overall impacts. In contrast, the climate change category is strongly influenced by the WTT phase, reflecting the importance of upstream emissions associated with fuel production. The introduction of HOEF blends shows clear benefits compared to the conventional MGO pathway. Among the analysed options, HOEF I blends, particularly HOEF I_50, demonstrates the largest reductions across local air pollution impacts (AP, AFP and EP), while HOEF II blends also provide noticeable improvements.

5.2 Trawler case study

The LCA results for the fishing trawler Jadran Tri are presented for the defined functional unit of one fishing cycle and include both WTT and TTW contributions. Figure 20 illustrates the WTW GHG emissions for the analysed fuel pathways. The highest WTW emissions are observed for the conventional MGO pathway. Among the alternative options, HOEF II blends show only modest emission reductions, amounting to approximately 6% and 12% for HOEF II_10 and HOEF II_20, respectively, compared to MGO. In contrast, HOEF I blends demonstrate significantly greater mitigation potential. The HOEF I_30 blend achieves a reduction of around 23%, while the HOEF I_50 blend results in a substantial decrease of approximately 42% relative to MGO. The lowest WTW GHG emissions are observed for the BtL and e-methanol pathways. This is primarily driven by their negative WTT emissions, which offset the positive TWW emissions associated with onboard fuel combustion.

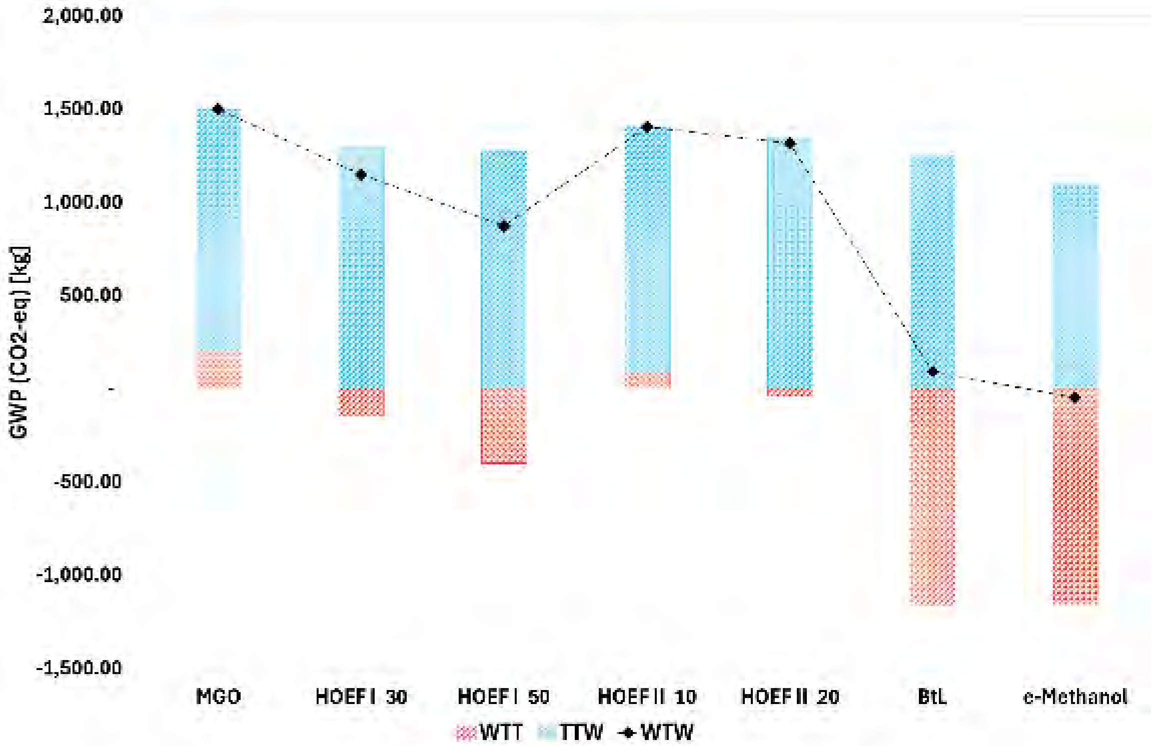

Figure 20. WTW GHG emissions (GWP, CO_2-eq) for the trawler case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

The AP results for the analysed fuel pathways are presented in Figure 21, considering both WTT and TTW contributions of one fishing cycle. The highest AP values are observed for the conventional MGO pathway, primarily driven by emissions occurring during the TTW phase. All alternative fuel options demonstrate a reduction in AP compared to MGO, although the magnitude of reduction varies across pathways. HOEF blends show consistent mitigation potential relative to MGO, specifically the HOEF I blends which achieve reductions of 39% for HOEF I_10 and 42% for HOEF I_50, indicating improved performance with higher blending ratios. Similarly, HOEF II blends result in reduction of 37% and 36% for HOEF II_10 and HOEF II_20, respectively.

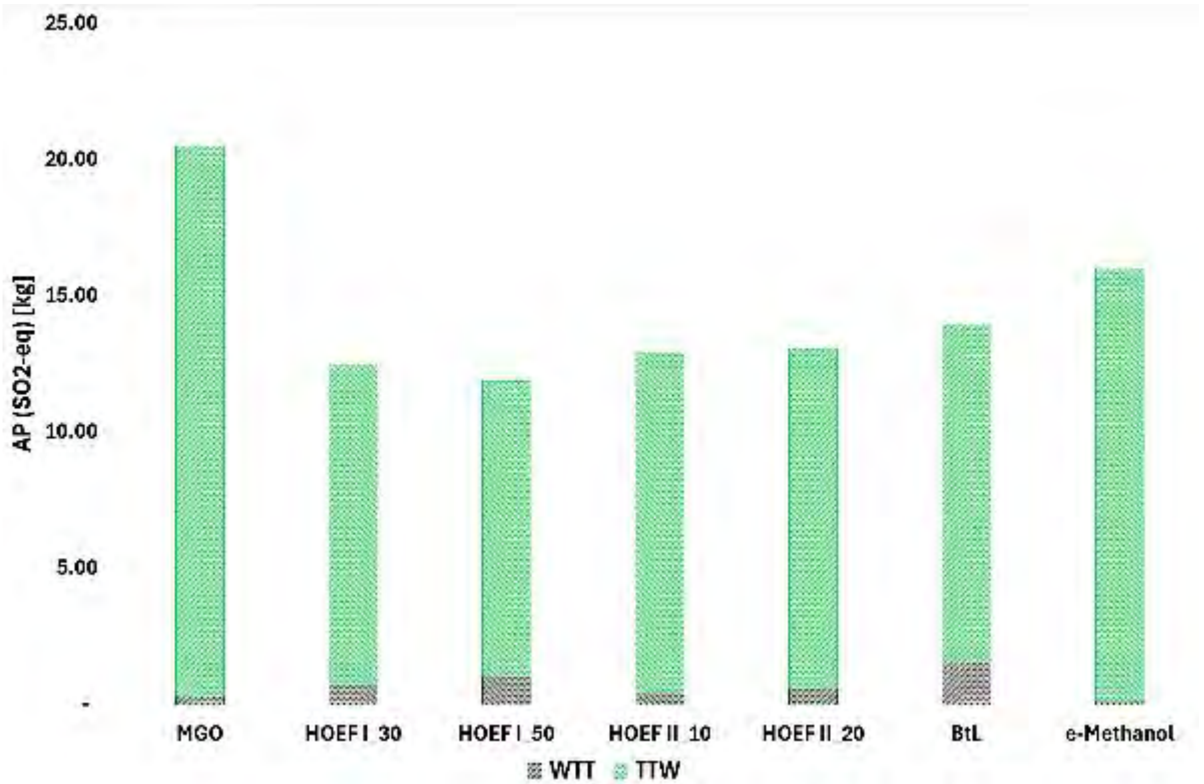

Figure 21. WTW acidification potential (AP, SO_2-eq) for the trawler case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

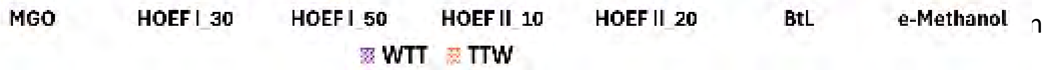

Figure 22. The highest AFP values are observed for the MGO pathway, followed by e-methanol and BtL. In comparison, all HOEF blends achieve a noticeable reduction in AFP, confirming their potential to mitigate PM-related impacts in the maritime applications. The HOEF I blends result in AFP reductions of 25% for HOEF I_30 and 29% for HOEF I_50 relative to MGO, indicating improved performance with increasing blending share. Similarly, HOEF II blends achieve reductions of 22% and 21% for HOEF II_10 and HOEF II_20, respectively, although with a less pronounced dependence on blend ratio.

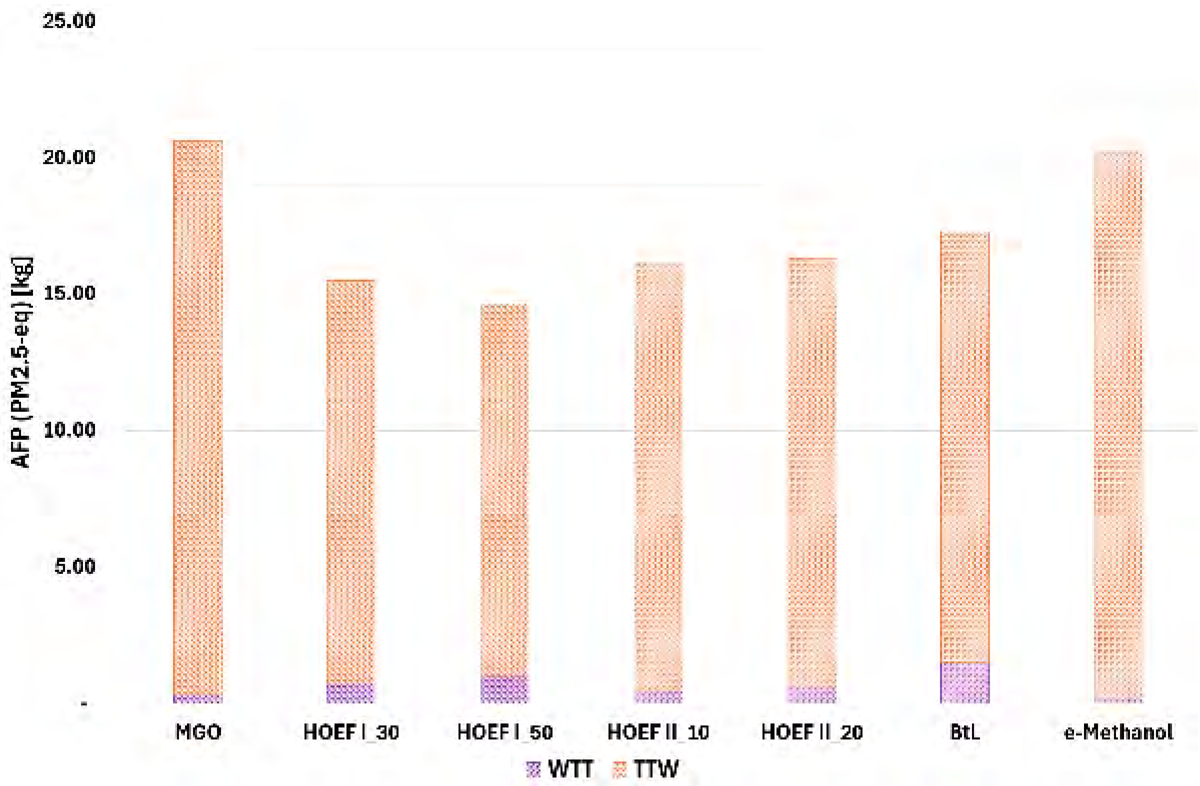

Figure 22. WTW particulate matter formation (AFP, $PM_{2.5}$-eq) for the trawler case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

The EP results for the analysed fuel pathways are presented in Figure 23. The highest EP values are observed for e-methanol, followed by BtL and HOEF II blends. In contrast, the lowest EP values are achieved for HOEF I blends. Specifically, reductions of approximately 3% and 9% are observed for HOEF I_30 and HOEF I_50, respectively, compared to MGO pathway. Although these reductions are relatively modest, they indicate a slight environmental benefit of HOEF I blends in this impact category.

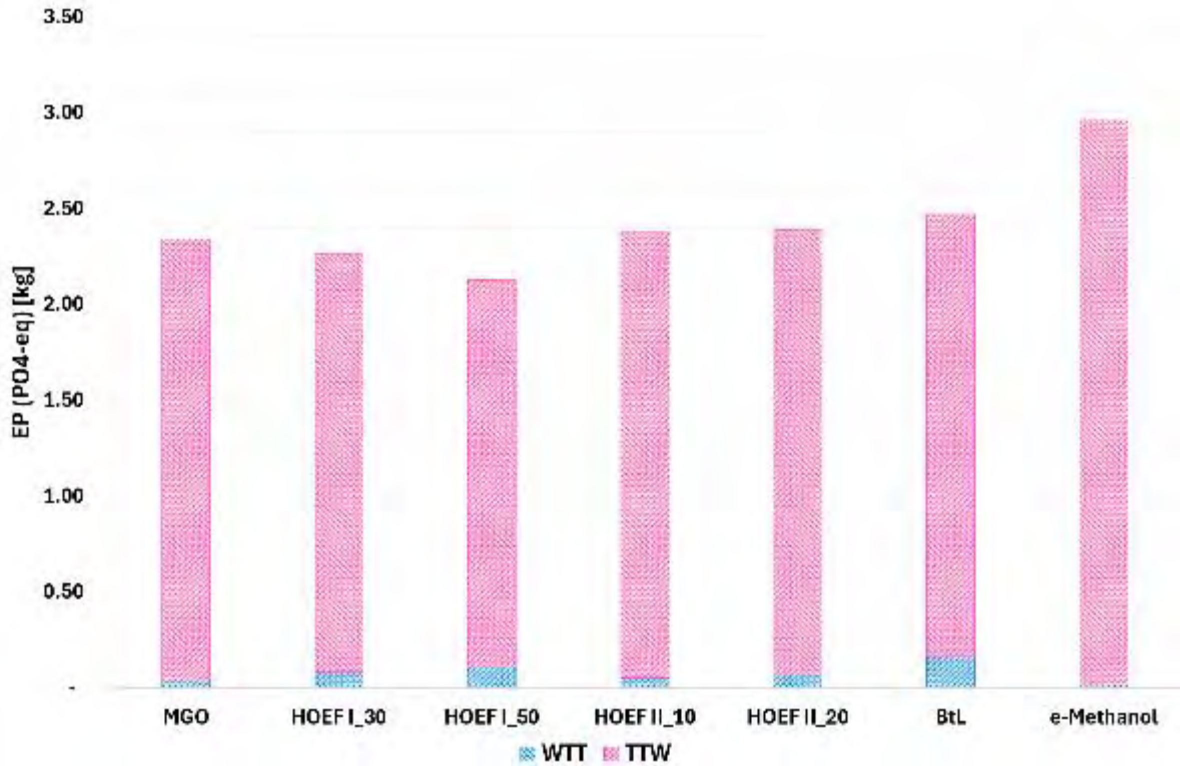

Figure 23. WTW eutrophication potential (EP, PO_4^{3-}-eq) for the trawler case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

A trend consistent with the ferry Mljet case study is observed for local air pollution impact categories, including AP, AFP and EP, where the TTW phase represents the dominant contributor. In contrast, GHG emissions are significantly influenced by the WTT phase, reflecting the importance of upstream processes in determining overall lifecycle performance. Across all local air pollution impact categories, HOEF I blends demonstrate the most favourable performance, with the HOEF I_50 blend achieving the highest reductions. This highlights the strong potential of HOEF I blends for mitigating TTW emissions in small-scale fishing operations.

5.3 Purse seiner case study

The LCA results for the purse seiner Noa are presented for the defined functional unit of one fishing cycle and include both WTT and TTW contributions.

Figure 24 present the WTW GWP results for purse seiner case study. The highest GHG emissions are observed for the conventional MGO pathway. Among the alternative options, e-methanol achieves the lowest emissions, followed by BtL, primarily due to negative WTT contributions. HOEF blends show a clear reduction compared to MGO, with HOEF I blends exhibiting significantly stronger performance than HOEF II blends. Specifically, HOEF I_30 and HOEF I_50 achieve GWP reductions of 23% and 42%, respectively, while HOEF II blends result in more moderate reductions of 6% for HOEF I_10 and 12% for HOEF II_20.

