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Applying the International Maritime Organisation Life Cycle Assessment Guidelines to Pyrolysis Oil-Derived Blends: A Sustainable Option for Marine Fuels

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Abstract: Reducing maritime greenhouse gas (GHG) emissions is challenging. As efforts to address climate change are gaining momentum, reducing the environmental impact becomes crucial for maritime short-to-medium-term sustainability. The International Maritime Organisation (IMO) has adopted Life Cycle Assessment (LCA) guidelines for estimating GHG emissions associated with alternative fuels. This paper proposes an examination of the latest IMO-adopted LCA guidelines, comparing them with existing methodologies used for the transport sector. By scrutinising these guidelines, the paper aims to provide a better understanding of the evolving landscape for GHG emission estimation within the maritime sector. The paper presents a case study that applies the newly established LCA guidelines to a promising alternative fuel pathway, i.e., waste-wood-derived pyrolysis oil. Pyrolysis oil offers an attractive option, leveraging waste materials to generate a sustainable energy source. The environmental impact of pyrolysis oils is quantified according to the IMO LCA guidelines, offering insights into its viability as a cleaner alternative as marine fuel. The results show the large potential for GHG savings offered by this pathway: upgraded pyrolysis oil can deliver significant GHG savings, and this contribution is linearly dependent of its energy share when blended with standard Heavy Fuel Oil.

Keywords: LCA; biofuels; pyrolysis oil; marine fuel; IMO; maritime decarbonisation

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1. Introduction

Among the hard-to-abate transport sectors, namely road heavy duty, aviation, and maritime, the latter has recently begun its journey towards decarbonisation, though with the initiative of the International Maritime Organisation (IMO) (i.e., many cargo ships have significantly reduced their average speed by around −15/−20%, compared to 2008, to allow for energy saving and emissions reduction). The IMO adopted in 2018 an initial strategy (revised in 2023) on the reduction in GHG emissions from ships, setting out a 2050 vision [1]. Among the various measures in place, from 1 January 2023, all ships have to calculate their "Carbon Intensity" in order to monitor and improve the global efficiency of the sector. Known as the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), these two parameters are key to reducing the greenhouse gasses of maritime transport.

According to Malouppas et al. [2], the IMO's 2050 targets can be achieved only through a radical technological shift, supported by social pressure, financial incentives, and regulatory and legislative reforms at the local and international level. In this context, several authors (e.g., Prussi et al. [3] and dos Santos et al. [4]) identified alternative fuels as a promising short-to-medium-term option.

In Europe, as part of the Fit-for-55 package [5], the proposed FuelEU Maritime regulation [6] aims at promoting sustainable alternative fuels for European maritime transport and ports. Furthermore, in the recent amendment to the directive on the emissions trading system (EU-ETS), the need to act also on emissions from maritime transport is clearly underlined.

Among the current and future options for alternative fuels, Lagemann et al. [7] found that LNG is today a robust choice for a broad range of GHG reduction ambitions but that for higher GHG reduction targets, a retrofit to ammonia, produced from renewable electricity, is the most cost-effective option. Dos Santos et al. [4] performed a systematic review on the expected contribution of alternative fuels in the maritime sector, concluding that LNG is today a valid low-carbon alternative with many ships. LNG is generally considered an important fuel for GHG reduction and a vector toward a shift to bio-LNG. Ammonia resulted in a new recent resource, widely discussed in scientific literature.

In terms of potential GHG reduction, the life cycle environmental performance of liquefied natural gas (LNG) provides limited advantages, while the liquefied biogas (LBG) and the bio-methanol have significant potential to reduce the climate impact [8]. More specifically on bio-derived fuels, Stathatou et al. [9] measured emissions from a dry bulk vessel operating on an advanced biofuel, produced from used cooking oil (UCO). The CO_2 and NO_X were measured on a slow-speed, two-stroke marine diesel engine, powered with a 50:50 biofuel blend of UCO biodiesel and marine gas oil (MGO). From the measurements, the authors derived a life cycle (LCA-based) emissions balance, which resulted in a 40% emissions reduction.

Beside liquid alternative fuels, the sector electrification is also expected to play a crucial role: important results are expected from the increasingly widespread implementation of the so-called "cold ironing", referring to the practice of supplying electricity to ships at berth, allowing it to turn off the ship's main and auxiliary engines. However, Jeong et al. [10] reported limited support from the current maritime policies for encouraging battery-powered ships and stressed that, when electricity is the main energy source, the Carbon Intensity (CI) of the power grid is key.

An alternative way to use electricity in the sector is hydrogen and the so-called e-fuels. On hydrogen, Fernández-Ríos et al. [11] claimed that on an LCA basis, hydrogen has great potential to promote the energy transition but that the current technology's readiness level is quite low. Chen and Lam [12] detailed these advantages, assessing that hydrogen used in fuel cells has evident reduction potential in global warming (83.9–85%), acidification (45%), eutrophication (54%), and photochemical oxidation (50%).

With regard to the perspectives of e-fuels, Linstad et al. [13] identified that for the maritime sector they may come in two steps: first as e-hydrogen and e-ammonia and, at a later stage, as e-diesel, e-LNG, and e-methanol. Despite the clear GHG benefits expected for e-fuels, Linstad et al. noticed that these e-fuels will double or triple the maritime sector's primary energy consumption.

Among all these alternatives, bio-derived fuels appear today as the readiest option. However, a sustainable feedstock availability issue is often highlighted as a limiting factor: a recent analysis carried out by Prussi et al. [14] and Panoutsou et al. [15] confirmed, at the European level, that feedstock may not be the major barrier in the short term, while other aspects, such as feedstock costs, price volatility, infrastructure, policies, etc., are relevant aspects.

