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Quantifying Emissions in the European Maritime Sector

A review on life cycle assessments of maritime systems combined with an analysis of the THETIS-MRV portal

Istrate, I., Iribarren, D., Dufour, J., Ortiz Cebolla, R., Arrigoni, A., Moretto, P., Dolci, F.

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Contact information
Name: Alessandro Arrigoni
Address: Westerduinweg 3, 1755 LE Petten, Netherlands
Email: alessandro.arrigoni-marocco@ec.europa.eu
Tel.: +31 (0)224 56 5951

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Contents

Abstract

Shipping is a large and growing source of greenhouse gas (GHG) emissions as well as of local pollutants such as SO_2, NO_x, and particulate matter. Scientific-based evidences indicate the need for global action and policies to tackle these emissions. The EU is following an environmental strategy to reduce emissions from the shipping sector. Actions on energy efficiency, emission abatement systems and more efficient ship hulls are important in mitigating shipping emissions increase, but further actions are needed when pursuing a long-term downward trend. The most important additional decarbonisation action is the use of alternative clean fuels. When understanding the potential environmental impacts of maritime systems fuel emissions, a full life cycle perspective should be followed in order to avoid potential pitfalls. In this respect, this report performs two analysis:

1) An analysis of the GHG emitted by ships transiting in EU ports in 2019, based on the publicly available MRV-THETIS database;

2) A meta-study of the life cycle assessments (LCA) on maritime systems and alternative fuels for maritime propulsion available in the literature.

The trends and gaps discussed throughout this report can serve the EU decarbonisation goals by providing recommendations for future actions aimed at quantifying and reducing maritime emissions.

1 Introduction

According to the International Maritime Organisation (IMO) Fourth Greenhouse Gas Study, the overall contribution of shipping to global anthropogenic GHG emissions was approximately 3% in 2018 (IMO 2020). Considering this relatively low contribution and that international shipping transports more than 80% of global trade, it can be concluded that shipping "*is the most efficient and cost-effective method of international transportation for most goods*"[1]. While in relative terms the CO2 emitted by the maritime sector is smaller than that caused by other transportation modes, shipping is a relevant source of SO_2 and NO_x, corresponding approximately to 13% and 15% of the global emissions, respectively. Together with particulate matter, SO_2 and NO_x constitute a massive source of local pollution (Corbett et al. 2007). The need for policies able to tackle these emissions is especially relevant when considering near-shore impact. . This is the reason why, historically, the IMO has worked to regulate the maximum sulphur content in fuels and the emissions of NO_X, especially in the most affected coastal areas. IMO regulation entered in force in 2020 and foresees an incremental broadening of its applications areas.

Since the maritime sector is not among those delivering the highest contributions to the global GHG emissions, decarbonizing shipping was usually not considered the most urgent priority. There are however three major reasons for doing so as soon as possible. First, shipping is expected to increase significantly in the coming decades, increasing as a consequence its GHG emissions. According to the Fourth Greenhouse Gas Study of the IMO (IMO 2020), maritime CO_2 emissions are projected to increase by 90-130% in the period from 2008 to 2050, depending on assumptions made for the future economic and energy developments. Second, the decarbonisation of the shipping sector is very difficult since it lacks mature and easily deployable decarbonised technologies. Third, the typical long service life of vessels (30 to 40 years) requires to act quickly to avoid locked-in emissions for a long time.

These reasons explain why several global and European initiatives are already targeting specifically GHG emissions from shipping. The IMO has progressively adopted measures aimed at increasing energy efficiency and capping GHG emissions. An important milestone has been the introduction in 2011 of the Energy Efficiency Design Index (EEDI), expressed as g_{CO2}/tonne·mile (IMO 2014). Ships built since 2013 has to respect a mandatory limit of the EEDI, and to provide an energy efficiency management plan (IMO 2018a). More recently, in 2018, the IMO adopted a strategy aligned to the Paris agreement "…*to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out*" (IMO 2018b) . Actions aimed at improving the energy efficiency are important in mitigating shipping emissions, but they are not enough. Other actions are needed when pursuing a long-term downward emission trend (IMO 2015; Lindstad et al. 2015): these include for instance cleaner fuels, lower speeds, emission abatement systems, and more efficient ship hulls.

In Europe, the path towards improving the environmental performance of the maritime sector started several years ago with the *EU Maritime transport strategy 2009-2018* (European Commission 2009). This strategy already included a set of environmental objectives for international shipping, such as the reduction of GHG emissions, NO_x, and SO_x, and the promotion of alternative fuels in ports. Later on, the European Commission white paper: *Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system* set an objective of 40% reduction for EU CO_2 emissions from maritime transport by 2050 compared to 2005 levels (European Commission 2011b).

It is clear however that the decarbonisation efforts for the maritime sector have to be integrated and aligned with the broader policy frame for the decarbonisation of the whole energy and transport system, as set up originally by the European Green Deal and further structured in set of coordinated measures by the Fit-for-55 policy packages. For example, the 2030 Climate Target Plan aims at reaching at least a 55% economy-wide GHG emission reduction, and it projects a high share of alternative fuels such as renewable and low carbon liquid fuels (European Commission 2021b). Moreover, other relevant fuel policies for the maritime context are:

[1] From the IMO website https://www.imo.org/en/About/Pages/Default.aspx

- the second version of the Renewable Energy Directive REDII (European Union 2018), with the proposal for its amendment (European Commission 2021b), and the expected Delegated Act on Renewable Fuel of Non-Biological Origin;
- the proposal of Proposed Regulation on the internal markets for renewable and natural gases, and for hydrogen (European Commission 2021a)

Given the critical importance of new infrastructure to enable the uptake of alternative fuels, in 2014 the EU published the Directive 2014/94/EU (European Union 2014) on the deployment of alternative fuels infrastructure for all transport modes. For clean and sustainable shipping, the Directive required the deployment of LNG refuelling points and shore-side electricity supply infrastructure, both in maritime ports and along the major inland waterways. In 2020, the European Commission assessed the state of deployment of the Directive 2014/94/EU. Based on the results, the Commission proposed a Regulation replacing the Directive of 2014 with more ambitious targets (European Commission 2021c). This Regulation will require docked ships to use shore-side electricity, and ports will need to address the demand for decarbonised fuels. To overcome the typical chicken-and-egg problem, mandatory targets will be set on the minimum number of infrastructure elements along the main waterways and at the main sea-going ports. The regulation foresees also the development of standards to guarantee interoperability throughout the EU.

In the frame of the Fit-for-55 package, the FuelEU Maritime is the most recent and complete EU initiative dedicated specifically to the shipping sector (European Commission 2021b). It aims at ensuring a high penetration of renewable and low-carbon fuels in this sector to promote climate-neutrality by 2050, and at the same time it aims at tackling air pollution. Among the specific objectives supporting these goals are: a clear regulatory frame, the upscaling in the production of the more mature renewable and low-carbon fuels, the creation of demand for this type of fuels at ports, and the avoidance of carbon leakage, which could occur by the development of bunkering facilities outside the EU.

The above sketched international and European regulatory frameworks set the general policy requirements enabling deep decarbonisation of the transportation sector. They provide a basket of measures, and they do not set a unique path towards the targets. The implementation of the measures has to be supported by a comprehensive methodology that is able to assess their impact.

Therefore, it is necessary to first map all of the GHG emissions arising from the maritime sectors to a high level of granularity: i.e., down to the individual ships and to the different phases of waterborne travels, such at berth, in- and out-of-port manoeuvring and open sea propulsion. To this purpose, the EU Regulation 2015/757 (European Union 2015a) sets the rules for the monitoring, reporting, and verification of the CO_2 emissions from maritime transport. Their implementation brought to the creation of the THETIS-MRV database and to the first annual European CO2 emission report in 2019 (European Commission 2020a). In this report, these data are analysed in detail.

Furthermore, to understand the potential environmental impacts of maritime systems, the scope of GHG emissions assessment from maritime transport has to cover the whole supply chain with a life cycle perspective. To this purpose, the FuelEU Maritime initiative (European Commission 2021b) provides in the annexes methods for determining the GHG emission factors for the Well-to-Tank and the Tank-to-Wake phases, including the related fugitive emissions. Other emission sources not directly related to propulsion, such as refrigerant and air conditioning, should also be considered. A comprehensive and coherent methodology is therefore required, not only to assess the current situation, but also to evaluate the overall environmental impact consequences of the available options. For this purpose, Life Cycle Assessment (LCA) is considered by the European Commission as the best available framework (European Commission 2003; S. Sala et al. 2021). LCA is a standardised methodology to evaluate the potential environmental impacts of product systems (ISO 2006a, 2006b). The LCA methodology involves four interrelated stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. Despite the availability of ISO standards on LCA and the International Reference Life Cycle Data System (ILCD) Handbook (European Commission 2010), LCA practitioners are relatively free to make a high number of methodological choices (e.g., regarding the definition of the functional unit and the system boundaries, the choice of the impact categories and the evaluation method, the modelling approach in the case of multifunctional processes, etc.). This has inevitably a large influence on the outcome of the studies. Hence, a meta-analysis of the available scientific literature (articles, reports, etc.) investigating the environmental impacts of maritime systems is needed. In this report, a meta-study on the available LCA literature on maritime systems is carried out, identifying key information, areas where sources converge, gaps, and uncertainties.

This report is therefore composed of two main parts, each aiming at providing original insights to one of the two dimensions of data collection and assessment mentioned above:

- Chapter 2 presents a JRC analysis of the data uploaded in 2019 on the THETIS-MRV database. To our knowledge, it is the first independent assessment of the available data. Based on different data analyses from the official report (European Commission 2020b), it allows an independent verification of the results.
- Chapter 3 presents a detailed review performed by IMDEA of the available literature on the LCA of the maritime sector up to mid-2020. To our knowledge, this is the first meta-study of this type dedicated to the maritime sector.

The implications of our findings for future LCA analyses are presented in Chapter 4. Finally, chapter 5 contains concluding remarks and recommendations.

2 Analysis of THETIS-MRV data

From the 1st of January 2018, the Regulation (EU) 2015/757 (European Union 2015b) on the monitoring, reporting, and verification of CO_2 emissions from maritime transport, is applied to passenger and cargo ships above 5,000 gross tonnage, regardless of their flag, calling at EU ports. This includes ports within member states, plus Iceland, Norway (except Svalbard), and some ports in overseas and dependant territories: Açores, Madeira, Canarias, Guadeloupe, French Guyana, Martinique, Mayotte, Saint Martin, and Reunion.

According to the regulation, all the CO_2 emissions coming from the ship must be reported. These include emissions from the main engines, auxiliary engines, gas turbines, boilers, and from inert gas generators. Reported emissions account for the travel between two port calls, falling under the Regulation (EU) 2015/757, and for the time spent in the port. Before the submission to the European Commission, the emission report must go through a third-party verification. Once verified, the EC makes the information publicly available, as required by the Article 21 of Regulation (EU) 2015/757. This is done through the THETIS-MRV portal, where emissions reported from 2018 and 2019 are currently available. In the reported data, every ship is assigned to a ship category (e.g., oil tanker or LNG carrier)

As reflected in Annex I of Regulation (EU) 2015/757, four different methods (A, B, C and D) can be applied by the ship operators to calculate the CO_2 emissions. Three of them (A, B and C) are based on fuel consumption, while the other (Method D) is based on direct measurement of emissions. CO_2 emissions derived from fuel consumption are calculated using the fuel emission factors provided in *Resolution MEPC.245(66) – 2014 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships,*(IMO 2014) collected in Table 1. The fuel emission factors define the tonnes of CO_2 emitted per tonne of fuel burned in the engine. Therefore, the emissions reported in the frame of the Regulation (EU) 2015/757 are tank-to-wake (TTW) emissions.

Table 1. Fuel emissions factor as indicated in Resolution MEPC.245(66)

Type of fuel	Reference	Emission factor (t-CO_2/t-fuel)
1. Diesel/Gas oil	ISO 8217 Grades DMX through DMB	3,206
2. Light fuel oil (LFO)	ISO 8217 Grades RMA through RMD	3,151
3. Heavy fuel oil (HFO)	ISO 8217 Grades RME through RMK	3,114
4. Liquefied petroleum gas (LPG)	Propane	3,000
	Butane	3,030
5. Liquefied natural gas (LNG)		2,750
6. Methanol		1,375
7. Ethanol		1,913

Source: Resolution MEPC.245(66), 2014.

2.1 Scope and methodology of the analysis

The analysis presented here is based on data reported in the frame of the Regulation (EU) 2015/757. The dataset analysed corresponds to the reporting year 2019, and is publicly available on the THETIS-MRV portal.

