Supplementary data

1. Fuel properties

Table 1: Physicochemical properties relevant for maritime fuel specifications

Properties	**Description**
Density (ρ)	Indicates the weight present in a given volume of fuel. Its specification is useful in determining fuel aromaticity (Calculated Carbon Aromaticity Index, CCAI) and ignition (Calculated Ignition Index, CII) index. The higher the density, the higher are the CCAI and CII, and more difficult is for the fuel to ignite [1].
Cinematic viscosity (μ)	Viscosity is crucial for maritime fuels specification, as it determines the storage and handling conditions and the need of a heating system prior to injection. As well as density, it is useful for determining CCAI and CII. Viscous oils must be heated to reach ideal viscosity levels for operation [1].
Cetane number (CN)	Cetane number represents fuel ability to ignite when compressed. The higher it is, the easier fuel starts to ignite (cold start)[1–3]. This parameter is applied only to marine diesel or diesel. For HFO, the ignition quality is indirectly controlled by the CCAI (Calculated Carbon Aromaticity Index) and the CII (Calculated Ignition Index). Higher the CCAI and CII values indicate easier ignition. Low CII values indicate that the fuel hampers the engine start and reduces the operating load [4].
Calculated Ignition Index (CII) and Calculated Aromaticity Index (CCAI)	For marine fuel oil, the ignition quality is indirectly controlled by the CCAI (Calculated Carbon Aromaticity Index) and the CII (Calculated Ignition Index). As for CN, the higher the CCAI and CII values, easier it is for the fuel to ignite. Low CII indicates that the fuel delays the engine starts and reduces the operating load, increasing combustion temperature and pressure, producing NOx and noise. Low-speed marine diesel engine manufacturers recommend CII values above 30 [4].
Low heat value (LHV)	The low heat value indicates the energy density of the fuel. It can be expressed on a volumetric (MJ/L) or mass (MJ/kg) basis.
Flash point (FP)	Flash point indicates the lowest temperature at which a liquid can form a flammable mixture in the air near the liquid's surface. Fuels with high flash point are less flammable and/or dangerous. The lower the flash point, the greater the need of safety operational measures of a given fuel.
Cloud point (CP)	Cloud point represents the temperature below which the formation of crystals in the fuel occurs. This parameter indicates the tendency of the fuel to clog filters or small holes at low operating temperatures.
Pour point (PP)	Pour point indicates the temperature below which a liquid loses its flow characteristics. It represents the minimum temperature at which an oil can flow under the action of gravity.

Table 2: Physico-chemical properties of alternative fuels

	ρ (kg/L)	μ (40°C) (cSt)	CN (CII)	LHV (MJ/kg)/ (MJ/nm3)	FP (°C)	References
HFO	0.96-0.99	180-380a	(32.7)	40.0-41.0	60	[2,4–11]
MDO/ MGO	0.89-0.90	2.0-11.0	35.0-40.0	45.6	60	
Soybean oil	0.91b	65.00b/9.00c	37.9	39.6	254	
Corn oil	0.92b	48.00b/10.50c	37.6	37.8	277	
Sunflower oil	0.88b	10.00b/7.50c	45.00-52.00	40.6	274	
Biodiesel	0.88	4.00-6.00	47.00-65.00	37.2	>130.00	
HVO	0.78	2.00-4.00	>70.00	44.1	>61.00	
HDPO	0.84-0.90	2.8	Highe	45.20d	35.00-39.00	
FT-diesel	0.77	2	>70.00	43	74	
ATD	0.76f	2.1f	~50	43-44g	49	
Bio-LNG	0.47	Low	n/a	55.2/(35.80)	-188	[12–14]
Bio-methanol	0.79	Low	n/a	19.9	11.1	
Bio-ethanol	0.79	Low	n/a	26.7	16.6	
Hydrogen	0.07e	Low	n/a	120/(10.75)	Flammable	[15]
Ammonia	0.7	Low	n/a	18.6/(14.10)	132	

Notes:
LHV: Low heating value
n/a: Non applicable
a: at 38°C
b: at 15°C
c: Minimum value
d: High calorific value (HHV) (MJ/kg)
e: References found presented high variability, so it was classified as high or low.
e: Liquid hydrogen
f: Reference values for ATJ
g: Middle distillate average

2. Evaluation of alternative fuels

2.1 Availability

2.1.1 Group 1 - Liquid distilled biofuels

- SVO

SVO are produced on a large scale around the world [16]. In Brazil, soy is the main oilseed processed for producing vegetable oil, followed by sunflower and cotton [17]. Currently, main markets for SVO are the food industry and biodiesel production. Forecasts presented by the Sustainable Shipping Initiative (SSI) indicate that, although the supply of sustainable biomass is greater than the estimated demand from the maritime transport sector, its use to produce fuels for other sectors should also be considered [18]. In addition, pressure on SVO production may lead to the expansion of agricultural boundaries and deforestation [1][19]. Thus, it is attributed to the SVO poor performance in the availability (score 2).

- Biodiesel

Biodiesel represents an alternative to replace MDO and MGO in ships with low and medium-speed diesel engines [9]. The availability of sustainable biomass and biodiesel current use in road transport may compromise its availability for use in the maritime sector or promote its production in a non-sustainable way [18]. As biodiesel is produced from SVO, it presents the same challenges associated with availability. Thus, biodiesel is evaluated with a poor performance in availability (score 2).

- HVO

HVO is a drop-in fuel produced from the hydro-processing of oils or fats. HVO has been produced on commercial scales around the world (IEA Bioenergy 2017a). Table 3 shows the installed and planned HVO production plants.

Table 3: Installed and planned HVO production plants in the world

Company	**Location**	**Capacity**
AltAir Fuels	USA	125,000 MT
Diamond Green Diesel	USA	500,000 MT (expansion to 800,000 MT)
REG	USA	250,000 MT
Emerald Biofuels	USA	280,000 MT (status not known)
Petrobrás	Brazil	230,000 MT (status not known)
CEPSR	Spain	180,000 MT (co-processing)
REPSOL	Spain	60,000 MT (co-processing)
TOTAL	France	500,000 MT
ENI	Italy (Venice)	600,000 MT
	Italy (Gela)	750,000 MT
PREEM	Sweden	180,000 MT (co-processing)
UPM	Finland	100,000 MT
NESTE	Netherlands	1,000,000 MT
	Finland	260,000 MT
	Finland	260,000 MT

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[1] Only land-use models or integrated assessment models (IAMs) are able to foresee the combined impacts of food, energy and materials demand on land use.

	Singapore	1,000,000 MT
PETRIXO	UAE	400,000 MT (status not known)
SINOPEC	China	200,000 MT (status not known)

Source: [20–25]

Global HVO production is expected to grow by more than 40% by the end of 2020 [20]. However, the total volumes produced are much lower than the demand from the maritime transport sector, and the availability of sustainable feedstock (SVO) may limit new production units [9,26]. Nevertheless, as HVO does not have a consolidated use in the transport sector yet, it may favour its availability for marine use. As HVO is produced from SVO, it presents the same challenges regarding availability. Thus, HVO was evaluated with a poor performance in availability (score 2).

- HDPO

HDPO is a drop-in biofuel produced from rapid pyrolysis of biomass followed by upgrade. Using lignocellulosic biomass as feedstock is a great advantage of the process, given its availability around the world, especially in Brazil [27], [28], [29]. Even though initiatives to produce pyrolysis-based biofuels are being implemented [30], the technology is still in development stage and is not produced or commercialized worldwide. For this reason, HDPO is evaluated with an average performance in availability (score 3).