Van der Kroft et al. [16] proposed various scenarios to estimate the potential of biofuel for the maritime sector: a clear trade-off between costs and emissions was found to result in potential GHG reductions, ranging between 68 and 95% compared to Heavy Fuel Oil (HFO), at an 800–2300 €/ton cost level.

Among the bio-derived options, the use of lignocellulosic feedstock shows clear advantages, both from availability and GHG-saving potential standpoints. Several technologies allow for converting lignocellulosic material into fuels, for instance, intermediate and fast pyrolysis. Yacout et al. [17] reported a Life Cycle Assessment estimation of the usage of forest-based biofuels as a promising alternative to conventional fossil fuels in marine shipping for the Arctic region. Galindo et al. [18] proposed an alternative for reducing emissions from marine fuel by blending bio-oil from lignocellulose non-edible feedstocks with standard fossil fuels. The author tested four homogeneous blends of bio-oil of eucalyptus–bioethanol–marine gasoil, confirming that they respected the most important

fuel parameters for marine engines: water content, flash point, low heating value, viscosity, and acidity. Tanzer et al. [19] developed an integrated techno-economic model of 33 "drop-in" marine biofuels. This study indicates that today marine biofuels from lignocellulosic feedstocks have a higher minimum fuel selling price than current fossil marine fuels but with a 40–100 kg/GJ decrease in life cycle GHG emissions.

From an LCA standpoint, the cited articles use different methodological approaches and system boundaries, so results are hardly comparable. This is not peculiar to maritime fuels, as it is a general trend for such kinds of publications, also for road and aviation sectors. For this reason, in June 2023, IMO adopted LCA guidelines for marine fuels [20] (MEPC/80/7/4) (revised in 2024, with resolution MEPC.391(81)). This tailor-made methodology has been the result of a common effort from experts from IMO member states, and it represents a fundamental milestone toward sector decarbonisation.

This paper aims to apply the recently approved IMO LCA guidelines for evaluating the GHG-saving potential of a lignocellulosic residue to the fuel supply chain. Based on literature data, the main elements and potential environmental benefits of this supply chain are presented, performing the energy balance of the conversion step. The results of the evaluation are presented together with considerations related to the current sector initiatives, with the aim of identifying the potential role of such a value chain for supporting the effort of the maritime sector towards decarbonisation.

2. State-of-the-Art of LCA Methodologies for Marine Fuels

As of today, methodologies for GHG assessment of energy applications can be defined as a fairly mature brunch of the wider LCA methodology, as defined in the ISOs (ISO14040, 2006) (ISO14044, 2006). These standards include general requirements for all aspects of a product lifecycle, but many methodological aspects have to be defined to be applied to a specific field or technology. Complementing the ISO standard, another high-level relevant source is the ILCD handbook [21], prepared by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC).

Specifically for the fuels, the European Renewable Energy Directive (RED, REDII(I)) has to be considered that has set a relevant framework for applying LCA to legislative acts for the transport sector. Considering that the scope of RED and its recasts is to provide a robust and clear method for allowing certification schemes to verify operators' claims, some approaches are fairly rigid and, in a certain extent, approximated. The typical example is the energy-based co-product allocation criteria.

Transport sector comprehensive Life Cycle Assessment (LCA) tailored methodologies for alternative fuels encompass the existing European regulations (e.g., REDII and FQD) and global standards, such as CORSIA [22]. A review of such an LCA-based tool is here presented, focusing on existing studies such as the JEC Well-To-Wheels report [23]; JEC vs. GREET comparisons [24]; Annexes V and VI of the REDII (2018/2001/EU) directive; CORSIA methodology [25]; RICARDO: Life cycle GHG emission assessment methods for alternative marine fuels; the JRC report 2022 [26] on the quantification of emissions in the European Maritime Sector; and the ICCT report 2023 [27] on LCA methodologies for marine fuels. Other relevant examples of applications of the LCA framework with legislative purposes are the U.S. Renewable Fuel Standard (RFS), the California Low-Carbon Fuel Standard (LCFS), and the Brazil RenovaBio.

It is worth noticing that the need for focusing on the above-mentioned documentation is twofold: on the one hand, these sources are fundamental references for creating an operative tool for regulating a specific sector and to be able to implement a robust certification scheme; on the other hand, the scientific literature is very fragmented and specifically for marine fuels; even when LCA is part of the paper, this is used as a mere tool with very little methodological considerations. This is possibly related to the infant stage of the subject; for the maritime sector, as for road or aviation, the results would have appeared significantly different.

2.1. REDII (2018/2001/EU) Methodology

The recast of the Renewable Energy Directive (REDII) extended the GHG calculation methodology of its predecessor. This methodology allows for calculating the Carbon Intensity (gCO_{2e}/MJ_{fuel}) for a specific fuel production pathway.

Default GHG emission values and calculation rules are provided in Annex V (for liquid biofuels) and Annex VI (for solid and gaseous biomass for power and heat production) of the REDII. Economic operators have the option to either use default GHG intensity values provided in REDII or to calculate actual values for their pathway. The various parameters listed in the equation de facto define the system boundaries for the analysis.

The assessment of the Carbon Intensity of a fuel production pathway is a key element in the REDII; however, verifying a specific set of sustainability criteria needs to be counted towards the overall target. In particular, REDII introduces sustainability for forestry feedstock as well as GHG criteria for solid and gaseous biomass fuels.

The potential rising demand for crop-based biofuels might stimulate cropland expansion, leading to potential greenhouse gas (GHG) emissions resulting from subsequent Land-Use Change (LUC). These emissions can stem from a direct alteration in land use/management (Direct Land-Use Change, DLUC) or from changes occurring in other lands outside the system boundaries, influenced by the shift of land towards biofuel production (Indirect Land-Use Change, ILUC). Several papers have reviewed the existing literature on ILUC values, mainly for road biofuels [28–32]. Existing literature, primarily focused on the road sector, highlights significant disparities among models concerning baseline assumptions, shock magnitude, simulation methods, and data utilised for emission calculations. As a result, estimated ILUC emissions among models exhibit high uncertainties and demonstrate considerable variation depending on the type of biofuels, feedstocks employed, and production locations. Specifically, regarding ILUC, in the REDII, a risk-based approach is preferred to a direct calculation for the biofuels, mainly due to the high uncertainty related to such kinds of evaluations.