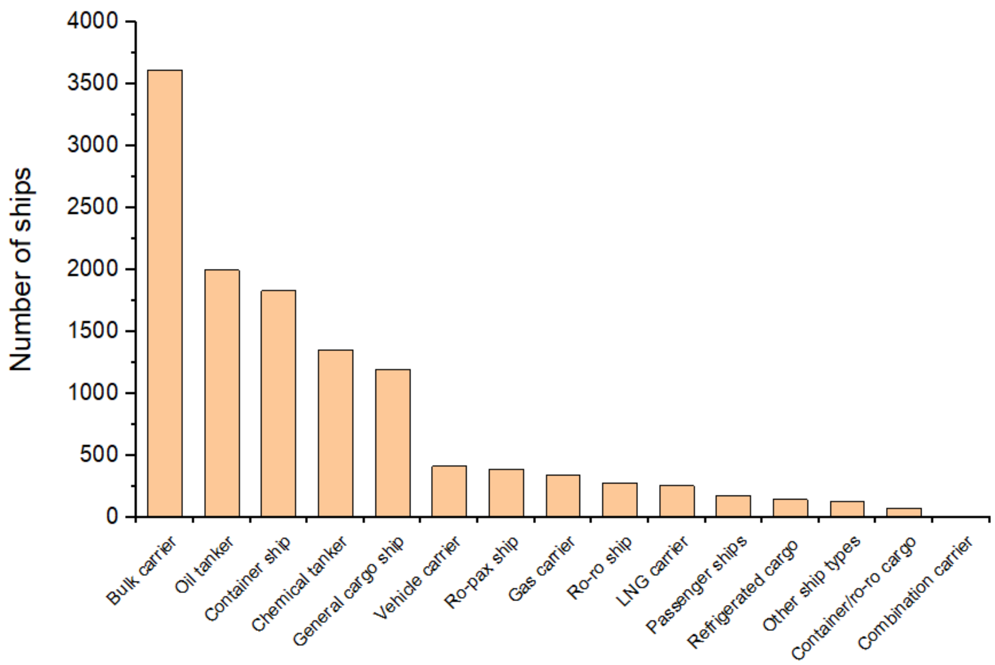
The dataset includes environmental (e.g., emissions per distance) and/or operational (e.g., time at sea) parameters.

The data provided are analysed here in order to benchmark the environmental performance of the ships, within their ship category (e.g., chemical tankers) and between different ship categories. Some ship categories might not be present in the following figures due to the lack of enough data to perform a representative statistical analysis. Additionally, some values present in the dataset have been excluded from the analysis presented here. These values were considered as not representative within their respective dataset (e.g. values several orders of magnitude bigger than the rest of the data sample). In the view of the authors of this report, these values were probably either a typo when introducing the value in the data file or the consequence of a wrong reporting from the ship owner to the data verifier.

2.2 Analysis results

In 2019, 12,204 ships reported their CO_2 emissions. The spread of these ships among the different ship categories, can be seen in Figure 1.

Figure 1. Number of ships reporting in 2019 classified by ship category



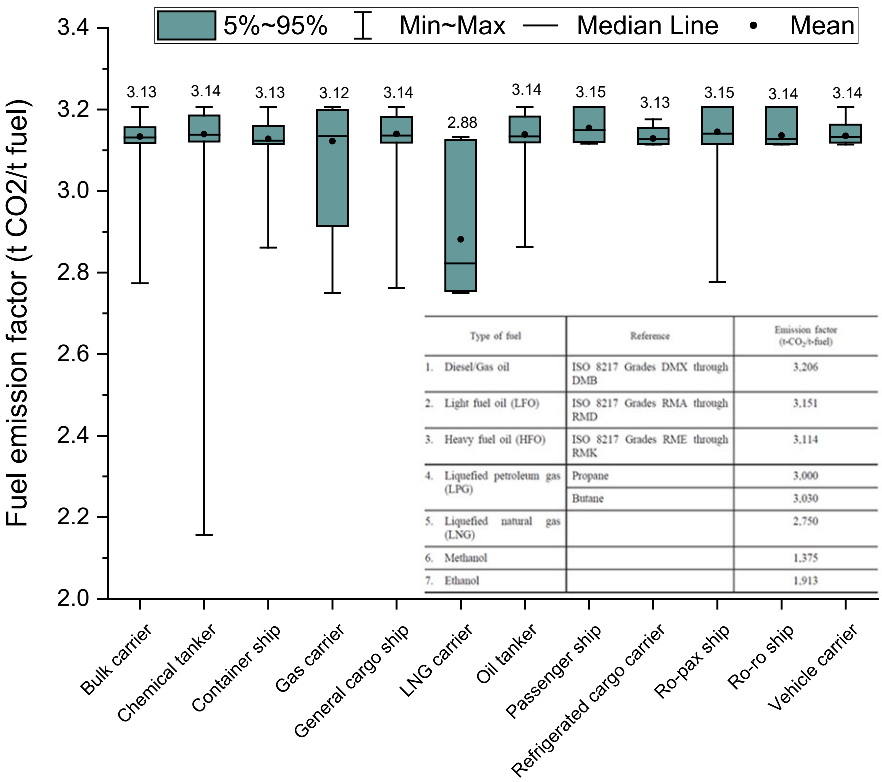
Source: JRC, 2022.

According to the data reported, ships falling under Regulation (EU) 2015/757, emitted more than 145.5 million tonnes (Mt) of CO_2 and consumed around 46.6 Mt of fuel. The total amount of fuel refers to all types of fuel used on-board. Based on total emissions and fuel consumptions, an average fuel emission factor of 3.12 t CO_2/t fuel can be found for the whole reporting fleet.

The fuel emission factor for every ship can be calculated dividing the total CO_2 emissions of the ship by its total fuel consumption. The result is shown in Figure 2, where the mean, median, 5-95% percentile, and maximum and minimum values of the fuel emission factors for each ship category are presented. Numbers labelled in Figure 2 refers to the mean value of the fuel emission factors for that ship category. Similar representations are used for other parameters in the following figures; however, to facilitate the visualisation of the data, minimum and maximum values are not presented.

Considering the three types of fuel more relevant in the maritime sector, i.e. Heavy fuel oil (around 75% of total worldwide fuel consumption), marine diesel oil (20 %) and LNG (5%) (CONCAWE 2017), and that a ship would normally use no more than two different type of fuels, it is possible to estimate the fuel mix used by the ships from the fuel emissions factor presented in Figure 2. The analysis is in line with the share of maritime fuel identified in (CONCAWE 2017), where fuel mix used by reporting ships is dominated by heavy fuel oil (HFO) with contributions by marine diesel oil (MDO) and a marginal role for LNG. LNG is a relevant fuel when referring to gas carriers, particularly in the case of LNG carriers. This ship category has the lowest average fuel emission factor (2.88 t CO_2/t fuel), suggesting that around 65% of the fuel consumed by the LNG carrier fleet is LNG.

Figure 2. Distribution of calculated fuel emission factor per ship category



Type of fuel	Reference	Emission factor ($t\text{-}CO_2/t\text{-}fuel$)
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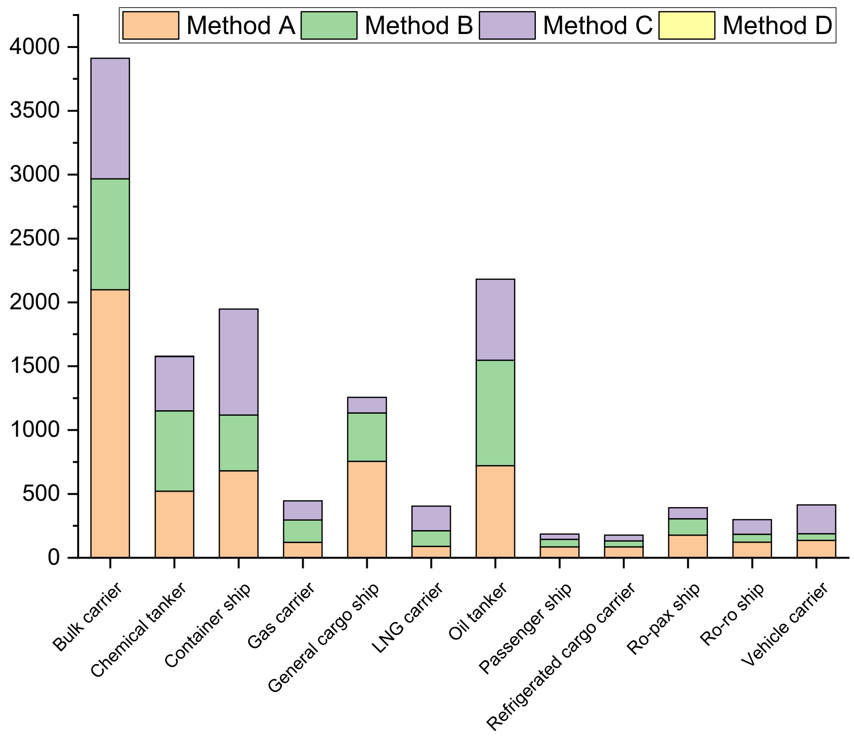
4. Liquefied petroleum gas (LPG)	Propane	3.000
	Butane	3.030
5. Liquefied natural gas (LNG)		2.750
6. Methanol		1.375
7. Ethanol		1.913

Source: JRC, 2022.

The analysis of the methods used to determine the CO_2 emissions of the ships provides the following numbers: 5,723 ships used method A, 3,841 used method B, 3,855 used method C, and only 2 boats (chemical tankers) used method D. The sum of these numbers is bigger than the number of reporting ships, indicating that some ships have used more than one method to report emissions. The distribution by ship category of methods used by the reporting fleet is shown in Figure 3.

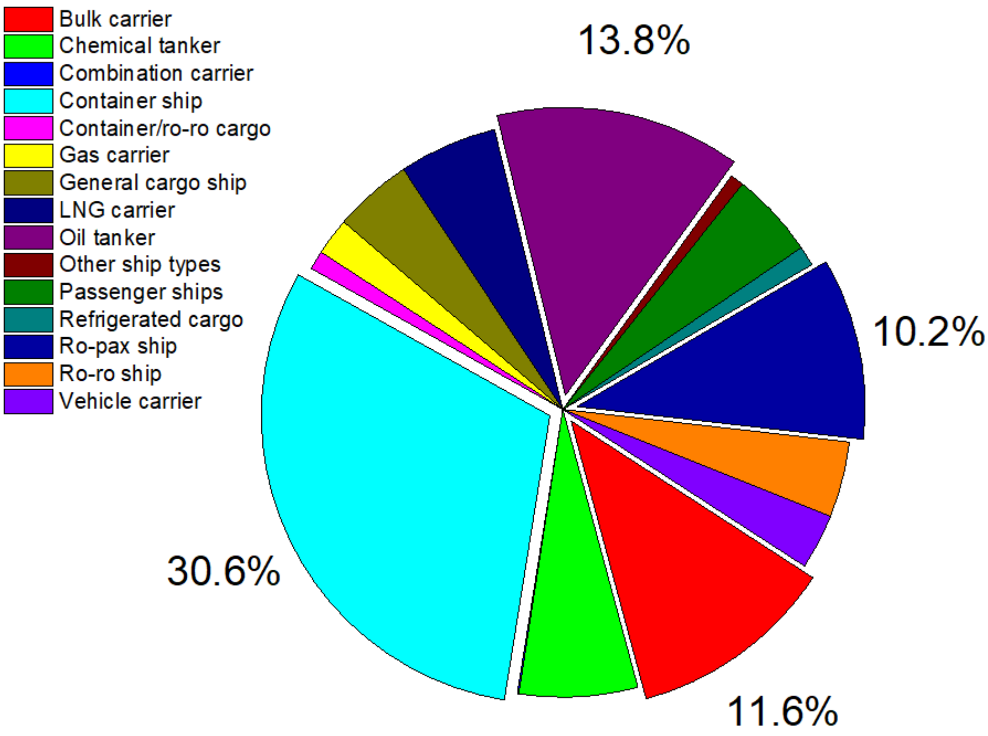
Figure 3. Distribution per ship category of the methods used to determine CO2 emissions by reporting ships



Source: JRC, 2022.

In terms of CO_2 emissions, almost 45 Mt CO_2 (30.6% of total emissions) were emitted by container ships and together with oil tankers (20 Mt CO_2 emitted), bulk carriers (17 Mt CO_2 emitted), and ro-pax ships are responsible for approximately 2/3 of the total CO_2 emissions reported. From the ships reporting under Regulation (EU) 2015/757, freight transport activities account for 85% of CO_2 emissions. The share of CO_2 emissions per ship category is shown in Figure 4.