- FT-diesel

FT-diesel is a drop-in biofuel for maritime transportation. Using lignocellulosic biomass as feedstock is a great advantage of the process, in view of its high availability around the world, especially in Brazil [27–29]. To date, the FT-BTL process has been demonstrated in pilot plants and some ongoing projects aim to increase production scale [31–34]. Thus, FT-diesel was evaluated with a good performance in availability (score 4).

- ATD

Bioethanol produced from starch- or sugar-based biomass is the feedstock for ATD production. Ethanol is currently the most produced and consumed biofuel, being Brazil the second world major producer [35]. The existence of a consolidated market for ethanol as fuel, may reduce its availability for maritime fuel production. However, the development of second-generation ethanol would be an advantage for this pathway, considering the high availability of lignocellulosic feedstock around the world, especially in Brazil.

Regarding fuel conversion, the upgrading steps[2] to produce medium distillate hydrocarbons from alcohols are well known industrial technologies applied at commercial scales [36]. The main challenge relies on process integration [37].

Thus, ATD is evaluated with medium performance in terms of availability (score 3).

2.1.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Biogas can be produced from different feedstocks, including animal manure, agricultural and agro-industrial residues, solid waste and sewage sludge. For utilization on ships, biogas should be upgraded to increase methane content and liquefied. Even though biogas production has been increasing in Brazil, the upgrade and, principally, liquefaction processes are not widespread in the country [38]. Also, the dispersed location of feedstock poses logistic challenges for fuel production.

Thus, bio-LNG was evaluated with a poor performance in availability (score 2).

- Biomethanol

In order to assess biomethanol availability, the specificities of each production route (**Erro! Fonte de referência não encontrada.**) should be taken into account. In the case of biomethanol produced by steam reform of bio-LNG, the analysis of the availability indicator is similar to that performed for bio-LNG (score 2). For biomass gasification pathway, the assessment is similar to FT-diesel (score 4).

Considering the production pathway that requires available resources and that methanol production infrastructure is well developed, biomethanol was evaluated with a good performance in availability (score 4).

- Ethanol

Ethanol is currently the most produced and consumed biofuel, being the United States its largest producer, followed by Brazil [35]. Globally, there is a large experience in using ethanol as a fuel or additive, especially in Brazil [39].

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[2] Dehydration, oligomerization and hydrogenation. See **Erro! Fonte de referência não encontrada.**.

Bioethanol can be produced from sugar and starch biomass. The development of technologies to produce ethanol 2G represents a great advantage (see ATD). However, the existence of a consolidated market for ethanol compromises its availability for the maritime transport, at least in the short-to-medium terms.

Thus, ethanol is evaluated with a median performance in terms of availability (score 3).

2.1.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

The existing hydrogen production infrastructure is almost entirely based on fossil sources and electrolysis represents less than 5% of installed capacity. On the other side, huge wind and solar power potential [40] could stimulate green H_2 production. However, water requirements for electrolysis may limit its production [41].

Thus, green H_2 is evaluated with an average performance in availability (score 3).

- Green NH3

Green ammonia availability is limited by green hydrogen availability. Also, its production depends on atmospheric N_2 supply which does not offers limitations regarding resources or infrastructure. Thus, it is considered that the availability of green ammonia is similar to green H_2 (score 3).

- e-diesel

The e-diesel evaluation is similar to green hydrogen, as it is a feedstock for fuel production. CO_2, another input resource, should be produced from technologies not available in large scales yet (CCS and DAC). Furthermore, there are no infrastructure in place for converting syngas into e-diesel (FT synthesis) in scales comparable to marine fuel demands.

Thus, e-diesel is evaluated with a very poor performance in availability (score 1).

- e-methane

The evaluation presented for methane also applies to electromethane. The production of electro-LNG would depend on renewable hydrogen supply (with high water consumption) and carbon capture. However, the infrastructure for chemical synthesis not available in large scales yet. Furthermore, its use depends on the availability of liquefaction plants, currently not unavailable in the required amount.

Thus, electromethane is evaluated with a very poor performance in availability (score 1).

- e-methanol

Similar to previous e-fuels, electromethanol depends on the production of renewable H_2 and on the availability of recycled CO_2. Therefore, electromethanol is evaluated with a very poor performance in availability (score 1).

2.2 Applicability

2.2.1 Group 1 - Liquid distilled biofuels

- SVO

SVO can fully replace HFO in diesel engines and does not require any modifications in supply infrastructure [9]. SVOs are technically compatible with all types of engines [2]. However, their high viscosity and boiling points may affect their flow properties and compromise the combustion in engines[3] (Table 4). Such problems can be reduced by blending SVOs with HFOs or less viscous oils and/or by heating them prior to injection in the engines [42–44]. However, in areas with higher average annual temperatures, their viscosity is reduced [2].

Table 4: Viscosity of different SVO

Fuel	μ (cSt)
Soybean oil	29^b-33^a
Palm oil	40^a-45^b
Sunflower oil	34^a-36^b
Corn oil	31-35^a
Rapeseed oil	35-37^a
Cotton oil	34^b
Peanut oil	40^b
Sesame oil	36^b
MDO	2-11
MGO	2-6
HFO	180-380

^{a} 37,8°C
^{b} 40,0°C

The CN of the main vegetable oils is in the range of 37 to 42, values near those of MGO (>40) and MDO (>35) [1–3]. For HFO, the ignition quality is indirectly controlled by

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[3] Its use can cause problems in the pumping and fuel injection systems, formation of deposits in the engine, among others.

two parameters: the CCAI and the CII. Manufacturers of low-speed marine diesel engines recommend CII values above 30 for fuels. All, SVO fits the recommended specifications presenting values higher than those of HFOs (Table 5).

Table 5: SVO and HFO properties

Fuel	**ρ kg/m^3 (15°C)**	**μ (cSt, mm^2/s) (at 38°C)**	**CII**
HFO	960-990	180-380[a]	32.7
Soybean oil	910	32.6	47.4
Palm oil	920	39.6	45.4
Sunflower oil	920	37.1	45.2
Corn oil	920	34.9	47.6
Rapeseed oil	910	37.0	47.8
Cotton oil	910	33.5	44.9
Peanut oil	900	39.6	50.5
Sesame oil	910	35.5	47.6

The parameters presented above indicate that SVOs have high applicability in the maritime transport sector. The only limitation is associated with the high viscosity of some SVOs at low temperatures and the need for pre-combustion heating.

Thus, SVO is evaluated with a good performance in applicability (score 4).

- Biodiesel

Biodiesel has good combustion characteristics, higher flash point and CN when compared to conventional marine fuels. Its viscosity is lower than HFO's but in the same range of MDO and MGO (Table 6). In addition, biodiesel can act as a lubricant, preventing wear on fuel pumps and injectors, and reducing the formation of smoke and soot [2,9,45]. However, the high cloud point may clog filters and hamper its flow at temperatures below 32ºC [9].