2.2. CORSIA Approach to Calculate Life-Cycle GHG Emissions for Aviation Fuels

The International Civil Aviation Organisation (ICAO) initiative called CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims at reducing the sector impact on climate change. A specific methodology has been defined by a specific technical group of experts (the Fuel Task Group) and agreed upon by the 193 ICAO member states. The LCA-based methodology aims at evaluating the life-cycle GHG emissions of Sustainable Aviation Fuels (SAFs).

The CORSIA initiative is based on an international effort to agree on LCA rules for calculating the GHG savings offered by the use of alternative fuels. To this extent, there are many similarities with the IMO attempt, and therefore it must be considered as relevant work for LCA practitioners.

Under CORSIA, an Eligible Fuel (CEF) must meet the sustainability criteria, in particular to provide a GHG saving of at least 10% when compared with the petroleum jet. Additionally, alternative fuels shall not be produced from biomass obtained from land with a high carbon stock.

Based on a thorough technical assessment, the benchmark GHG of petroleum jet fuel has been set at 89 gCO_{2e}/MJ. This value includes the crude oil recovery stage, transportation and refining, jet fuel transportation, and fuel combustion.

Interestingly, in the CORSIA package clear definitions for the feedstock used for SAF production:

- Primary [M] and co-products [C] are the main products of a production process. These products have significant economic value and elastic supply.
- By-products [B] are secondary products with inelastic supply and economic value.
- Residues [R] are secondary materials with inelastic supply and little economic value.
- Wastes [W] are materials with inelastic supply and no economic value.

From a methodological standpoint, the SAFs produced from main and co-products and all GHG emissions for the feedstock cultivation are included in the LCA. For feedstocks categorised as residues, waste, and by-product feedstocks, no upstream emissions are included in the LCA of SAFs.

The ILUC value is directly calculated in the CORSIA methodology, but it is not applied to waste and residues.

The core LCA methodology (excluding ILUC) includes the terms for:

$$CoreLCA\left[\frac{gCO_{2eq}}{MJ}\right] = e_{fe_c} + e_{fe_hc} + e_{fe_p} + e_{fe_t} + e_{fefu_p} + e_{fu_t} + e_{fu_c}$$

- e_{fe_c}: feedstock cultivation;
- e_{fe_hc}: feedstock harvesting and collection;
- e_{fe_p}: feedstock processing;
- e_{fe_t}: feedstock transportation to process facility;
- e_{fefu_p}: feedstock-to-fuel conversion;
- e_{fu_t}: fuel transportation and distribution;
- e_{fu_c}: fuel combustion.

When reporting or accounting for emissions from the combustion of biofuels, the term e_{fu_c} is regarded as zero for the fuel portion derived from biomass. The functional unit is MJ of fuel, and the results are in grammes of CO_{2e} per MJ of fuel (gCO_{2e}/MJ) combusted. The CO_{2e} equivalent includes the CO_2, N_2O, and CH_4, using their 100-year global warming potentials of each molecule (IPCC AR5).

Regarding ILUC, the calculation involves evaluating the demand for crop-based biofuels, estimating potential cropland expansion, and assessing related GHG emissions from consequent Land-Use Change. Conversely to many other legislative provisions, in the ICAO/CORSIA methodology, the ILUC is directly calculated and summed to the final Carbon Intensity of the fuel.

Apart from the GHG saving, other sustainability themes have been defined by the ICAO Committee on Aviation Environmental Protection (CAEP), such as water, soil, air, conservation, waste, chemicals, etc. This is an important aspect of using alternative fuels in the aviation sector, as GHG emissions are a key point but cannot ensure, alone, the sustainability of large productions.

2.3. Summary of the Main Elements of an LCA Legislative Tool

Table 1 outlines the fundamental components of a -Life Cycle Assessment (LCA) methodology tailored for the transport sector, encompassing methodological considerations like attributional versus consequential approaches and specific factors for application in the shipping sector, such as defining the goal and scope, inventory analysis specifications, and impact assessment criteria. Emphasis is placed on the widely accepted attributional approach and the explicit indication of co-product allocation criteria, particularly evident in REDII and CORSIA (refer to Table 1). In all examined studies, a distinct fossil benchmark is established, enabling the determination of greenhouse gas (GHG) savings across different options.

The overarching attributional approach is in this methodology intended as the specific focus on the description of relevant physical flows entering and exiting the system boundaries [33] for all the relevant processes along the supply chain. This framework approach is widely adopted by relevant international/regional/national standards and regulations, among others: the ICAO/CORSIA, the Renewable Energy Directive II, the California Low-Carbon Fuel Standard, the Canadian Clean Fuel Standard, and the Brazilian RenovaBio programme, etc.

It has to be highlighted that recent developments in many feedstock to fuel pathways, for instance, including carbon capture and utilisation (CCU), require opening the system boundaries and introducing consequential LCA elements; for instance, expanding the

system boundaries may be warranted for pathways where the feedstock displaces its current use, potentially diminishing the overall environmental advantages linked to a particular alternative fuel.

Table 1. Summary of the main elements considered in REDII and CORSIA methodologies.

