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Assessing the Environmental Impact of Eight Alternative Fuels in International Shipping: A Comparison of Marginal vs. Average Emissions

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Abstract: Global warming and other environmental concerns drive the search for alternative fuels in international shipping. A life-cycle analysis (LCA) can be utilized to assess the environmental impact of different fuels, thereby enabling the identification of the most sustainable alternative among the candidate fuels. However, most LCA studies do not consider marginal emissions, which are important when predicting the effects of large-scale fuel transitions. The research purpose of this study was to assess the marginal emissions of several currently available marine fuels to facilitate the identification of the most promising marine fuel. Thus, marginal and average emissions for eight marine fuels (high-sulfur fuel oil, very-low-sulfur fuel oil, marine gas oil, liquified natural gas, biomethane, biomethanol, fossil methanol, and hydro-treated vegetable oil) were compared in terms of their environmental impact. Non-intuitively, the results indicate that biofuels exhibit equally or higher marginal greenhouse gas emissions than conventionally used fuel oils (162–270 versus 148–174 kg CO_2/MJ propulsion), despite their significantly lower average emissions (19–73 vs. 169–175 kg CO_2/MJ). This discrepancy is attributed to the current limited availability of climate-efficient biofuels. Consequently, a large-scale shift to biofuels cannot presently yield substantial reductions in the shipping industry's climate impact. Additional measures, such as optimized trading routes, more energy-efficient ships, and research on more climate-friendly biofuels and electro-fuels, are thus required to significantly reduce the climate footprint of shipping.

Keywords: marine fuels; global warming; marginal emissions; LCA; crude oil demand

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1. Introduction

International shipping has grown significantly during the past three decades because of the globalization of markets and the lower fuel consumption of shipping compared to other transportation options. Nowadays, more than 80% of all globally traded goods are transported via international shipping [1].

In parallel with the growth of international shipping, there is an increasing concern regarding its emission of pollutants and greenhouse gases (GHGs). The global GHG emissions must rapidly decrease to mitigate global warming and fulfill the Paris Agreement, i.e., "avoid dangerous climate change by limiting global warming to well below 2 °C and pursuing efforts to limit it to 1.5 °C" [2]. The total GHG emissions from shipping were 1056 Mton in 2018 [3], which is a substantial share (3%) of the global GHG emissions (36,800 Mton in 2022) [4]. Determined actions must, therefore, be applied to reduce the emissions from the shipping industry.

The main strategy for reducing GHG emissions is to initiate a fuel shift in the shipping industry, but complementary actions such as optimized trade routes, more energy-efficient motors, use of partially wind-propelled ships, and carbon-capturing devices are also possible [5,6]. Determined actions must, therefore, be applied to reduce the emissions from the shipping industry.

The transition to alternative shipping fuels was further accelerated in 2020 when the International Maritime Organization (IMO) reduced the fuel sulfur limit in international shipping from 3.5 wt.% to 0.5 wt.% [7]. This regulatory change had several consequences, one of which was a demand shift from the previously popular high-sulfur fuel oil (HSFO) to both marine gas oil (MGO) and very-low-sulfur fuel oil (VLSFO) [8]. The aim of reducing sulfur dioxide (SO_2) emissions near densely populated areas was especially impacting the marine industry, as international shipping accounts for 13% of global SO_X emissions [9].

A fuel shift in the shipping industry is thus strongly desired, but which of the alternative fuels is most sustainable, and how large reductions in GHG gas emissions can be expected? This important topic has been examined in many recent scientific studies, but very few have analyzed the marginal effects of a large-scale fuel shift. In order to answer those questions, this study will assess both average and marginal environmental impacts for eight marine fuels with high relevance for today's shipping industry. The objective and motivation of the study is to facilitate emission reductions in the marine industry by performing life-cycle assessments considering marginal emissions, which are important when predicting the outcome of large-scale transitions such as global fuel shifts.

2. Background and Literature Review

As part of the European Green Deal and the European Climate Law, the European Union (EU) aims to achieve climate neutrality by 2050 and has raised its 2030 climate ambition to cut emissions by at least 55% by 2030 [10]. To achieve this higher target in emissions reduction for 2030, the EU is working on revising its transport-related legislation under the *Fit for 55* package. As part of this package, the FuelEU Maritime proposal sets ambitious targets for reducing the shipping industry's climate change impact by 2% by 2025, 6% by 2030, and 75% by 2050 relative to 1990.

In the short term, the shipping industry has increased its demand for sustainably produced biofuels with lower average climate change impact [11]. In the long term, liquid biofuels alone are not sufficient to achieve the drastic transition to low-carbon alternative fuels targeted between 2030 and 2050. Thus, the future fuel mix of international maritime transport should rely heavily on emerging decarbonized hydrogen-derived fuels (mostly methane, methanol, and ammonia) [12] (Figure 1).

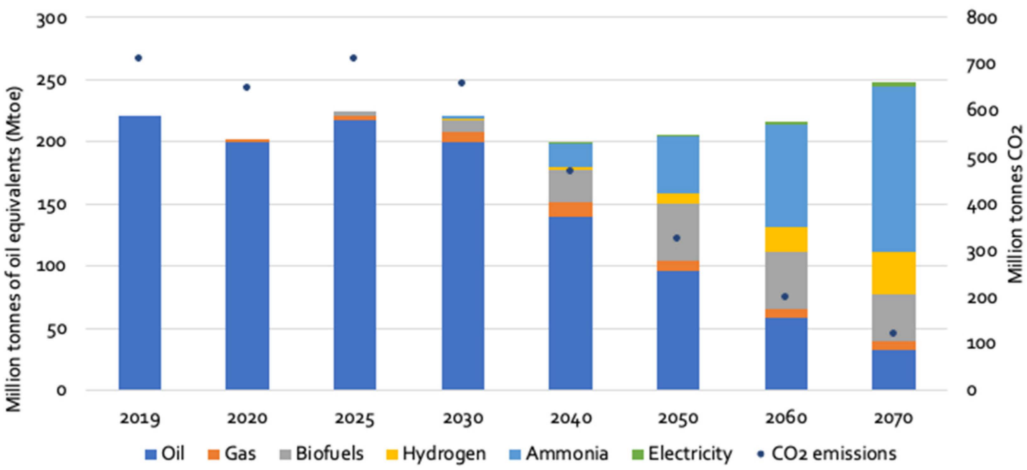


Figure 1. Long-term prediction of global energy consumption and CO_2 emissions in international shipping in the Sustainable Development Scenario, 2019–2070 (IEA 2019) [13].