Table 6: Biodiesel and marine fuels properties

Fuel	**ρ (kg/L)**	**μ (40°C) (cSt)**	**CN**	**FP (°C)**
Biodiesel	0.88	4-6	47-65	110-195
MDO/MGO	0.89-0.90	2-11	35-40	60
HFO	0.99	180-380	n/a	60

Main issues regarding biodiesel applicability are associated with water contamination, low oxidative stability, reduced performance at low temperatures and solubilization of solid deposits in fuel systems. Adding antioxidants, chemical additives and biocides to biodiesel prevents damage to engines and fuel systems [9]. Biodiesel blends of up to 20% with conventional diesel does not cause operational problems in the engines [2,46]. However, IUMI (International Union of Marine Insurance) reported problems with biodiesel blends utilization [47]. Therefore, it is recommended that engine manufacturers are consulted on the amount of biodiesel to be used [48].

In this way, biodiesel is evaluated with a median performance in applicability (score 3).

- HVO

HVO is compatible with current supply infrastructure and can be used directly in diesel engines. It is oxygen-free, which guarantees its stability for long periods. Also, HVO density is slightly lower than conventional marine fuels, due to its paraffinic content (Table 7) [49]. HVO viscosity complies with fuel standards and CN is higher than MDO and MGO, indicating that the fuel has high performance, cleaner and efficient combustion [5–7] (Table 7).

Table 7: HVO properties compared to conventional bunker fuels

	ρ (kg/L)	**μ (40°C) (cSt)**	**CN**
HVO	0.78	2-4	>70
MDO/MGO	0.89-0.90	2-11	35-40
HFO	0.99	180-380	n/a

Source: [2,5,7,49]

For this reason, HVO was evaluated with a very good performance in applicability (score 5).

- HDPO

HDPO is a drop-in fuel that can be directly used in diesel engines, without requiring adaptations in engines or infrastructure. HDPO density and viscosity are in the same range as MDO/MGO and HFO and has higher CN than fossil fuels (Table 8), indicating its high performance [2,5,50].

Table 8: Properties of HDPO and conventional bunker fuels

	ρ (kg/L)	**μ (40°C) (cSt)**	**CN**	**LHV (MJ/kg)**
HDPO	0.84-0.90	2.80	"High"[a]	45.20
MGO/MDO	0.89-0.90	2.00-11.00	35-40	45.60

HFO	0.99	180-380	n/a	42.30

Note:
[a] Reference values present wide range that only a reference such as "high" could be made.

Source: [2,5]

For such reasons, HDPO is evaluated with a very good performance in applicability (score 5).

- FT-diesel

FT-diesel is a drop-in fuel and can be directly used on diesel engines. Its density is slightly lower than conventional fuels and viscosity in the same range as MDO/MGO. FT-diesel high CN, indicates its good performance in diesel engines (Table 9)[5].

Table 9: Properties of FT-diesel and conventional bunker fuels

	ρ (kg/L)	**μ (40°C) (cSt)**	**CN**
FT-diesel	0.77	2	>70
MDO/MGO	0.89-0.90	2-11	35-40
HFO	0.99	180-380	n/a

Source: [5]

Therefore, FT-diesel was evaluated with a very good performance in applicability (score 5).

- ATD

It is expected that the produced ATD has similar properties than ATJ. The produced diesel has near-zero sulfur/polyaromatic content and higher content of branched alkanes and may differ from FT-diesel only in cetane number [10]. Experiments at pilot scale using novel catalysts produced middle distillates with cetane number of 50 [11]. ATD has slightly lower density than conventional fuels, viscosity in the same range as MDO/MGO and higher CN. Therefore, it is expected that the fuel has high performance (Table 10).

Table 10: Properties of ATD compared to conventional bunker fuels.

	ρ (kg/L)	**μ (40°C) (cSt)**	**CN**
ATD	0.76[a]	2.10[a]	50[b]
MDO/MGO	0.89-090	2-11	35-40
HFO	0.99	180-380	n/a

[a]: ATJ properties from [10]
[b]: CN from [11]

Thus, ATD is evaluated with a very good performance in applicability (score 5).

2.2.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

The LNG-powered fleet has increased in recent years. However, Brazil does not have ships powered by LNG yet [51]. For bio-LNG bunkering, it would be necessary to develop new infrastructure to supply ships. LNG supply infrastructure is concentrated in Europe and USA. And some Asian ports are developing LNG supply facilities [52]. Up until now, no liquefaction plants were built in Brazil that has only 3 regasification terminals in operation.

Therefore, bio-LNG was evaluated with median performance in applicability (score 3).

- Biomethanol

Despite not being a drop-in fuel, biomethanol is suitable for operation in dual-fuel engines, requiring incremental adaptations [53–55]. Also, biomethanol would benefit from the existing infrastructure of fossil methanol, especially in Chinese and European ports, the major Brazilian trade partners [55–57].

Thus, biomethanol is evaluated with good performance in applicability (score 4).

- Ethanol

Regarding ethanol use on ships, the properties that make ethanol suitable for Otto engines, make it unattractive for Diesel engines. To date, no projects of bioethanol use in ships have been identified. To become a drop-in fuel in diesel engines, additives should be used to increase its cetane number and lubrification. Also, metal-based materials may suffer corrosion by ethanol use [58]. Ethanol use in diesel engines has been encouraged for road transport, especially in buses [59]. The development of multifuel diesel engines would incentive its use as marine fuel, but this technology is far from readiness [14]. Also, ethanol can be fuelled in direct or indirect (with a reformer) fuel cells, a technology already tested in road transportation, but not widespread yet [60] and starting to be seen as an alternative to smaller ships [61].

Thus, bioethanol was scored with poor performance in applicability (score 2).

2.2.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

The main technological alternative for hydrogen utilization in ships is the fuel cell. It is a different technology than the current fleet, which would require a complete remodeling of propulsion systems. Also, hydrogen requires a complex distribution chain, as it needs to be gasified or liquefied to be stored in cryogenic tanks and transported. The bunkering activities are also a concern because given the limited experience of maritime industry [62].

Thus, green H_2 is evaluated with a very poor performance in applicability (score 1).

- Green NH3

Ammonia can be used in fuel cells and ICE. To be used fuel cells, NH_3 requires the development of new powertrain systems, especially for its use in solid oxide cells (SOFCs). For ICE, it also poses technical challenges and requires a backup fuel.

Thus, green ammonia is evaluated with poor performance in applicability (score 2).

- e-diesel

The evaluation of the electrodiesel in this indicator is equivalent to that of FT-diesel (section 4.1.4.2).

Thus, e-diesel is evaluated with a very good performance in applicability (score 5).

- e-methane

Despite their different production processes, bio-LNG (section 4.2.1.2) and electro-LNG are, from the physical and chemical point of view, the same fuel. Thus, e-methane is similarly evaluated in this indicator.

For this reason, e-methane is evaluated with an average performance in applicability (score 3).

- e-methanol

Electromethanol is identical to biomethanol regarding its properties as a fuel and is similarly evaluated in this indicator.

Thus, electromethanol has a good performance in applicability (score 4).

2.3 Technological maturity

2.3.1 Group 1 - Liquid distilled biofuels

- SVO

SVO production is greatly developed worldwide. In view of its use in the food industry and for biofuels production, SVOs may not be available to supply maritime transportation demand (SSI 2019). Notwithstanding, given that their production is well-established worldwide, SVOs received the highest score in the technological maturity indicator (score 5).

- Biodiesel

Biodiesel production technology is well-developed and is largely produced worldwide [63].

Thus, biodiesel is evaluated with a very good performance in technological maturity (score 5).

- HVO

HVO is already produced on commercial scales. The technology has reached technological maturity and the fuel produced is destined to different applications in the transportation sector [5,20,64].

Thus, HVO was evaluated with a very good performance in the technological maturity indicator (score 5).