	REDII Annexes V and VI	CORSIA
General approach	Purely attributional approach. Consequential elements (e.g., CO_2 source and accounting, etc.) are part of the Delegated Act for RFNBO.	Purely attributional for the CoreLCA calculations. Consequential approach for ILUC part.
Feedstock definition	Specific definitions for allowed feedstock are provided in Annex IX, Part A and Part B.	Specific definitions are provided for various feedstock types. The feedstock list is a positive list, constantly revised and updated.
System boundary	Defined for all the stages of production (feedstock and fuels) up to the distribution of the finished fuel.	Defined for all the stages of the feedstock and fuel production and distribution, up to the bending point. System boundary expansion is included for the ILUC calculations.
Co-product allocation	Emissions are allocated among products and co-products on the basis of their energy content. This ensures homogeneity in the calculation and verifiability.	
ILUC	Not directly calculated. ILUC is regulated by specific provisions on the feedstock risk (link to Annex IX).	Directly calculated by ILUC modelling teams. Calculation by third parties is not allowed. The ILUC value is summed up to the CoreLCA to define the final default value for a specific fuel.
GWP	100 years. IPCC AR4	100 years. IPCC AR5
Default values	Available for road fuels. Actual value allowed in the certification process.	Available for aviation fuels. Actual value calculations are allowed for the CoreLCA but not for ILUC.
Fossil benchmark	The fossil fuel comparator is a general value valid for all the fossil fuels: 94 gCO_{2e}/MJ	The fossil fuel comparator specifically refers to kerosene. The world average has been agreed in 89 gCO_{2e}/MJ.

3. IMO LCA Guidelines

Specific LCA guidelines were adopted by IMO with resolution MEPC/80/7/4 in June 2023 [20] and revised in 2024 (MEPC.391(81)). The proposed methodological approach aimed at determining the life-cycle greenhouse gas (GHG) intensity of marine fuels for both the production and use of the fuel on a Well-to-Wake basis, including the so-called Well-to-Tank (WTT) and Tank-to-Wake (TtW) stages.

- Well-to-Tank (WTT): encompassing the production and distribution stages of the fuel or energy carrier involves accounting for emissions associated with fuel sourcing, production, conversion, transportation, and delivery, irrespective of the eventual use of the fuels or energy carriers.
- Tank-to-Wake (TTW): accounting for the emissions resulting from the use of the fuel, which are quantified regardless of the sourcing/production/conversion/transport and delivery steps of the fuel/energy carrier.
- Well-to-Wake (WTW): emissions obtained as the sum of the two parts (WTT + TTW), providing the full emission associated with fuel production and use.

The selected functional unit chosen is the MJ of finished fuel, and the Carbon Intensity (CI) is reported in gCO_{2eq}/MJ_{fuel}. The use of the term CO_{2e} equivalent captures the global warming effect of emissions related to other relevant gasses, i.e., CH_4 and N_2O.

3.1. System Boundaries

A proper system boundary must be defined to clarify which are the main inputs to be collected to calculate the Carbon Intensity and the overall energy conversion efficiency (Figure 1).

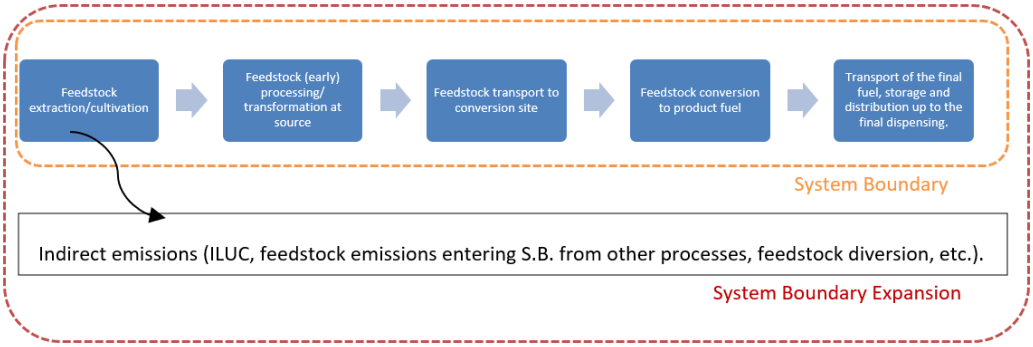


Figure 1. System boundary options for WTT, considering expansion.

In the IMO methodology, the fuel utilisation on board a specific ship is accounted for in the TTW part. In the IMO LCA guidelines, emissions for the construction and decommissioning of electricity-producing facilities are not accounted for, as these emissions are considered not relevant for the traditional fuel pathway. It has to be stressed that these emissions may be relevant to fuel produced by using high electrical input, for example, in the case of e-fuels.

Comparable assessments can be conducted regarding emissions linked to the end-of-life phase of particular equipment, like batteries. While overlooking these aspects has been largely acknowledged thus far, it is important to recognise that for e-fuels and the direct utilisation of electricity, any emissions tied to the kWh consumed can markedly influence the ultimate greenhouse gas intensity of the resultant fuel.

The IMO methodology (MEPC.391(81)) currently excludes any emission from the manufacturing and end-of-life treatment of energy generation plants.

3.2. Feedstock Categorisation

The type of feedstock used for a certain fuel production can have a significant impact on the final GHG emissions. Feedstocks categorisation is key to properly accounting upstream emissions; at IMO, feedstocks are categorised as main products [M], co-products [C], residues [R], and wastes [W]. A co-product is defined as "an outcome of a production process, which has economic value and elastic supply [...]". A waste as a material with no economic value, while a residue as unavoidably produced and with negligible economic value, also needs further processing to be used in the main conversion process. In case the feedstock is a waste, a residue, or a by-product, emissions considered as WTT start from the feedstock collection point onwards. Upstream emissions are not considered for these classes.