Decisions concerning alternative fuels should generally be based on the life-cycle assessment (LCA) methodology [14], e.g., the EU uses LCA to calculate the GHG mitigation potentials of alternative fuels [15] in the EU's legislations for alternative fuels, i.e., the Renewable Energy Directive [12] and the Fuel Quality Directive [16]. GHG mitigation potentials are calculated as differences in life-cycle GHG emissions between fossil and alternative fuels, where the former are termed "the fossil fuel comparators".

Several LCA studies for marine fuels are available in the literature, and some of these results are summarized in Table 1. Brynolf et al. compared the climate impact of liquid natural gas (LNG), MGO, and HSFO, concluding that these alternatives differed by less than 10% [17] and highlighted the high potential in climate change mitigation of liquefied biogas and bio-based methanol [17]. Bouman et al. reviewed the CO_2 reduction potential of different options for international shipping, concluding that reducing CO_2 emissions by 75% in 2050 is feasible and that biofuels are one of the options that will provide the highest potential [18]. Balcombe et al. [19] compared GHG emissions for HSFO, LNG, and methanol and found that methanol has the lowest emissions. Gilbert et al. [20], Andersson et al. [14], and Gray et al. [11] also examined this topic. Bilgili provided one comprehensive study of the environmental impact of four fossil marine fuels, concluding that heavy fuel oil (HFO) is a preferable alternative [21], and compared eight alternative marine fuels with LCA, concluding that biogas has the lowest total environmental impact [22]. In addition to these comprehensive studies, a large number of other good studies also exist, e.g., describing individual fuels (LNG [23–29], methane [30] methanol [31–35], HVO [36,37], hydrogen [38], ammonia [38,39] and electricity [40]), comparing different fuels [9,14,41–59], or assessing other ways of improving the sustainability of the maritime industry [1,60–79].

Table 1. Average well-to-wheel GHG emissions (g CO_2 eq/MJ_{fuel}) emissions for marine fuels. Data compilation from the literature, converted to a common functional unit. Ranges represent different feedstocks. LBG is liquefied biogas.

HSFO	HVO	LNG (Fossil)	LBG	Bio-LNG	Biomethane	Methanol (Fossil)	Methanol (Biobased)	Source
84	-	56				78	9	(EcoInvent 2021) [80]
84		62	27			89	17	(Brynolf 2014) [81]
94	30–700	76.5			13–17		36–46	(Gray, et al., 2021) [11]
86		82		53		92		(Gilbert, et al., 2018) [20]
100	35–45	95		50	19	105	14	(Balcombe, et al., 2019) [19]

Even though there is an abundance of scientific literature examining the environmental impact of alternative marine fuels, very few studies consider the marginal effects of the different fuels [82,83]. Environmental marginal effects are calculated with (change-oriented) consequential LCA (cLCA) in contrast to (static) attributional LCA (aLCA). The choice of LCA methodology can lead to significantly different outcomes [84]

The definitions of the two LCA methods are, according to the United Nations Environmental Environment Program, that "*the attributional approach attempts to provide information on what portion of global burdens can be associated with a product*" whereas "*the consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision*" [85].

With aLCA, the environmental impact of a product is computed as the sum of all emissions occurring during its life-cycle based on static historical data averaged over a recent time period. In contrast, cLCA should include all consequences of producing one extra functional unit of that product, including indirect effects outside of the product's life-cycle. Such effects can, e.g., be resource limitations or changed production output due to new cost competitiveness. Therefore, cLCA is the most appropriate tool to predict the potential consequences of policy decisions generating a market shift [86]. The cLCA methodology is consistent with the EU's fossil fuel comparator, which uses marginal emissions for petroleum refining and is based on the linear programming (LP) model developed by CONCAWE [87].

3. Method

3.1. Goal and Scope

In this study, the environmental impact of today's fuel substitution options in the marine industry was quantitatively assessed using both (average) aLCA and (marginal) cLCA. The temporal scope was the short-term 2022–2025 ("current market"). Eight marine fuels were analyzed: very-low-sulfur fuel oil (VLSFO), marine gasoil/diesel-oil (MGO/MDO), high-sulfur fuel oil (HSFO), liquefied natural gas (LNG), biomethane, fossil methanol, biomethanol, and biodiesel (=hydrotreated vegetable oil, HVO). All the selected alternative fuels are either currently used in international shipping or could have the potential to reduce the environmental impact of shipping. Electro-fuels, such as green H_2 and ammonia, were not included in the LCA analysis because the technology for using them is still too premature to assess them with the same LCA methodology as the other fuels. Such fuels can, however, become sustainable fuel options in the future.

Detailed information about the fuels is found in Appendix B (Life-cycle Inventory). The risks for climate change, ozone formation, acidification, marine eutrophication, and terrestrial eutrophication were included in the analysis because these environmental aspects are important and/or are affected by SO_x emissions from fuel production and usage. The functional unit was defined as "1 MJ of power output for propulsion" because this functional unit allows for an assessment of differences in fuel energy content, fuel combustion emissions, and engine efficiencies for various fuels.

3.2. Computational Strategy

For all the fuels, the environmental impact included emissions from fuel production and combustion, which are usually the two dominant environmental factors in well-to-wheel analyses [15]. For instance, the climate change impact $P_{CC,i}$ (kg CO_2 eq/MJ propulsion) for fuel i becomes:

$$P_{cc,i} = a_i b_i / c_i + \sum_j A_{ij} d_j \tag{1}$$

where a_i is the carbon footprint to produce fuel i (typically in kg CO_2 eq/kg fuel) and b_i is the specific fuel consumption of the propulsion combustion (MJ fuel/MJ propulsion). Typically, b_i is around 2.0 [20], corresponding to an engine efficiency of 50%. The variable c_i is the lower heating value (MJ/kg fuel), which converts the results from kg fuel to MJ. The elements A_{ij} in matrix A are combustion emissions (g/MJ propulsion) for emission type j (CO_2, CH_4, N_2O, SO_x, or NO_x), and fuel i. d_j is the characterization factor for emission j.

A_{ij} and b_i were retrieved from Gilbert et al., 2018, with all biogenic CO_2 combustion emissions set to zero [20]. Values for c_i were obtained from Moretti 2017 [87] for oil products and from Ecoinvent [88] for the other fuels. The d_i data were based on "*Environmental Footprint (EF) 3.0 v1.02 emissions' characterization factors*" (European Commission 2019). For a_i, the LCA software SimaPro v.9.3, with the database "*Ecoinvent 3.8*" [80,88] was used when possible. The settings "*conseq*" [88] and "*cut-off*" [80] were used for cLCA and aLCA, respectively. The used values are summarized in Table 2.