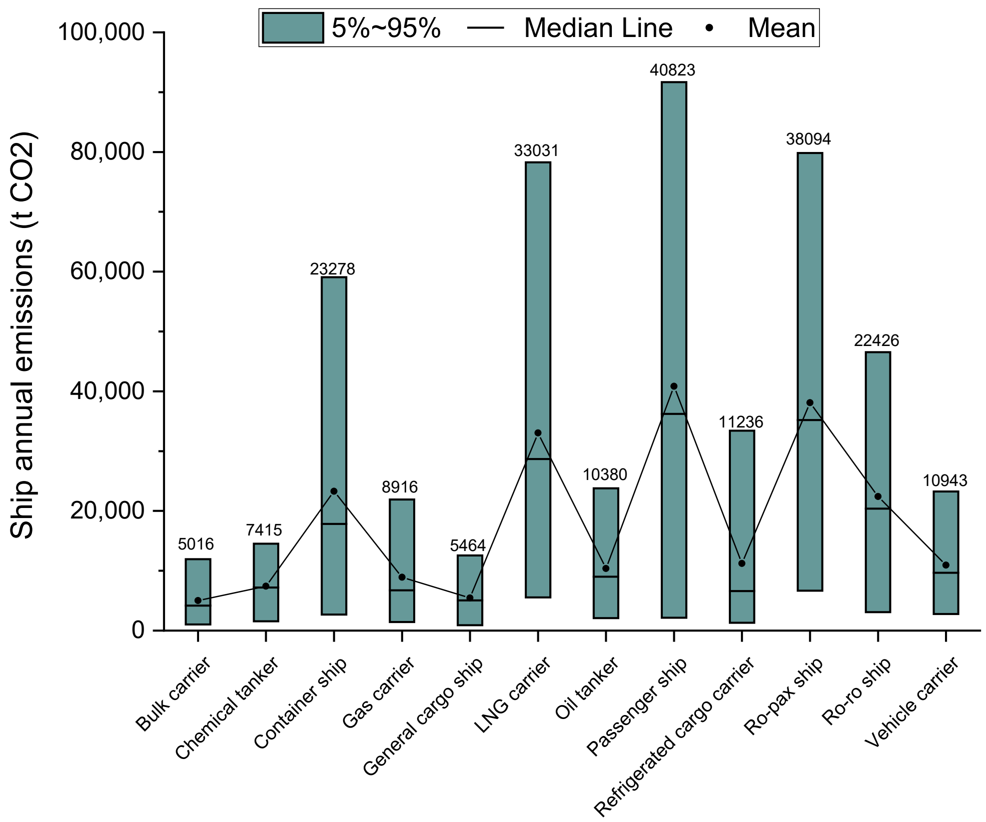
Figure 4. Share on total CO_2 emissions per ship category



Source: JRC, 2022.

The analysis of the 2019 CO_2 emissions of the reporting fleet, by ship category is shown in Figure 5. Among all categories considered, ships involved in the transport of people, that is, passenger ships and ro-pax ships are the ones showing higher average CO_2 emission per ship during 2019 (around 40 kt CO_2/ship). Regarding freight transport, LNG carriers, appear to be the ship category with the highest average CO_2 emissions per ship (33 kt CO_2/ship). On the other hand, bulk carriers are the ones with the lowest CO_2 emissions per ship (5 kt CO_2/ship during 2019).

Figure 5. Ship CO_2 emissions. The lines are simply a guide for the eye.

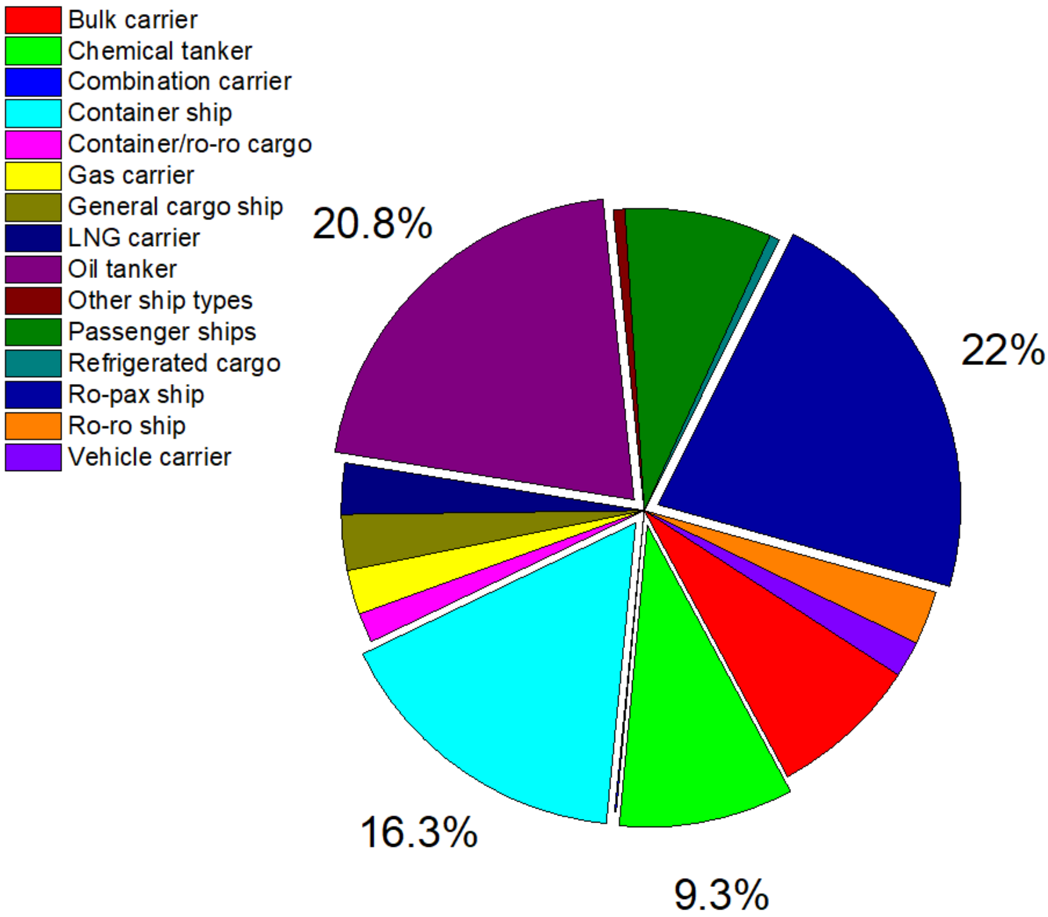


Source: JRC, 2022.

Emission reporting also helps identifying the location of the emissions: i.e., if they happened at sea or at berth. Emissions at sea are reported in three different categories: trip between EU ports, trip from EU ports, and trip to EU ports. The share of emissions among these categories is quite similar, around 45 Mt CO_2 each. The remaining 10.6 Mt CO_2 of emissions during 2019 were emitted at berth, representing 7% of total emissions. Regulation (EU) 2015/757 defines a ship at berth as a ship which is securely moored or anchored in a port falling under the jurisdiction of a Member State while it is loading, unloading or hotelling, including the time spent when not engaged in cargo operations.

Examination of the values provided in the report shows (see Figure 6) that ro-pax ships (22%) and oil tankers (20.8%) are the main CO_2 emitters at berth. Container ships also represent a good share (16.3%) of total CO_2 emissions at berth.

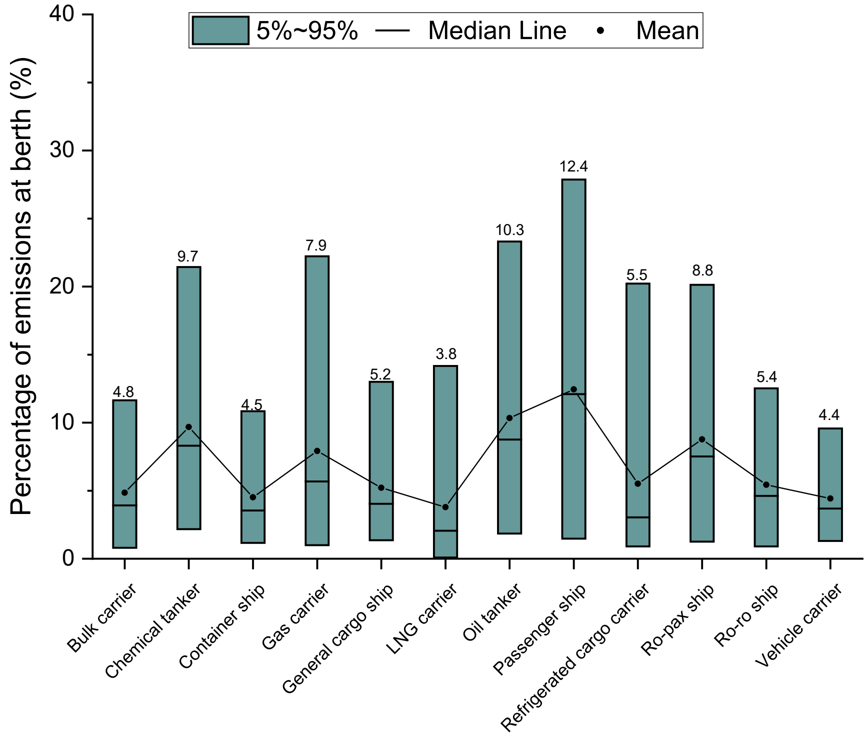
Figure 6. Share of CO_2 emissions at berth per ship category



Source: JRC, 2022.

The results of the statistical analysis on the percentage of total emission happening at berth for each ship category is shown in Figure 7. Passenger ships, which typically have a higher number of port calls per year, appear to be the ship category with higher share, in average, of their CO_2 emissions at port 12.5%, followed by oil and chemical tankers. According to data reported, an oil tanker would emit at berth, on average, 10.3 % of its annual emissions (9.7% in the case of chemical tankers).

Figure 7. Statistical analysis of reported percentage emission during time spent at berth, per ship category. The lines are simply a guide for the eye.

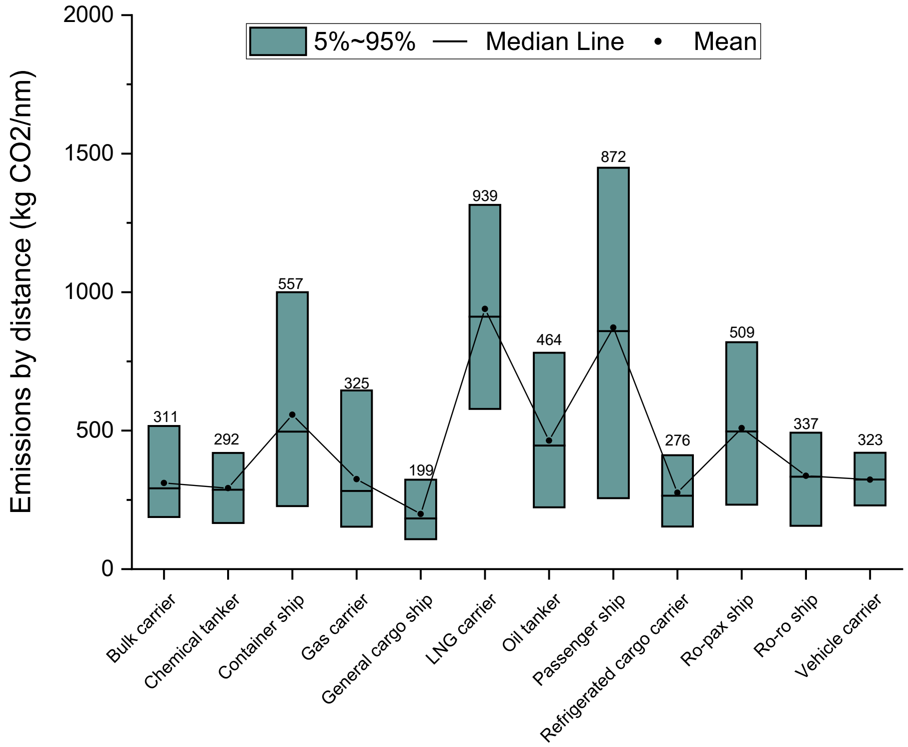


Source: JRC, 2022.

The analysis presented in Figure 5 provides the amount of CO_2 emitted, but it does not reflect the efficiency of the different boats, since factors as the distance travelled by the ship, or the cargo transported (or the size of the ship) are not considered.