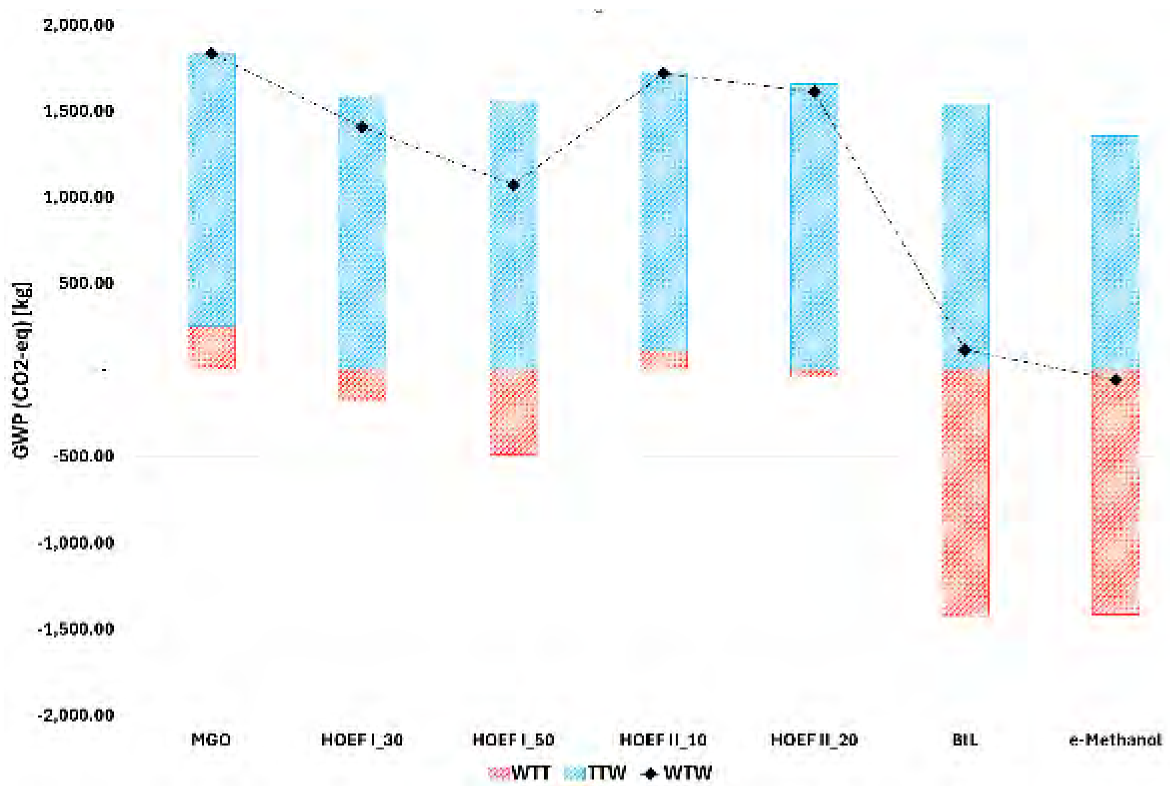

Figure 24. WTW GHG emissions (GWP, CO_2-eq) for the purse seiner case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

The WTW AP results are shown in Figure 25. The highest acidification impacts are associated with MGO, followed by e-methanol and BtL. In contrast, all HOEF blends demonstrate substantially lower emissions. HOEF I blends achieve the greatest reductions, reaching 39% for HOEF I_30 and 42% for HOEF I_50 compared to MGO. HOEF II blends show slightly lower but still significant reductions of 37% for HOEF II_10 and 36% for HOEF II_20, indicating a consistently strong performance across both HOEF pathways for this impact category.

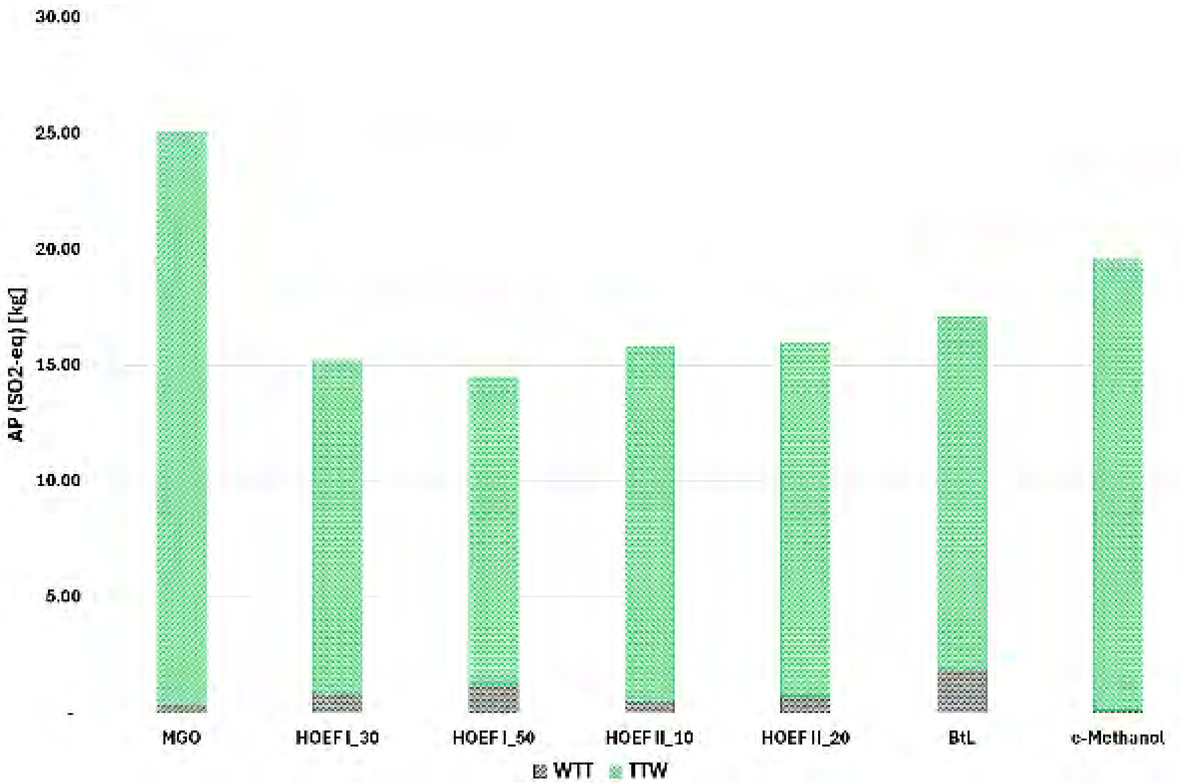

Figure 25. WTW acidification potential (AP, SO_2-eq) for the purse seiner case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

Figure 26 illustrates the WTW AFP results. As in previous categories, the highest PM formation is observed for MGO, followed by e-methanol and BtL. All HOEF blends contribute to reduced AFP impacts compared to MGO, with HOEF I_50 showing the largest reduction (29%), followed by HOEF I_30 (25%). HOEF II blends achieve slightly lower reductions, amounting to 22% for HOEF II_10 and 21% for HOEF II_20, but still demonstrate a consistent improvement over MGO.

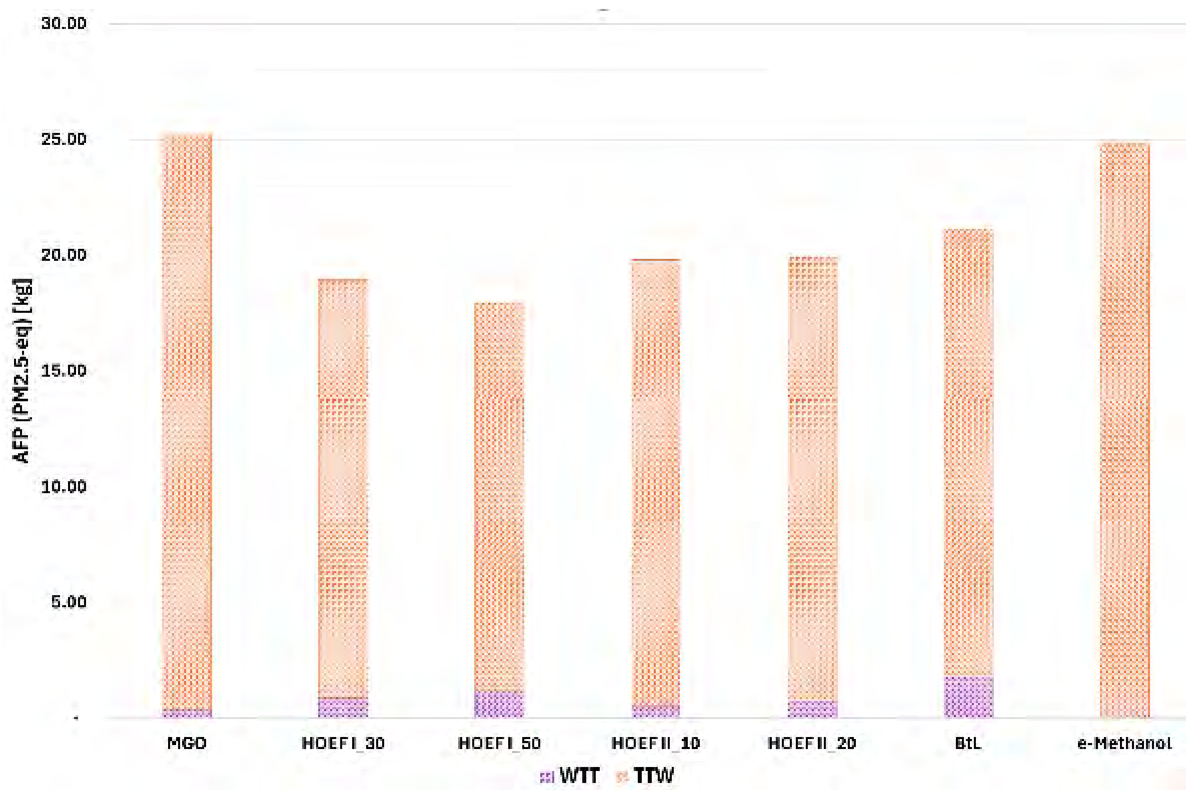

Figure 26. WTW particulate matter formation (AFP, PM2.5-eq) for the purse seiner case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

The WTW EP results are presented in Figure 27. In contrast to other impact categories, the highest eutrophication impacts are observed for e-methanol.

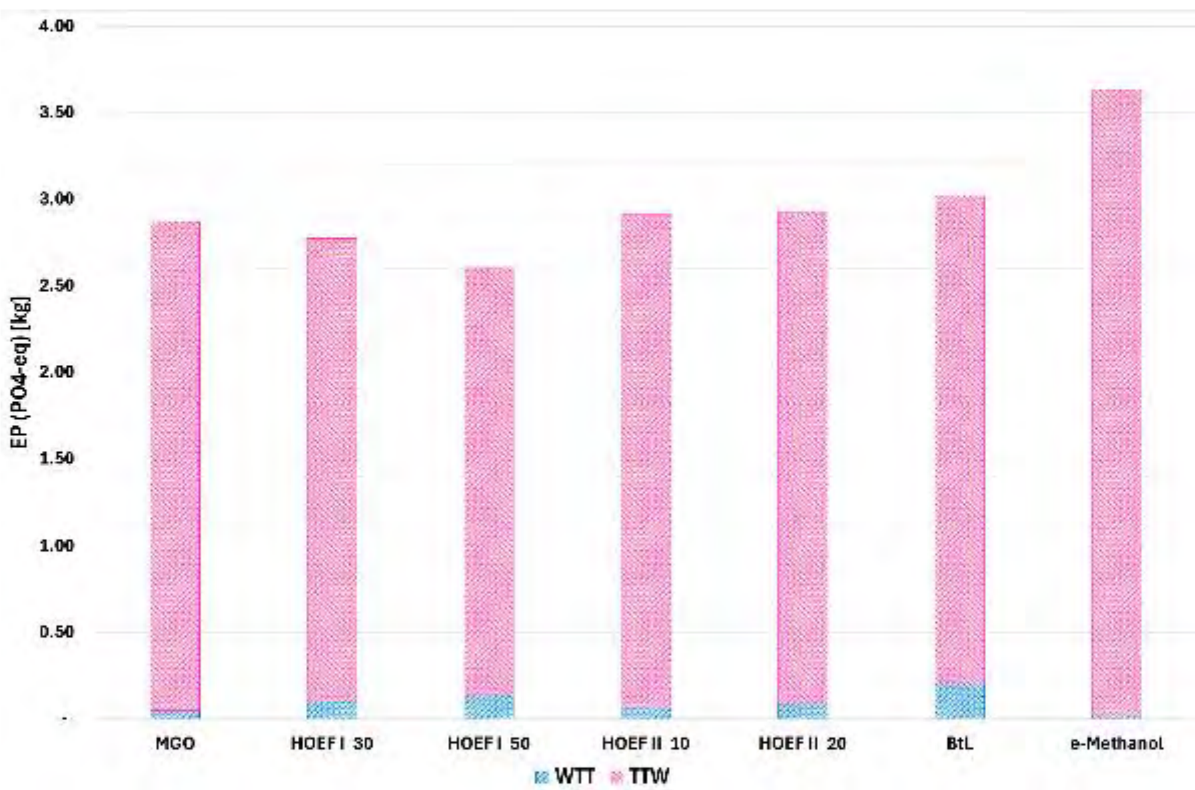

Figure 27. WTW eutrophication potential (EP, PO_4^{3-}-eq) for the purse seiner case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

5.4 Bulk carrier case study

Figure 28 illustrates the WTW GWP results for the bulk carrier ship. The lowest emissions are observed for HFO/e-methanol and HFO/BtL pathways. Among HFO/HOEF-based pathways, HFO/HOEF I blends show moderate reductions compared to the HFO/MGO pathway, with higher blending ratios resulting in greater reductions, while HFO/HOEF II blends exhibit only limited improvements. The highest emissions are consistently associated with HFO/MGO pathway.

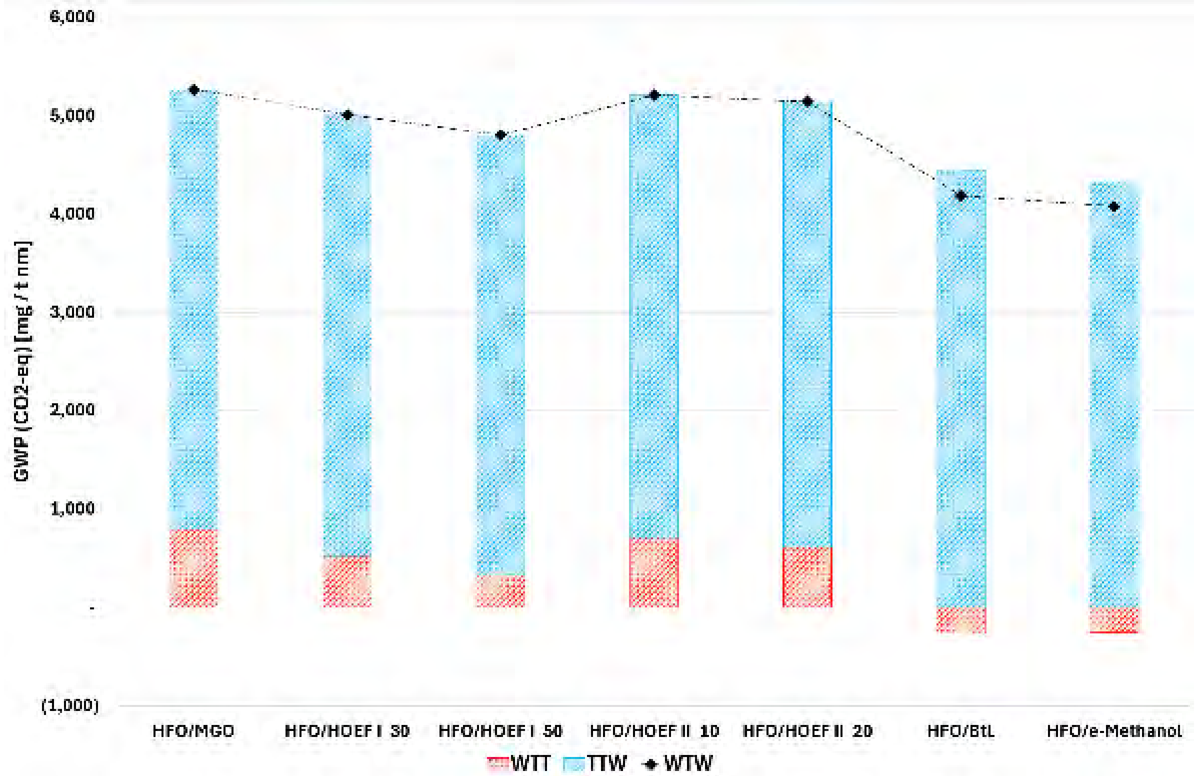

Figure 28. WTW GHG emissions (GWP, CO_2-eq) for the bulk carrier case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

For local air pollution impact categories (AP, AFP and EP) shown in Figure 29-Figure 31, the differences between the analysed fuel pathways remain relatively small.