- HDPO

Some biomass-based pyrolysis plants are already in operation around the world. ETIP Bioenergy mapped and classified these units according to their stage of development [65]. None of the units produce HDPO-diesel. Also, HDPO is still in the development stage (bench scale) [5].

Thus, HDPO was evaluated with poor performance in technological maturity (score 2).

- FT-diesel

Although the individual components of FT-BTL process are well known and have been demonstrated in industrial scales, the process integration and demonstration are yet to achieve commercial stage (TRL 6)[4] [66]. To date, FT-BTL process has been demonstrated in pilot plants and large-scale plants are not yet in operation. While some industrial scale demonstration projects have been cancelled [67], several initiatives are still underway [31–34].

In this context, FT-diesel is evaluated with an average performance in technological maturity (score 3).

- ATD

Ethanol production from biomass is a well-developed process applied on large scales worldwide. The upgrading steps to produce medium distillate hydrocarbons from alcohols are industrial technologies applied at commercial scales. The main challenge lies in the process integration [37]. Currently, several companies are developing this technology to produce jet fuels, such as Gevo Inc., Byogy, Vertimass, LanzaTech and Swedish Biofuels [36,68].

Thus, ATD is evaluated with good performance on technological availability (score 4).

2.3.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

All technological processes to produce biomethane until liquefaction have are already reached maturity [38]. Technologies to upgrade biogas to biomethane separation process are economically nowadays and liquefaction has been applied since the 1950s.

Thus, Bio-LNG was evaluated with very good performance in technological maturity (score 5).

- Biomethanol

Regarding biomethanol production via biomethane reform, the technology is mature (see section 4.2.1.3). Methanol synthesis from syngas is also a mature process. However, when considering lignocellulosic biomass as feedstock the technology is less developed, since biomass gasification has not reached large scales yet (see FT-diesel, section 4.1.4.3). Biomethanol use as fuel is ships has reached maturity [69].

Thus, biomethanol was evaluated with good performance in this indicator (score 4).

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[4] The Technology Readiness Level (TRL) is a methodology to measure technological development. TRL 6 indicates that the technology has already been demonstrated in relevant environment, that is, very similar to real conditions [128].

- Bio-ethanol

Bioethanol production from sugar and starch is a mature technology. For second generation ethanol, technologies are being developed to increase its competitiveness [70]. However, regarding its use as marine fuel in diesel engines, bio-ethanol still has low technological maturity [14].

Thus, bio-ethanol is evaluated with a median performance in technological maturity (score 3).

2.3.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Given the specificities regarding renewable sources (especially its intermittency), the most suitable hydrogen production technology is the polymeric membrane electrolysis (PEM). PEM electrolysers are in initial development stage and presents, lower efficiencies, high investment costs and short life span.

Regarding fuel cell use on ships, three technologies are promising: PEMFC, HT-PEMFC and SOFC[5] [71]. While PEMFCs are a mature technology, SOFCs and HT-PEMFCS have low to intermediate maturity. Then, hydrogen has a reasonable technological maturity in terms of use as a fuel, but low in terms of production from intermittent renewables.

Thus, H_2 is attributed an average performance from the point of view of technological maturity (score 3).

- Green NH3

Regarding green ammonia production, the analysis is similar to green hydrogen, since the electrolysis from intermittent renewable sources limits its production. Ammonia production from hydrogen (via Haber-Bosch synthesis) is mature and largely applied in industry. Regarding ammonia utilization as a fuel, little knowledge about NH_3 burning in ships engines is available and fuel cells do not seem to be an option in the medium term.

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[5] PEMFC: Proton Exchange Membrane Fuel Cell
HT-PEMFC: High-Temperature Proton Exchange Membrane Fuel Cell
SOFC: Solid Oxide Fuel Cell

Thus, green ammonia is evaluated with poor performance technological maturity (score 2).

- e-diesel

In terms of e-diesel use as a marine fuel, the technological maturity is the highest possible, considering the widespread use of diesel in ships. However, regarding fuel production, e-diesel entirely depends on technologies that have not reached maturity yet, such as green H_2 production, CO_2 production from capture technologies and large-scale Fischer-Tropsch synthesis.

Thus, e-diesel is evaluated with a medium performance in terms of technological maturity (score 3).

- e-methane

Technological maturity for electro-LNG is similar to bio-LNG only considering fuel use. Regarding fuel production, the technological is far from maturity, depending on renewable H_2 production.

Thus, e-LNG is evaluated with a poor performance in terms of technological maturity (score 2).

- e-methanol

To evaluate electro-methanol in this indicator it is necessary to consider the maturity of its use as marine fuel and electrochemical production route. As discussed in 4.2.2.2, dual-fuel engines can be adapted to operate with methanol. However, fuel production via PEM electrolysis and chemical synthesis are not mature technologies.

Therefore, e-CH3OH evaluated with poor performance in this indicator (score 2).

2.4 Energy Density

2.4.1 Group 1 - Liquid distilled biofuels

- SVO

SVOs' energy density is slightly lower than that of conventional marine fuels. Such difference does not imply a considerable increase in weight and storage space on ships.

For this reason, SVOs were evaluated with a very good performance in energy density (score 5).

- Biodiesel

Biodiesel has lower energy density than conventional marine fuels (HFO, MDO and MGO) due to its higher oxygen content. However, this difference is not significant and does not imply in considerable increase in weight and storage space on ships.

For this reason, biodiesel is evaluated with a very good performance in the energy density (score 5).

- HVO

HVO has similar energy density than conventional marine fuels (**Erro! Fonte de referência não encontrada.**) [5,7,64]. Therefore, additional space requirements for storage and increase in weight due to HVO utilization as fuel on ships would not be observed.

Thus, this alternative was evaluated with a very good performance in the energy density indicator (score 5).

- HDPO

Regarding energy density, HDPO is very close to MGO/MDO and HFO. Thus, HDPO does not require additional storage space or increase the weight carried by ships.

Thus, HDPO was evaluated with very good performance in energy density (score 5).

- FT-diesel

Regarding energy density, FT-diesel are close to MGO/MDO and HFO. Thus, utilization of FT-diesel would not require additional storage space or significantly increase ships weight (**Erro! Fonte de referência não encontrada.**).

Thus, the FT-diesel was scored with a very good performance in energy density (score 5).

- ATD

No data regarding alcohol-based diesel energy density was found in the literature. However, it is expected that its energy density is in the range of HVO-diesel and FT-diesel and, therefore, similar to conventional bunker fuels.

Then, according to the scale proposed (**Erro! Fonte de referência não encontrada.**), ATD has a good performance in energy density (score 4).

2.4.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Bio-LNG LHV is 52 MJ/kg. However, on a volumetric basis, its LHV is 20.3 MJ/L, which indicates that the fuel requires approximately 50% more storage space on the ship compared to HFO (**Erro! Fonte de referência não encontrada.**) [72].

Thus, regular performance was attributed to bio-LNG in this energy density (score 3).

- Biomethanol

Biomethanol has low LHV (around 20 MJ/kg) and volumetric energy density (16 MJ/L - 57% lower than that of diesel). It is expected that methanol requires twice of the space for fuel storage in relation to conventional marine fuels (**Erro! Fonte de referência não encontrada.**) [64].

Thus, biomethanol is evaluated with poor performance in energy density (score 2).