CO_2 emissions per distance by each ship during 2019 is also reported by ship operators under the request of Regulation (EU) 2015/757. This parameter is calculated by dividing the total annual CO_2 emissions by the total distance travelled by the ship. The statistical analysis of this data, displayed by ship categories in Figure 8, identifies LNG carriers (940 kg CO_2/nm) and passenger ships (872 kg CO_2/nm) as the ship categories with higher average CO_2 emissions per nautical mile travelled during 2019, followed by container and ro-pax ships. General cargo ships, with less than 200 kg CO_2/nm per ship, appears as the ship category with the lowest average CO_2 emissions per distance.

Figure 8. Ships CO_2 emissions per distance. The lines are simply a guide for the eye.



Source: JRC, 2022.

The data available at the THETIS-MRV portal also includes annual average CO_2 emissions per transport work, for every ship. This parameter is calculated by dividing the total annual CO_2 emissions by the total transport work. Transport work is determined by multiplying the distance travelled by the amount of cargo carried. Therefore, this parameter is usually expressed in gram of CO_2 per tonne transported per nautical mile.

In the case of ro-ro ships, cargo carried is defined as the number of cargo units (trucks, cars, etc.) or lane-metres multiplied by default values for their weight. For container ships, cargo carried is defined as the total weight in metric tonnes of the cargo or, failing that, the amount of 20-foot equivalent units (TEU) multiplied by default values for their weight. For all other categories of ships, the amount of cargo carried is expressed either as metric tonnes or as standard cubic metres of cargo, as appropriate.

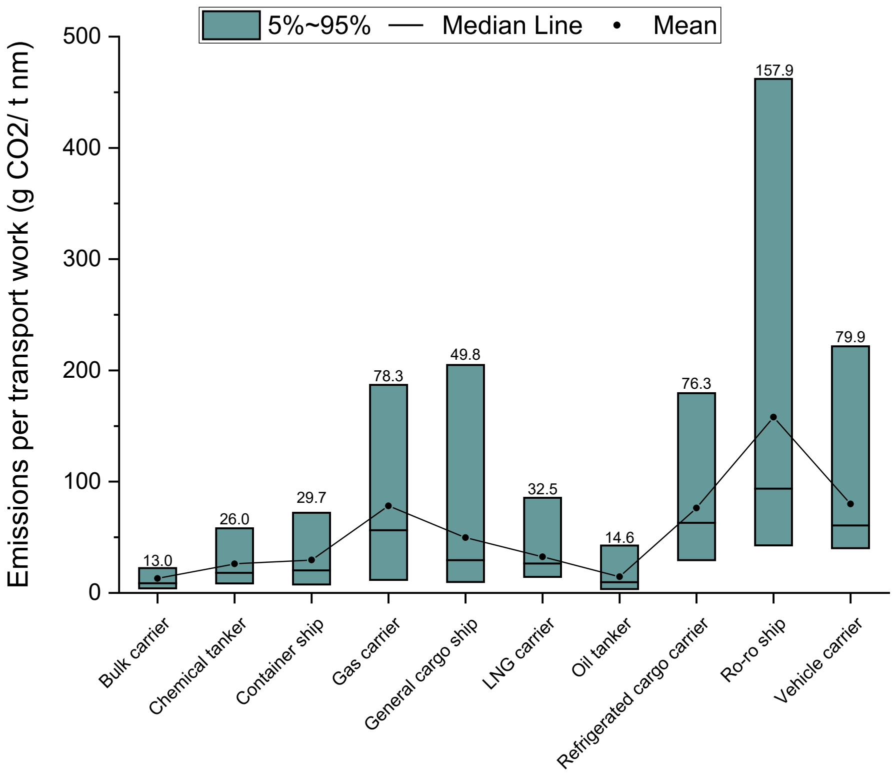
Ships involved in the transport of passengers (i.e., passenger ships and ro-pax) are not assessed using this parameter, in this case, the number of passengers is used to express cargo carried, not allowing the comparison against other ship categories. Moreover, most of the LNG carriers and container/ro-ro cargo ships, preferred to report their transport work per volume (cubic meters) instead of mass (tonnes). Therefore, it is problematic to present these data as transport work in Figure 9.

In the case of LNG carriers, two ships were identified providing CO_2 emissions per transport work both in volume and in mass. From these values it is possible to identify a cargo density of 0.43 t/m^3 (LNG density is 0.45 t/ m^3). Hence, the value of 0.43 t/m^3 is used as reference to transform the LNG carriers data of emissions per volumetric transport work from g CO2/m^3·nm to g CO_2/t·nm, allowing their inclusion in the following analysis.

In Figure 9 it can be seen that bulk carriers are, on average, the most transport-efficient ships in terms of transport work, with 16.4 g CO_2/t·nm, followed by oil (20 g CO_2/t·nm) and chemical tankers (26 g CO_2/t·nm).

On the other hand, ro-ro ships appear to have the worst environmental performance when referring to CO_2 emissions per transport work, with a value of 158 g CO_2/t·nm on average.

Figure 9. CO_2 emissions per transport work. The lines are simply a guide for the eye.

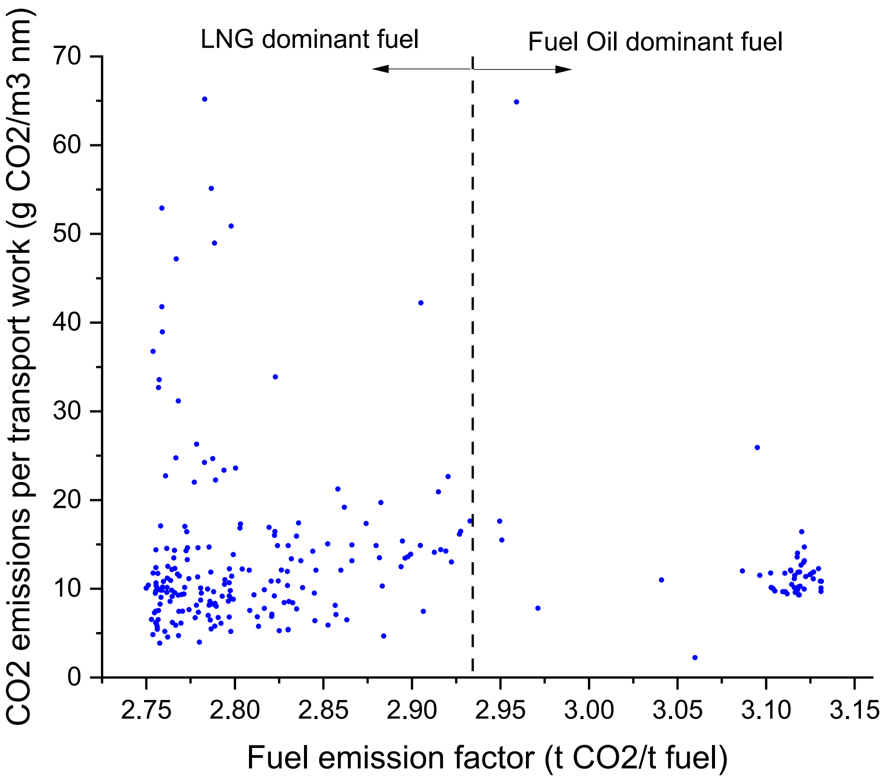


Source: JRC, 2022.

By identifying the fuel emission factor of each ship and comparing it against its value for CO_2 emissions per transport work it is possible to assess if a particular fuel emission factor (i.e. a type of fuel) is related to a worse emissions performance. This analysis is done in the case of LNG carriers, where the number of ships using natural gas, fuel oil, or a combination of both is big enough (see Figure 2) to assess if the use of a fuel with less carbon content (lower fuel emission factor) such as LNG, will lead to a better emissions performance (g CO_2 per transport work).

In Figure 10, CO_2 emissions per transport work in volume (g CO_2/m^3·nm) of every LNG carrier are reported against their respective fuel emission factor. Best emission performance (2.23 g CO_2/m^3·nm) is obtained by a LNG carrier with a fuel emission factor above 3.06, indicating that this ship probably used fuel oil as the main fuel (around 85%). While low emissions per transport work are reached by LNG carriers running on (almost) 100% natural gas (fuel emission factor around 2.75), they are not significantly lower than the ones for LNG carriers running mostly on fuel oil. Moreover, Figure 10 also shows that LNG carriers with LNG as dominant fuel can have worse emission performance than LNG carriers where fuel oil is the dominant fuel. The lack of further information (e.g. operational profile or type of engine) challenges the explanation for this worse environmental performance. For instance, the fact that dual-stroke engines (fuelled with HFO) have higher efficiency than dual-fuel engines and steam turbines could partially explain the trend observed in Figure 10,

Figure 10. CO_2 emissions per transport work for LNG carriers as function for the emission factor reported



Source: JRC, 2022.

The Energy Efficiency Design Index (EEDI), calculated as indicated in resolution MEPC.245(66) (IMO 2014), is to be reported by ships falling under the EU MRV.

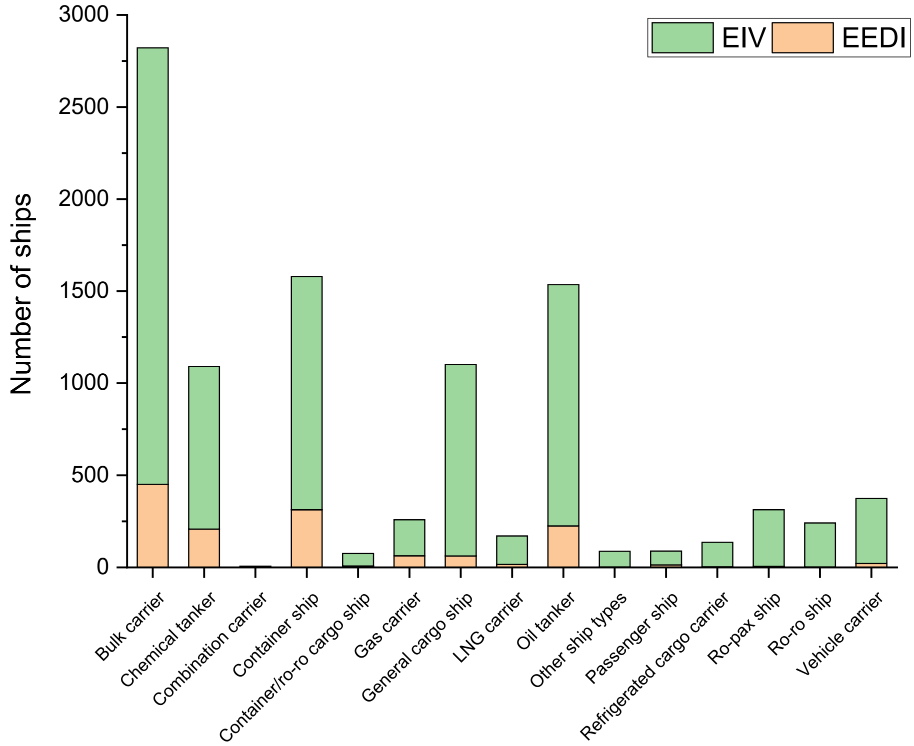
According to MEPC.203(62) (Marine Environment Protection Committee 2011), EEDI is mandatory for new ships above 400 gross tonnage (GT). According to MEPC.1/Circ.795/Rev.3 a ship is considered new if:

1. the building contract is placed on or after 1 January 2013; or
2. in the absence of a building contract, the keel of which is laid or which is at a similar stage of construction on or after 1 July 2013; or
3. the delivery of which is on or after 1 July 2015

For ships where the EEDI is not compulsory, the Estimated Index Value (EIV) has to be reported. EIV is calculated as described in resolution MEPC.214(63) (Marine Environment Protection Committee 2012). Nevertheless, ships are encouraged to report voluntary EEDI values, if available, instead of the EIV. Both indexes provides reference for the energy efficiency of the ship and it is expressed as (g CO_2/t·nm).

Out of 12,204 ships, 9,883 reported their efficiency index. EIV was the most reported index by far (8,489), suggesting that, since the condition of more than 400 GT is fulfilled by the boats falling under Regulation (EU) 2015/757 (ships above 5,000 GT), most of the reporting ships were built before 2013. Figure 11 depicts the share of the efficiency indexes reported per ship category.