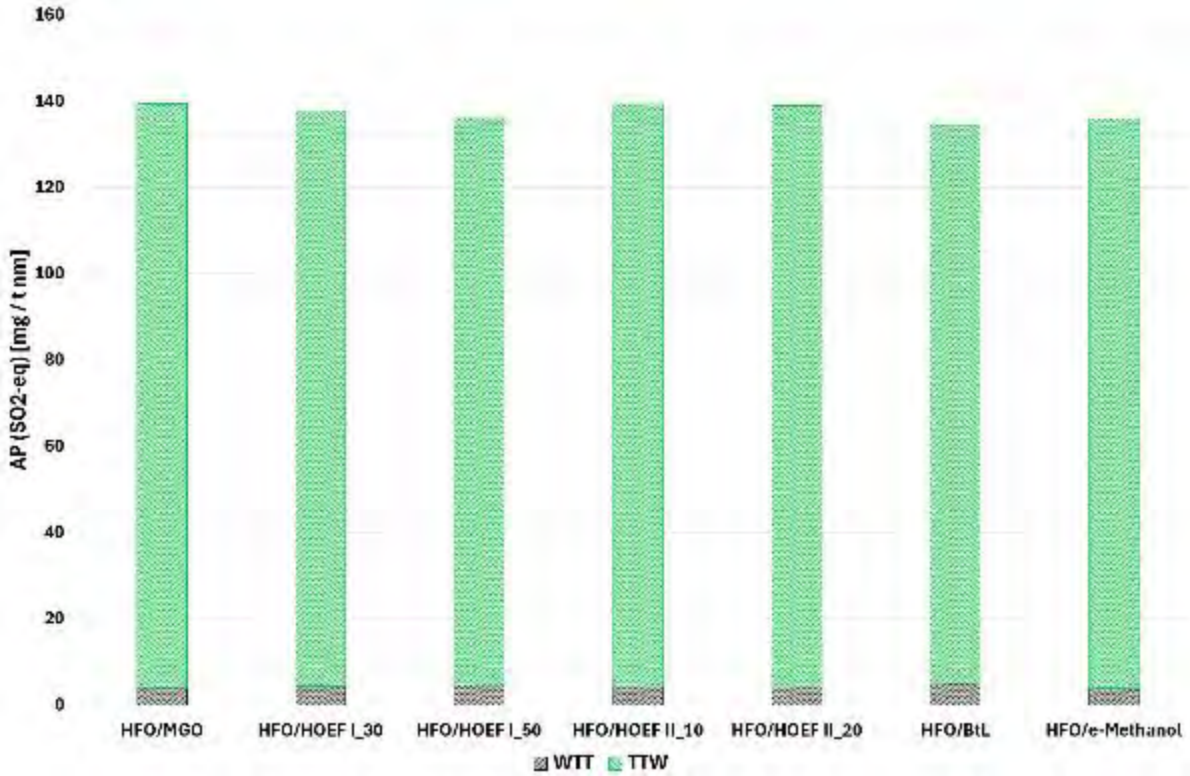

Figure 29. WTW acidification potential (AP, SO_2-eq) for the bulk carrier case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

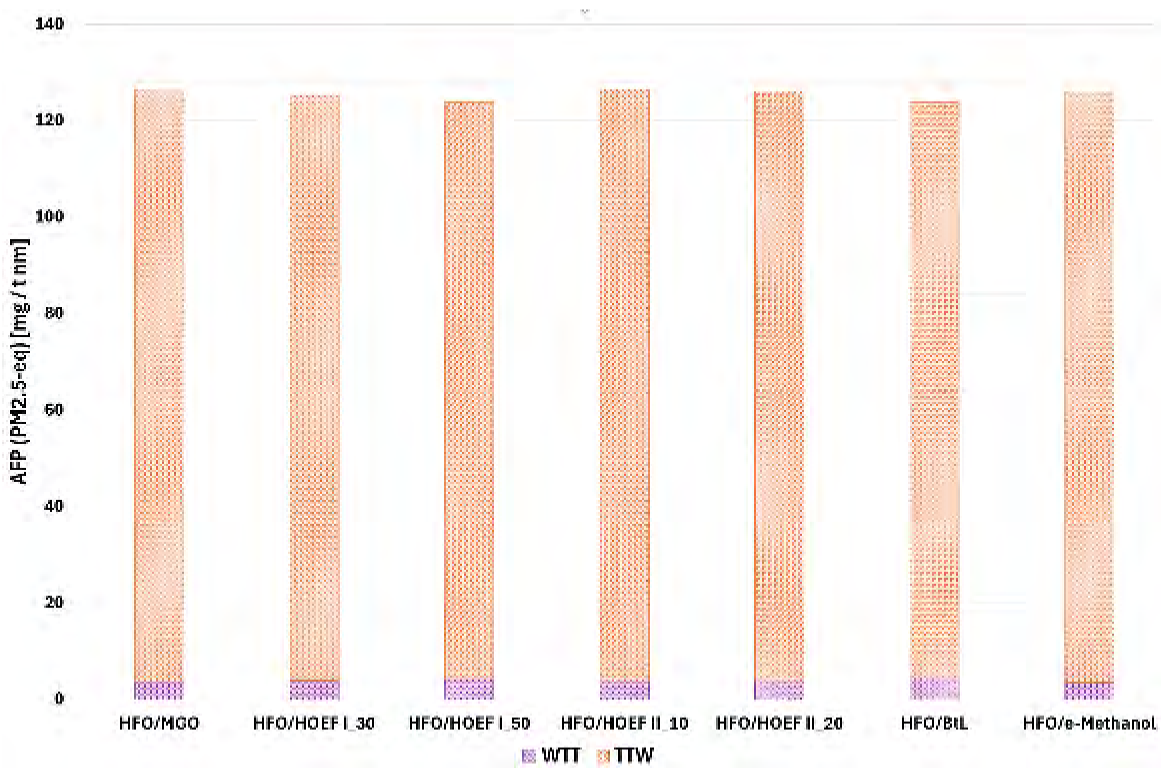

Figure 30. WTW particulate matter formation (AFP, $PM_{2.5}$-eq) for the bulk carrier case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

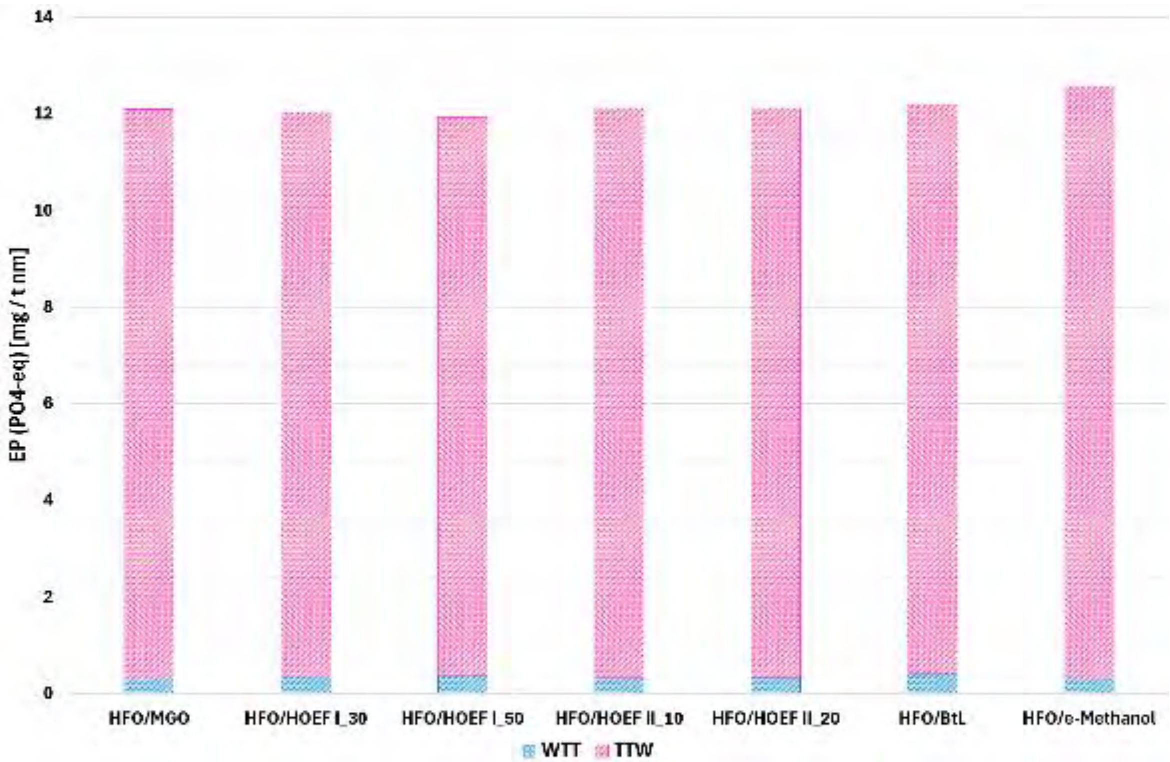

Figure 31. WTW eutrophication potential (EP, $PO_4{}^{3-}$-eq) for the bulk carrier case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

Across all impact categories, a consistent pattern is observed, with the TTW phase representing the dominant contributor to overall impacts, particularly for local air pollution indicators. In contrast, the climate change category shows a stronger influence of the WTT phase, reflected in more pronounced differences between the investigated fuel options. Overall, the results indicate that while alternative fuel pathways provide reductions in GWP, particularly in the case of HFO/e-methanol and HFO/BtL, the differences across local air pollution categories remain limited, with no clear overall distinction between the analysed fuel options.

5.5 Cruise ship case study

The LCA analysis results for the cruise ship Norwegian Star are presented for the analysed impact categories, based on the defined functional unit of transporting one passenger over one nautical mile, and include both WTT and TTW phases.

Figure 32 presents the WTW GWP results for the cruise ship case study. The highest overall emissions are observed for HFO/MGO. In contrast, HFO/e-methanol and HFO/BtL achieve the lowest WTW GWP values, primarily due to their negative WTT contributions, which significantly offset emissions form the TTW phase. Among HOEF-based pathways, a moderate reduction in GWP is observed compared to the HFO/MGO pathway. HFO/HOEF I blends show more pronounced improvements, with reductions of approximately 8% for HFO/HOEF I_30 and 15% for HFO/HOEF I_50. In comparison, HFO/HOEF II blends provide only limited reductions, amounting to around 2% for HFO/HOEF II_10 and 4% for HFO/HOEF II_20.

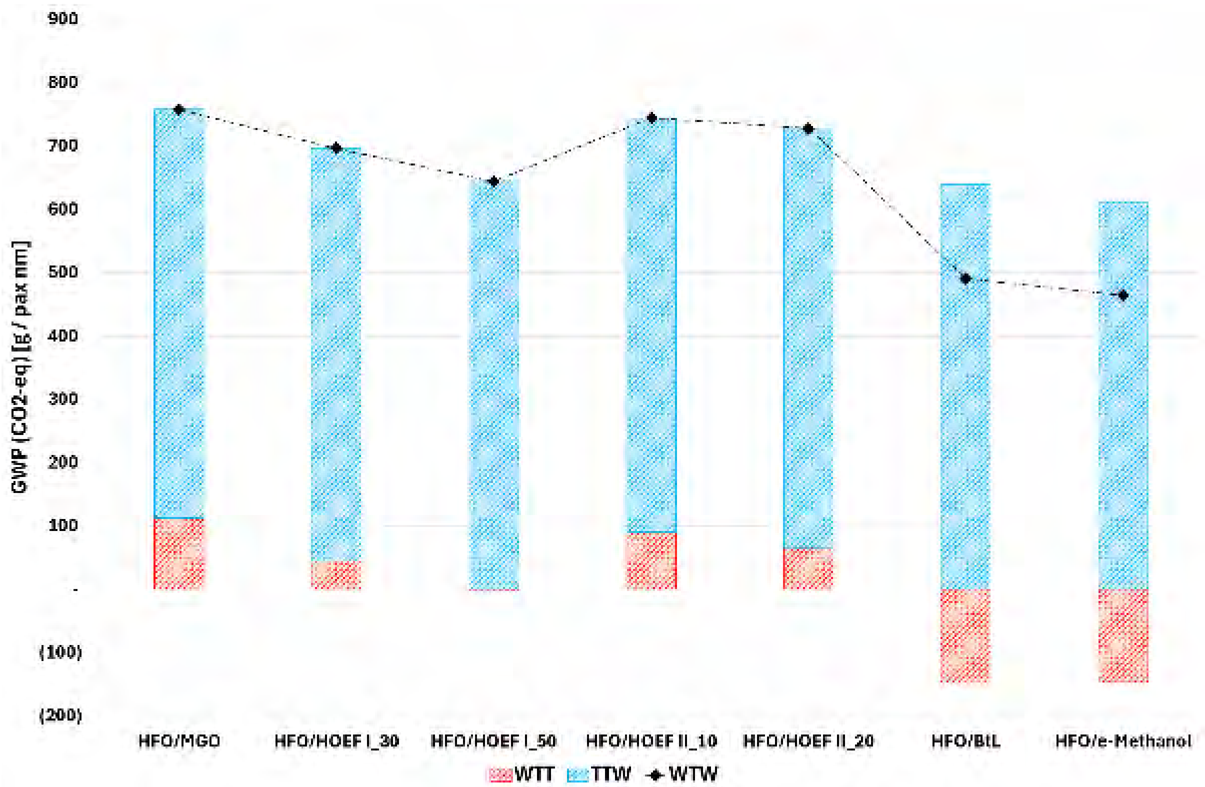

Figure 32. WTW GHG emissions (GWP, CO_2-eq) for the cruise ship case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

The WTW AP results for cruise ship case study are presented in Figure 33. Overall, only minor differences between the analysed fuel pathways are observed, indicating limited potential for reducing acidification-related impacts in this application. The highest AP values are associated with the conventional HFO/MGO pathway. Among the alternative options, HFO/BtL and HFO/e-methanol show the lowest AP results. HFO/HOEF I blends provide only modest improvements, with reductions of around 2.3% for HFO/HOEF I_30 and 4.6% for HFO/HOEF I_50. In contrast, HFO/HOEF II blends exhibit negligible changes, showing little to no reduction in AP values relative to HFO/MGO.