3.3. Co-Product Allocation Criteria

When quantifying greenhouse gas emissions for a particular fuel production pathway that yields multiple products through conversion, the approach used to allocate emissions among various co-products and residues greatly influences the outcomes [34,35]. IMO LCA guidelines share with REDII, CORSIA, and other relevant methodologies that process emissions are allocated across the co-products based on their energy content. In this context, it is worth noting that apart from energy-based allocation, alternative allocation methods exist (such as mass allocation, economic allocation, or product substitution). These approaches serve either to better reflect the reality of the process (for instance, when the co-product is not necessarily used for energy recovery) or to address accounting challenges when the co-product lacks a Lower Heating Value (as in the case of oxygen produced through water electrolysis for hydrogen production). However, when crafting an international standard, only energy allocation can be universally applied and independently verified by a third party, given that Lower Heating Value (LHV) is widely understood and/or easily measured. Assigning an economic value to a co-product necessitates consideration of specific market dynamics, sectors, and other factors.

3.4. LUC and ILUC

Given the high variability in the results that can be obtained by using different models, the existing fuel policies often diverge in addressing the DLUC and ILUC emissions. As mentioned, the REDII considers the emissions resulting from carbon stock changes and improved agricultural practice in the WTT formula, addressing ILUC with a feedstock risk-based approach (low and high risks). A similar approach is proposed, but not detailed, in the IMO LCA guidelines.

3.5. IMO WTT Equation

The WTT emissions for the investigated alternative fuel production chain can be calculated according to:

$$WTT\ emissions\left[\frac{gCO_{2eq}}{MJ_{(LCV)}}\right] = e_{fecu} + e_l + e_p + e_{td} - e_{sca} - e_{ccs}$$

This equation encompasses emissions originating from the extraction, collection, or cultivation of raw materials, as well as those arising from the utilisation of primary energy sources during the production process, transport, and distribution of the fuel, which also includes bunkering.

Two terms, e_l and e_{sca}, account for the dLUC effect, reflecting the changes in carbon stocks due to feedstock cultivation. An additional term, e_{CCS}, was included to account for an emission credit stemming from the emissions avoided through capture and sequestration of CO_2.

The e_p term includes all the emissions due to the processing of the feedstock, from the transformation at source (e.g., the pre-treatment of the feedstock) to the conversion of the feedstock to the final fuel. The term e_{td} encapsulates all emissions associated with the transportation and distribution of both the feedstock and fuel, encompassing processes such as transformation and conditioning to render the products transportable (e.g., compression and cooling).

The emission credit e_{ccs} reflects all the avoided emissions that are not already accounted for in the e_p term. All the emissions related to the process of capturing, storing, and transporting CO_2 concur with the reduction in this emission credit.

4. Modelled Production Pathway

In this work, the IMO LCA guidelines are used to calculate the emissions related to the production of pyrolysis oil, obtained from forestry residues. The advantages of using lignocellulosic residues are numerous, among others the avoided need for using arable land (and related ILUC), the high-energy density of wood residues, the lower costs with respect to another feedstock, etc. The pyrolysis conversion process allows for producing biofuels by blending components or intermediates from such kinds of feedstock. The saving, potentially offered by converting wood waste into a marine fuel, is derived by comparing the emissions with the ones related to the use of Heavy Fuel Oil (HFO). The technical viability of thermochemical pathways to produce marine fuels from residues has been presented by Kass [36], more recently demonstrated by Rizzo et al. [37], and considered by other authors (e.g., Cortez et al. [38] for Brazil). In particular, in the work of Rizzo et al., the bio-oil composition and miscibility in residual marine fuel were studied using elemental analysis and FT-IR, with blends prepared at 10 wt.% and 20 wt.%. Analytical results suggested that the blend met ISO 8217:2017 quality standards, indicating potential for biocrude in marine fuels. In spite of this technical viability, no default value was proposed in Annex I of the IMO LCA guidelines: Line 84, pathway code: UPO_b_UPO_2ndgen_gm.

The typical pyrolysis throughput is made of three products: the non-condensable gasses, the condensable fraction (the pyrolysis oil), and the solid residues (also referred to as bio-char). The ratio among the fractions is a function of the process parameters, mainly temperature, heating rate, and vapour residence time (see Table 2).

Table 2. Pyrolysis oil typical composition (source [39]).

Mode	Conditions	Liquid	Solid	Gas
Fast	~450–500 °C vapour residence time ~1 s	75%	12% char	13%
Intermediate	~450–500 °C vapour residence time ~10–30 s	50% in two phases	25% char	25%
Slow	~400–450 °C vapour residence hours > hours	30%	35% char	35%

Pyrolysis oil is obtained by a thermochemical decomposition of biomass through rapid heating in a temperature range of 400–650 °C in the absence of oxygen. In fast pyrolysis, thermal degradation of biomass takes place at a higher heating rate (°C/s) with a very short residence time (<1 s for fast pyrolysis), resulting in a higher bio-oil yield (up to 75–80 wt%). In particular, the fast pyrolysis process is followed by vapour condensation (pyrolysis oil production stage) and can be followed by a section of oil stabilisation/upgrading. Fast pyrolysis can achieve an overall energy conversion efficiency close to 70% when considering the total energy output over the biomass feedstock chemical energy input.

Among the available pyrolysis reactor technologies, many layouts have been explored in the past decades. The choice of reactors is highly influenced by the heat transfer medium used; for instance, ablative reactors make use of particle contact over a heated surface. However, especially for fast pyrolysis, carrier gasses are proven to be a more effective solution; in particular, the circulating fluidised bed (CFB) reactors use a fluidizing gas or solid for promoting heat transfer to biomass particles. In spite of the advances related to homogenous conditions and heat transfer rates, the CFB concept also has some drawbacks, among the others the limitations on acceptable particle size, the need for effective solid recycling, etc. [40].

The modelled production pathway (Figure 2) starts with pinewood waste collection, which is seasoned for one year in the forestry yard, reaching a final moisture content of approximately 35%, before being chipped. The chipping operation is performed with a 565 kW on-field diesel supply machine. Wood chips are subsequently transported to the plant, located 100 km from the forestry cutting and collection area. This distance is in line with the design approach for modular pyrolysis plants, as this technology is easily scalable in order to be supplied with local feedstock. This distance is in line with the assumption of Edward et al. [41] for the wood-to-liquid fuel-related pathway.