Equation (1) can be used to compute environmental impacts with aLCA, and it is also useful for computing impacts with cLCA for fuels not originating from crude oil, i.e., LNG, HVO, biomethane, fossil methane, and methanol. However, for oil-based fuels (i.e., VLSFO, MGO, and HSFO), external marginal effects must also be considered when using cLCA. The reason is that a shift in demand between oil fuels influences the efficiency of the oil refining system and, consequently, the marginal demand for crude oil [8]. One additional (third) term is then required for the equation:

$$P_{cc,i} = a_i b_i / c_i + \sum_j A_{ij} d_j + (q_i - q_{ref}) a_p b_i \tag{2}$$

Table 2. (a) carbon footprint to produce the fuel (typically in kg CO_2 eq/kg fuel), for consequential- and attributional LCA (b) specific fuel consumption of the propulsion combustion (MJ fuel/MJ propulsion), (c) heating values for converting the results to from kg fuel to MJ (MJ/kg fuel), (d) characterization factors for different molecules (here in kg CO_2 eq/g molecules), (A) operational fuel emission factors per MJ of propulsion (g molecules/MJ propulsion).

Fuel (and Vector d)	a: (cLCA)kg CO_2/kg	a: (aLCA)kg CO_2/kg	b: MJ/MJ	c: MJ/kg	A: g/MJ Propulsion				
					CO_2	CH_4	N_2O	SO_x	NO_x
HSFO (3.5% S)	0.336	0.332	2.01	40.5	150	0.00278	0.00750	3.14	4.39
VLSFO (0.5%S)	0.463	0.459	2.01	43.1	150	0.00278	0.00750	0.449	4.39
MGO (0.1% S)	0.571	0.568	2.04	43.1	146	0.00278	0.00722	0.0889	4.11
LNG	0.674	0.664	1.96	39.0	114	0.833	0.00444	0.00083	0.325
Biomethane	3.796	0.937	1.96	45.8	0	0	0	0	0
Fossil Methanol	1.106	0.703	2.12	20.0	145	0	0	0	0.847
Biomethanol	1.801	0.686	2.12	20.0	0	0	0	0	0
HVO	5.883 *	0.387 *	2.03	44.4	0	0.00178	0.00361	0.103	4.75
...									
d: (kg CO_2/g)					0.001	0.0368	0.298	0	0

(*) Since HVO production is not available in Ecoinvent, foreground HVO data were taken from Moretti et al. [89] and background data from Ecoinvent. The lower heating value c_i of HVO was assumed to be 44 MJ/kg [90]. For HVO, a was calculated as the emissions for vegetable oil divided by the amount of HVO produced per kg vegetable oil plus the emissions for fossil H_2 times required H_2 per kg HVO, such that, for instance, a_{cLCA} = 4.611/0.839 + 9.445 × 0.041 = 5.883 kg CO_2/kg.

The variable q_i is the marginal crude oil demand to produce fuel i and q_{ref} is the corresponding value for the reference fuel VLSFO, which is the dominating shipping fuel today. The q_i-values for VLSFO, MGO, and HSFO are 0.0015, 0.0009, and −0.0012 kg crude oil/MJ product, respectively, using data from Concawe [91], computed with a linear programming model based on Tehrani et al. [92]. Negative crude oil demands and emissions reflect that increased demand for oil by-products (i.e., HSFO) decreases the crude oil demand per unit of total production in the oil refineries, i.e., the oil refining efficiency increases.

The variable a_p is the environmental impact of producing 1 kg of petroleum and burning it in a refinery, using data from Ecoinvent. The environmental impact of crude oil production was here based on the ecoinvent dataset "*Petroleum {GLO}|market for |Conseq*". For the combustion of crude oil (equivalent) in the refinery furnace, a proxy dataset from ecoinvent was used "*Heavy fuel oil, burned in refinery furnace {Europe without Switzerland}|processing |Conseq)*". For climate change, a_p = 0.248 kg CO_2 eq/kg + 3.581 kg CO_2/kg = 3.829 kg CO_2/kg crude oil.

3.3. Monetarisation of Emissions

The total environmental impact of fuel includes several factors, such as climate change, ozone formation, and acidification. One way of finding the environmentally preferable fuel among several candidates is to apply monetarization of the emissions, i.e., to assign costs for all categories of environmental influence [93]. In this study, monetarisation was performed using data from the European Commission 2020 [90] using the medium-cost alternative for all emissions. The used data are summarized in Table 3, and for reference, the full table is found in Appendix A (Table A4).

Table 3. Monetarisation costs for environmental impacts.

Environmental Category	Unit	Monetary Cost (EUR/Impact Unit)
Climate Change	kg CO_2 eq	0.1025
Ozone formation, human health	kg NMVOC eq	1.19
Acidification	mol H+ eq	0.344
Eutrophication, marine	kg N eq	3.21

4. Results

Attributional (average) environmental impacts for the eight marine fuels were computed with aLCA using Equation (1) (Figure 2). The setting "cut-off" was used in the Ecoinvent 3.8 database, and it was assumed that HVO was produced from used cooking oil, which does not generate any environmental impact for its production. In order to facilitate comparison between the categories, all data were normalized such that the highest emission in each category was given a value of 100%. Raw data without normalization are found in Appendix A, Tables A2 and A3.

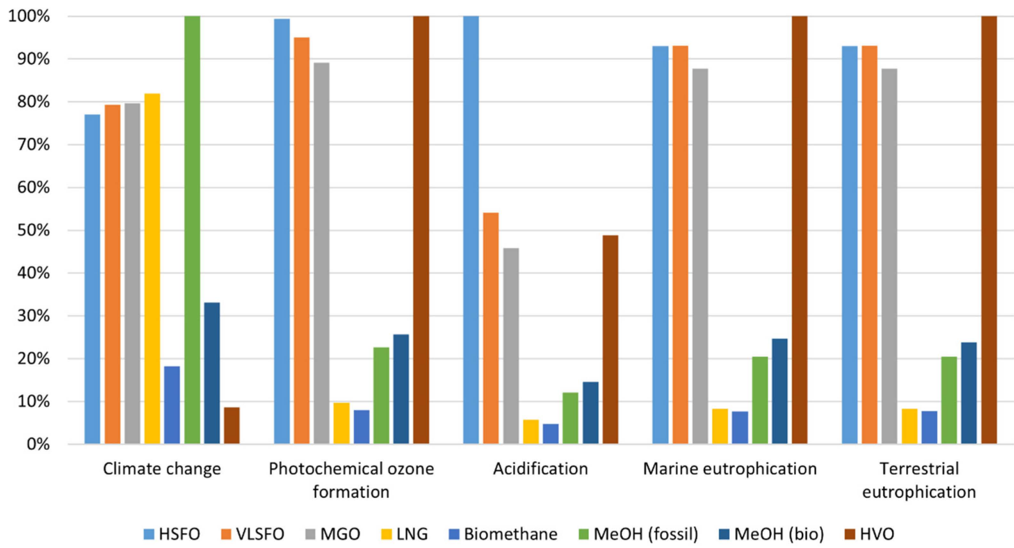


Figure 2. Attributional (aLCA) cradle-to-grave environmental impact of 1 MJ of power propulsion for eight marine fuels.