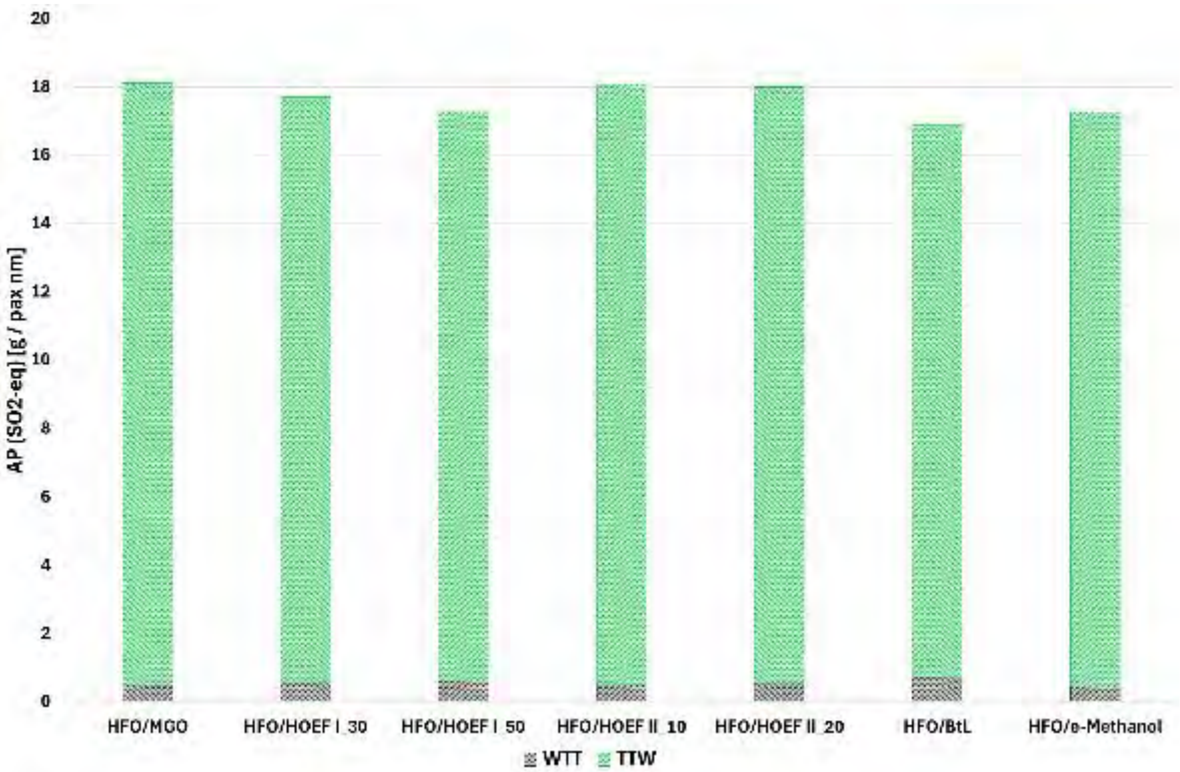

Figure 33. WTW acidification potential (AP, SO_2-eq) for the cruise ship case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

Figure 34 presents the WTW AFP results for the cruise ship case study. Similar to the AP category, only minor differences between the analysed fuel pathways are observed, indicating limited potential for reducing PM-related impacts. The highest AFP values are associated with the HFO/HOEF II_10 pathway, followed by HFO/MGO. Among alternative options, HFO/HOEF I_50 shows the lowest emissions, which achieve only modest reductions compared to the reference pathway with approximately 3.9% reduction. followed by HFO/BtL with similar results. In contrast, HFO/HOEF II_20 and HFO/e-methanol exhibit little to no reduction relative to HFO/MGO pathway.

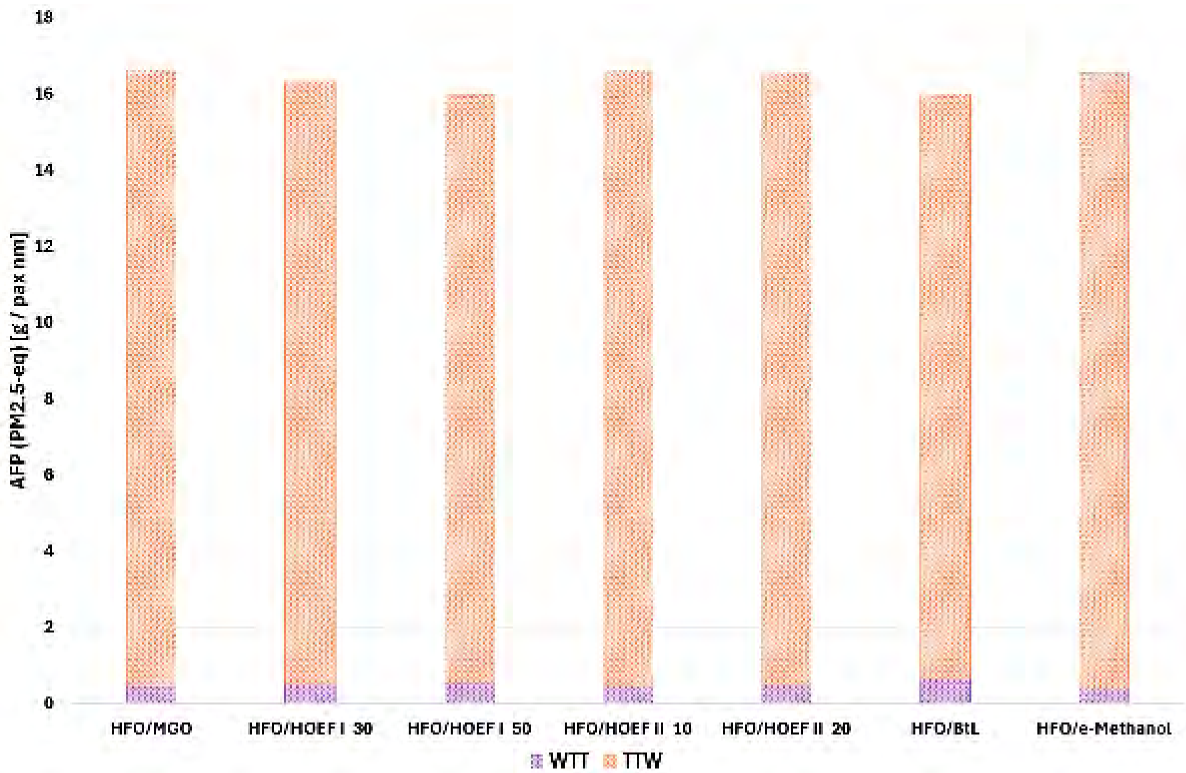

Figure 34. WTW particulate matter formation (AFP, PM2.5-eq) for the cruise ship case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

The WTW EP results for the cruise ship case study are presented in Figure 35. Similar to other local air pollution impacts, only minor differences between the analysed fuel pathways are observes, indicating a limited sensitivity of eutrophication impacts to fuel selection in this application. The highest EP values are associated with the HFO/e-methanol, followed by HFO/BtL, HFO/HOEF II_20 and HFO/HOEF II_10. The lowest emissions are observed for HFO/HOEF I_50 pathway. HFO/HOEF I_30 exhibit negligible changes, remaining close to the HFO/MGO level.

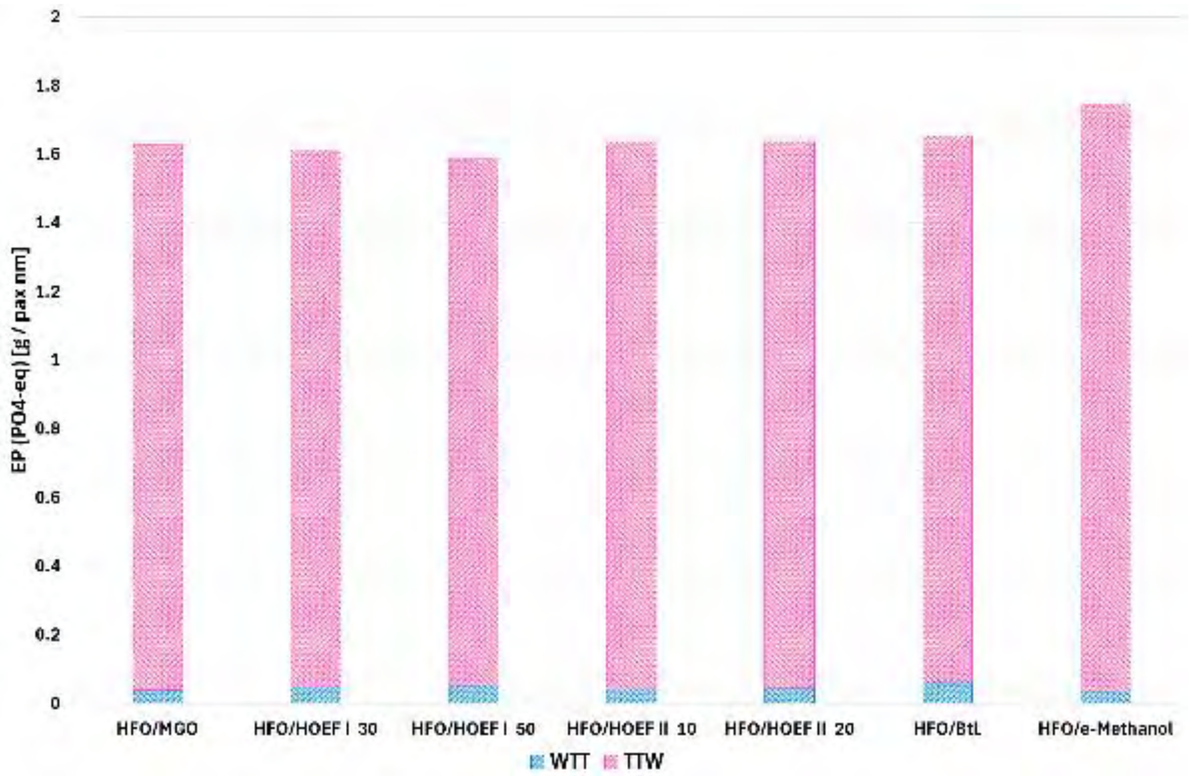

Figure 35. WTW eutrophication potential (EP, PO_4^{3-}-eq) for the cruise ship case study. HOEF blends with MGO are denoted as HOEF I_30, HOEF I_50, HOEF II_10, and HOEF II_20.

Across all analysed impact categories, a consistent pattern is observed, with the TTW phase representing the dominant contribution to overall impacts, particularly for local air pollution indicators, resulting in relatively small differences between analysed fuel pathways. While the climate change category shows a stronger influence of the WTT phase, reflected in lower GWP values for HFO/e-methanol and HFO/BtL pathways, this trend is not consistently observed across other impact categories. For local air pollution impacts, no single fuel pathway demonstrates a clear overall advantage. HFO/BtL and HFO/e-methanol pathway generally achieve lower values for AP, while HFO/HOEF I blends, particularly HFO/HOEF I_50, show the lowest values in AFP and EP. In contrast, HFO/HOEF II blends and HFO/e-methanol in certain cases exhibit impacts comparable to or higher than the HFO/MGO pathway. Overall, HOEF I based pathways provide only marginal improvements, while HFO/HOEF II blends remain largely comparable to the HFO/MGO pathway, indicating no distinct performance advantage.

6 Sensitivity and robustness analysis

To evaluate the robustness of the obtained results and assess the influence of key modelling assumptions, a sensitivity analysis was conducted. Sensitivity analysis represents an important step in LCA studies, as it allows the identification of parameters that may significantly influence the environmental performance of the investigated fuel pathways [12]. In particular, the analysis examines the influence of the electricity mix used in HOEF production and the operational speed of the vessel. These parameters were selected due to their strong impact on upstream energy requirements and TTW emission profiles.

6.1 Sensitivity to electricity mix

To evaluate the sensitivity of the results to the electricity supply used in HOEF production, several electricity mix scenarios were considered. These scenarios represent different regional electricity generation structures with varying shares of renewable and fossil-based energy sources. The analysed electricity mixes include a fully renewable electricity scenario (RE), as well as national or regional electricity mixes for Croatia (HR), Germany (DE), France (FR), Poland (PL), Norway (NO), the European Union average (EU), and the United States (USA). The RE scenario represents a hypothetical electricity system based entirely on renewable energy sources. The HR electricity mix is characterised by a relatively balanced structure, combining hydropower, wind energy and fossil-based generation. The DE includes significant shares of renewable energy sources, particularly wind and solar power, but still relies partly on fossil-based generation. The PL electricity mix is largely dependent on coal-based power generation, representing a high-carbon electricity scenario [49]. In contrast, the FR electricity mix is dominated by nuclear power, resulting in comparatively low carbon intensity. The NO mix is characterised by a very high share of hydropower and therefore represents one of the lowest carbon electricity systems [50]. The EU scenario represents the average electricity mix across the EU, reflecting a combination of renewable, nuclear and fossil-based electricity generation sources. Finally, the USA scenario reflects a diversified electricity system consisting of natural gas, coal, nuclear energy and an increasing share of renewable sources [51]. It should be noted that the differences between electricity mix scenarios originate exclusively from the WTT phase, where electricity is required for e-fuel production processes. The TTW emissions remain unchanged, as they are determined by fuel combustion characteristics in the marine engine and are therefore independent of the electricity supply used during the fuel production. This sensitivity analysis was performed for the ferry, trawler and purse seiner case studies, while it was not applied to the bulk carrier and cruise ship cases. For these vessel types, the baseline results already indicated limited improvements of HOEF-based pathways under the renewable electricity scenario, and therefore further variation of electricity supply was not expected to significantly affect the overall conclusions.

Figure 36 presents the sensitivity of LCA GHG emissions (GWP) to different electricity mix scenarios for the analysed HOEF blends in the ferry Mljet case study. The results show that the environmental performance of the investigated blends is strongly influenced by the electricity mix used in the WTT phase of fuel production. The influence of electricity supply becomes particularly pronounced for HOEF I blends, especially in the HOEF I_50 scenario, where the share of HOEF is higher. As the proportion of HOEF increases, the contribution of electricity-intensive fuel production processes becomes more significant, leading to greater variability on WTT emissions across different electricity mixes. Among the analysed electricity scenarios, the PL electricity mix results in the highest GWP values due to its strong reliance on coal-based electricity generation. In contrast, the RE and the NO electricity mix show the lowest GWP emissions, reflecting their high shares of renewable electricity generation, particularly hydropower. Similarly, the FR scenario also results in comparatively low GWP values, primarily due to the dominant share of nuclear power in the national electricity generation mix, which is characterised by low lifecycle carbon intensity.

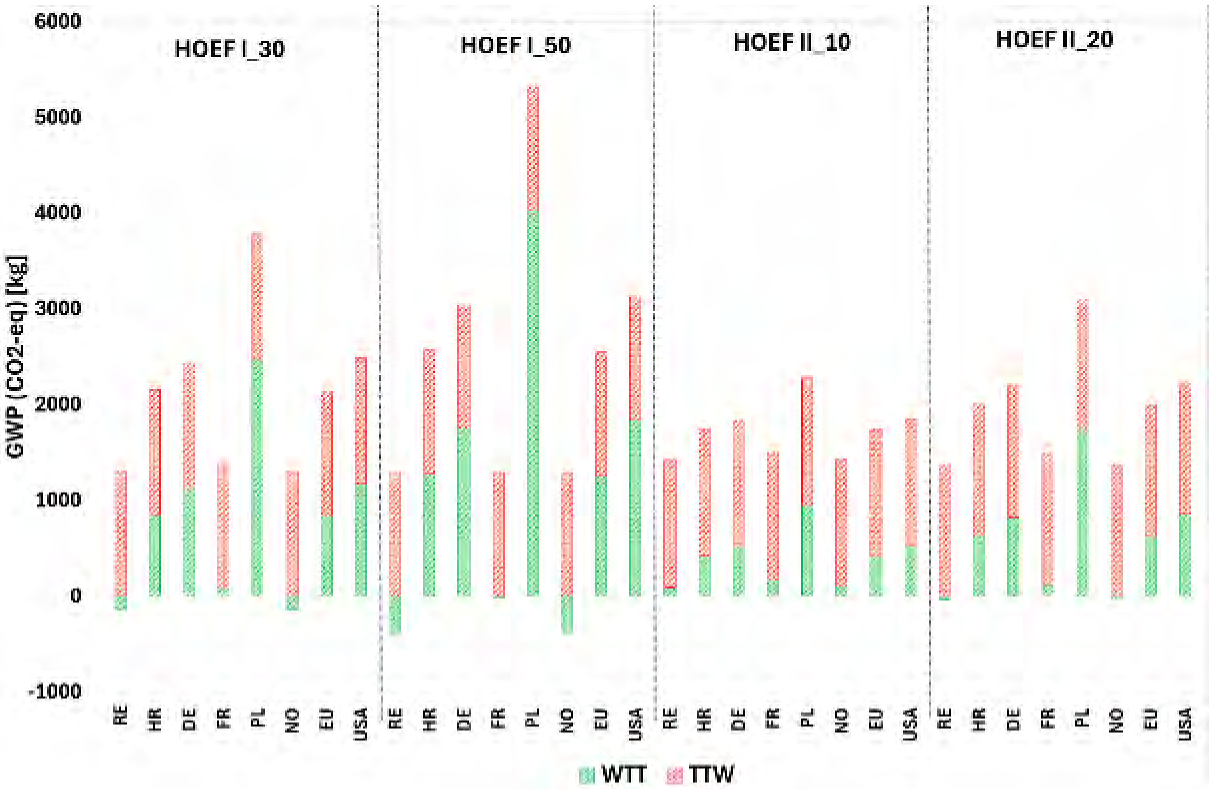

Figure 36. Sensitivity of GWP indicator to different electricity mix scenarios for analysed HOEF blends (the ferry case study).