The fast pyrolysis process (Figure 3) has been studied and reviewed by many authors, among others, refs. [39,42–44]. Few commercial-scale plants are today in operation [45–47], demonstrating the technological readiness level of this solution. According to Venderbosch (2021) [48], pyrolysis technology can convert lignocellulosic biomass residues into fast pyrolysis bio-oil (FPBO), obtaining as by-products heat (steam) and power (electricity).

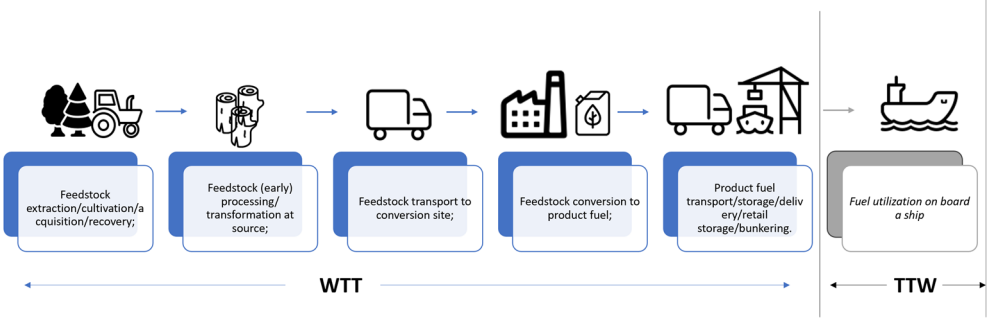


Figure 2. System boundary for the modelled pathway.

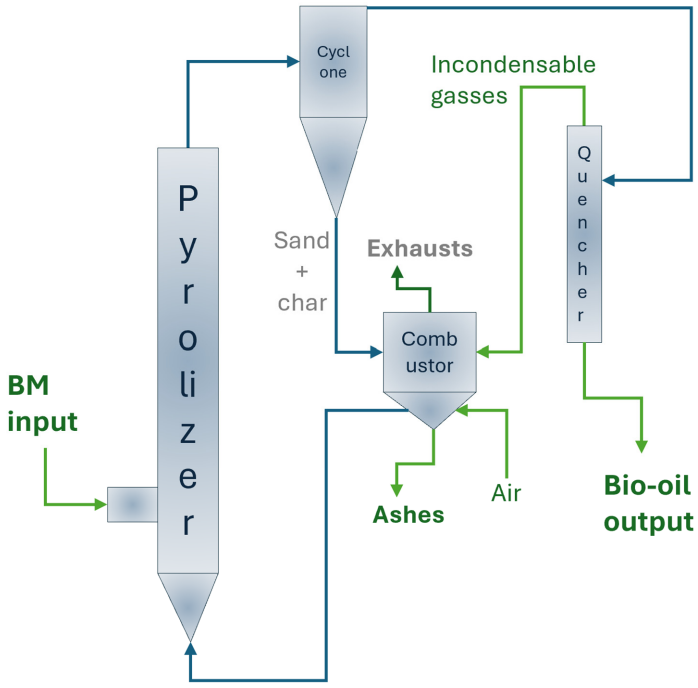


Figure 3. Schematic of a fluidised bed pyrolizer.

The conversion process (Figure 4) includes a first drying section, required to reduce the moisture below 10% [46]. The energy for the drying stage [49] is supplied by the excess heat of the process, obtained by recovering incondensable gas and char. In fact, the net input in terms of biomass chemical energy is used to supply the process, and the resulting excess energy is available as steam. As reported by Fambri et al. [50], a surplus of useful heat (16% of the chemical energy contained in the original biomass) is available at a temperature of around 700 °C and can be used for other processes. However, as the IMO LCA guidelines do not consider credits for energy resulting from the process, this excess heat has not been considered in the LCA calculations. Similarly, it is worth noting that in this analysis additional energy recovery plants have not been modelled, even if they could have led to excess electricity.

The obtained oil, commercially known as FPBO (fast pyrolysis bio-oil) [46], has an energy density of 16–23 MJ/litre (LHV). Due to the content of oxygenated components, the oil does not mix with hydrocarbons: bio-oils are complex mixtures of water and various organic compounds, including acids, alcohols, ketones, aldehydes, phenols, esters, sugars, furans, various hydrocarbons, etc. Water contents typically range in 15–30 wt%. An upgrade stage is therefore required to improve the characteristics of the oil in order to be blended with standard fuels.

To improve the quality of the crude bio-oil, various physical or chemical methods have been proposed; according to Yang et al. [51], upgrading technologies can be classified in four main groups: physical methods (such as emulsion, filtration, solvent addition, distillation, etc.); chemical refining route (such as catalytic hydrogenation, catalysed cracking, steam reforming, etc.); co-pyrolysis refining; and physical–chemical refining route. Given the need for obtaining a bendable fuel, a water separation plus chemical upgrading has been considered.

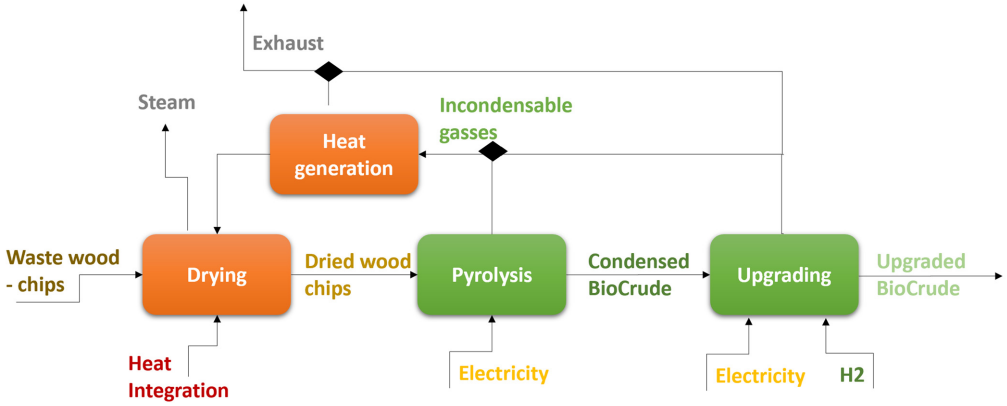


Figure 4. Pyrolysis and upgrading main input/output.