According to the aLCA calculations, the climate change potential for biofuels (biomethane, biomethanol, and especially HVO) was considerably lower than for fossil fuels. This trend is in agreement with previous aLCA studies from the literature, e.g., those summarized in Table 1. (Note, however, that Table 1 has emissions per MJ fuel, whereas the results of this study have emissions per MJ propulsion.) In the remaining four categories (ozone formation, acidification, marine eutrophication, and terrestrial eutrophication), LNG and biomethane, as well as biomethanol and fossil methanol, exhibited notably lower emissions compared to the other fuels.

Consequential (marginal) impacts for the fuels were computed with cLCA, using Equations (1) and (2) and the setting "conseq" in Ecoinvent 3.8 (Figure 3). Based on the cLCA analysis, the variations in climate change potential among the fuels were relatively minor, although it was observed that HVO and fossil methanol exhibited the most significant impacts (0.27 and 0.26 kg CO_2 eq/MJ propulsion, respectively). The lowest climate change potentials were computed for biomethane and HSFO (0.16 and 0.15 kg). The differences in the other categories were more pronounced, with the highest impacts for HVO and crude oil-based fuels (VLSFO, HSFO, MGO) and clearly lowest for LNG. The high acidification value for HSFO was due to high SO_x combustion emissions, assuming the absence of a scrubber.

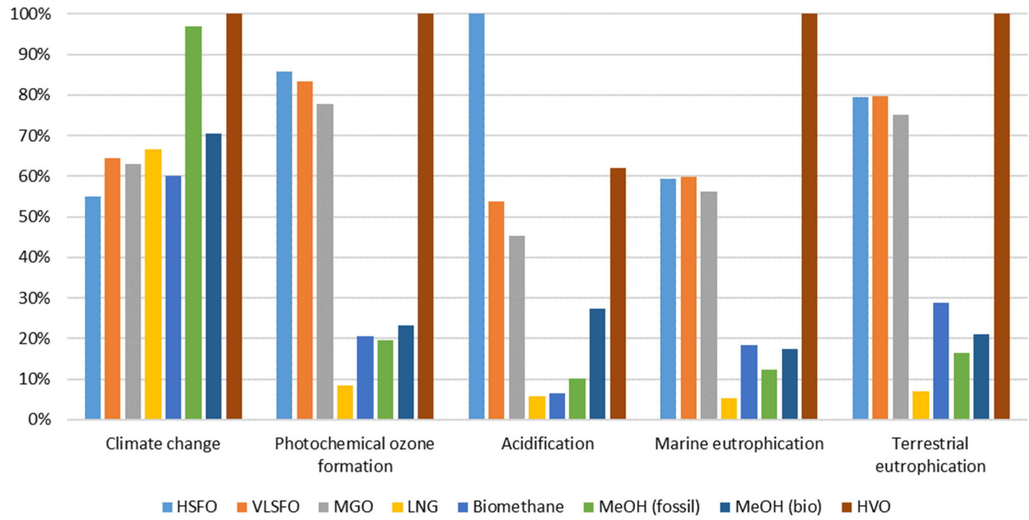
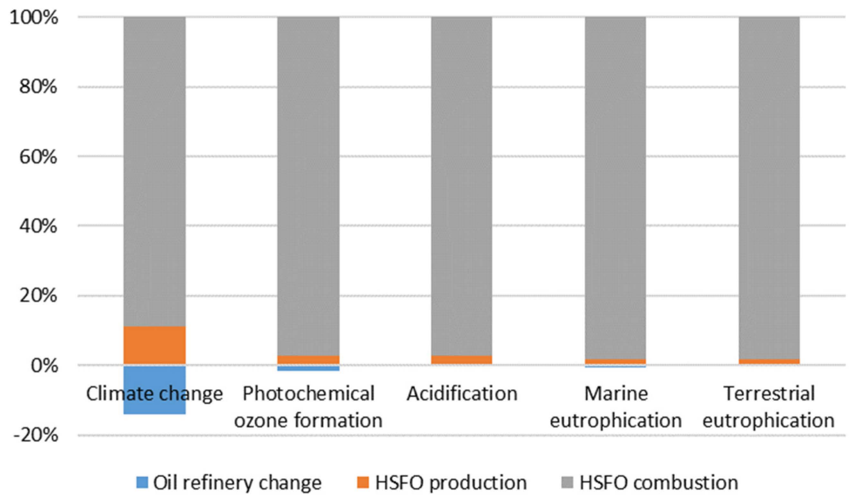


Figure 3. Consequential (cLCA) cradle-to-grave environmental impact of 1 MJ of power propulsion for eight marine fuels. VLSFO is considered as the reference (baseline) fuel replaced by the modeled market shift in marine fuel. One hundred percent is taken as the alternative fuel having the highest impact in each category. MeOH = methanol (CH_3OH).

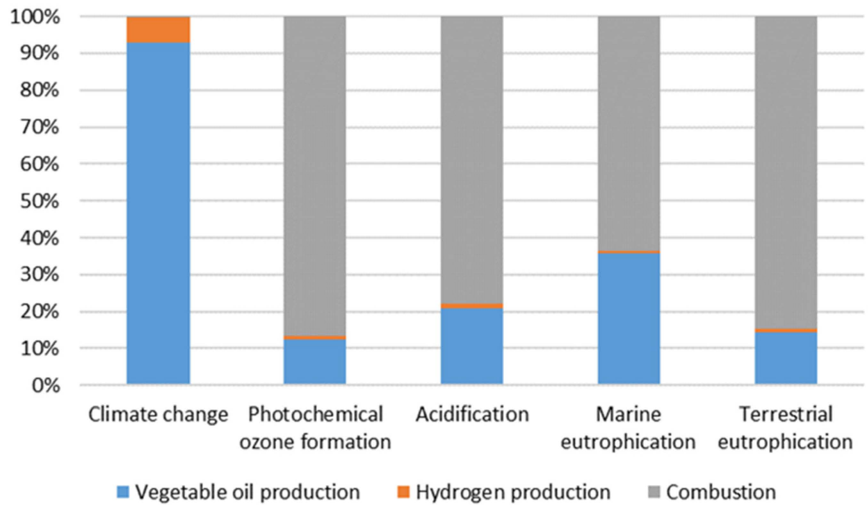
For fossil fuels, combustion typically dominates the environmental impact in all emission categories, while for biobased fuels, production takes precedence, especially in the climate change category. This phenomenon is exemplified in Figure 4, showing consequential cradle-to-grave environmental impacts for HSFO (Figure 4a) and HVO (Figure 4b). For HSFO, the (marginal) production accounts for 11% of the climate change emissions and 2–3% of the other impacts, whereas for HVO, it accounts for 100% of the GHG emissions and 13–37% of the other impacts.