Figures B2–B4. show that the electricity mix used in fuel production strongly influences AP, AFP, and EP results for all HOEF blends. In all cases, the PL scenario yields the highest impacts due to its coal-intensive electricity mix, leading to higher emissions of acidifying pollutants, particulate matter, and upstream emissions. Conversely, the RE scenario consistently shows the lowest impacts, followed by NO and FR mixes, reflecting their lower emission intensities.

Overall, the results indicate that the electricity mix, and particularly its carbon intensity, has a significant influence on the WTT phase, which consequently affects the overall WTW environmental performance of the analysed HOEF blends. The sensitivity analysis shows that this influence is most pronounced for HOEF I blends, particularly for the HOEF I_50 scenario, due to the higher share of e-fuel in the blend. As the share of e-fuel increases, the contribution of electricity-intensive fuel production processes becomes more significant, making the overall results more sensitive to the electricity mix used. Furthermore, the results demonstrate that the relative performance of HOEF blends depends strongly on the carbon intensity of the electricity supply. Under carbon-intensive electricity mixes, such as PL scenario, HOEF I blends exhibit higher emissions than HOEF II blends, due to the greater electricity demand associated with their production. In contrast, in RE scenarios HOEF I blends show lower emissions than HOEF II blends, highlighting the importance of renewable electricity for achieving the environmental benefits of e-fuel pathways.

Although the absolute values of the environmental impacts differ between the trawler and purse seiner case studies, the sensitivity to electricity mix follows the same overall trend as observed for the ferry case. This indicates that the results are primarily driven by upstream fuel production processes rather than vessel-specific operational profiles. Detailed results for the trawler and purse seiner case studies are provided in **Error! Reference source not found.**

6.2 Sensitivity to vessel speed

To further evaluate the robustness of the obtained results, an additional sensitivity analysis was conducted focusing vessel speed as a key operational parameter. Vessel speed directly affects propulsion power demand and engine operating conditions, and within the applied model, changes in speed influence the required main engine power, which in turn affects total onboard power, fuel consumption and resulting emissions. For each case study, vessel speed was varied relative to the reference operating speed, with variation ranges defined according to the specific vessel type and operational profile (Table 9). This sensitivity analysis was not applied to fishing vessels, as their operational profile are characterised by a variable and activity driven speed patterns, making speed variation scenarios less representative.

Table 9. Speed variation ranges applied in the sensitivity analysis.

Vessel type	Speed variation range
Ferry	-30% to +30%
Bulk carrier	-20% to 0% (slow steaming scenarios)
Cruise ship	-20% to 0%
Trawler	Not applicable
Purse seiner	Not applicable

For a given transport task, variations in vessel speed affect both propulsion power demand and total operating time. As a result, the overall environmental impact reflects combined effect of changes in energy demand and operation duration. The sensitivity analysis was performed for all investigated fuel pathways and covers the following impact categories: GWP, AP, AFP and EP.

6.2.1 Ferry case study

Figure 37 presents the sensitivity of GWP to variations in vessel speed for the analysed fuel pathways. The results show clear differences in the magnitude of emissions between the investigated fuels. Among the analysed scenarios, MGO consistently exhibits the highest GWP values across the entire speed range. This is followed by the HOEF II blends, which show lower emissions compared to MGO but remain higher than the other alternative options. The HOEF I blends demonstrate further reductions in GWP values compared to HOEF II blends, indicating improved environmental performance within this fuel group. The lowest GWP values across the speed range are observed for e-methanol and BtL.

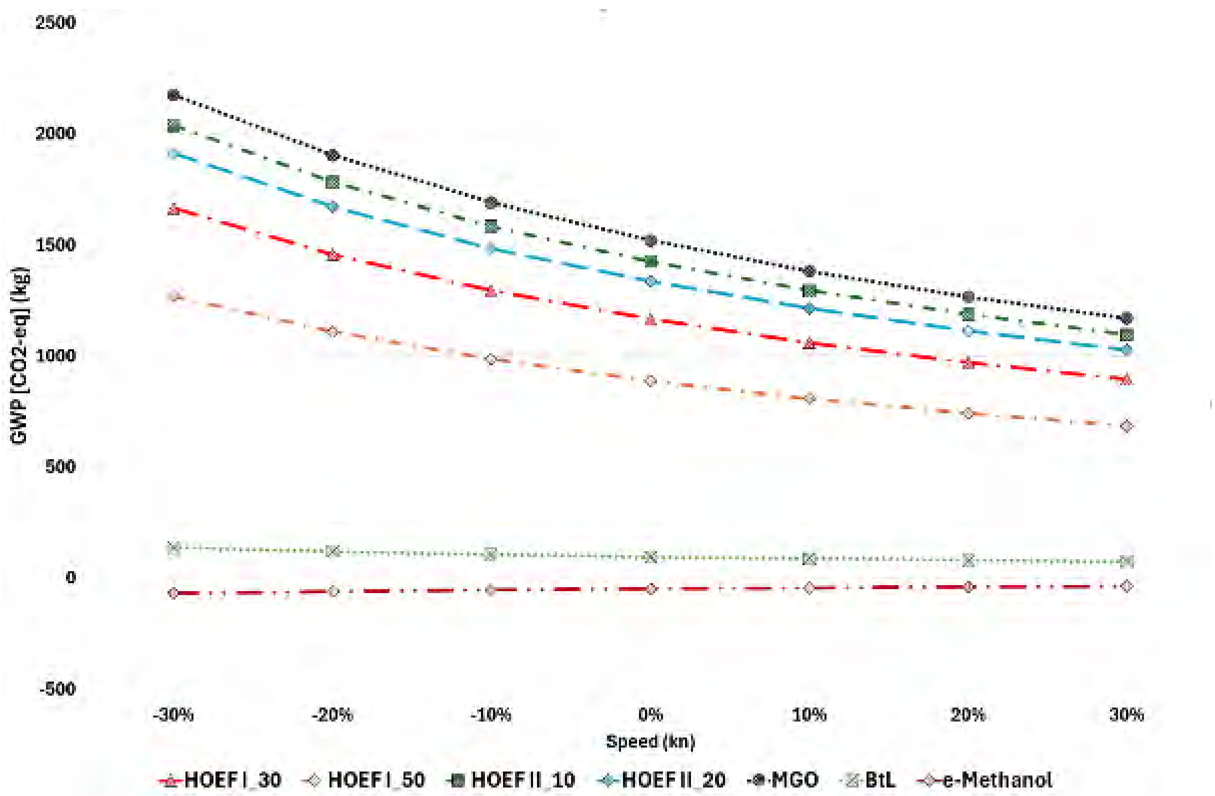

Figure 37. Sensitivity of GWP indicator to different operational vessel speeds for analysed fuels (the ferry case study).

Figures B13–B15 show that vessel speed variations do not change the overall ranking of fuel pathways but significantly affect emission levels. MGO consistently has the highest AP and AFP, while e-methanol shows particularly high EP (and high AFP), whereas alternative fuels generally perform better. Among them, HOEF II_10 (and BtL for EP) achieves the lowest impacts across the analysed speed range, with other HOEF blends showing intermediate results.

Overall, the results indicate a consistent trend across all analysed impact categories. For most fuel pathways, the environmental impacts decrease with increasing vessel speed, while a slight increase is observed only in the case of GWP indicator for e-methanol. Across the analysed scenarios, MGO consistently exhibits the highest emissions, except for EP indicator, where e-methanol shows the highest values. In contrast, the lowest environmental impacts are generally observed for HOEF II_10, which consistently demonstrates the best environmental performance across the analysed speed scenarios.

6.2.2 Bulk carrier case study

HFO/HOEF II_20 HFO/BtL HFO/e-Methanol

Figure 38 presents the sensitivity of GWP to variations in vessel speed for the analysed fuel pathways in the bulk carrier case study, reflecting slow steaming operational scenarios. The results show clear differences in emission levels between the investigated fuels. Among the analysed scenarios, HFO/MGO consistently exhibits the highest GWP values across the entire speed range. This is followed by the HFO/HOEF II blends, which show lower emissions compared to HFO/MGO but remain higher than the other alternative options. The HFO/HOEF I blends demonstrate further reductions in GWP values compared to HOEF II blends. The lowest GWP values across the analysed speed range are observed for HFO/e-methanol and HFO/BtL.

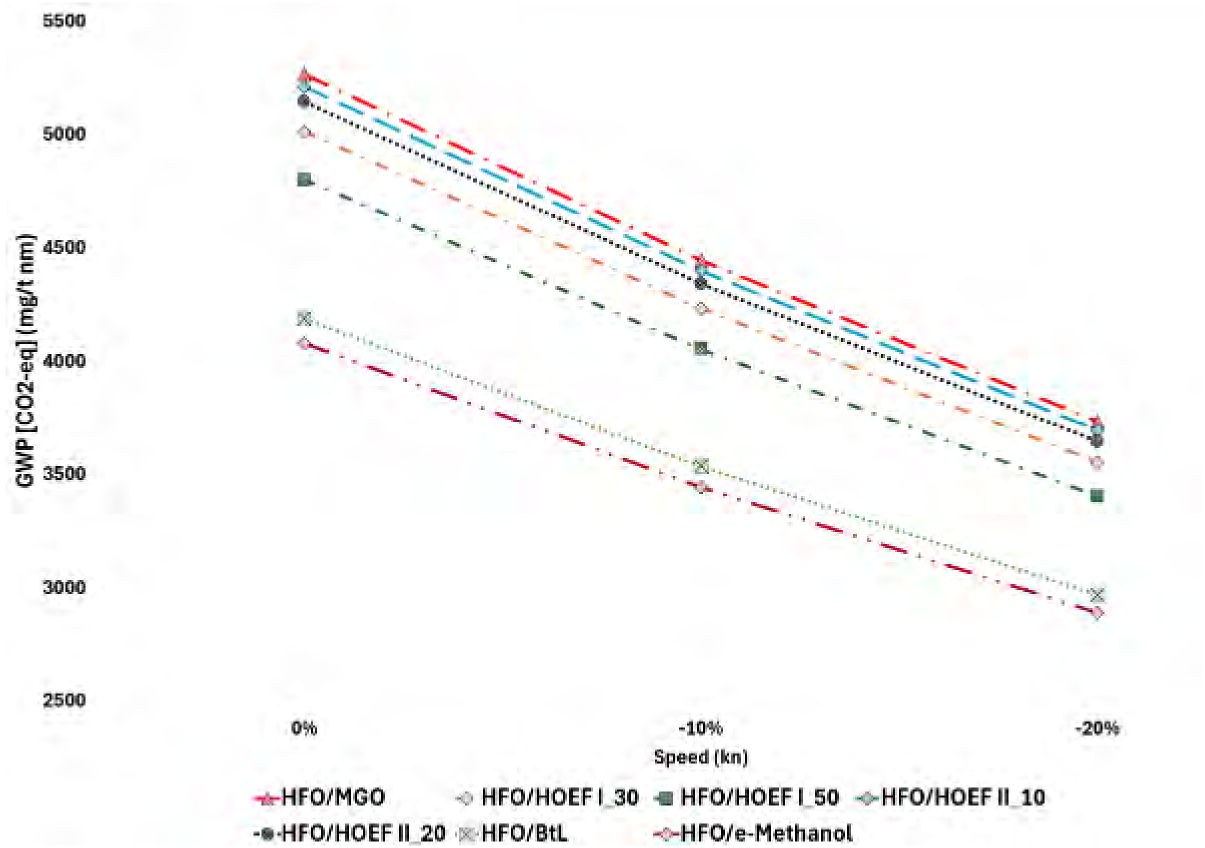

Figure 38. Sensitivity of GWP indicator to different operational vessel speeds for analysed fuels (the bulk carrier case study).

Figures B16–B18 indicate that vessel speed has a limited influence on differentiating fuel pathways, as only minor differences are observed across AP, AFP, and EP. HFO/MGO and HFO/HOEF II blends generally show the highest AP and AFP values, while HFO/e-methanol exhibits the highest EP. In contrast, HFO/BtL and HFO/HOEF I_50 consistently achieve the lowest impacts, with other blends showing similar intermediate performance.

Overall, the results indicate a consistent trend across all analysed impact categories under slow steaming conditions. For all fuel pathways, the value of environmental impacts decrease with decreasing vessel speed, reflecting the strong influence of propulsion power demand on total energy consumption.

6.2.3 Cruise ship case study

Figure 39 presents the sensitivity of GWP to variations in vessel speed for the analysed fuel pathways in the cruise ship case study. The results show clear differences in emission levels between the investigated fuels. Among the analysed scenarios, HFO/MGO consistently exhibits the highest GWP values across the entire speed range. This is followed by the HFO/HOEF II blends, which show lower emissions compared to HFO/MGO but remain higher than the alternative options. The HFO/HOEF I blends demonstrate further reductions in GWP values compared to HFO/HOEF II blends. The lowest GWP values across the analysed speed range are observed for HFO/e-methanol and HFO/BtL.

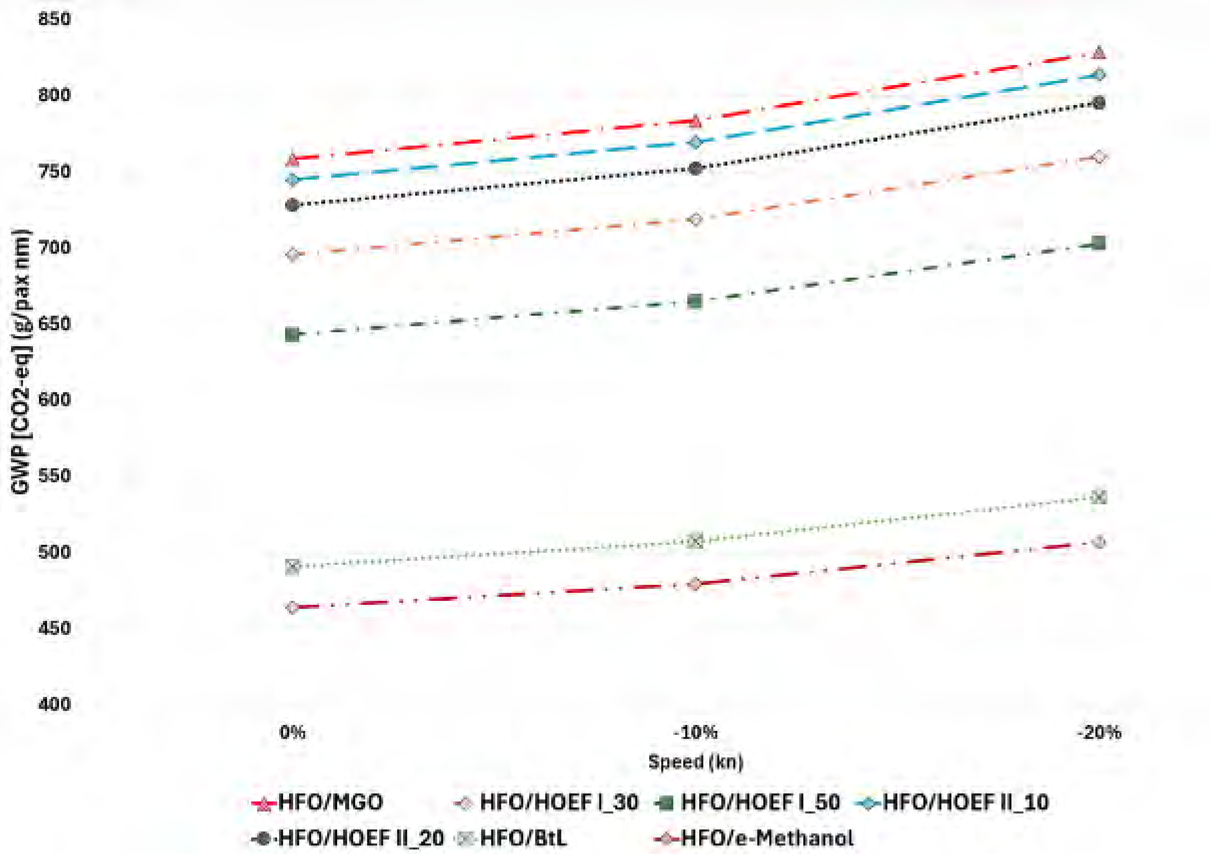

Figure 39. Sensitivity of GWP indicator to different operational vessel speeds for analysed fuels (the cruise ship case study).