Figure 11. Efficiency indexes reported by ship category



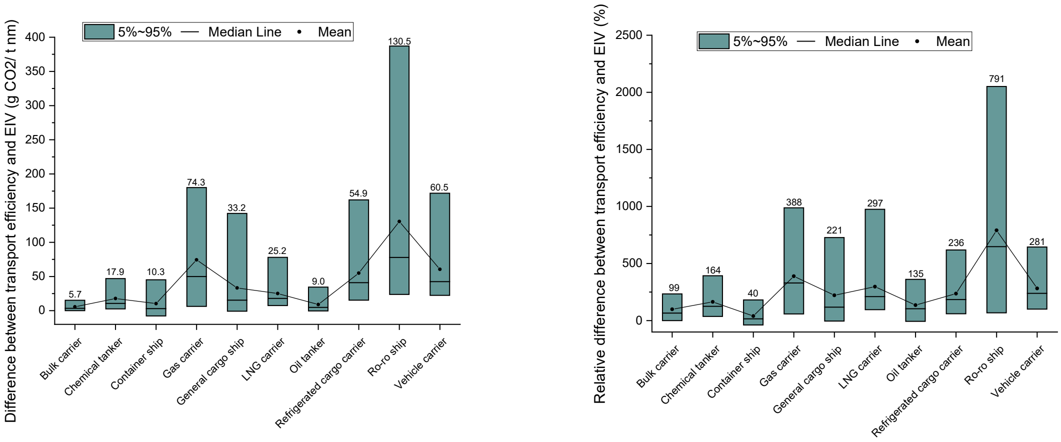
Source: JRC, 2022.

The efficiency indexes can be compared against the emissions per transport work reported by the ships. This comparison is done to identify if these efficiency indexes are representative of the actual ship emissions performance, assuming that reported emissions performances are equivalent to the actual emissions performances. As the EEDI should be a more accurate index than the EIV, the comparative analysis against the actual performance has been done separately for EEDI and EIV. For every ship, the absolute and relative differences between the efficiency indexes and the actual performance (emissions per transport work, see Figure 9) are calculated. The statistical analysis of the calculated differences, per ship category, can be seen in Figure 12 (for EIV) and Figure 13 (for EEDI).

While in some particular cases the efficiency indexes are quite representative of the reported performance, the analysis indicates that this is not generally the case. In container ships, for instance, reported emissions are, on average, 40% higher than the value indicated by the EIV (see Figure 12, right side). In the EEDI case, this value goes down to 24.8 % for container ships (see Figure 13, right side). The differences observed are even bigger for other ship categories, as in the case of chemical tankers, where emission performances reported are, on average, 164% higher than the respective EIV (170% in the case of EEDI). It has to be noted that, in the reporting of emissions per transport work, trips without cargo (e.g. the returning trip of an empty oil tanker) are part of such calculations. This fact can explain, partially, the differences observed between this parameter and the efficiency indexes (EEDI and EIV).

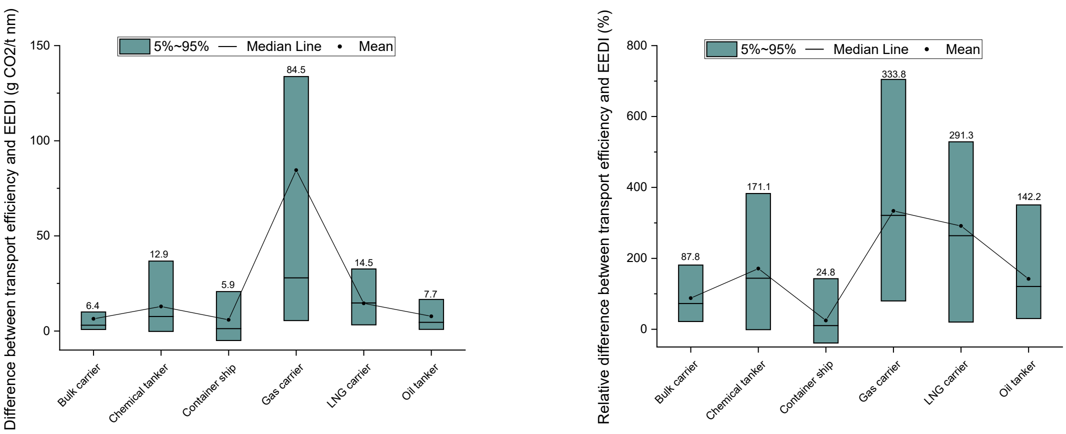
Comparing mean values of relative differences from Figure 12 and Figure 13 it can be observed that the deviation of EIV and EEDI from the reported performance is quite similar.

Figure 12. Analysis of differences between EIV and transport efficiency of the ship. The lines are simply a guide for the eye.



Source: JRC, 2021.

Figure 13. Statistical analysis of differences between EEDI and actual performance of the ship.

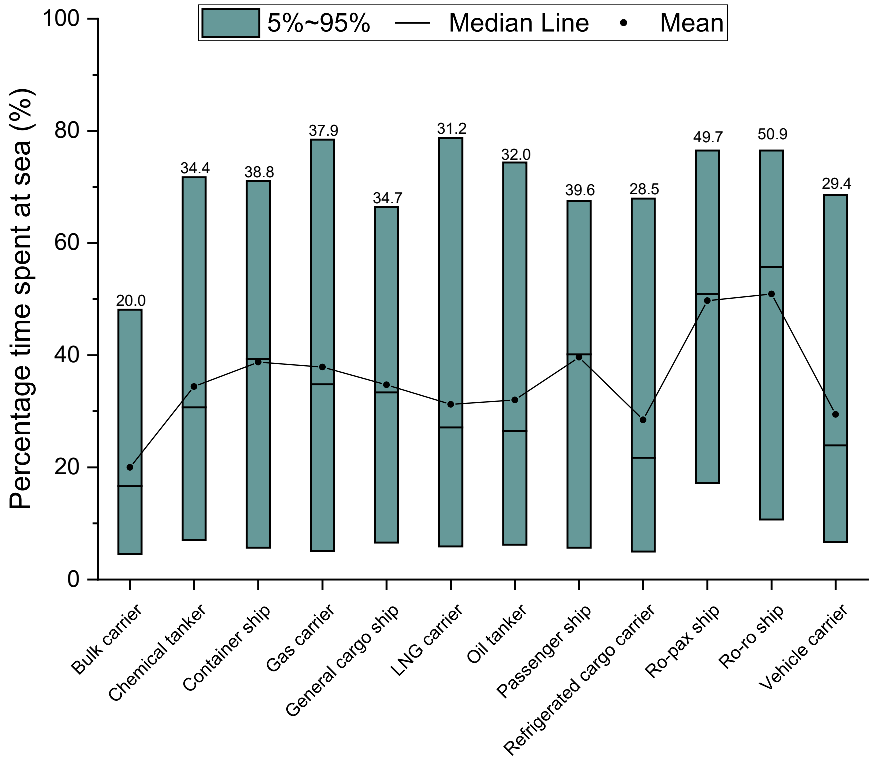


Source: JRC, 2022.

Operational parameters of the reporting ships have also been analysed. For instance, the average percentage of time spent at sea (considering 8,760 hours per year) by ship category is shown in Figure 14. The time spent at sea is calculated by ship operators based on port departure and arrival information and it excludes anchoring. Moreover, it has to be noticed that what qualifies as time spent at sea is not defined in Regulation (EU) 2015/757, and that according to such regulation, the procedures, responsibilities, formulae and data sources for determining and recording the time spent at sea between the port of departure and the port of arrival must be included in the documentation reported. This suggest that there is not a harmonised way of reporting time at sea, which brings certain level of uncertainty to the data analysis presented in Figure 14.

Ships spent, at least, 50% of the year at port, or engaged in trips between ports that do not fall under the Regulation (EU) 2015/757. Bulk carriers spent less than the 20 % of their time at sea. This might indicate that operations at port take more time for this ship category, but it could also be related to other operational reasons (e.g. trips taking place outside the Regulation (EU) 2015/757).

Figure 14. Percentage of time spent at sea during trips to, from or between ports falling under the Regulation (EU) 2015/757. The lines are simply a guide for the eye.

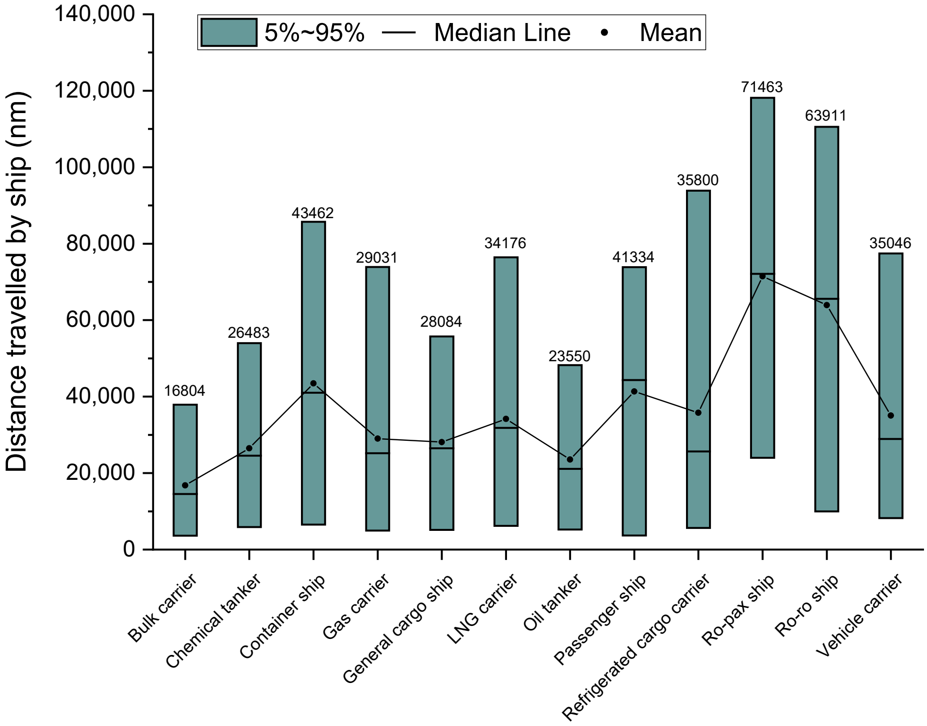


Source: JRC, 2022.

Another operational parameter that can be analysed is the distance travelled by a ship during 2019 in trips falling under the Regulation (EU) 2015/757. Nautical miles travelled by each reporting ship are calculated by dividing the total CO_2 emissions of the ship by its CO_2 emissions by distance, which are part of the data reported by the ships. According to the Regulation (EU) 2015/757 distance travelled may be either the distance of the most direct route between the port of departure and the port of arrival, or the real distance travelled. In the event of use of the distance provided by the most direct route between the port of departure and the port of arrival, a conservative correction factor should be taken into account to ensure that the distance travelled is not significantly underestimated. The ship operator shall specify which distance calculation is used and, if necessary, the correction factor used.

Ro-pax and ro-ro ships are the ship categories that show, on average, the longest travelled distance by ship in 2019 (around 71,500 nm and 64,000 nm per ship, respectively, see Figure 15). On the other hand, bulk carriers travelled only around 16,800 nm per year on average.

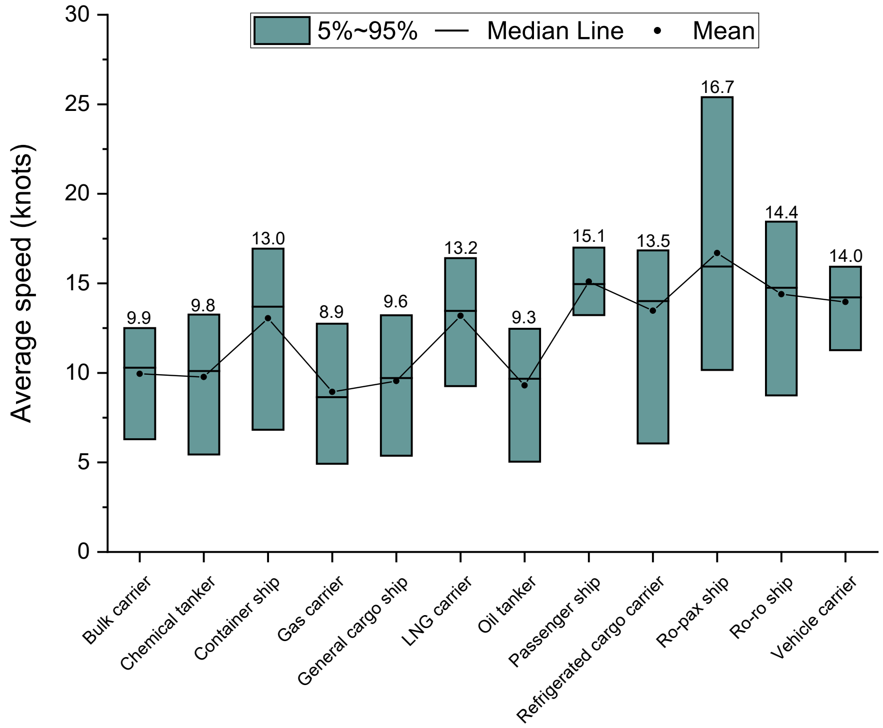
Figure 15. Statistical analysis of distance travelled per ship. The lines are simply a guide for the eye.