- Bioethanol

Ethanol has approximately half the energy density of conventional bunker fuels (22.35 MJ/L), thus requires more space for on-board storage. It has an intermediary energy density among the fuels evaluated in this study (**Erro! Fonte de referência não encontrada.**).

Thus, ethanol was evaluated with a median performance in energy density (score 3).

2.4.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Despite its high mass-basis energy density (120 MJ/kg), hydrogen has a very low volumetric energy density (0.01 MJ/L). When compressed or liquefied, the energy content per volume increases are well below diesel values (**Erro! Fonte de referência não encontrada.**). Also, the loss of space on board due to the cryogenic storage system or pressurization should be considered.

Thus, H_2 is evaluated with very poor performance in energy density (score 1).

- Green NH3

Low volumetric energy density of ammonia (12MJ/L) would imply losses in ships autonomy and an increase in space requirements for fuel tanks (**Erro! Fonte de referência não encontrada.**). However, its energy density is considerably higher than H_2.

Therefore, green ammonia is evaluated with poor performance in this indicator (score 2).

- e-diesel

E-diesel evaluation in terms of energy density is similar to FT-diesel (score 5).

- e-methane

The evaluation of electro-LNG in this indicator is identical to that of bio-LNG (score 3).

- e-methanol

The evaluation of e-methanol in this indicator is identical to that of biomethanol (score 2).

2.5 Economic

2.5.1 Group 1 - Liquid distilled biofuels

- SVO

SVOs are commodities with high value-added and, therefore, have higher prices than HFOs [73,74].

However, according to the normalization proposed (**Erro! Fonte de referência não encontrada.**), SVOs were well evaluated in this indicator (score 4).

- Biodiesel

The high demand for biodiesel and competition with other markets makes it a less viable alternative to supply the maritime transport sector. Biodiesel prices negotiated in recent Brazilian auctions were 60% higher than HFO prices [75,76]. Considering the international price of biodiesel (FAME), the difference is almost three times the price of HFO [77]. Further, considering the production of entirely renewable biodiesel may increase its prices due to the use of renewable alcohols in transesterification. Nevertheless, the utilization of residual feedstock such as UCO[6], non-energy oil crops and tallow may reduce its costs [78]. According to the normalization scale proposed (**Erro! Fonte de referência não encontrada.**), biodiesel would receive score 5 ("Very good") in this indicator. However, due to the possibility of using renewable alcohols, this alternative will be penalized.

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[6] Used cooking oil

Thus, biodiesel was evaluated with a good performance in the economic indicator (score 4).

- HVO

The high feedstock costs reduce HVO's competitiveness in relation to bunker fuels [2,5,9,64,79]. Average HFO and MGO prices in 2017 were US$ 0.70/L and US$ 0.41/L, respectively [80]. HVO prices estimates range from $0.72/L to $ 1.15/L [5]. Estimates for the levelized costs of HVO-diesel produced in Brazil range from US$1.22/L to US$ 1.41/L [79].

In view of the proposed scale (**Erro! Fonte de referência não encontrada.**), HVO has a good performance in economic indicator (score 4).

- HDPO

Given the premature stage of development, HDPO cost estimates are high, ranging from US$0.76/l to US$1.50/l [5], [81,82]. Compared to conventional marine fuel prices (US$ 0.41/l – HFO; US$0.70/l - MGO), HDPO would increase fuel costs by up to three times [80] .

Thus, according to the cost scale proposed (**Erro! Fonte de referência não encontrada.**) HDPO is evaluated with median performance in the economic indicator (score 3).

- FT-diesel

Estimates reveal that FT-diesel has high costs [5]. FT-diesel produced in Brazil from pine and eucalyptus residues cost estimates ranges from US$ 1.26/l to US$ 1.31/l, respectively [28]. Considering different plant scales, levelized costs for FT-diesel produced in Brazil ranges from US$ 0.88/l to US$ 0.50/l[7] [79]. Also, the high investment required may affect the attractiveness of FT-BTL projects and compromise fuel competitiveness [2,5,79].

For this reason and, according to the scale proposed (**Erro! Fonte de referência não encontrada.**), FT-diesel was evaluated with an average performance in the economic indicator (score 3).

- ATD

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[7] Estimates for Nth of a kind plants (NOAK). These estimates tend to underestimate production costs and overestimate plant performance.

Cost estimates from Staples et al. reveal that middle distillates produced from sugarcane-based alcohols are approximately US$ 0.61/l [83]. Geleynse et al. estimate for alcohol-based diesel range from US$1.17/l to US$3.87/l, considering the added costs for an alcohol production facility to produce distillate fuels and the total costs to produce them from sugar, respectively [68]. Tao et al. results indicate that MSP[8] for co-produced diesel in ATJ plants is US$ 0.07/l [36]. Thus, considering diesel as a co-product of ATJ production may increase its competitiveness.

According to the cost scale proposed (**Erro! Fonte de referência não encontrada.**), ATD is evaluated with a good performance in the economic indicator (score 4).

2.5.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Estimated bio-LNG price is approximately US$ 900-1000/metric-ton. Also, bunkering costs should be considered and range from US$ 90/metric-ton to US$ 250/metric-ton [84].

Thus, according to scale proposed (**Erro! Fonte de referência não encontrada.**), bio-LNG was evaluated with a good performance in the economic indicator (score 4).

- Biomethanol

Biomethanol costs are higher than fossil methanol (around US$ 0.008/MJ). However, compared to other potentially carbon-neutral fuels, biomethanol may be an interesting alternative (**Erro! Fonte de referência não encontrada.**). Average cost for gasification route is US$ 0.025/MJ. For the biomethane route, average cost estimated is US$ 0.017/MJ [85].

Therefore, biomethanol is evaluated with a very good performance in economic indicator (score 5).

- Ethanol

The sugar and starch-based bioethanol are less costly than other biofuels (around 0,6 USD_{2020}/l in the United States and 0.77 USD_{2020}/l in Brazil) [86]. However, to be used as marine fuel, bioethanol needs to upgraded with fuel additives and becomes less economically attractive [87]. According to the scale proposed (**Erro! Fonte de**

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[8] Minimum selling price

referência não encontrada.), ethanol costs would be approximately, 3 times higher than HFO.

Thus, it can be considered that the fuel has an average economic performance (score 3).

2.5.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

In addition to the fact that electrolysis, in general, constitutes a less economical technology to produce H_2 than those based on fossil resources, the most suitable technology to produce H2 from renewables is based on polymeric membranes, which is even more expensive. Furthermore, the price of hydrogen as a marine fuel could be strongly affected by additional costs for transport, storage and bunkering. According to the economic scale presented (**Erro! Fonte de referência não encontrada.**), the cost of marine green H_2 would be 7 times the price of the bunker [40,88].

Thus, the fuel is evaluated with a very poor performance in the economic indicator (score 1).

- Green NH3

Green ammonia cost is strongly affected by renewable hydrogen cost. The synthesis of NH_3 itself is not an expensive process. Considering H_2 production from natural gas, ammonia costs are approximately 150 USD/t. However, from renewable hydrogen, the cost goes up to 800 USD/t [89].
Thus, according to the cost scale proposed (**Erro! Fonte de referência não encontrada.**) green ammonia is evaluated with poor performance in economic indicator (score 2).

- e-diesel

E-diesel production cost in 2015 was between 0.04 and 0.20 USD/MJ and is expected to reduce to 0.03-0.10 USD/MJ until 2030 (Table 11) [90].