Figures B19-B21 show clear differences between fuel pathways despite changes in vessel speed. HFO/MGO and HFO/HOEF II blends generally exhibit the highest AP and AFP, while HFO/e-methanol shows the highest EP values. In contrast, HFO/HOEF I blends, particularly HFO/HOEF I_50, consistently achieve the lowest impacts, with HFO/BtL also showing relatively low emissions.

Overall, the results indicate a consistent trend across all analysed vessel speed, while the relative ranking between fuels remains largely unchanged. This behaviour reflects the operational characteristics of cruise ships, where a significant share of total energy demand is associated with auxiliary (hoteling) loads, which remain relatively constant over time and increase total emissions under longer operating durations at lower speeds.

6.3 Sensitivity to ECA share

Sensitivity to ECA share is analysed for the bulk carrier and cruise ship case studies to assess the influence of operational conditions on the calculated environmental impacts. The ECA share represents the fraction of the total route operated within Emission Control Areas, where fuel switching from HFO to alternative fuels is required. In this study, the ECA share is varied between 10% and 40% of the total route length, while all other parameters are kept constant. This approach enables evaluation of how changes in the extent of ECA operation influence the environmental performance of the analysed fuel pathways.

Figure 40 presents the sensitivity of GWP to variations in ECA share for the analysed fuel pathways in the bulk carrier case study. The results show distinct differences in behaviour between the investigated fuels. For HFO/MGO and HFO/HOEF II blends, GWP values slightly increase with increasing ECA share.

In contrast, HFO/HOEF I blends, HFO/BtL and HFO/e-methanol show a clear decrease in GWP with increasing ECA share, with most pronounced reductions observed for HFO/e-methanol and HFO/BtL.

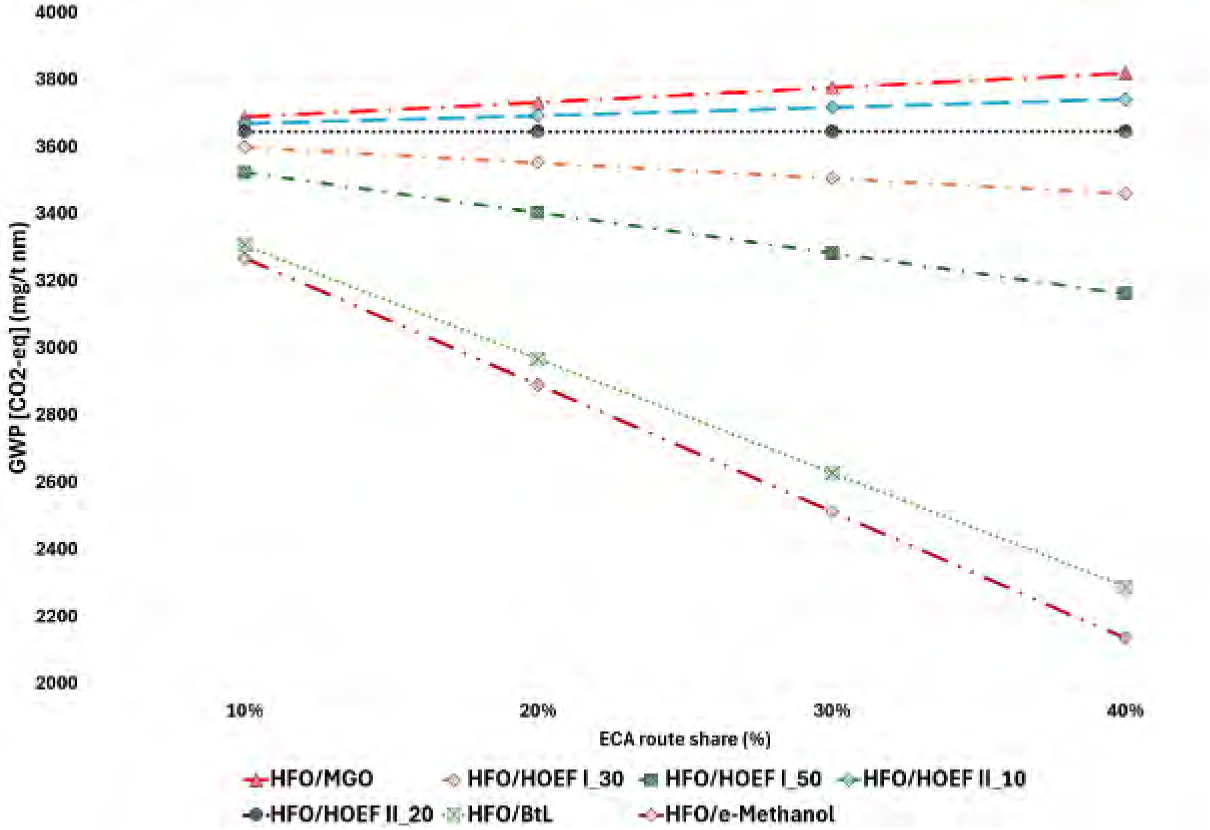

Figure 40. Sensitivity of GWP indicator to variations in ECA share.

The trends observed in Figure 40 can be explained by the change in fuel consumption patterns with increasing ECA share. As the proportion of operation within ECA regions increases, the use of low-sulphur fuels such as MGO or HOEF blends replaces HFO. For conventional fuels, this shift leads to an increase in upstream (WTT) emissions due to the higher processing requirements of MGO compared to HFO, while combustion-related emissions (TTW) may decrease. For HOEF blends, the effect depends on the relative contributions of the HOEF fraction and the fossil MGO component. As ECA share increases, the contribution of HOEF fuels becomes more pronounced, which can lead to different GWP trends depending on the balance between reduced fossil fuel use and increased upstream emissions associated with fuel production. In contrast, for fuels such as e-methanol and BtL, which are already low-carbon and sulphur-free, the variation in ECA share has a smaller impact on overall GWP, as their lifecycle emissions are dominated by upstream production processes rather than operational fuel switching.

Figures B22–B24 show that increasing ECA share consistently reduces AP, AFP, and EP across all fuel pathways. HFO/MGO and HFO/HOEF II blends generally exhibit the highest AP and AFP, while HFO/e-methanol shows the highest EP values. In contrast, HFO/HOEF I_50 and HFO/BtL consistently achieve the lowest impacts across the analysed scenarios.

Overall, the results indicate that increasing the ECA share leads to a consistent reduction in local air pollution impacts (AP, AFP and EP) across all fuel pathways, reflecting the reduced use of high-sulphur HFO within ECA regions. In contrast, the response of GWP depends on the fuel type, with reductions observed for HFO/HOEF I blends, HFO/BtL and HFO/e-methanol, while HFO/MGO and HFO/HOEF II blends show a slight increase.

The same trends are observed for the cruise ship case study in terms of local air pollution impacts (AP, AFP and EP), where all fuel pathways show a consistent decrease with increasing ECA share. However, slight differences are observed in the GWP response, particularly HOEF II blends, as presented in **Error! Reference source not found.**.

6.4 Sensitivity to fuel blend

The additional analysis presented in this subsection extends the previously discussed results by introducing a comparison between neat fuel pathways, including pure HOEF I (higher alcohols), pure HOEF II (higher ethers), BtL and e-methanol for ferry case study. This comparison enables a consistent evaluation of alternative fuels without the influence of fossil blending components, thereby addressing the limitations associated with earlier comparisons between HOEF–MGO blends and neat fuels.

The WTW GHG emissions of the analysed fuels are presented in Figure 41. The results clearly show that both pure HOEF I and HOEF II achieve substantially lower GWP values compared to HOEF blends discussed previously, confirming that the presence of MGO was a dominant contributor to total emissions. However, e-methanol and BtL still exhibit the lowest GWP values among the considered fuels.

Despite this, the difference between HOEF fuels and the benchmark alternatives is significantly reduced when considering pure HOEF. This indicates that the performance of the HOEF production pathway is more competitive than suggested by the blend-based results.

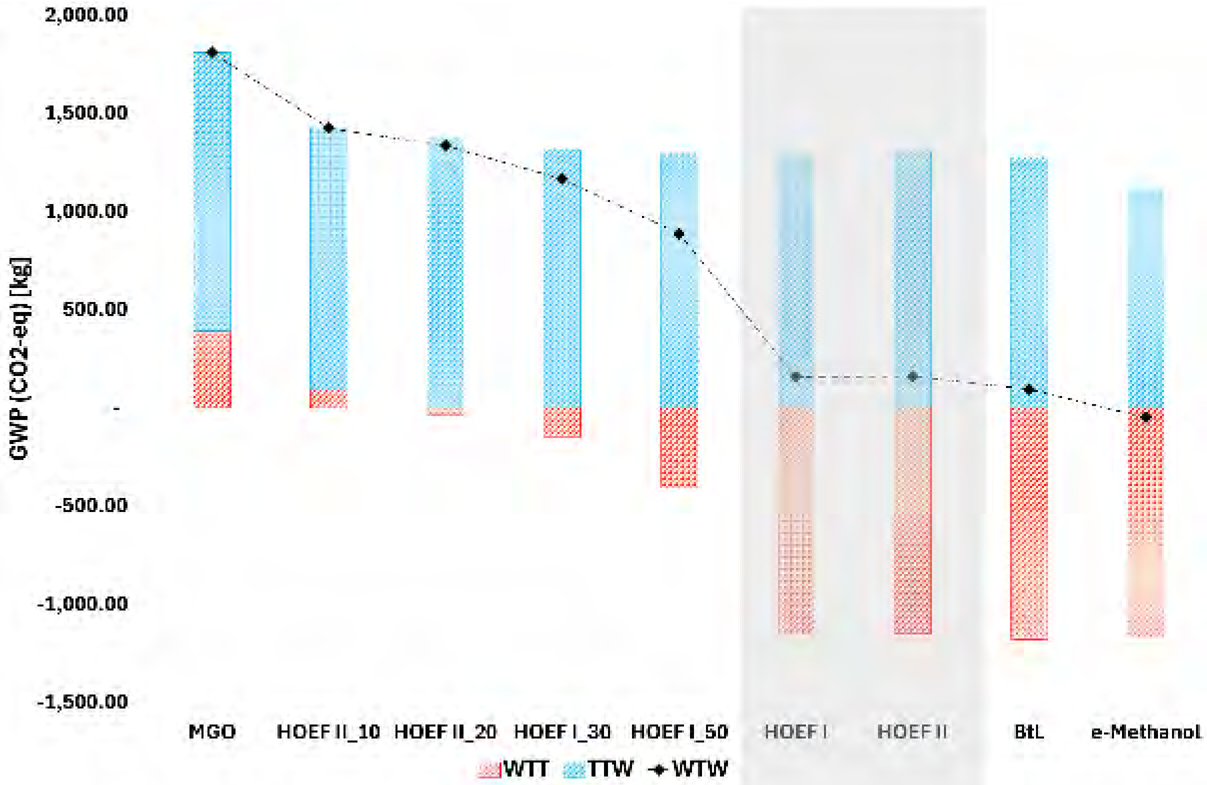

Figure 41. WTW GHG emissions (GWP, CO_2-eq) for the ferry case study with pure HOEF I and HOEF II.

Figures B29-B31 highlight the environmental benefits of HOEF fuels across local impact categories. Both HOEF I and HOEF II show low AP due to the absence of sulphur, while also achieving reduced AFP through cleaner, more complete combustion. For EP, HOEF I performs comparably to e-methanol, whereas HOEF II demonstrates slightly lower impacts.

From the perspective of onboard application, the results shown in this chapter should be interpreted together with fuel properties and engine compatibility. Both HOEF I and HOEF II blends are liquid fuels with diesel-like combustion characteristics, enabling their use in conventional marine diesel engines with limited or no modifications. This represents a key advantage over e-methanol, which, despite its strong performance in Figure 41, requires dedicated fuel systems, modified injection strategies and additional safety measures due to its lower flash point and different physicochemical properties.

BtL fuels also demonstrate excellent compatibility with existing engine technologies, combining low GWP values (Figure 41) with favourable local emission profiles (Figures B29-B31). However, unlike HOEF fuels, BtL production is constrained by biomass availability.

The relatively low AP, AFP and EP values observed for HOEF fuels (Figures B29-B31) further support their suitability for maritime applications, particularly in emission-controlled regions where local air quality is a key regulatory concern.

6.5 Sensitivity to inclusion of paraffinic co-products

This subsection presents an additional sensitivity analysis performed for the ferry case study, focusing on the impact of including paraffinic co-products in the HOEF fuel system. The analysis compares the environmental performance of the HOEF I_30 blend under two configurations: (i) the base case, where only the oxygenated fraction of the E-TANDEM fuel is considered, and (ii) an extended case, where the co-produced paraffinic hydrocarbons are included as part of the fuel pool. The motivation for this analysis originates from the techno-economic assessment of the E-TANDEM process, where both oxygenated products and paraffinic hydrocarbons are considered valuable fuel outputs. The production process generates not only higher alcohols (or ethers) but also a significant fraction of oxygen-free paraffinic hydrocarbons, which can be directly utilised as diesel-like fuel components. This additional product stream increases the total fuel output of the system and effectively improves both electricity-to-fuel and feedstock-to-fuel conversion efficiencies. Therefore, excluding these paraffinic fractions in the LCA leads to a conservative estimation of the environmental performance of the HOEF pathway.

The effect of including paraffinic co-products on climate performance is illustrated in Figure 42, which presents the WTW GHG emissions for the ferry case study. The results show a clear reduction in GWP when paraffinic hydrocarbons are included in the HOEF I_30 system. This reduction is primarily driven by the redistribution of upstream environmental burdens over a larger amount of usable fuel output. In the base case, the environmental impacts of the entire production system are allocated solely to the oxygenated fraction (approximately 13 kg/h), resulting in relatively high specific emissions. In contrast, when the paraffinic fraction (approximately 19 kg/h) is also considered, the same upstream impacts are distributed across a significantly larger total fuel output. This leads to a lower impact per functional unit and thus improves the overall GWP performance of the HOEF fuels.

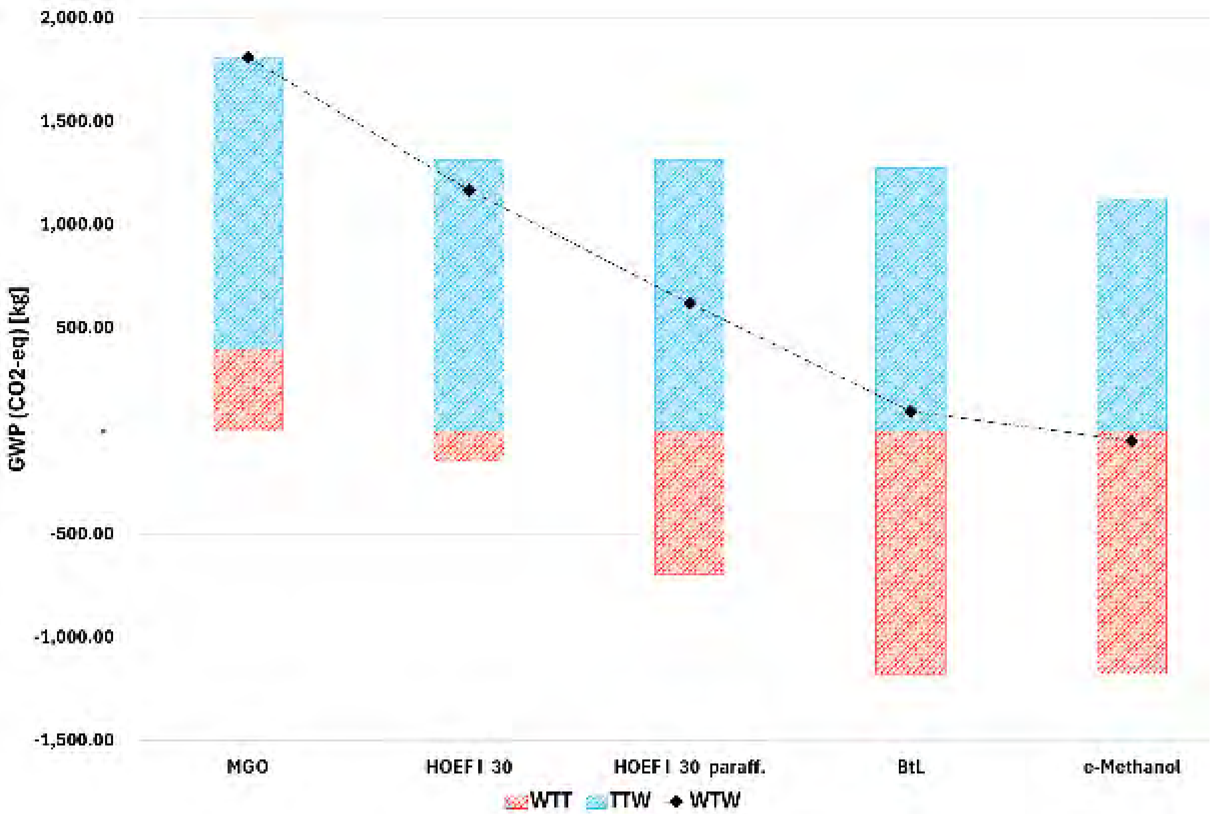

Figure 42. Sensitivity of WTW GHG emissions (GWP, CO_2-eq) to inclusion of paraffinic co-products for the HOEF I_30 blend (ferry case study).