Source: JRC, 2022.

Considering the distance travelled per ship and the hours spent at sea, it is possible to perform a rough estimation of the average speed of each ship. The results of this estimation can be seen in Figure 16. Ships involved in the transport of passengers are the ones showing the highest average speeds, with Ro-pax ships having the highest mean average speed (16.7 knots). On the other hand, gas carriers appear as the slowest ship category, with a mean average speed of 8.9 knots.

Figure 16. Average speed per ship category. The lines are simply a guide for the eye.

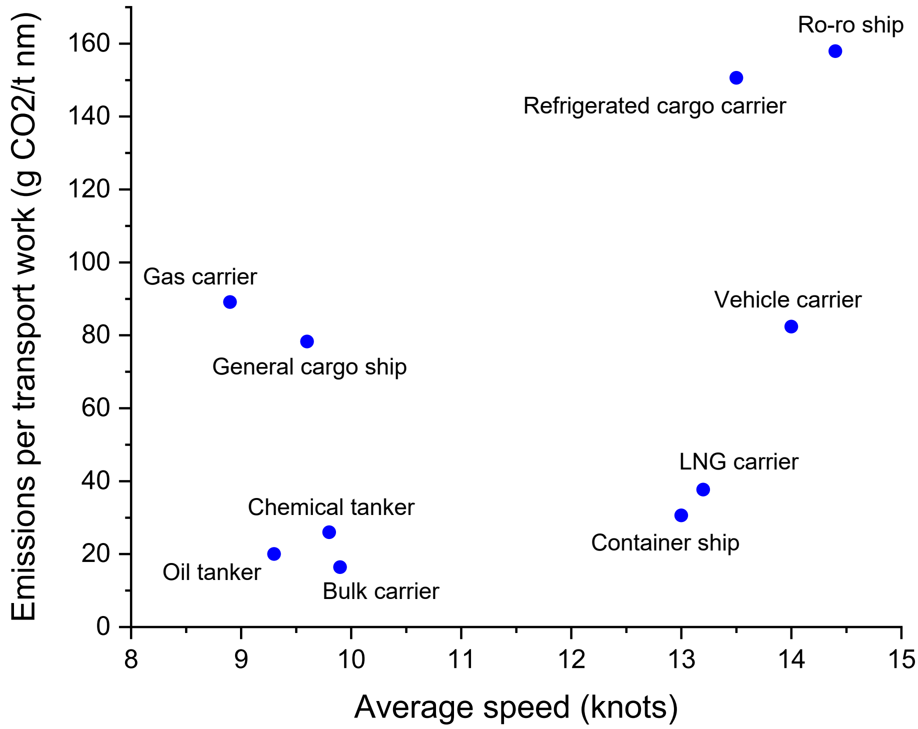


Source: JRC, 2022.

The means, per ship category, of the emissions per transport work are compared in Figure 17 against their respective average speed. As mentioned before, emissions per transport work are not applicable to passenger and ro-pax ships, therefore, this ship categories are not included in the analysis.

It is not possible to identify a simple trend linking higher speeds with a worse emissions performance. Nevertheless, the ship category with the highest average speed (ro-ro ship) is the one with the highest emissions per transport work, in average. This result suggests that other parameters (e.g. ship size) in addition to speed should play a relevant role in the emissions performance of the ship.

Figure 17. Comparison between average emissions per transport work and average speed



Source: JRC, 2022.

2.3 Conclusions

CO_2 emissions are accounted in a tank-to-wake basis. Emissions are reported by ships following methodologies based on the measurement of the fuel consumed on board. This fuel amount is transformed in to CO_2 emissions accordingly to its fuel emission factor (see Table 1).

From the analysis on fuel emissions factor it is concluded that heavy fuel oil is the most used fuel among the reporting ships. LNG as fuel has a relevant role in the case of LNG and gas carriers.

Freight transport accounts for 85% of the CO_2 emissions reported under Regulation (EU) 2015/757 in 2019. Most of the CO_2 is emitted by three types of cargo ships, namely container ships, oil tankers, and bulk carriers, which are also the most numerous ship categories reporting under Regulation (EU) 2015/757.

Emissions at ports represent 7% of total emissions reported in 2019. Almost 30% of these emissions arise from ships transporting passengers, while container ships, together with oil and chemical tankers were responsible for 46% of the total reported emissions at berth.

Regarding environmental performances, the boats emitting the most of the CO_2 are also the ones with a better environmental performance in terms of emissions per transport work (g CO_2/t nm). Bulk carriers, followed by oil and chemical tankers have the lowest average value of emissions per transport work. This could be partially explained by the density of the cargo these types of ship usually carry.

Although LNG carriers use a fuel mix with a lower CO_2 emission factor (mostly LNG) than other types of cargo ships, their environmental performance results appear be worse than for instance containers, oil tankers, or bulk carriers. This could be also related to the density of the cargo transported, which it is probably lower in the case of LNG carriers than, for instance, an oil tanker. Moreover, there is a relevant share of steam turbine engines in the LNG carrier fleet (MAN 2014). As steam turbine engines are less efficient than internal combustion engines, this could also explain the worse environmental performance compared to other cargo ships.

The analysis of the environmental performance of the LNG carrier fleet shows that a fuel with lower content in carbon (i.e. LNG) might not necessarily lead to a lower emissions per transport work. The higher efficiency of dual-stroke engines (fuelled with HFO) compared to dual-fuel engines and steam turbines could partially explain the better environmental performance of LNG carriers running on fuel oil (Huan et al. 2019)

Comparison of annual transport work against the different efficiency indexes shows that these indexes are not a representative value of the reported ship emissions performance.

In many cases the dispersion of the values of a certain parameter within a ship category is quite big. This dispersion can only be explained by the variety of sizes and operational profiles that can be found within the same ship category. The lack of data provided in this regard does not allow for a further refinement of the analysis (e.g. influence of ship size), that would lead to more accurate conclusions.

Data reported and published through the THETIS-MRV portal should be revised: typos and wrong inputs leading to non-logic values have been found. For instance, fuel emission factors higher than the highest possible value (i.e., 3.206 t CO_2/t fuel, corresponding to diesel/gasoil) have been identified.

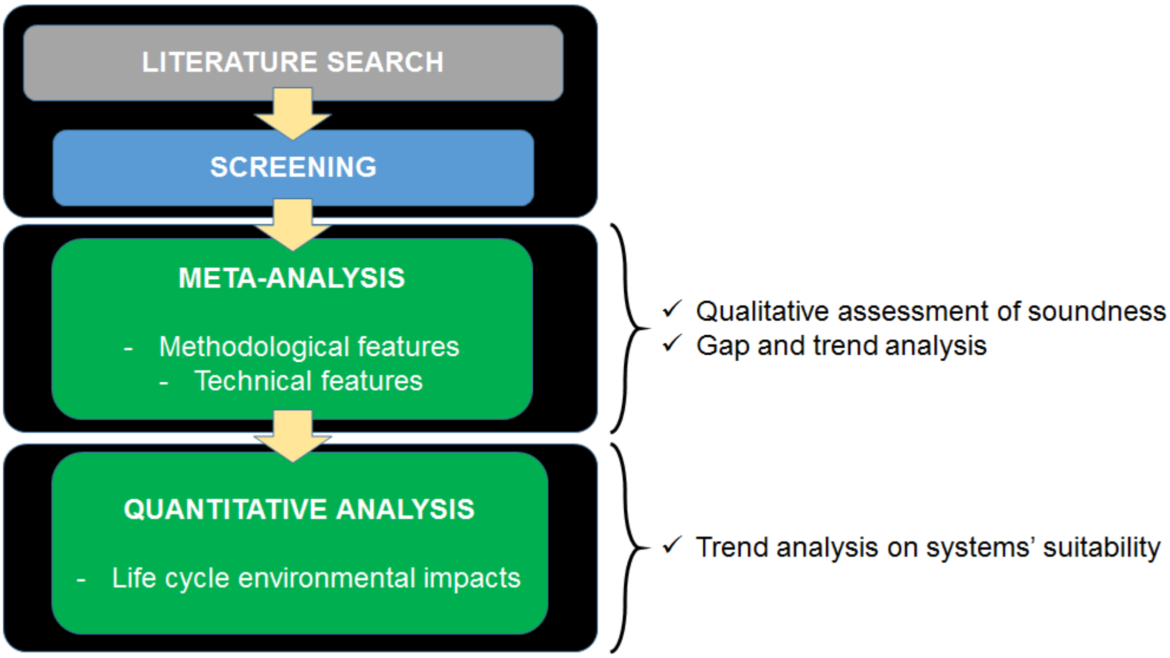
3 Meta-study LCA literature on maritime systems

3.1 Research approach

This report involves a complete review of LCA studies on maritime systems available until June 2020. The scientific literature under consideration included not only scientific articles but also relevant reports and other studies of interest such as indexed conference proceedings. The main goal of the review is to identify the areas where sources converge, contentious topics, and the main gaps and uncertainties currently present according to the available scientific literature.

Figure 18 presents the overall approach to the review of LCA studies on maritime systems. After an exhaustive literature search and screening, the final sample was subject to a meta-analysis of both methodological and technical features. The outcomes of this meta-analysis include a qualitative assessment on the soundness of the reviewed LCA studies and a gap and trend analysis. A joint quantitative assessment of the LCA results was also performed whenever possible and appropriate. The list of studies subject to such a quantitative analysis was determined based on the outcomes of the meta-analysis. It should be noted that LCA harmonisation for robust comparison was not pursued in this study, and therefore left out of the scope of this review.

Figure 18. Review approach and main outcomes.



Source: IMDEA, 2022.

3.1.1 Literature search and screening

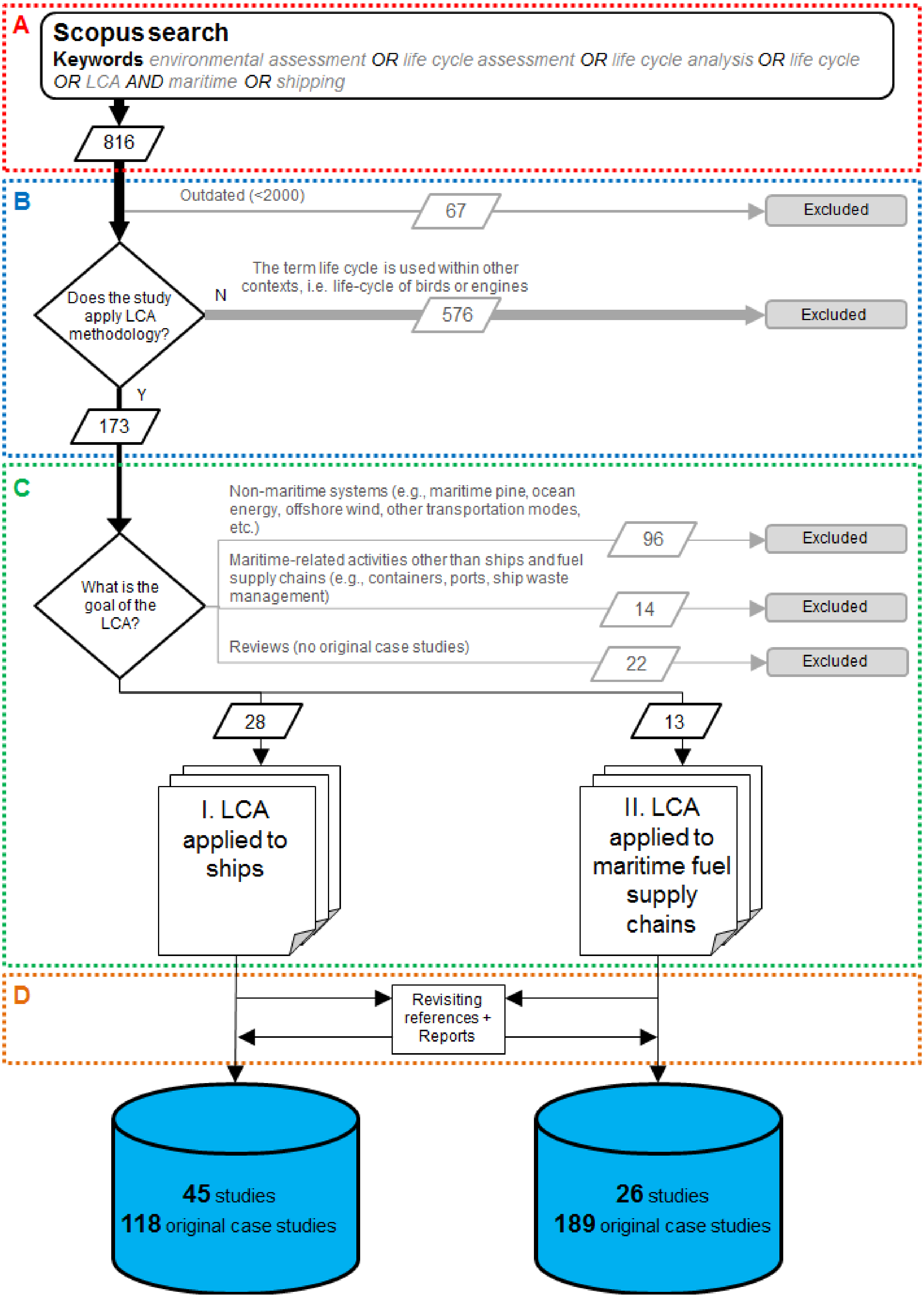
A systematic literature search procedure was followed to transparently identify relevant publications for the purpose of the review (Figure 19). The initial stage consists of a literature search via the Scopus database and including publications until June 2020 (stage A in Figure 19). When carrying out this search, the keywords “environmental assessment”, “life cycle assessment”, “life cycle analysis”, “life cycle”, “LCA”, “maritime” and “shipping” were used. In this regard, LCA was used as a first discriminant when it comes to searching for relevant scientific literature. This initial search resulted in 816 documents. The metadata of the documents was exported in csv format for further screening. The metadata included authors, title, year of publication, source, DOI, abstract, and document type.