The cLCA findings indicate that the marginal CO_2 emissions from bio-based marine fuels currently surpass the corresponding attributional (average) emissions, as computed both in this and previous aLCA studies [19]. Thus, the cLCA modeling emphasizes that increased production of renewable fuels, with constrained feedstock availability, may yield an environmental performance that falls short of expectations. This scenario arises when the subsequent feedstock is produced under lower environmental standards or necessitates the utilization of more precious virgin resources. Such considerations are revealed when marginal data are considered instead of average data.

In Figure 5, a comparison between GHG emissions computed using cLCA and aLCA was presented for the eight fuels. The differences between the two LCA techniques were limited for the fossil fuels but pronounced for the biobased fuels (HVO, biomethane, and biomethanol). According to our aLCA results, it seems realistic to reduce climate emissions from the shipping industry by 75–90% just by performing a fuel shift from VLSFO to biomethane, HVO, or biomethanol, thereby making a huge leap towards climate-neutral shipping. Unfortunately, our corresponding cLCA calculations indicate that monitoring measures are required to evaluate the consequences of market shifts. In fact, certain feedstocks for low-carbon biofuels, e.g., used cooking oil, might be quickly saturated if scaled up to a much higher production volume. Hence, a rapid and large-scale fuel transition from fuels such as VLSFO to biofuels or LNG alone is deemed insufficient for effectively minimizing the GHG emissions stemming from the global shipping industry.



(**a**)



(**b**)

Figure 4. Breakdown of the consequential cradle-to-grave environmental impact of 1 MJ of power propulsion. (**a**) HSFO. (**b**) HVO.

To overcome the barrier given by the limited feedstock, electrochemical fuels using green hydrogen and carbon recycling-based fuels are viable paths toward carbon neutrality. Substantial reductions in GHG emissions can also be achieved by other measures, such as installing carbon-capture devices on large ships, optimizing trade routes, and utilizing wind-power on ships [5,6].

Despite climate impact being arguably the most crucial environmental consideration for marine fuels, it is essential to acknowledge the relevance of other factors as well. To comprehensively evaluate and rank various candidate fuels based on their effects on multiple environmental aspects, the monetarization of emissions offers a viable approach. In this study, monetarization was performed following the guidelines set forth by the European Commission [90]. As shown in Figure 6, the fuel with the lowest total environmental cost, as assessed with aLCA, is biomethane, followed by biomethanol and HVO. Biomethane has, together with LNG, the lowest environmental costs also in the cLCA analysis. The analysis suggests that, at present, biomethane stands out as the most promising biofuel, while LNG emerges as the most favorable option among fossil fuels. It should, however, be remembered that HSFO has the lowest marginal GHG emissions and that the acidification values for HSFO would improve if the compulsory use of scrubbers was included in the analysis.

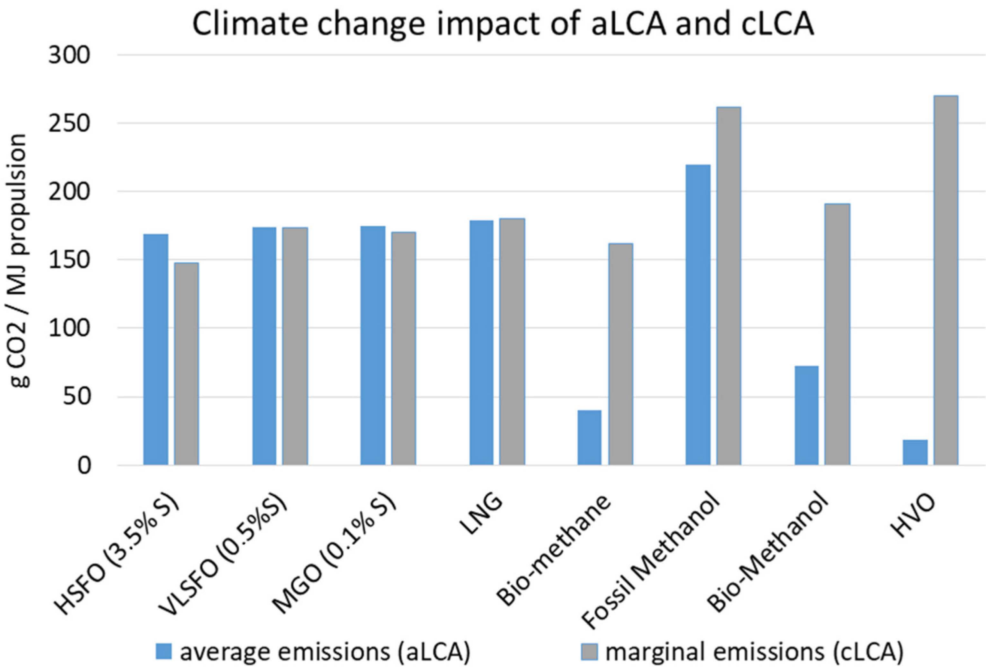


Figure 5. Greenhouse gas emissions for eight selected marine fuels, computed with both attributional LCA (aLCA) and consequential LCA (cLCA).