Figures B32-B34 show that including paraffinic hydrocarbons reduces AP, AFP, and EP values. This reduction is mainly due to the allocation of upstream emissions over a larger total fuel output, lowering the specific impact per functional unit. As a result, considering co-products significantly improves the overall environmental performance of the fuel system.

The results presented in this chapter demonstrate that the inclusion of paraffinic co-products has a significant positive impact on the environmental performance of HOEF-based fuel systems. This finding highlights an important methodological aspect of LCA modelling: the treatment of co-products can strongly influence the results and should be aligned with the intended system representation. From a system perspective, the paraffinic hydrocarbons represent a valuable fuel stream that can directly substitute fossil diesel components, thereby reducing the need for MGO blending. Their inclusion in the analysis therefore provides a more realistic representation of the E-TANDEM fuel concept, in which multiple fuel fractions are co-produced and utilised. Furthermore, this analysis demonstrates that the environmental performance of HOEF fuels is not solely determined by the efficiency of the core conversion process but also by the extent to which all useful outputs of the system are valorised.

7 Environmental positioning of HOEF

The environmental performance of HOEF pathways is assessed across representative vessel case studies (Figure 43). For ferries and fishing vessels (trawler and purse seiner), consistent trends show that results are driven mainly by fuel properties and upstream production rather than vessel type.

HOEF blends offer clear benefits in local air pollution impacts, especially AP and AFP. Higher-share HOEF I blends perform best, largely due to cleaner combustion in the TTW phase. In contrast, GWP behaves differently: although reductions are observed under renewable electricity, sensitivity analysis shows strong dependence on the electricity mix. Higher HOEF shares increase reliance on electricity-intensive production, leading to greater variability in GWP results.

This dual behaviour is reflected in the overall positioning of fuels. Under renewable electricity, HOEF blends, particularly HOEF I, show strong performance across both climate and local impacts. Under carbon-intensive electricity, their climate benefits diminish significantly. MGO remains in an intermediate position, while e-methanol and BtL show distinct trade-offs. The comparison is conceptual, illustrating relative performance rather than precise quantitative differences.

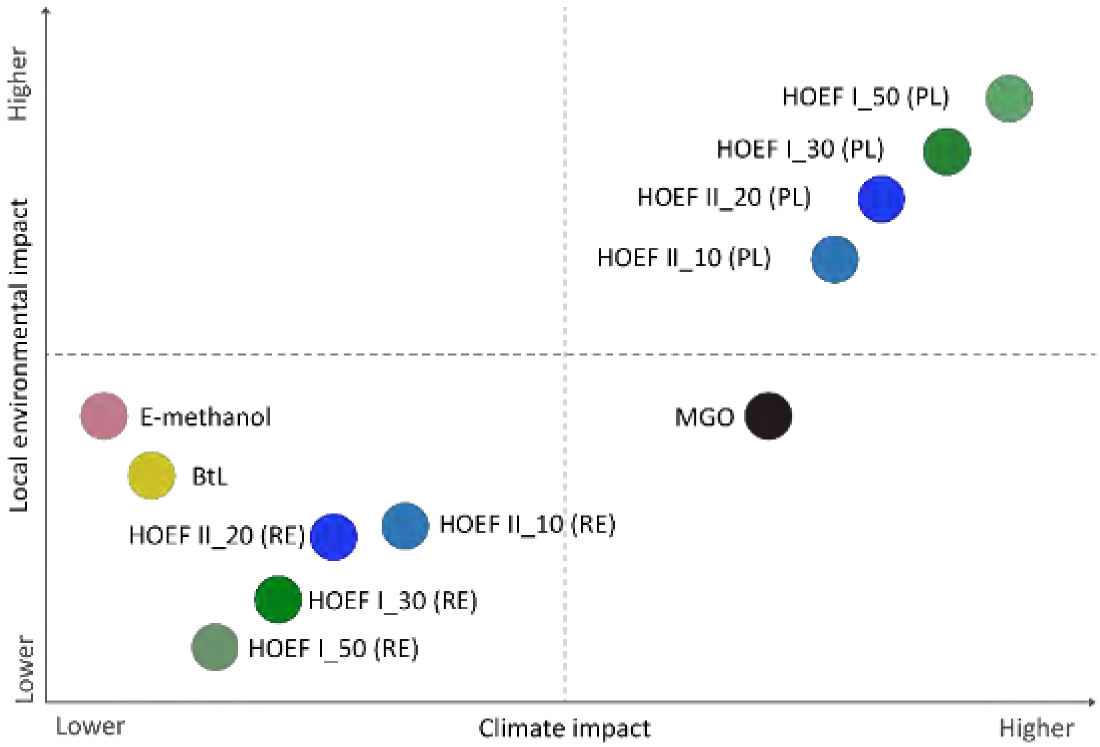

Figure 43. Conceptual positioning of HOEF pathways based on climate and local environmental impacts.

In contrast to the ferry and fishing vessels, the environmental performance of HOEF pathways in deep-sea applications, represented by the bulk carrier and cruise ship, shows a different behaviour. HOEF blends show only limited advantages in local air pollution-related impact categories, with no consistent reductions observed to other fuel options. For climate change impacts, moderate reductions in climate impact category are observed for HOEF I blends. However, lower values are consistently achieved by e-methanol and BtL pathways. The environmental positioning of the analysed fuel pathways in deep-sea applications therefore shows reduced differentiation between fuel options, in contrast to the more pronounced trends observed in short-sea and fishing vessel case studies.

8 Decision support systems (DSS) framework

The DSS is developed to support fuel selection in maritime transport based on LCA results. While LCA provides a comprehensive evaluation of environmental impacts associated with different fuel pathways, it does not directly indicate which option should be selected under specific operational and regulatory conditions. Therefore, the DSS serves as a structured framework that translates LCA into actionable decision support.

The DSS is developed as a transparent, LCA-based decision framework for fuel selection across different vessel types and operational contexts. It uses pre-calculated environmental indicators for each fuel pathway and combines them through normalization and weighted scoring, allowing users to rank fuel options according to climate-oriented, local air pollution-oriented, or balanced decision priorities. By linking user-defined input parameters with pre-calculated LCA results, the DSS enables a consistent comparison of fuel options and provides a clear recommendation, including an assessment of trade-offs and robustness of the selected option.

The overall structure of the DSS is illustrated in Figure 44. The DSS is organised as a sequence of interconnected layers, in which user-defined inputs are combined with pre-calculated LCA data and processed through a decision logic based on normalization and weighted scoring. This process results in a ranked selection of fuel options, accompanied by a recommendation and an assessment of robustness, thereby ensuring a transparent and systematic translation of LCA results into decision-relevant outputs.

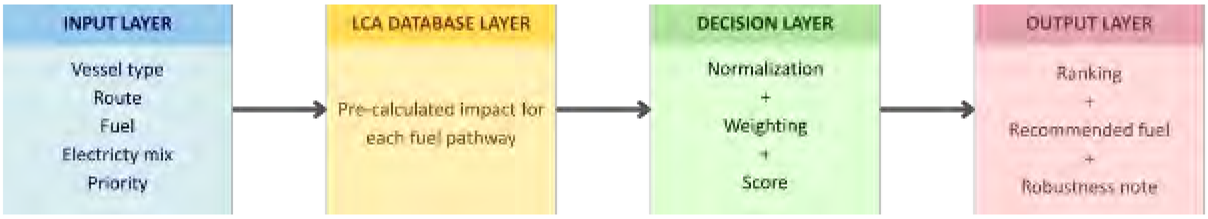

Figure 44. Structure of the DSS framework for LCA-based fuel selection.

8.1 Input parameters

The DSS requires a set of user-defined input parameters that describe the vessel characteristics, operational conditions, regulatory framework and decision priorities. These inputs define the specific context in which fuel options are evaluated and allow the DSS to select the appropriate set of pre-calculated LCA results for comparison. The main input parameters considered in the DSS are summarised in Table 10.

Table 10. Input parameters for the DSS.

Input parameter	Options
Vessel type	Ferry, bulk carrier, cruise ship, purse seiner, trawler
Operational context	Short-sea, long-distance, fishing, cruise voyage
Regulatory context	Global (non-ECA), ECA-relevant, fuel-switching route scenario
Electricity mix	EU average, USA average, France, Germany, Croatia, Poland, renewable energy, Norway

Fuel options	MGO, HFO, BtL, e-methanol, HOEF I_30, HOEF I_50, HOEF II_10, HOEF II_20
Weighting of impact categories	Climate-focused, local air quality focused, balanced
ECA share	0-100% of operation within ECA
Speed regime	Normal operation, slow steaming

8.2 Decision logic

The decision logic of the DSS is based on the comparison of pre-calculated LCA results for each considered fuel pathway. In order to enable a consistent comparison across different environmental impact categories, the original LCA results are first normalised and then combined through a weighted scoring procedure. This allows fuel options to be ranked according to the selected decision priorities.
Since the selected impact categories are expressed in different units and may differ substantially in magnitude, direct comparison is not possible. Therefore, the results are normalised using normalisation according to Eq. (24):

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \qquad (24)$$

Where X represents the original value of given impact category for a specific fuel option, while X_{min} and X_{max} denote the minimum and maximum values of the impact category among all compared fuel options. In this way, all indicators are transformed to dimensionless values between 0 and 1, here lower values indicate better environmental performance.
To reflect different decision contexts, weighting factors are assigned to each impact category. These weighting factors represent the relative importance of the individual environmental criteria in the final decision and are selected according to predefined decision scenarios. In this study, three weighting scenarios are considered: a climate-oriented scenario, a local air quality focused scenario and a balanced scenario, shown in the Table *11*.

Table 11. Weighting factors applied in the DSS for different decision scenarios.

Scenario	**Weighting factors (w_i)**			
	GWP	AP	AFP	EP
Climate-focused	0.60	0.15	0.15	0.10
Local air quality focused	0.25	0.30	0.30	0.15
Balanced	0.40	0.20	0.20	0.20

This enables the DSS to adapt the ranking of fuel options depending on whether the decision priority is focused primarily on GHG emissions, local air pollutant emissions, or an equal consideration of all selected impact categories.
Following normalisation and weighting, an overall score is calculated for each fuel option using a weighted sum approach, as given in Eq. (25):

$$Score = \sum_i (w_i \times X_{norm,i}) \qquad (25)$$

Where w_i is the weighting factor assigned to impact category i, and $X_{norm,i}$ is the corresponding normalised value. The resulting score represents the aggregated environmental performance of each fuel option under selected decision scenario.

Fuel options are then ranked according to their calculated scores, with lower scores indicating more favourable overall environmental performance. Based on this ranking, the DSS identifies the most suitable fuel option for the selected vessel type, operational context and decision priority.

8.3 Example application

The developed DSS is applied to an illustrative ferry case study representing short-sea maritime transport. The selected case considers a ferry operating within an emission-regulated environment, with an ECA share of 100% and operating under normal operating conditions. A renewable electricity scenario is assumed for all e-fuel pathways to ensure methodological consistency across the compared options. The analysis includes a set of fuel options, such as MGO, BtL, e-methanol and HOEF blends (HOEF I_30, HOEF I_50, HOEF II_10 and HOEF II_20). To reflect environmental priorities, all three decision scenarios are applied.

For each fuel pathway, pre-calculated WTW LCA results are used, covering four impact categories: GWP, AP, AFP and EP. These indicators were first normalised to enable comparability across categories. Subsequently, weighting factors are applied, and score is calculated for each fuel option. The calculated scores are then used to rank the fuel options, with lower scores indicating better overall environmental performance. The DSS scores and their contributions across impact categories for the ferry case are presented in Figure 45.

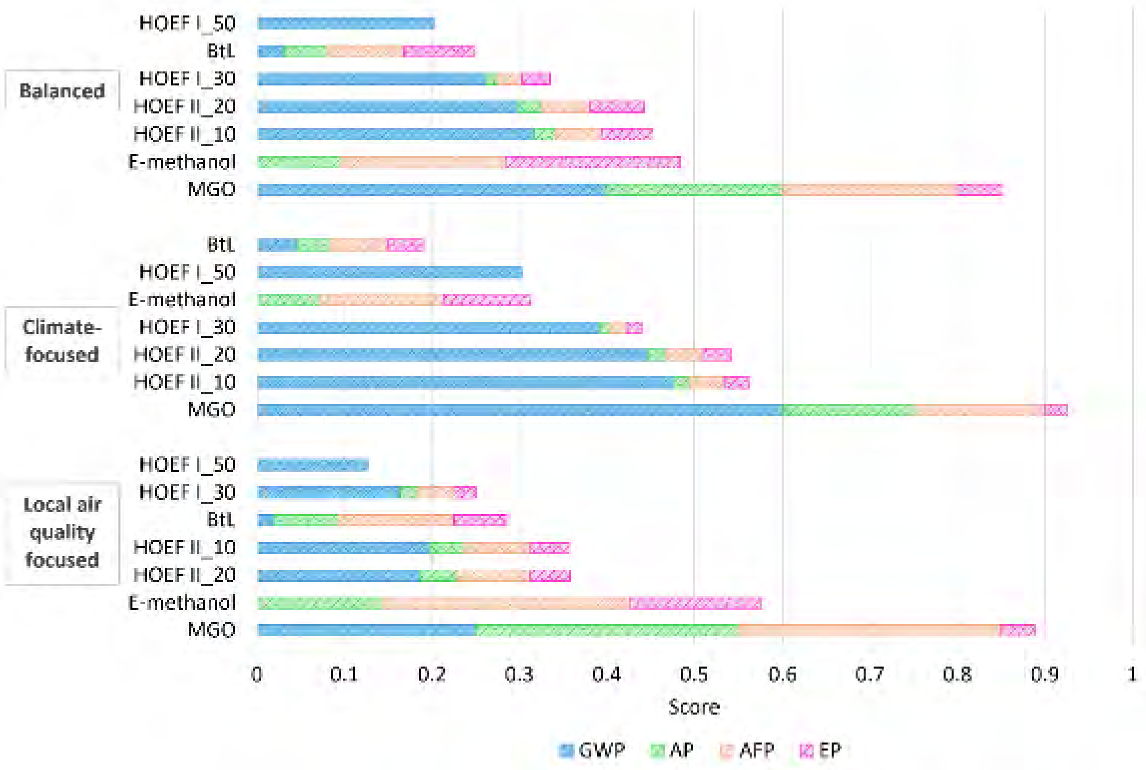

Figure 45. DSS results for the ferry case.

8.4 Interpretation of outputs

The results of the DSS application for the ferry case highlight the influence of weighting strategies on the ranking of alternative fuels. Three decision scenarios are considered: climate-focused, balanced, and local air quality focused, each reflecting different environmental priority.