The initial sample was screened in order to identify the scientific literature actually relevant to environmental LCA of maritime systems. A well-defined set of criteria was applied. The first and second screening criteria focused on identifying, and excluding, both outdated documents and studies that do not refer to the LCA methodology (stage B in Figure 19). The documents published before year 2000 were considered outdated and therefore excluded (67 documents). For the rest of the documents, the title and the abstract were reviewed in order to identify actual applications of LCA. Above 70% of the initial sample was disregarded at this point because of the lack of LCA application (576 documents). The excluded documents often use the term life cycle within contexts such as life cycle of birds or life cycle of engines.

After the application of the first and second criteria, 173 documents were selected for further screening. The third screening criterion focused on identifying studies that actually address the LCA of maritime systems (stage C in Figure 19). To that end, the goal and scope of each of the 173 documents were reviewed. Two well-differentiated categories of studies were identified at this point based on their goal and scope: studies that apply LCA to ships (28 documents), and studies that apply LCA to maritime fuel supply chains (13 documents). The first category covers studies that focus on the life cycle environmental profile of ships (e.g., ferries, tankers, and container ships) or specific parts of a ship such as the power system or the hull. These studies include activities involved in the shipbuilding or the manufacturing of the specific parts, whereas fuel production and combustion (if included) are not explicitly modelled but retrieved from databases or literature. The second category, in contrast, covers studies that focus on fuel supply chains. These studies explicitly model the activities involved in the supply of maritime fuels, such as the extraction of resources, fuel production, fuel distribution, and fuel combustion. The activities involved in shipbuilding or manufacturing of ship's parts are not generally included in this second type of studies. The studies outside these two categories were excluded (132 documents).

The sample obtained after the application of the screening criteria consists of 41 studies: 28 studies applying LCA to ships (or specific parts of a ship), and 13 studies applying LCA to maritime fuel supply chains. Therefore, approximately 95% of the initial sample retrieved from the Scopus database was disregarded (775 documents). This first finding highlights that the application of LCA within the maritime sector is still in its infancy. In order to seek for potentially missed studies, the references of each of the 41 documents were also explored (stage D in Figure 19). This practice, along with the search for reports, resulted in the addition of 17 studies that apply LCA to ships (or specific parts of a ship) and 13 studies that apply LCA to maritime fuel supply chains. With regard to the inclusion of reports, it should be noted that the approach followed in this study calls for works that actually involve a life cycle scope. This means that the selected studies have to address the upstream/downstream processes associated with at least one stage in the maritime system's life cycle. In consequence, several reports on the maritime sector were ruled out. For instance, IMO greenhouse gas studies provide an inventory of GHG emissions from shipping, but the scope is limited to fuel combustion (IMO 2015). Other reports excluded for the same reason are the 2019 Annual Report from the European Commission on CO_2 Emissions from Maritime Transport (European Union, 2020) and the Greenhouse Gas Emissions from Global Shipping 2013–2015 report by The International Council on Clean Transportation (Olmer et al., 2017). Furthermore, reports on LCA of fuel supply chains intended for road and/or air transportation, such as the JEC Well-to-Wells report (Prussi et al., 2020), were not included since the performance of fuel supply chains for road and/or air transportation is not generally translatable to shipping. Overlaps between project reports and articles already included in the sample were also avoided.

Figure 19. Literature search and screening procedure for the identification of the scientific literature on LCA of maritime systems.



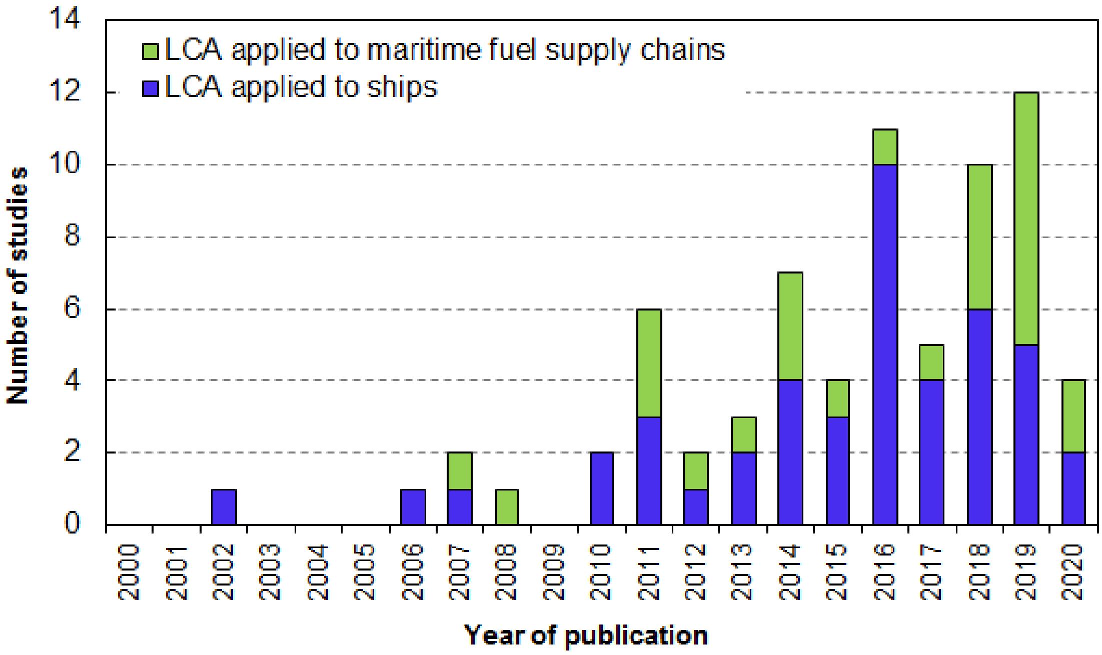
Source: IMDEA, 2022.

3.1.2 Overview of the final sample

The final sample of LCA studies of maritime systems includes 45 studies on LCA of ships (or specific parts of a ship), in which 118 original case studies were identified, and 26 studies on LCA of maritime fuel supply chains, in which 189 original case studies were identified. For the studies on LCA of ships, each variation in technological aspects (e.g., type of ship, hull material, and engine power) was considered to define an original case study for the purpose of this review. For the studies on LCA of fuel supply chains, each variation in technological aspects (e.g., fuel, feedstock, and fuel processing technology) or location (e.g., feedstock origin) was also considered to define an original case study. Sensitivity analysis was not considered to be a source of original case studies. Documents with a very high number of original case studies (> 30) were not excluded, but their contribution to the results is highlighted when relevant in order to avoid potential distortions.

The lists of LCA studies reviewed are presented in the corresponding sections: the list of LCA studies on ships (or specific parts of a ship) is presented in Section 3.1 while the list of LCA studies on maritime fuel supply chains is presented in Section 4.1. Figure 20 provides further bibliometric details about the final sample. The publication trend in Figure 20 highlights an increasing interest in LCA of maritime activities, with more than 92% of the reviewed studies published in the period 2010-2020.

Figure 20. Year of publication of the reviewed studies on LCA of maritime systems.



Source: IMDEA, 2022.

3.1.3 Meta-analysis procedure

The final sample of studies on LCA of ships and maritime fuel supply chains was subject to a meta-analysis of both methodological and technical features. On the one hand, the methodological choices (e.g., functional unit, system boundaries, and impact categories) were investigated at the study level since these choices are generally homogeneous for each original case study within a particular study (Valente, Iribarren, and Dufour 2017). On the other hand, technical choices (e.g., type of ship, fuel, and feedstock) were investigated at the case study level. Table 2 presents the set of methodological and technical features under analysis. The analysed methodological features were the same for both categories of studies (i.e., LCA applied to ships and LCA applied to maritime fuel supply chains) since they are inherent in LCA regardless of the system assessed. In contrast, the technical features were defined for each category due to the different goal and scope.

Table 2. Set of methodological and technical features considered for the meta-analysis.

Study category	LCA applied to ships	LCA applied to maritime fuel supply chains
Methodological features	• Goal and scope • Modelling approach (attributional/consequential) • Functional unit • System boundary • Multifunctionality • Inventory data sources • Impact categories • Impact assessment methods • Normalisation • Weighting • Sensitivity analysis	
Technical features	• Type of ship • Manufacturing year • Dimensions of ship • Lifespan • Weight of ship • Hull material • Design/average speed • Type of main engines • No. of main engines • Power of main engines • Fuel used by main engines • End-of-life management	• Fuel • Feedstock • Fuel processing technology • Bunkering operation • Type of ship (for fuel combustion) • Type of engine (for fuel combustion) • Air pollution control system (APC)

Source: IMDEA, 2022.

3.1.4 Quantitative assessment of life cycle environmental impacts

A quantitative assessment of life cycle environmental impacts was performed when feasible and appropriate. This activity involved the collection of life cycle impact assessment results from selected studies and their processing. The scope of the quantitative assessment for the studies on LCA of ships (or specific parts of ships) differed from that for the studies on LCA of maritime fuel supply chains. The studies grouped under the first category cover a variety of goals and scopes as detailed in Section 3.1.1. This heterogeneity hampers a systematic quantitative assessment of the LCA results. In this regard, the quantitative assessment focused only on the studies performing LCA of ships with a Cradle-to-Grave scope (i.e., from raw materials extraction to end-of-life). For these studies, the contribution of upstream (raw materials extraction and shipbuilding), downstream (ship use) and end-of-life processes to the global warming impact was investigated. In this sense, the life cycle global warming impact was used as a representative indicator of the environmental impacts.

The studies grouped under the second category, LCA applied to maritime fuel supply chains, are homogenous in terms of goal and scope (Section 4.1.1). This allowed a more systematic quantitative assessment of the life cycle environmental impacts. A range of analyses were performed and included in Section 4.2. A breakdown between well-to-tank and tank-to-propeller results was applied as far as possible. Furthermore, an analysis of the case studies on alternative fuels was singled out and presented as a self-standing section to serve as the basis for any future action aimed at analysing the impact alternative fuels can have on the decarbonisation of the maritime sector.

3.2 LCA of ships

This section reviews LCA studies of ships. The sample includes 45 studies in which 118 original case studies were identified (Table 3). These studies involve a variety of goals and scopes. While a number of studies evaluate or compare the life cycle environmental performance of a ship or ships, other focus on specific parts of a ship and/or specific activities related to a ship. For example, a number of studies compare different configurations of the power system. In this regard, the system studied generally includes the life cycle stages related to the power system such as its manufacturing, operation, and end-of-life. Other ship-specific parts assessed are the hull or the ballast water treatment system. With regard to ship-related activities, several of the reviewed LCA studies focus on end-of-life strategies, hull maintenance strategies or shipbuilding methods. Hence, the first finding refers to the fact that the available scientific literature on LCA of ships is very heterogeneous in terms of goal and scope, which hampers a systematic assessment of the studies gathered.

Table 3. List of reviewed studies on LCA of ships.