Table 11: e-fuels costs in 2015 and 2030

Production costs (USD/t*)	**2015**	**2030**
Electrodiesel	1700-10.000	1400-4400
Electromethane	1900-9900	1500-4400
Electromethanol	800-4200	700-1500
*1,1 USD/€.		

Source: [90]

Even so, e-diesel costs estimates are far higher than other potentially carbon-neutral fuels (**Erro! Fonte de referência não encontrada.**), given that its production combines expensive technologies (water electrolysis via renewable power and Fischer-Tropsch synthesis).

Thus, e-diesel is evaluated with a very poor performance in economic indicator (score 1).

- e-methane

As with e-diesel, the economic performance of the electromethane route is poor. In 2015, fuel production costs ranged in the range of 0.04 to 0.20 USD/MJ (Table 11). It is expected that the fuel price drops by 2030 to 0.03-0.09 USD/MJ. Also, bunkering costs (around 0.01 USD/MJ) should be considered.

Given the cost scale proposed (**Erro! Fonte de referência não encontrada.**), e-methane is evaluated with a very poor performance in economic indicator (score 1).

- e-methanol

Similarly to other e-fuels, electromethanol has poor economic performance, even with the perspective of reduction to 2030 (Table 11).

Therefore, given the cost scale proposed (**Erro! Fonte de referência não encontrada.**), e-methanol is evaluated with a very poor performance in economic indicator (score 1).

2.6 Safety

2.6.1 Group 1 - Liquid distilled biofuels

- SVO

SVOs have a flash point much higher than those of conventional marine fuels (Table 12), are non-toxic and, therefore, do not require additional safety procedures for operation [2,4,64].

Table 12: Flash point of conventional bunker fuels and SVO

Fuel	FP (°C)
HFO	60
MGO	60
MDO	60
Soybean oil	254
Palm oil	267

Sunflower oil	274
Corn oil	277
Rapeseed oil	246
Cotton oil	234
Peanut oil	271
Sesame oil	260

Thus, SVOs were evaluated with a very good safety performance (score 5).

- Biodiesel

Regarding the safety, biodiesel has a high flash point (**Erro! Fonte de referência não encontrada.**), offering no flammability risks. Also it is not toxic [78].

Therefore, biodiesel was evaluated with very good performance in safety (score 5).

- HVO

HVO is non-toxic and its flash point (>61°C) is approximately the same as that of conventional marine fuels (> 60°C) (**Erro! Fonte de referência não encontrada.**).

In this way, HVO has a very good performance in the safety indicator (score 5).

- HDPO

Few data regarding safety and toxicity of HDPO-diesel were found. Some studies revealed that its low flash point may limit its use as a fuel (inflammation risk) (Table 13). Also, HDPO is not toxic.

Table 13: Flash point of HDPO and conventional bunker fuels

Fuel	**FP (°C)**	**Reference**
HDPO	35-39	[91]
	35-53	[92]
MGO/MDO	>60	[2]
HFO	>60	

Thus, the HDPO was evaluated with median performance in the safety indicator (score 3).

- FT-diesel

Regarding safety and toxicity, studies show that the flash point of FT-diesel is higher than marine fuels (Table 14) [93,94]. So, FT-diesel do not offer operational security risks. Also, it is a non-toxic fuel.

Table 14: FT-diesel e conventional maritime fuels flash point.

Fuel	FP (°C)
FT-diesel	74
MGO/MDO	>60
HFO	>60

Source: [2,5,94]

Thus, FT-diesel was evaluated with a very good performance in safety indicator (score 5).

- ATD

Few data regarding safety and toxicity of ATD was found. Considering ATJ flash point as reference, it is expected that the fuel does not offer operational risks [10]. However, its flash point is lower than for HVO-diesel (>61°C), FT-diesel (87-91°C) and conventional marine fuels (**Erro! Fonte de referência não encontrada.**). Regarding toxicity, ATD is a non-toxic fuel.

Table 15: Flash point for ATD (ATJ) and conventional marine fuels

Fuel	FP (°C)
ATD (ATJ)	49
MGO/MDO	>60
HFO	>60

Therefore, ATD is evaluated with a very good performance in safety (score 4).

2.6.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Bio-LNG presents additional risks compared to traditional marine fuels (**Erro! Fonte de referência não encontrada.**). Given its cryogenic conditions, risks associated with extremely low temperatures and heat transfer must be controlled to ensure the integrity and safety of fuel tanks and ships. Its flammability characteristics[9] requires that fuel transfers are carried out by trained staff and the low temperatures require that special materials are used. Also, handling and storage temperatures (–162°C) are dangerous for

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[9] LNG burns when it vaporizes in the gas phase.

human health [95]. Minimum ignition energy for methane is almost 100 times inferior than that of MDO, indicating that small sparks are sufficient for ignition [64,95].

Thus, bio-LNG was evaluated with regular performance in safety (score 3).

- Biomethanol

Table 3 (main paper) presents safety aspects of methanol and other marine fuels. Methanol, although less toxic than conventional marine fuels, is very explosive, with relatively wide flammability range and a flash point. Such characteristics may pose risks to ship's crew, especially during transportation and supply activities. However, as biomethanol is liquid at room temperatures, it dismisses cryogenic storage needs.

Thus, biomethanol is evaluated with an average performance in safety (score 3).

- Bioethanol

Bioethanol is not toxic to humans, water-soluble and biodegradable. Therefore, its impacts in the event of spills are much smaller compared to fossil fuels [14]. Ethanol flash point is bellow all maritime fuels (**Erro! Fonte de referência não encontrada.**), offering some flammability risks [96].

Thus, ethanol is evaluated with a good performance in safety (score 4).

2.6.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Safety aspects of H_2 were summarized in **Erro! Fonte de referência não encontrada.**.Although not toxic, hydrogen is a highly explosive substance with a wide range of flammability. Therefore, safe operation requires frequent monitoring and ventilation systems installation [97]. For H_2 storage in liquefied form, there are additional risks regarding cryogenic temperatures.

Thus, hydrogen is evaluated with given a poor performance in safety (score 2).

- Green NH3

Despite not being highly explosive (narrow flammability range, ≈15-25%), ammonia is a very toxic fuel, constituting a significant threat to human health and environment, even though the industry has well-specified and dominated safety procedures (**Erro! Fonte de referência não encontrada.**). The dissolution of ammonia in water forms ammonium hydroxide that increases water pH, is destructive to flora and fauna and is not safe for human consumption [98].

Thus, ammonia is evaluated with a poor performance in the safety indicator (score 2).

- e-diesel

Eletrodiesel's evaluation in this indicator is similar to that of FT-diesel (score 5).

- e-methane

The evaluation of bio-LNG applies to electro-LNG (score 3).

- e-methanol

The evaluation of biomethane and electromethane are identical in this indicator (score 4).

2.7 Standards

2.7.1 Group 1 - Liquid distilled biofuels

- SVO

Up until now, no regulations have been defined for using SVO as maritime fuel, but manufacturers of diesel engines have already tested and proven its possibility to replace HFO (IEA 2013; ECOFYS 2012a). Further, concerns associated with biofuels sustainability, especially first-generation ones, indicate the necessity to certificate their production chain, what is not stablished yet (SSI 2019).

For this reason, an average performance in the standards indicator was attributed to SVO (score 3).

- Biodiesel

The most recent edition of the specifications for marine fuels (ISO 8217: 2017) incorporated a new class of specifications that allowed blends of up to 7% biodiesel (FAME) on a volumetric basis [99,100]. For blends with higher biodiesel content, additional specifications are required [9]. Similarly to SVO, concerns regarding sustainability indicate the necessity to certify the production chain.