Under balanced scenario, HOEF I_50 achieves the lowest overall score, indicating the most favourable compromise between climate change and local air pollution impacts. This is followed by BtL and HOEF I_30, which also demonstrate relatively low contributions across all impact categories. In contrast, e-methanol, despite exhibiting the lowest GWP, is penalised due to higher contribution to AP, AFP and EP, resulting in a higher overall score. MGO clearly performs the worst, driven by consistently high impacts across all categories.

A shift in ranking is observed under climate-focused scenario, where greater importance is assigned to GWP. In this case, fuels with strong climate performance, such as e-methanol and BtL, become more competitive. However, fuels with higher local air pollution impacts, such as e-methanol, still remain penalised, illustrating that even under climate prioritisation, trade-offs between impact categories persist.

Under the local air quality focused scenario, fuels with low AP, AFP and EP contributions are prioritised. These results improve ranking of HOEF blends, particularly those with higher shares, which exhibit consistently low local pollution emissions. In this scenario, the advantage of e-methanol is reduced due to its higher contributions to non-climate impact categories.

Overall, the comparison across scenarios demonstrates that fuel ranking is highly dependent on the selected decision context. While some fuels, such as HOEF I_50, maintain strong performance across multiple scenarios, other, such as e-methanol are more sensitive to weighting approach.

9 Discussion

9.1 Gender-sensitive interpretation of air-pollution-related health impacts

The introduction of HOEF fuels leads to substantial reduction in emissions of local air pollutants such as PM, SOx and NOx compared to MGO. These pollutants are widely associated with adverse health effects in environmental epidemiology studies. Although emission reductions occur across both the WTT and TTW stages of the fuel life cycle, potential human exposure is most directly associated with emissions released during vessel operation, where pollutants are emitted near workers, passengers and coastal communities. Consequently, the reduction of these emissions through HOEF fuel blends may contribute to lowering potential human health impacts associated with maritime transport. In environmental epidemiology, the relationship between air pollutant emissions and health outcomes is often conceptualised as a pathway linking pollutant concentrations, human exposure, internal dose and subsequent health effects. Both gender-related exposure patterns and sex related biological factors may influence different stages of this pathway and therefore affect how population groups experience air pollution impacts [52]. Conceptual pathway linking maritime fuel emissions to human health outcomes, considering gender-related exposure factors and sex-related physiological differences is illustrated in Figure 46.

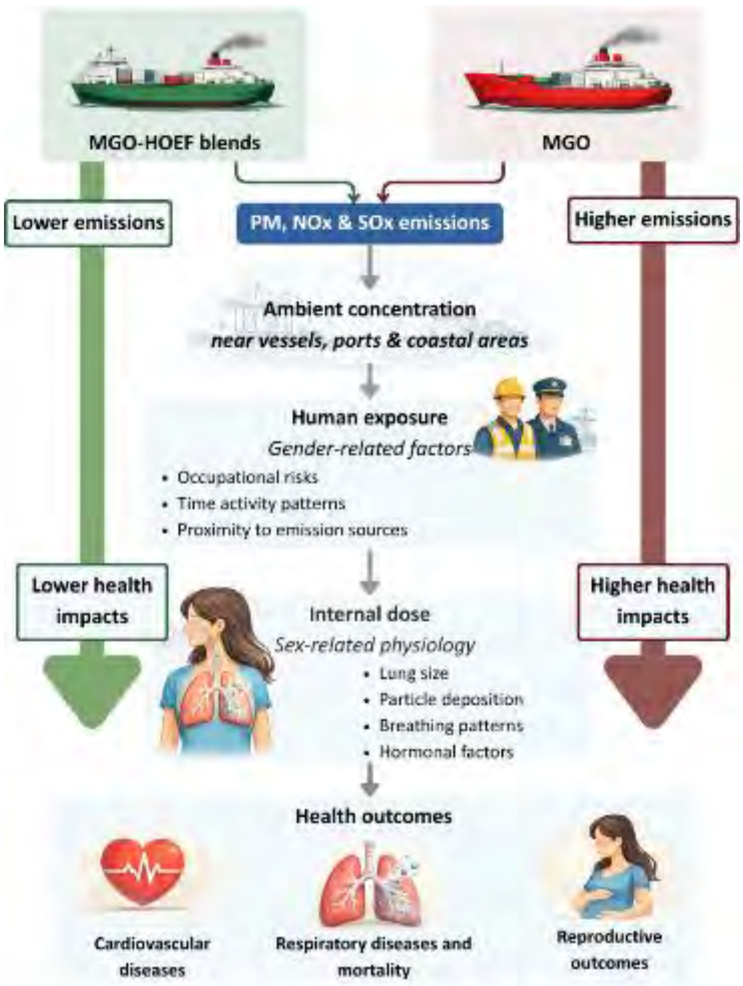

Figure 46. Conceptual pathway linking maritime fuel emissions to human health outcomes.

Gender-related factors primarily influence the transition from pollutant concentration to human exposure. In maritime sector, exposure patterns are strongly shaped by social roles, occupational activities and time-activity patterns. Shipping remains a highly gender-imbalanced industry, with women representing only around 1-2% of the global seafaring workforce and less than one fifth of the total maritime workforce [53]. Consequently, the gender imbalance observed in maritime occupations may influence exposure patterns, since operational roles in shipping and port activities frequently involve prolonged presence near emission source. Occupational roles most likely to experience such exposure include ship crew and port workers, whose daily activities often take place in close proximity to vessels and associated emission sources. Crew members may experience continuous exposure during vessel operation, while port workers and terminal personnel may be repeatedly exposed during port calls, manoeuvring and cargo handling activities [54]. In addition to occupational groups, other population groups may also experience exposure in maritime environments, including passengers and populations living or working in port areas [55].

The transition from exposure to internal dose may be influenced by both gender and sex related factors, including differences in activity patterns, duration of exposure and physiological characteristics that affect pollutant uptake. Individuals performing physically demanding tasks or spending prolonged periods in outdoor or transport-related environments may inhale larger volumes of air, increasing the amount of pollutants entering the respiratory system under comparable ambient concentrations. Consequently, occupational settings associated with higher activity levels and longer exposure durations may lead to greater internal doses compared to short-term or low-intensity exposure scenarios [56]. In addition, sex-related physiological differences may further influence inhaled dose. On average, males tend to have large lung volumes, which may result in higher inhaled air volumes under comparable exposure conditions, while females often exhibit smaller airway dimensions that may influence particle deposition within the respiratory tract [57]. Differences in breathing patterns and ventilation rates may also affect the amount of pollutants inhaled during exposure [56]. Furthermore, hormonal factors have been suggested to influence inflammatory and cardiovascular responses to air pollution, potentially contributing to sex-related differences in susceptibility to pollutant exposure [52].

The health outcomes associated with exposure to local air pollutants depend on the internal dose received by the human body and resulting biological response, which may differ between women and men due to sex-related physiological factors. Epidemiological studies suggest that women may experience stronger health effects associated with air pollution exposure for certain outcomes [58]. These include cardiovascular diseases such as ischemic heart disease, as well as respiratory mortality and diseases such as chronic bronchitis, chronic obstructive pulmonary disease and asthma [59]. In addition, air pollution exposure may have implications specific to women's reproductive health, with studies linking exposure to ambient air pollution to adverse pregnancy outcomes such as lower birth weight and preterm birth [60]. Among the considered pollutants, PM is generally associated with the broadest range of adverse health effects, including cardiovascular, respiratory and reproductive outcomes. NOx, particularly nitrogen dioxide (NO_2), are most consistently linked to respiratory diseases and reduced lung function. SOx, especially sulphur dioxide (SO_2), are primarily associated with acute respiratory irritation and exacerbation of existing respiratory conditions such as asthma [59]. Therefore, reducing emissions of these pollutants through the introduction of cleaner marine fuels such as HOEF blends has the potential to decrease the associated health risks compared with MGO [61].

10 Conclusions and recommendations

This report presents a comprehensive life cycle assessment of marine fuel pathways within an integrated source-to-propeller framework, with a particular focus on the environmental performance of Higher Oxygenate E-Fuels (HOEF) developed within the E-TANDEM project. The applied methodology combines detailed modelling of upstream fuel production processes with vessel-specific energy demand and emission modelling, enabling a consistent comparison of conventional and alternative fuels across multiple maritime applications. The results provide important insights into both the decarbonisation potential of HOEF fuels and their impact on local air pollution.

One of the key findings of the study is that the environmental performance of marine fuels cannot be evaluated solely based on onboard emissions, as upstream processes play a decisive role in determining overall life cycle impacts. This is particularly evident in the case of electrofuels, including HOEF and e-methanol, where the WTT phase contributes significantly to total GHG emissions. The results show that the carbon intensity of electricity used in fuel production is a critical parameter influencing overall performance. Under low-carbon or renewable electricity scenarios, HOEF fuels demonstrate substantial reductions in life cycle GHG emissions compared to conventional fuels such as MGO. However, under carbon-intensive electricity mixes, these benefits are significantly reduced or may even be reversed.

Across all analysed case studies, a consistent pattern is observed in the contribution of life cycle stages to total environmental impacts. For local air pollution indicators, including acidification potential (AP), particulate matter formation (AFP) and eutrophication potential (EP), the TTW phase dominates the results. In contrast, climate change impacts (GWP) are strongly influenced by the WTT phase, reflecting the importance of upstream fuel production. This highlights the need for a holistic WTW perspective when evaluating marine fuels and supports the use of LCA as a key decision-making tool in maritime decarbonisation strategies.

The results further indicate that HOEF blends provide consistent environmental benefits compared to conventional MGO across most impact categories, particularly for local air pollution. Among the analysed options, HOEF I blends demonstrate the most favourable performance, achieving significant reductions in AP, AFP and EP across multiple vessel types. HOEF II blends also show environmental benefits, although generally to a lesser extent compared to HOEF I. The magnitude of these benefits depends on the blending ratio, with higher shares of HOEF resulting in greater emission reductions.

In terms of climate change mitigation, HOEF blends achieve moderate reductions in GHG emissions compared to MGO, with performance strongly dependent on the share of HOEF in the blend and the characteristics of the upstream production process. While HOEF pathways do not consistently outperform other alternative fuels such as BtL or e-methanol in terms of GWP, they offer a balanced performance across multiple environmental indicators. This highlights their potential as a transitional or complementary fuel option within a diversified fuel portfolio for maritime decarbonisation.

The analysis of pure HOEF fuels (demonstrates that the intrinsic environmental performance of the HOEF pathway is significantly more favourable than indicated by blend-based results, highlighting the importance of consistent comparison between neat fuels. The inclusion of paraffinic co-products significantly improves the environmental performance of HOEF fuels and represents a more realistic system representation.

The analysis also demonstrates that the effectiveness of HOEF fuels varies across different vessel types and operational profiles. The most pronounced benefits are observed in applications with dynamic operating conditions and significant contributions of TTW emissions to total impacts, such as short-sea shipping and fishing vessels. In contrast, for large vessels operating under steady conditions, such as bulk carriers and cruise ships, the relative differences between fuel pathways are less pronounced, particularly for local air pollution indicators. This suggests that the deployment of HOEF fuels should be prioritised in segments where their environmental advantages can be maximised.

Sensitivity analyses confirm that the results are robust but highlight several key parameters that significantly influence the outcomes. In particular, the electricity mix used in HOEF production has a dominant impact on GWP results, while operational parameters such as vessel speed, payload and time spent in emission control areas (ECA) influence both energy demand and emission intensity. These findings underline the importance of integrating both technological and operational measures when evaluating and implementing alternative fuels.

Based on the results of this study, several recommendations can be formulated for the implementation of HOEF fuels in maritime transport.

First, the environmental benefits of HOEF are strongly dependent on the availability of low-carbon electricity. Therefore, the deployment of HOEF fuels should be closely aligned with the development of renewable energy infrastructure. Ensuring access to renewable electricity is essential for achieving meaningful GHG emission reductions and maximising the decarbonisation potential of these fuels.

Second, HOEF fuels show particular advantages in reducing local air pollution, especially particulate matter and acidifying emissions. As such, their implementation could be prioritised in regions with strict air quality regulations, such as Emission Control Areas, as well as in coastal and port areas where air pollution has significant impacts on human health. This positions HOEF as a promising option for compliance with current and future emission regulations targeting local pollutants.

Third, further research and development are required to better understand the combustion behaviour of HOEF fuels in marine engines and to optimise engine performance for these fuel blends. The current analysis assumes similar engine efficiency across fuels, but real-world applications may involve differences in combustion characteristics, fuel injection strategies and engine calibration. Experimental validation and engine testing are therefore necessary to refine emission factors and improve the accuracy of TTW modelling.

Finally, the results highlight the importance of using integrated assessment tools, such as the developed LCA framework and Decision Support System (DSS), to support fuel selection in maritime transport. These tools enable stakeholders to evaluate trade-offs between different environmental impacts and to identify fuel pathways that best meet specific operational and regulatory requirements.

In conclusion, HOEF fuels represent a promising alternative for reducing both greenhouse gas emissions and local air pollution in maritime transport, particularly when produced using low-carbon electricity and applied in suitable operational contexts. While they are not a universal solution for all vessel types and impact categories, they can play an important role within a broader portfolio of alternative fuels. Continued research, technological development and integration with renewable energy systems will be essential to fully realise their potential and to support the transition toward a more sustainable maritime sector.

11 Risks and interconnections

The main methodological risks in this report are associated with uncertainties in key input data and modelling assumptions within both the WTT and TTW phases. In particular, the environmental performance of HOEF fuels is highly sensitive to the assumptions related to electricity mix, CO_2 sourcing and process efficiencies used in Task 4.3 mass and energy balances, which directly influence WTT results. Additional uncertainties arise from the use of generic emission factors in the TTW phase and the assumption of identical engine performance across different fuel types.

The results are strongly interconnected with other project tasks, particularly Task 4.3 and Task 5.1. Any changes in process parameters, fuel properties or operational profiles would directly affect the life cycle inventory and final LCA results. Therefore, continuous alignment between tasks was essential to ensure consistency, reduce uncertainties and maintain the robustness of the integrated source-to-propeller assessment

12 Deviations from Annex 1

Not applicable.

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2	MPG	MAX-PLANCK-GESELLSCHAFT ZUR FORDERUNG DER WISSENSCHAFTEN EV
3	DTU	DANMARKS TEKNISKE UNIVERSITET
4	OWI	OWI SCIENCE FOR FUELS GMBH
5	UNR	UNIRESEARCH BV
6	T4F	TEC4FUELS GmbH
7	AVL	AVL LIST GMBH
8	*GF*	*GOODFUELS BV (Terminated)*
9	UZ	SVEUCILISTE U ZAGREBU, FAKULTET STROJARSTVA I BRODOGRADNJE
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11	KAUST	KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY
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15 Appendix A - Quality Assurance Review Form

The following questions should be answered by all reviewers (WP Leader, reviewer, Project Coordinator) as part of the Quality Assurance procedure. Questions answered with NO should be motivated. The deliverable author will update the draft based on the comments. When all reviewers have answered all questions with YES, only then can the Deliverable be submitted to the EC.

NOTE: This Quality Assurance form will be removed from Deliverables with dissemination level "Public" before publication.

Question	WP Leader	Reviewer	Project Coordinator
	Nikola Vladimir (UZ)	Jord Peter Haven (CSIC)	Gonzalo Prieto (CSIC)
1. *Do you accept this Deliverable as it is?*	Yes	Yes	Yes
2. *Is the Deliverable complete?* - *All required chapters?* - *Use of relevant templates?*	Yes	Yes	Yes
3. *Does the Deliverable correspond to the DoA?* - *All relevant actions preformed and reported?*	Yes	Yes	Yes
4. *Is the Deliverable in line with the E-TANDEM objectives?* - *WP objectives* - *Task Objectives*	Yes	Yes	Yes
5. *Is the technical quality sufficient?* - *Inputs and assumptions correct/clear?* - *Data, calculations, and motivations correct/clear?* - *Outputs and conclusions correct/clear?*	Yes	Yes	Yes
6. *Is created and potential IP identified and are protection measures in place?*	Yes	Yes	Yes
7. *Is the Risk Procedure followed and reported?*	Yes	Yes	Yes
8. *Is the reporting quality sufficient?* - *Clear language* - *Clear argumentation* - *Consistency* - *Structure*	Yes	Yes	Yes