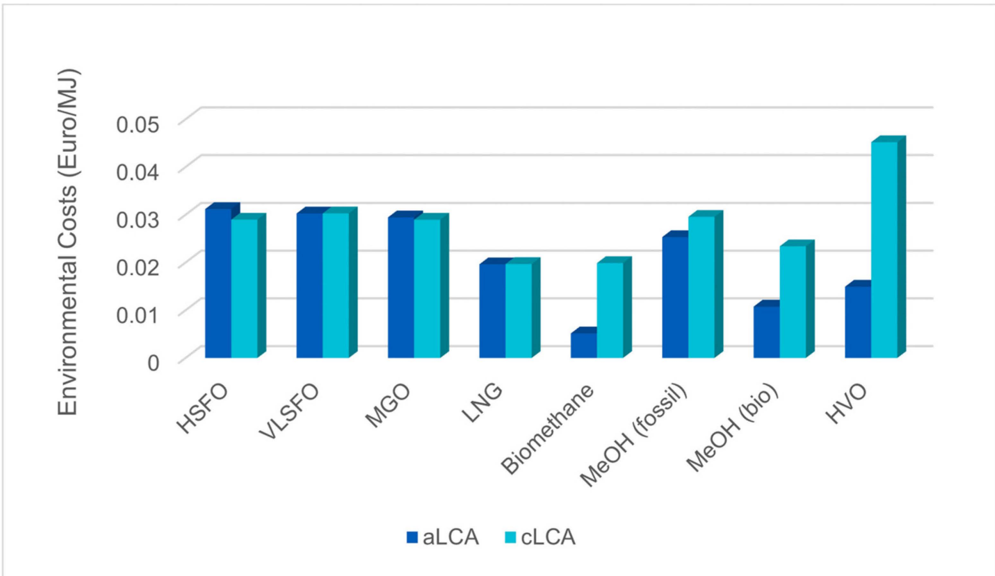


Figure 6. Monetarised environmental costs for eight marine fuels, using both attributional LCA (aLCA) and consequential LCA (cLCA).

5. Discussion

In order to handle the climate crisis, fossil fuels must, without a doubt, be phased out from all sectors, including the maritime industry. However, since the supply of renewable fuels is unfortunately still limited, it is important to use the available resources as efficiently as possible. From a climate perspective, it is typically more beneficial to use biofuels to substitute high-value oil products, such as gasoline and diesel, than low-value products, such as HSFO. The reason is that gasoline/diesel are determining oil products, whereas HSFO is a dependent oil side-product (or by-product); substitution of the former will, thus, lead to a more pronounced decrease in crude oil demand [8]. If this replacement methodology is applied to other transport sectors where high-value oil products can be substituted with biofuels, e.g., aviation and road transports, the climate impact of using renewable fuels will become better than otherwise anticipated.

HSFO use without a scrubber was considered in our analysis. With an added scrubber operating in closed loop mode, the GHG emissions of HSFO would increase by ca. 3.5%, [81] whereas the other emissions are considerably reduced [94]. A closed loop can be assumed due to the regulatory framework, where several countries disallow scrubber discharge in their terrestrial waters [24].

Marginal emissions are more sensitive to changes in supply/demand than average emissions. Therefore, it is important to emphasize that the presented cLCA data should be considered as snapshots, assumingly valid for 3–5 years, rather than constants or long-term forecasts. If, for instance, the global diesel and petroleum demand decreases dramatically because of vehicle electrification, HSFO production will also decrease, leading to higher marginal GHG emissions for HSFO if its use in the economy does not decrease at a similar rate.

6. Conclusions

Five environmental impacts (climate change, ozone formation, acidification, and marine and terrestrial eutrophication) of eight marine fuels (HSFO, VLSFO, MGO, LNG, biomethane, biomethanol, fossil methanol, and HVO) were assessed using both attributional and consequential LCA. The former (aLCA) was used to analyze average emissions, whereas the latter (cLCA) was used to predict marginal environmental impacts.

Calculations with attributional aLCA showed that bio-based fuels (HVO, biomethane, and biomethanol) had the lowest average GHG emissions (19–73 and 169–220 kg CO_2/MJ propulsion for biofuels and fossil fuels, respectively). Corresponding consequential cLCA results showed, however, that the marginal GHG emissions of the biofuels were clearly higher than their average emissions (169–220 and 148–262 kg CO_2/MJ propulsion for biofuels and fossil fuels, respectively). Non-intuitively, high-sulfur fuel oil (HSFO) had the lowest GHG emissions (148 kg CO_2/MJ) but high emissions in all the other categories, assuming that scrubber was not used. Biomethane had the second-lowest marginal GHG emissions (162 kg CO_2/MJ) and low emissions in all other categories. LNG had the lowest emissions in four out of five categories and medium–high GHG emissions (180 kg CO_2/MJ). HVO performed worst or second worst in all five categories. When the monetization of all emissions was applied, the lowest total average environmental cost was achieved for biomethane (0.005 EUR/MJ propulsion), whereas the lowest marginal cost was shared between biomethane and LNG (0.02 EUR/MJ propulsion).

Since the underlying demand for bio-based fuels is currently higher than the supply, there is a potential risk that GHG emissions of marginal biofuels are currently considerably higher than their average emissions. This must be considered before initiating a rapid large-scale fuel switch, e.g., in the shipping industry. Biofuels can potentially reduce the GHG emissions from shipping significantly, but that requires that the marginal emissions from biofuel production be significantly reduced, e.g., via the use of more sustainable feedstocks. According to the cLCA analysis, the substitution of fossil oil products (VLSFO, MGO, and HSFO) with biofuels or LNG will currently give only a limited positive climate impact (biomethane) or be directly contra-productive (biomethanol and HVO from dedicated crops instead of residues). Additional measures are therefore required to reach the climate goals of the maritime industry, such as more climate-efficient production of biofuels, more energy-efficient ships, reduced shipping volumes, and the use of carbon capture techniques. In the long term, the utilization of climate-neutral electrochemical fuels, such as hydrogen and ammonia, is of paramount importance.

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Glossary and Abbreviations

GHG	Greenhouse gas
Fuel oil	Oil product that does not reach boiling temperature in the crude distillation unit.
HFO	Heavy fuel oil—oil product that does not enter the distillation process in a refinery with a vacuum distillation unit.
HSFO	High-sulfur fuel oil.
MFO	Medium-sulfur fuel oil
LSFO	Low-sulfur fuel oil
VLSFO	Very-low-sulfur fuel oil, less than 0.5 wt.% sulfur.
ULSFO	Ultra-low-sulfur fuel oil, less than 0.1 wt.% sulfur.
MGO	Marine gasoil, less than 0.1 wt.% sulfur.
mb/d	Millions of barrels per day
LCA	Life-cycle assessment
LNG	Liquid natural gas
LPG	Liquified petroleum gas
IEA	International Energy Agency
EIA	U.S. Energy Information Administration
IMO	International Maritime Organization
aLCA	Attributional Life-Cycle Assessment (based on average data)
cLCA	Consequential Life-Cycle Assessment (based on marginal data)
RoW	Rest of World (abbreviation in Ecoinvent)
GLO	Global (abbreviation in Ecoinvent)
RER	Europe (abbreviation in Ecoinvent)

List of symbols in the equations

a_i	Carbon footprint to produce fuel i (typically in kg CO_2 eq/kg fuel)
b_i	Specific fuel consumption of the propulsion combustion (MJ fuel/MJ propulsion)
c_i	Lower heating value, converting the results from kg fuel to MJ (MJ/kg fuel)
d_j	Characterization factor for emission type j
A_{ij}	Combustion emissions for fuel i and emission type j (g/MJ propulsion)
q_i	Marginal crude oil demand to produce fuel i (kg crude oil/MJ product)
q_0	Marginal crude oil demand for reference fuel (VLSFO) (kg crude oil/MJ product)
a_p	Environmental impact of producing 1 kg of petroleum and burning it in a refinery.