One of the primary chemical processes utilised in fuel refineries is the addition of hydrogen, commonly known as hydrogenation, aimed at enhancing the quality of the end products. Without concurrent cracking, hydrogen is employed to saturate olefins and/or convert aromatics. Commercially, the hydrogenation processes involved in transforming petroleum and alternative fuels are termed hydrotreating. For pyrolysis oil, hydrogenation can also be used to remove oxygenated compounds, together with sulphur, nitrogen, and other impurities: hydrodeoxygenation (HDO), hydrodesulphurisation (HDS), and hydrodenitrogenation (HDN) [52]. Catalysts may be added, such as sulphide $CoMo/Al_2O_3$, $NiMo/Al_2O_3$ [53]. Hydrotreating operates under mild conditions, albeit with a relatively low yield of bio-oil. In contrast, hydro-cracking, employed in the petroleum industry, is a thermal process (>350 °C) involving hydrogenation alongside cracking. Hydro-cracking, necessitating more severe conditions than hydrogenation, serves to decrease the average length of final products, thereby adjusting various physical parameters, including viscosity reduction. In large-scale facilities, hydrogen is commonly generated through methane reforming. Steam methane reforming (SMR) is the most adopted technology. For the case of pyrolysis oil upgrading, Chen et al. [54] show that an integrated SMR process could upgrade pyrolytic oil with a high conversion rate and good operational flexibility. A natural gas input of 0.379 $Nm^3_{Nat.Gas}$ per kg of bio-crude pyrolysis oil has been derived by Chen et al.

Finally, the transport to the final fuel up to the port has been assumed as per Edward et al. [41]: transport to the port depot via 40 trucks over a distance of 305 km (one way).

5. GHG Saving Estimation According to the IMO Methodology

All the relevant inputs are reported in Annex I, which is filled according to the template proposed in the IMO LCA methodology. The main inputs used for deriving the final product's Carbon Intensity (CI) are reported in Table 3. The electrical input is the sum of the energy requests for both the pyrolysis process and the upgrading stage.

The considered inputs can be used to calculate the energy needed to produce MJ of alternative fuel. Considering the sum of all the inputs over the MJ of fuel, the value of 1.7 results to be more conservative than the figures from other studies, such as the JEC V5 [23].

For determining the greenhouse gas-saving potential, the Carbon Intensity (gCO_{2e}/MJ) of the diesel and of the natural gas are crucial. As the CI of fossil production is subjected to many assumptions and can diverge significantly due to different methodological approaches, a single, widely accepted study has been used as a reference [23]. For the Carbon Intensity of the used electricity, the value represents the 2022 average EU27 grid [55].

Table 3. Main input reported in MJ per $MJ_{final\ fuel}$.

Input	UM	Value
Waste wood	MJ	2.03
Diesel for chipping	MJ	7.06×10^{-3}
Raw BCO input to upgrade	MJ	1.32
Natural gas for H2 production	MJ	0.37
Electricity for the whole process	MJ	3.90×10^{-3}
Upgraded BCO	MJ	1.00
Diesel for transport	MJ	1.59×10^{-2}

The resulting Carbon Intensity for the upgraded pyrolysis oil is 32.3 gCO_{2e}/MJ (Table 4). The specific contribution of the relative inputs is presented in Figure 5. It has to be noticed that the most important contribution to emissions is associated with the natural gas, mostly used in the upgrading stage for the H_2 production.

Table 4. Proposed default emission factors for waste wood converted into an upgraded production pathway using GWP100.

Fuel Pathway Code	Region	e_ee_cu Feedstock Cultivation/ Extraction (gCO_{2eq}/MJ)	e_td Feedstock and Fuel Transportation/Storage/ Distribution (gCO_{2eq}/MJ)	e_p Fuel Production (gCO_{2eq}/MJ)	WtT GHG Intensity (gCO_{2eq}/MJ) Emission Factors
UPO_b_UPO_2ndgen_gm	EU	0.65	1.46	30.4	32.5

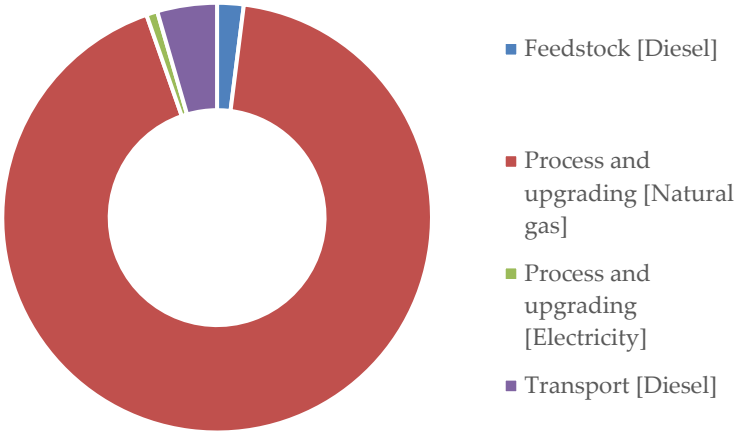


Figure 5. Contributions of the different process inputs to the overall emissions.