Thus, biodiesel is evaluated with an average score in the standardization indicator (score 3).

- HVO

Up until now, no specifications are applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of up to 100% HVO on ships, if the fuel meet the required specifications [64]. However, as in the case of SVO and biodiesel, concerns regarding biofuel sustainability indicate the need to certify fuel production chain (SSI 2019).

Thus, HVO is evaluated with a good performance in standards (score 4).

- HDPO

As previously mentioned, there are no specifications applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of alternative fuels on ships if they meet the required specifications [64]. The possibility of using lignocellulosic biomass reduces sustainability concerns. However, the production chain should be certified, proving its potential to reduce GHG emissions and the absence of impacts on land use, water resources, food production and biodiversity [18].

In this way, the HDPO is evaluated with good performance in standards (score 4).

- FT-diesel

As before mentioned, there are no specifications applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of alternative fuels on ships if they meet required specifications [64]. The possibility of using lignocellulosic biomass as feedstock reduces concerns associated with sustainability. However, it is important that production is certified, proving its potential to reduce GHG emissions and the absence of impacts on land use, water resources, food production and biodiversity [18].

In this way, FT-diesel was evaluated with good performance in standards (score 4).

- ATD

As mentioned before, there are no specifications applied exclusively to marine drop-in biofuels. ISO 1217: 2017 allows the use of alternative fuels on ships if they meet required specifications [64]. Ethanol (process feedstock) production in Brazil has specific regulations and guidelines. However, it is important that its production is certified, proving its potential to reduce GHG emissions and the absence of impacts on land use, water resources, food production and biodiversity [18].

In this way, ATD is evaluated with a very good performance in the standards indicator (score 5).

2.7.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Standards for LNG use as marine fuel, production and bunkering are already in place. The new ISO 20519 guides operators to select fuel suppliers that comply with the safety and quality standards (ISO 2017a, b). For bio-LNG, currently produced mainly from industrial or municipal waste, it is relatively easy to prove its non-fossil origin.

Therefore, good performance is attributed to bio-LNG in standards (score 4).

- Biomethanol

Handling, transportation and use of methanol as marine fuel is relatively new, but regulations are already available. **Erro! Fonte de referência não encontrada.** provides a summary of the main existing regulations for using methanol as fuel.

In this context, methanol was evaluated with a very good performance in standards, especially when compared to other fuels (score 5).

- Ethanol

Despite standards for ethanol handling, transport and in automotive vehicles has well-specified regulations and guidelines, for use in ships, ethanol regulations should be developed. However, it could benefit from other sectors experience (**Erro! Fonte de referência não encontrada.**).

Considering the current standardization of bioethanol, it was evaluated with a very good performance in standards (score 5).

2.7.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Currently, there are no specifications applied exclusively to hydrogen as a marine fuel. In addition, the certification of its production chain is necessary, to prove its renewable origins.

Thus, the fuel is evaluated with a very poor performance in the standards criteria (score 1).

- Green NH3

To date, there are no specifications applied exclusively to ammonia as a marine fuel. In addition, it is necessary to certify the production chain, to prove its renewable origin.

Therefore, ammonia is evaluated with a poor performance in the standards indicator (score 1).

- e-diesel

Eletrodiesel's evaluation in this indicator is similar to FT-diesel (score 4).

- e-methane

The evaluation of biomethane and electromethane are identical in this indicator (score 4).

- e-methanol

The evaluation of biomethanol and electromethanol are identical in this indicator (score 4).

2.8 Local sustainability

2.8.1 Group 1 - Liquid distilled biofuels

- SVO

Regarding air pollutant emissions, SVOs do not present additional impacts when compared with conventional fuels. Due to the high CII values (section 4.1.1.2), better combustion properties are observed, decreasing NO_x formation. SVOs are practically sulfur free and, therefore, do not produce SO_x emissions. Also, there is no formation of PM by the utilization of SVOs in diesel engines. Also, the use of SVOs reduces black carbon emissions (ICCT 2019; Comer 2019).

Thus, SVO performance in local sustainability indicator was classified as good (score 4).

- Biodiesel

Several studies show that the use of biodiesel as an alternative to fossil fuels reduces emissions of SO_x, PM and black carbon, but increases NO_x [101–108]. This increase is associated with the high oxygen content of biodiesel.

Thus, biodiesel is evaluated with a good performance in local sustainability (score 4).

- HVO

Divergent opinions regarding HVO potential to reduce NO_x emissions were found. Some authors argue that using HVO in diesel engines has no significant impact on NO_x emissions [7]. Others indicate that HVO can reduce NO_x emissions by up to 25% [6,49,109]. HVO is a sulfur-free fuel and, thus, drastically reduces SO_x, PM and black carbon emissions by replacing fossil alternatives [5,49].

For this reason, HVO is evaluated with a good performance in local sustainability (score 4).

- HDPO

Regarding local air pollution, it is expected that HDPO will perform similarly to HVO. The absence of sulfur in the fuel significantly reduces emissions of SO_x, PM and black carbon. Regarding NO_x emissions, experiments carried on diesel engines revealed that HDPO may increase NO_x emissions, given the fuel easy ignition properties [110].

In this way, the HDPO is evaluated with good performance in the local sustainability indicator (score 4).

- FT-diesel

FT-diesel is practically sulfur-free, what expressively reduces SO_x and PM emissions [5]. Regarding NO_x emissions, experiments with FT-diesel produced from forest residues in diesel engines, indicate reduction compared to conventional diesel [111].

Thus, FT-diesel was evaluated with a very good performance in the global sustainability indicator (score 5).

- ATD

ATD may reduce emissions of local air pollutants. It is practically sulfur-free, reducing SO_x and PM emissions [10]. No literature information regarding NO_x emissions from ATD consumption in diesel engines was found, but it is expected that it would be largely unchanged compared to conventional fossil fuels [112].

Thus, ATD was evaluated with a good performance in the local sustainability indicator (score 4).

2.8.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Emissions of local air pollutants are close to zero for bio-LNG [113], [114]. For NOx, emissions depend on engine technology [115].

Thus, bio-LNG was evaluated with a very good performance in local sustainability (score 5).

- Biomethanol

In general, methanol is a very clean fuel. Its use in marine engines may reduce SO_x emissions by more than 99%, particulate matter emissions by 95% and black carbon emissions between 55% and 95% compared to conventional fuels [116]. Also, methanol may considerably reduce NO_x emissions in mixtures with water [54].

Therefore, biomethanol was evaluated with good performance in local sustainability (score 4).

- Bioethanol

During bioethanol production, local emissions are mainly associated with boilers exhaust [27,116]. Sugarcane manual harvest that leads to air pollutants and GHG emissions are being discontinued by Brazilian government [58,117]. Bioethanol has a significant reduction in emissions of sulfur oxides (SO_x), hydrocarbons and other polluting compounds. It has higher emission of aldehydes[10] and, depending on engine characteristics, nitrogen oxides (NO_x). However, catalysts reduce these pollutants to tolerable levels.

Thus, bioethanol is evaluated with a good performance in the local sustainability indicator (score 4).

2.8.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Green H_2 is a clean fuel and does cause direct emissions of NO_x, SO_x, PM or black carbon. Furthermore, as it is produced from renewable electricity, there is no emissions of local pollutants in fuel production [114]. Nonetheless, the consumption of large amounts of water in electrolysis is a concern, unless the process uses recycled water.