Appendix A. Appendix Tables

Table A1. Marginal emission intensities per MJ product [91] (Concawe 2017).

Product	Allocation to Final Products (g CO_2/MJ)
Chemicals	31.1
LPG	5.2
Gasoline	5.5

Table A1. *Cont.*

Product	Allocation to Final Products (g CO_2/MJ)
Kerosine	6.1
Diesel Fuel	7.2
Heating oil	4.7
Marine gasoil	2.9
heavy fuel oil	−3.7
bitumen	−10.1
petroleum coke	−25.0
lubes and wax	14.1
sulfur	−1.3

Table A2. Results of the cLCA analysis.

Impact Category	HSFO	VLSFO	MGO	LNG	Biomethane	MeOH (Fossil)	MeOH (Bio)	HVO
Climate change (kg CO_2 eq)	1.49×10^{-1}	1.74×10^{-1}	1.70×10^{-1}	1.80×10^{-1}	1.62×10^{-1}	2.62×10^{-1}	1.91×10^{-1}	2.70×10^{-1}
Photochemical ozone formation (kg NMVOC eq)	4.71×10^{-3}	4.57×10^{-3}	4.27×10^{-3}	4.67×10^{-4}	1.13×10^{-3}	1.07×10^{-3}	1.27×10^{-3}	5.49×10^{-3}
Acidification (mol H+ eq)	7.55×10^{-3}	4.07×10^{-3}	3.43×10^{-3}	4.34×10^{-4}	4.93×10^{-4}	7.70×10^{-4}	2.07×10^{-3}	4.69×10^{-3}
Marine eutrophication (kg N eq)	1.73×10^{-3}	1.74×10^{-3}	1.64×10^{-3}	1.55×10^{-4}	5.38×10^{-4}	3.60×10^{-4}	5.10×10^{-4}	2.91×10^{-3}
Terrestrial eutrophication (kg N eq)	1.90×10^{-2}	1.91×10^{-2}	1.79×10^{-2}	1.69×10^{-3}	6.87×10^{-3}	3.95×10^{-3}	5.04×10^{-3}	2.39×10^{-2}

Table A3. Results of the aLCA analysis.

Impact Category	HSFO	VLSFO	MGO	LNG	Biomethane	MeOH (Fossil)	MeOH (Bio)	HVO
Climate change (kg CO_2 eq)	1.69×10^{-1}	1.74×10^{-1}	1.75×10^{-1}	1.80×10^{-1}	4.01×10^{-2}	2.19×10^{-1}	7.26×10^{-2}	1.90×10^{-2}
Photochemical Ozone formation(kg NMVOC eq)	4.78×10^{-3}	4.57×10^{-3}	4.29×10^{-3}	4.65×10^{-4}	3.83×10^{-4}	1.09×10^{-3}	1.23×10^{-3}	4.81×10^{-3}
Acidification (mol H+ eq)	7.58×10^{-3}	4.10×10^{-3}	3.47×10^{-3}	4.35×10^{-4}	3.59×10^{-4}	9.15×10^{-4}	1.10×10^{-3}	3.70×10^{-3}
Marine eutrophication (kg N eq)	1.74×10^{-3}	1.74×10^{-3}	1.64×10^{-3}	1.55×10^{-4}	1.43×10^{-4}	3.83×10^{-4}	4.61×10^{-4}	1.87×10^{-3}
Terrestrial eutrophication (kg N eq)	1.90 × 10−2	1.90 × 10−2	1.79 × 10−2	1.69×10^{-3}	1.59×10^{-3}	4.18×10^{-3}	4.88×10^{-3}	2.05 × 10−2

Table A4. Monetization values (year 2018) for different environmental categories.

Environmental Category	Unit	Monetary Cost (EUR/Impact Unit)		
		Low	Central	High
Climate Change	kg CO_2 eq	0.0615	0.1025	0.1936
Ozone Depletion	kg CFC-11 eq	22.8	31.4	127.2
Ionising radiation, Human health	kBq U235 eq	0.0008	0.0012	0.0461
Ozone formation, human health	kg NMVOC eq	0.87	1.19	1.9

Table A4. *Cont.*

Environmental Category	Unit	Monetary Cost (EUR/Impact Unit)		
		Low	Central	High
Particulate matter	Disease incidence	661,974	784,126	1,204,600
Human toxicity, non-cancer	CTUh	30,211	163,447	755,270
Human toxicity, cancer	CTUh	174,324	902,616	2,789,181
Acidification	mol H+ eq	0.176	0.344	1.617
Eutrophication, freshwater	kg P eq	0.26	1.92	2.18
Eutrophication, marine	kg N eq	3.21	3.21	3.21
Ecotoxicity, freshwater	CTUe	2.39×10^{-24}	3.82×10^{-5}	1.88×10^{-4}
Land use (Soil quality index)	dimensionless (pt)	8.7×10^{-5}	0.000175	0.000349
Water use	m^3 water eq	0.00419	0.00499	0.2359
resource use, fossils	MJ	0	0.0013	0.0068
Resource use, minerals and metals	kg Sb eq	0	1.64	6.53

Table A5. Total environmental costs of different fuels.

Environmental Costs EUR per MJ Propulsion	HSFO	VLSFO	MGO	LNG	Bio-Methane	MeOH (Fossil)	MeOH (Bio)	HVO
aLCA	0.0312	0.03028	0.02946	0.01963	0.00515	0.02533	0.01077	0.01494
cLCA	0.02898	0.03029	0.02897	0.01968	0.01988	0.02956	0.0234	0.0452

Appendix B. Life-Cycle Inventory

The life-cycle inventory gives further details about the eight marine fuels in this study and also details about how their emissions were assessed in the LCA calculations.

Appendix B.1. Very-Low-Sulfur Fuel Oil (VLSFO)

VLSFO is commonly used as it is the cheapest compliant fuel for international shipping. Fuel oil products that comply with the VLSFO specification account for over 75% of consumption in [3] and is therefore used as the reference fuel in this study. To model the production of VLSFO, the Ecoinvent dataset "*light fuel oil {Europe without Switzerland}|light fuel oil production, petroleum refinery operation|Conseq*" (Table 1) was used in Equation (1).