There are several technical reasons, such as typical plant scale, sustainable feedstock availability, costs, etc., suggesting that the best option for upgrading pyrolysis oil in the maritime sector is by means of blends with regular fuels. When possible, the use of blends is the easiest way to start introducing alternative fuels in a certain sector. This already happened in the road sector and is the current preferred option in aviation as well [56]. Table 5 shows the final CI and the related GHG savings of blends of pyrolysis oil and HFO. The figures are calculated by linearly weighting the contribution of each portion to the final value. As shown in the table, an increasing share of pyrolysis oils can contribute to reducing the Carbon Intensity of the HFO. Given the slightly different calorific value, the contribution in terms of volume is not linearly affecting the CI.

Table 5. CI reduction achievable by using increasing percentage of pyrolysis oil in blend with HFO.

Blending Rate		CI	GHG_Reduction *
%_volume	%_energy	gCO_{2e}/MJ_{fuel}	%
0	0	90.4	0.0
5	4.9	87.5	3.2
15	14.8	81.7	9.6
25	24.7	75.9	16.0

* CI of the HFO: 90.4 $gCO2_e$/MJ [57].

Even if the IMO LCA guidelines do not include a specific provision to determine the GHG saving, this can be easily derived by calculating the saving offered by using an alternative fuel per unit of energy with respect to the emissions associated with the HFO.

6. Discussion

This study highlights the significant potential of pyrolysis oil in contributing to the decarbonisation of the maritime sector through the utilisation of a waste stream. The technical feasibility of using pyrolysis oil as an alternative fuel source allows us to consider it as a sustainable and environmentally friendly option for the maritime industry. The approach taken in the present analysis demonstrates that, even under conservative conditions (i.e., bio-oil yields, energy demands, CI of utilised fossil feedstock for the upgrade, etc.), the use of pyrolysis oil results in substantial greenhouse gas (GHG) savings. This finding reinforces the viability of pyrolysis oil as a key player in the broader strategy for reducing carbon emissions within the maritime sector.

To assess the environmental impact of pyrolysis oil, the International Maritime Organisation's (IMO) Life Cycle Assessment (LCA) guidelines have been used; this method ensures a comprehensive and standardised evaluation, allowing for meaningful comparisons with other studies and alternative fuel sources.

The obtained CI value aligns with comparable studies (i.e., [23,45], among others), affirming the reliability and consistency of our findings. This congruence positions pyrolysis oil as a competitive option in the spectrum of alternative fuels for the maritime industry.

In terms of potential GHG reduction, it has to be highlighted that the emissions of the modelled pathway largely derive from the natural gas (NG) input for the oil upgrading stage. As the upgrading level is strongly related to the technical specifications for the blending, which indeed vary depending on the planned maximum share, additional research can be envisaged to define the optimal for pyrolysis–HFO blends. Clearly, substituting natural gas input with green hydrogen would deliver an immediate reduction in the final CI of the upgraded pyrolysis oil. Moreover, additional GHG reductions could be easily achieved by utilising biodiesel or pyrolysis oil in the chain, for instance, for supplying the forest tractors.

In terms of the feedstock used, the lignocellulosic residues can increase their availability without constraining food and feed production or the competition with biofuels already used in the road sector [58].

A noteworthy aspect of our investigation lies in the blending approach employed, which addresses several technical barriers hindering the large-scale deployment of alternative fuels in the maritime sector. This strategy offers solutions to typical bottlenecks such as sustainable feedstock availability and the need for new infrastructure. By blending pyrolysis oil with conventional fuels, a smoother transition to more sustainable practices can be expected, promoting the feasibility of alternative fuel adoption on a broader scale.

It must be noted that, in the IMO LCA guidelines, sustainability encompasses a broader spectrum beyond the sole Carbon Intensity. IMO LCA guidelines propose a comprehensive approach, considering themes such as carbon sources, waste management, and other key themes. This wider perspective ensures that the potential integration of pyrolysis oil into the maritime sector aligns with broader sustainability goals, addressing not only carbon emissions but also other critical aspects of environmental impact.

7. Conclusions

This paper undertakes a critical examination of the International Maritime Organisation's (IMO) latest Life Cycle Assessment (LCA) guidelines, employing a case study on pyrolysis oils to practically illustrate the application of these guidelines. The comprehensive analysis presented here aims to increase the understanding of the implications that these guidelines hold for the development of sustainable fuel pathways in the maritime industry.

The findings of this assessment quantify the potential for substantial greenhouse gas (GHG) reduction achievable through the integration of pyrolysis oils in maritime fuel blends. The Carbon Intensity of upgraded pyrolysis oil from waste wood resulted in 32.3 gCO_{2e}/MJ. It is noteworthy that the emissions modelled for the pathway predominantly stem from the natural gas (NG) input, used for hydrogen generation for the oil upgrading stage. The correlation between upgrading level and technical specifications for blending, contingent on the planned maximum share, indicates the need for further research to optimise pyrolysis–HFO blending rates. Substituting natural gas input with green hydrogen is a promising way for immediate reductions in the final Carbon Intensity (CI) of upgraded pyrolysis oil. Furthermore, exploring the utilisation of biodiesel or pyrolysis oil in ancillary processes, such as supplying forest tractors, presents additional opportunities for GHG reductions within the broader chain.

The blending approach allows addressing relevant technical barriers that may limit the large-scale deployment of alternative fuels in the maritime sector. By addressing challenges like large sustainable feedstock supply chains and the demand for new infrastructure, this strategy facilitates a smoother transition to more sustainable practices. The blend of pyrolysis oil with conventional fuels emerges as a practical solution, enhancing the feasibility of alternative fuel adoption on a broader scale.

As the sector attempts to curb emissions move forward, continued research and development will play a crucial role in optimising fuel blends, ensuring the long-term sustainability and efficiency of alternative fuel integration in maritime operations.

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