Thus, the fuel is evaluated with median performance in local sustainability (score 3).

- Green NH3

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[10] Aldehydes have carcinogenic potential and are local concern.

Green ammonia is a clean fuel, as it does not emit NO_x, SO_x, PM or black carbon. As its production is based on renewable electricity, no emissions of local pollutants occurs in fuel production process [114]. However, the consumption of large amounts of water in electrolysis is a concern, unless recycled water is used.

Thus, the fuel is evaluated with a median performance in local sustainability (score 3).

- e-diesel

The analysis of e-diesel in local sustainability indicator is partially equivalent to FT-diesel. However, the H2 used for e-diesel production requires huge amounts of high purity water.

Thus, e-diesel is considered to have an average performance in local sustainability (score 3).

- e-methane

Likewise, bio-LNG, electromethane has significant reductions in SO_x and PM emissions. However, the water consumption in electrolysis for green H2 production undermines fuel evaluation in this indicator.

Thus, the electro-LNG is evaluated with an average performance in local sustainability (score 3).

- e-methanol

Methanol combustion in diesel engines produce low emissions of air pollutants. However, considering the green H_2 utilization it should be penalized for huge water requirements.

Thus, electromethanol is evaluated with an average performance in local sustainability (score 3).

2.9 Global sustainability

2.9.1 Group 1 - Liquid distilled biofuels

- SVO

Biofuels in general have high potential to reduce GHG emissions when used as fuels. SVO may reduce up to 57% of GHG emissions compared to HFO [2]. Furthermore, SVO produced in Brazil from soybeans may reduce up to 86% of GHG emissions[79].

However, biofuels production may have indirect impacts on land use. Indirect impacts may induce changes in land use and/or deforestation [19]. Such concerns are more evident in the case of soy and palm-based biofuels [18]. The relationship between land use and production of agro-energy and biofuels is extremely complex, being influenced by endogenous and exogenous variables [118,119]. Notwithstanding, only integrated assessment models (IAMs) are able to foresee the combined impacts of food, energy and materials demand on land use.

Thus, SVOs have average performance in global sustainability indicator (score 3).

- Biodiesel

Biodiesel potential to reduce GHG emissions strongly depends on feedstock, process, location of production and fuel distribution. Studies show that biodiesel may reduce GHG emissions from 19% (from palm oil) to 83% (residual oil) [2]. Limitations in biodiesel content in fuel blends reduce its potential to reduce GHG emissions expressively. Also, as biodiesel uses SVO as feedstock, it may lead to direct and indirect impacts on land use (see 4.1.1.9) and increase GHG emissions. Nevertheless, the use of renewable alcohols in the transesterification process may contribute positively to its environmental performance.

In this context, similarly to SVO, biodiesel has an average performance in global sustainability (score 3).

- HVO

HVO potential to reduce GHG emissions depends on the type of feedstock and production location. Kass et al. estimate that HVO can reduce approximately 70% of GHG emissions compared to fossil alternatives [5]. Stengel et al. estimated that HVO produced from animal fat and rapeseed reduces emissions by 40% and 20%, respectively [7]. Additionally, Carvalho et al. estimates that HVO-diesel produced in Brazil from soybean oil may reduce GHG emissions by up to 66% [79]. Also, HFO production has the same challenges associated with global sustainability than SVO (see section 4.1.1.9).

In this way, HVO is evaluated with a medium performance in global sustainability (score 3).

- HDPO

HDPO potential to reduce GHG emissions depends on the type of feedstock and production location. The possibility of using residual biomass increases the fuel potential to reduce emissions. No data detailing life-cycle emissions for HDPO use in maritime transport were found. However, studies indicates that HDPO-diesel might reduce GHG emissions by 50% to 72% using corn straw and poplar as feedstock [120–122].

Thus, HDPO is evaluated with good performance in the global sustainability indicator (score 4).

- FT-diesel

FT-diesel potential to reduce GHG emissions depends on the feedstock and production location. LCA for FT-diesel produced in Sweden using forest residues indicate that it can reduce from 75% to 100% of GHG emissions compared to HFO [123]. Other studies indicate that FT-diesel produced from forest residues may reduce GHG emissions in approximately 94% compared to HFO [5]. Finally, LCA results of FT-diesel produced in Brazil from forest residues indicate a reduction of 98% in GHG emissions [79].

In this way, FT-diesel was evaluated with very good performance in global sustainability (score 5).

- ATD

Life-cycle analysis found in literature shows that GHG footprint for middle distillates produced from sugarcane ethanol are 92% lower than fossil middle distillates [83]. However, considering land use changes emissions may have significant impact in fuel mitigation potential results [124,125].

Therefore, ATD was evaluated with a good performance in this indicator (score 4).

2.9.2 Group 2 – Alcohol and liquefied gases

- Bio-LNG

Although emissions during operation are lower than conventional marine fuels, downstream emissions may reduce bio-LNG GHG mitigation potential. Even so, it may reduce GHG by 30% compared to LSHFO [114]. However, methane slip may negatively affect the fuel global sustainability, as methane has a GWP[11] 28 times higher than CO_2.

Therefore, bio-LNG was evaluated with a median performance in global sustainability (score 3).

- Biomethanol

Biomethanol life cycle GHG emissions estimates are, on average, 85% lower than conventional fuels [126]. Even so, its perfomance in this indicator is inferior to alternatives such as green hydrogen, e-diesel and electromethanol.

Thus, biomethanol was evaluated with a good performance in global sustainability (score 4).

- Bioethanol

Several studies assess the impacts of ethanol GHG emissions. A study published by EMSA reveals that the life-cycle emissions for ethanol produced from Brazilian sugarcane are well below than U.S corn ethanol, LNG and marine diesel [127].

Thus, ethanol is evaluated with a good performance in the global sustainability indicator (score 4).

2.9.3 Group 3 - Hydrogen, ammonia and e-fuels

- Green H2

Hydrogen use in fuel cells or ICE does not emit GHG. In addition, as green H_2 is produced by electrolysis from renewable sources of electricity, no GHG emissions occur in fuel production stage.

Thus, green hydrogen is evaluated with a very good performance in global sustainability (score 5).

- Green NH3

Ammonia use in ICEs or fuel cells does not produce GHG emissions. In addition, green ammonia production is entirely based on renewable electricity (for water electrolysis, N_2 production and Haber-Bosch synthesis).

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[11] Global warming potential

Therefore, green ammonia is evaluated with a very good performance in global sustainability (score 5).

- e-diesel

As e-diesel is produced from green hydrogen, it produces very low GHG emissions. In addition, e-diesel production in large scales would foster the development of carbon capture technologies.

Therefore, electrodiesel is evaluated with a very good performance in global sustainability (score 5).

- e-methane

As for e-diesel, life-cycle GHG emissions of electro-LNG are very low. Also, its production the development of negative emission technologies. Even so, the carbon intensity of e-LNG tends to be higher than other e-fuels, due to handling, transport and storage activities and the possibility of fugitive CH_4 emissions.

In this way, electro-LNG is evaluated with a median performance in global sustainability (score 3).

- e-methanol

Considering that e-methanol is produced from recycled CO_2 and hydrogen from renewable sources, its production and use has almost no GHG emissions. Furthermore, its development may promote CO_2 capture technologies.

Thus, e-methanol is evaluated with a very good performance in global sustainability (score 5).

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