Appendix B.2. High-Sulfur Fuel Oil (HSFO)

HSFO was a popular fuel in the shipping industry prior to 2020 but is now only compliant for ships equipped with scrubber devices, which capture H_2S and other pollutants from exhaust gases. Compliant use of HSFO, therefore, depends on the proportion of scrubber-equipped ships (a figure which currently stands at approximately 8% for international shipping [95]. Scrubbers can operate in open or closed mode, whereby the former emits the effluent into the sea, and the latter stores it onboard for port discharge. The scrubber impact is disregarded in the LCA analysis but is described in the discussion chapter.

The production of HSFO was modeled with the Ecoinvent dataset "*heavy fuel oil {Europe without Switzerland}|heavy fuel oil production, petroleum refinery operation|Conseq* and combustion emissions were computed neglecting any potential scrubber [20]. The oil refinery system is affected when performing a fuel shift from the reference fuel (VLSFO) to another oil-based fuel (e.g., HSFO), as described by the last term in Equation (2).

Based on CONCAWE LP, producing 1 MJ less of VLSFO and 1 MJ more of HSFO, 8.4 g CO_2 eq less is emitted at the EU oil refinery [91]. Taking CONCAWE's carbon content of EU crude oil (equivalent) feedstock of 73.3 g CO_2/MJ consistent with such figures, [87] such a reduction of emissions corresponds to the avoidance of combustion of 2.7 g of crude oil (equivalent) at the EU oil refinery level. Based on the abovementioned Ecoinvent data to model the production of HSFO, including the avoidance of combustion of 2.7 g of crude oil equivalent at the level of the oil refinery, the consequential well-to-tank emissions of HSFO are −2.0 g CO_2 eq/MJ. Subtracting from the well-to-tank GHG emissions of heavy fuel oil, i.e., 6.4 g CO_2 eq/MJ [87], the change in marginal refinery emissions by increasing by 1 MJ HSFO output and decreasing by 1 MJ HSFO output (8.4 g CO_2 eq/MJ), the consequential well-to-tank impact of HSFO is calculated as −2.0 g CO_2 eq/MJ, showing consistency between CONCAWE and Ecoinvent's data.

Appendix B.3. Marine Gasoil (MGO)

The environmental impact of marine gasoil was calculated with Equation (2), as for HSFO. The first term is the environmental impact caused by the production of MGO, modeled with the Ecoinvent dataset "*Diesel, low-sulphur* [96] | *market group for* | *Conseq*", the second is combustion emissions for MGO [20] and the third describes the effect of increased crude oil demand when changing from VLSFO to MGO, computed as for HSFO. (RER = Europe).

Appendix B.4. Liquified Natural Gas (LNG)

Liquified natural gas (LNG) is compressed and cooled in a stepwise process that, due to the build-up of energy density combined with the low occurrence of harmful substances, makes LNG a viable marine fuel [28]. The economy and environmental aspects are described by (Hönig, et al., 2019) [97]. Methane leakage is problematic in natural gas production pathways due to the comparably high global warming impact. Natural gas has multiple uses, both as process feedstock and as fuel. Global production of LNG was modeled using the ecoinvent dataset "*Natural gas, liquefied* [91] | *market for* | *Conseq*". (GLO = Global).

Appendix B.5. Biomethane (CH_4)

Biomethane can be produced from sewage sludge via anaerobic digestion [30]. Biomethanol can be produced from a wide range of feedstocks [35]. Marginal production of biomethane was modeled using the ecoinvent dataset "*Biomethane, low pressure* [39] | *market for biomethane, low pressure* | *Conseq*". LNG's combustion emissions were used as proxy for biomethane's combustion emissions, considering that biogenic (neutral) CO_2 instead of fossil CO_2 is emitted in the case of biomethane.

Appendix B.6. Methanol (Fossil)

Methanol (CH_3OH) can be produced along several pathways, where the currently most common is synthetization from methane [78]. Methanol has various applications (in order of decreasing value): as feedstock for the petrochemical industry, as drop-in fuel in gasoline, and as neat fuel in the marine segment. In this study, it was assumed that additional methanol is partly from fossil resources (natural gas) and partly produced from bio-based [11]. To produce marginal methanol via steam methane reforming, the Ecoinvent dataset "*Methanol* [91] | *market for* | *Conseq*" was considered.

Appendix B.7. Methanol (Biobased)

Biomethanol has identical material properties to fossil methanol. For marginal bio-based methanol, the Ecoinvent dataset "Methanol, from biomass [39] | market for | Conseq" was used. (RoW = Rest of World) The combustion emissions of bio-based methanol were set to zero since biogenic (neutral) CO_2 instead of fossil CO_2 is emitted.

Appendix B.8. Hydrotreated Vegetable Oil

Hydrotreated vegetable oil (HVO) is produced from vegetable or animal fats, and its production has increased rapidly since 2011. HVO can be blended with ultra-low-sulfur diesel, and with some adjustments, it can be blended with MGO. Currently, the vast majority of HVO is derived from oil crop feedstocks, such as camelina, palm oil, used cooking oil, and tallow. However, increase in HVO production volume is limited by feedstock availability. To model marginal vegetable oil for HVO production, the Ecoinvent dataset "*Vegetable oil, refined* [91] | *market for* | *Conseq*" was used. According to Ecoinvent, marginal vegetable oil production is made mostly of palm oil. From 1 kg of vegetable oil, 0.84 kg of HVO can be obtained [89]. A total of 41.3 g of hydrogen per kg of HVO is needed to convert vegetable oil into HVO [89].

It can be assumed that marginal hydrogen is produced by steam reforming of natural gas and fuel gas. The dataset for hydrogen from steam reforming is not available in Ecoinvent. Therefore, the dataset "*Hydrogen (reformer) E*" developed in 2005 by PlasticsEurope Association was used instead. According to this dataset, based on average instead of marginal data, the production of 1 kg of hydrogen generates 9.4 kg CO_2 eq. Marginal impact of producing hydrogen via steam reforming is, therefore, expected to be higher than the assumed figure. However, green hydrogen has reached commercialization in the meantime. CONCAWE's data for other impact categories than climate change were not available. According to the CONCAWE model, the well-to-tank climate change impact of marginal hydrogen is 139.7 g CO_2 eq/MJ [87], i.e., about 16.5 kg CO_2 eq/kg. This value is in line with the climate change impact of gray hydrogen (153 g CO_2 eq/MJ) and blue hydrogen (135–139 g CO_2 eq/MJ) [98]. For cLCA HVO calculations, a_{cLCA} = 4.611/0.839 + 9.445 × 0.041 = 5.883 kg CO_2/kg. For the corresponding aLCA calculations, used cooking oil (with zero emissions) is assumed, with the same H_2 requirements as above: a_{aLCA} = 9.445 × 0.041 = 0.3872 kg CO_2/kg.

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