ID	Reference	Goal	Type of ship involved	Scope according to Figure 22	No. original case studies
#1	(Dong and Cai 2020)	Non-comparative, ship	Bulk carrier	Cradle-to-Operation	1
#2	(Wang et al. 2020)	Comparative, power system configuration	Tugboat	GateOut-to-Grave	5
#3	(Pizzol 2019)	Comparative, ships	Ro-Ro	Cradle-to-Operation	13
#4	(Tuan and Wei 2019)	Non-comparative, ship	Bulk carrier	Cradle-to-GateOut	1
#5	(Wang et al. 2019)	Comparative, power system configuration	Ferry	GateOut-to-Grave	2
#6	(Hua, Cheng, and Hwang 2019)	Comparative, ships	Container ship	Cradle-to-Operation	2
#7	(Dong and Cai 2019)	Comparative, ships	Bulk carrier	Cradle-to-Grave	2
#8	(Favi, Campi, et al. 2018)	Comparative, ships	Yacht	Cradle-to-Grave	3
#9	(Jeong et al. 2018)	Comparative, power system configuration	Ferry	GateOut-to-Grave	5
#10	(Bicer and Dincer, 2018a)	Comparative, ships	Tanker, container ship	Cradle-to-Operation	2
#11	(Pagoropoulos et al. 2018)	Comparative, hull maintenance	Tanker	Cradle-to-Grave	1
#12	(Wang et al. 2018)	Comparative, hull maintenance	Ferry	GateIn-to-Grave	1
#13	(Favi, Germani, et al. 2018)	Comparative, hull material	Yacht	Cradle-to-Grave	4
#14	(Gilbert et al. 2017)	Comparative, end-of-life	Container ship	Cradle-to-Grave	3
#15	(Nian and Yuan 2017)	Comparative, ships	Tanker	GateIn-to-Grave	13
#16	(Favi et al. 2017)	Non-comparative, ship	Yacht	Cradle-to-Operation	1
#17	(Cucinotta, Guglielmino, and Sfravara 2017)	Comparative, shipbuilding method	Yacht	Cradle-to-Grave	1

#18	(Blanco-Davis and Zhou 2016)	Non-comparative, ship	Bulk carrier	Operation	1
#19	(Choi et al. 2016)	Comparative, end-of-life	Naval ship, tanker	Grave	2
#20	(J. Ling-Chin and Roskilly 2016)	Comparative, power system configuration	Ro-Ro	Cradle-to-Grave	2
#21	(Janie Ling-Chin and Roskilly 2016b)	Non-comparative, power system configuration	Ro-Ro	Cradle-to-Grave	1
#22	(Janie Ling-Chin and Roskilly 2016a)	Comparative, power system configuration	Ro-Ro	Cradle-to-Grave	3
#23	(Burman et al. 2016)	Comparative, hull material	Patrol boat	Cradle-to-Grave	5
#24	(Pommier et al. 2016)	Comparative, hull material	Boat	Cradle-to-Grave	4
#25	(Nahlik et al. 2016)	Comparative, ships	Container ship, tanker	Cradle-to-Operation	2
#26	(Ko and Gantner 2016)	Non-comparative, ship	Not specified	Cradle-to-Grave	1
#27	(Chatzinikolaou and Ventikos 2015b)	Non-comparative, ship	Tanker	Cradle-to-Grave	1
#28	(Chatzinikolaou and Ventikos 2015a)	Non-comparative, ship	Tanker	Cradle-to-Grave	1
#29	(Kjær et al. 2015)	Non-comparative, ship	Tanker	Cradle-to-Grave	1
#30	(Ko, Gantner, and Wehner 2015)	Comparative, end-of-life	Not specified	Cradle-to-Grave	2
#31	(Blanco-Davis and Zhou 2014)	Comparative, ballast water treatment system	Bulk carrier	Cradle-to-Grave	1
#32	(Zhang et al. 2014)	Comparative, ships	Cargo vessel, barge	Operation	2
#33	(Blanco-Davis, del Castillo, and Zhou 2014)	Comparative, hull maintenance	Ro-Ro	Cradle-to-Grave	2
#34	(Nicolae, Popa, and Beizadea 2014)	Non-comparative, ship	Container ship	Cradle-to-Grave	1
#35	(Schmidt and Watson 2013)	Comparative, hull material	Ferry	Cradle-to-Grave	2
#36	(Tchertchian, Yvars, and Millet 2013)	Comparative, ships	Ferry	Cradle-to-Grave	1
#37	(Dominic and Nandakumar 2012)	Comparative, hull material	Not specified	Cradle-to-Grave	1
#38	(Andersson and Winnes 2011)	Comparative, power system configuration	Ferry	Cradle-to-Operation	2
#39	(Zhao et al. 2011)	Non-comparative, ship	Tanker	Cradle-to-Operation	1
#40	(Ewing et al. 2011)	Non-comparative, maritime transportation company	Barge, boat	Cradle-to-Grave	1
#41	(Gratsos, Psaraftis, and Zachariadis 2010)	Comparative, ships	Bulk carrier	Cradle-to-Grave	4
#42	(Strazza et al. 2010)	Comparative, power system configuration	Not specified	Cradle-to-Operation	3
#43	(Tincelin 2007)	Comparative, ships	Passenger vessel, cargo vessel, catamaran, cruise ship	Cradle-to-Grave	6

#44	(Alkaner and Zhou 2006)	Comparative, power system configuration	Ferry	Cradle-to-Grave	2
#45	(Ellingsen, Fet, and Aanondsen 2002)	Comparative, power system configuration	Fishing vessel	Cradle-to-Grave	2

Source: IMDEA, 2022.

3.2.1 Methodological and technical features

3.2.1.1 Goal and scope

The LCA studies in Table 3 cover a variety of goals and scopes (Table 4):

- 46% of the studies were categorised as LCAs focused on ships, either non-comparative (22%) or comparative (24%). The ultimate goal of these studies is to quantify the life cycle environmental performance of a ship or to determine whether a ship outperforms other ships. These studies involve, for example, an LCA of a bulk carrier (#4), a comparative LCA of yachts (#8) and a comparative LCA of tankers (#15). Studies that perform a parameter variation analysis for a specific ship were categorised as non-comparative LCAs of ships. For example, #1 evaluates the influence of fuel consumption rate on the environmental performance of a bulk carrier. On the other hand, #3 compares different short-distance transportation routes across Scandinavia, but it was categorised as a comparative LCA of ships since each route involves a specific ship22% of the studies were categorised as LCAs of the power system. These studies focus on the life cycle environmental performance of different technical configurations of the power system in terms of, for example, the number and the total power of the main engines (#2, #5, #20, #22), the type of auxiliary engines (#44) and the use of hybrid diesel/solar engines (#5, #20, #21, #22). The scope of these studies is restricted to the life cycle stages specific to the power system such as its manufacture and operation.
- 11% of the studies focus on comparing hull material options such as steel and aluminium for a yacht (#13), wood, aluminium, and composite for a boat (#24), aluminium and composite for a patrol boat (#23), and steel and composite for a ferry (#35). These studies could be interpreted as comparative LCAs of ships (e.g., steel yacht versus aluminium yacht) since they involve the main life cycle stages of a ship such as shipbuilding and the ship operation. However, they were singled out since their ultimate goal is to identify the hull material that performs better from an environmental perspective.
- 7% of the studies compare the life cycle environmental performance of ship end-of-life strategies. #14 compares the environmental performance of recycling and reuse of the hull of a container ship, #19 compares the end-of-life of a naval ship and a tanker, and #30 evaluates the potential benefits of reuse in addition to recycling. Two of these studies (#14 and #30) involve all the life cycle stages of the ship and, therefore, could be considered as comparative LCAs of ships. However, the ultimate goal is to compare end-of-life strategies.
- 7% of the studies address the environmental performance of hull maintenance. #11 evaluates the environmental influence of hull cleaning frequency for a tanker, #12 investigates the environmental influence of the coating interval (from a yearly to two and three yearly basis) for a short route ferry, and #33 evaluates the application of a silicone-based fouling release coating as a retrofit for the underwater hull surface of a Ro-Ro ship.
- Other goals that arise as particularities in the reviewed studies are:
    - #31 compares the life cycle environmental performance of three ballast water treatment systems for a bulk carrier: ultraviolet irradiation, cavitation, and de-oxygenation.
    - #17 compares two methods, namely hand lay-up and vacuum infusion, for the building of a yacht.

- #40 performs the LCA of an inland marine transportation company using a hybrid input-ouput and process-based LCA.

Table 4. Categorisation of the studies according to their goal.

Goal category	Type of assessment	No. studies (% of the studies)	ID
LCA of ships	Comparative	11 (24%)	#3, #6, #7, #8, #10, #15, #25, #32, #36, #41, #43
	Non-comparative	10 (22%)	#1, #4, #16, #18, #26, #27, #28, #29, #34, #39
LCA of power system configurations	Comparative	9 (20%)	#2, #5, #9, #20, #22, #38, #42, #44, #45
	Non-comparative	1 (2%)	#21
LCA of hull material options	Comparative	5 (11%)	#13, #23, #24, #35, #37
LCA of ship end-of-life strategies	Comparative	3 (7%)	#14, #19, #30
LCA of hull maintenance strategies	Comparative	3 (7%)	#11, #12, #33
LCA of ballast water treatment system	Comparative	1 (2%)	#31
LCA of shipbuilding methods	Comparative	1 (2%)	#17
LCA of a marine transportation company	Non-comparative	1 (2%)	#40

Source: IMDEA, 2022.

In general, the reviewed studies do not mention the LCA modelling approach adopted (attributional/consequential). However, it could be deduced from the type of data used that attributional is the preferred approach (average data used). Only #35 applies a consequential approach based on marginal suppliers.

3.2.1.2 Functional unit

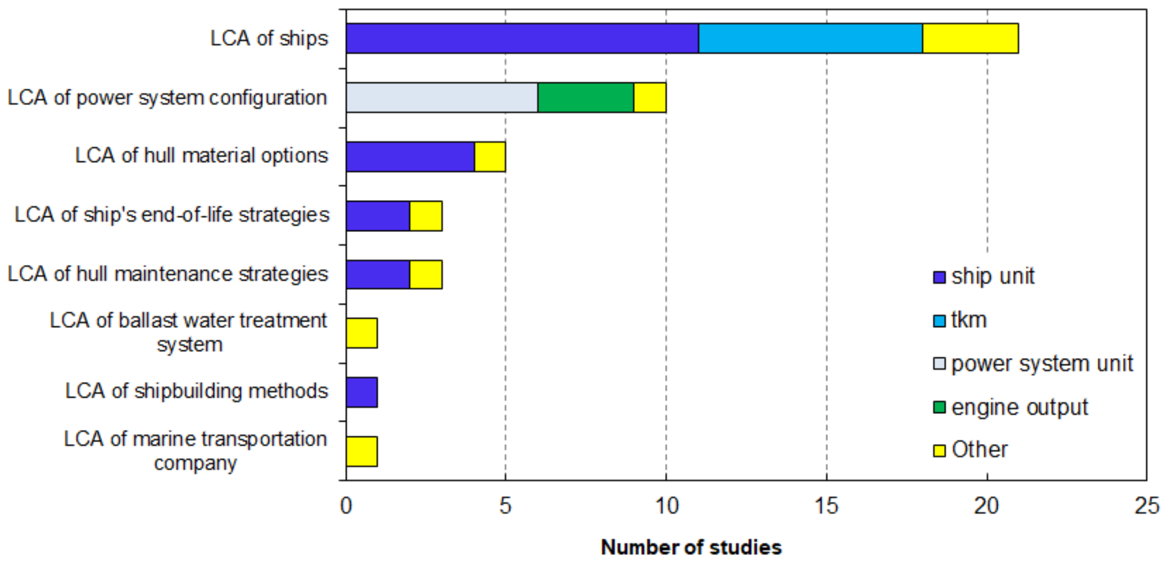
The functional unit quantifies the function of the product system and provides a reference unit to which the life cycle environmental impacts are reported (European Commission 2010). The choice of the functional unit must be defined in accordance with the goal and scope of the study. Therefore, Figure 21 shows the number of studies under each goal category broken down by the nature of the functional unit. It is remarkable that about 24% of the studies do not explicitly state the functional unit, although this could be deduced.

A functional unit based on a unit of ship was found to be the most recurrent choice for comparative/non-comparative LCAs of ships. This functional unit refers to the lifespan of a ship. For example, #13 literally defines the functional unit as: ''*the construction and the disposal of a vessel for the transportation of persons and goods and/or operational activities by sea for a period of T years, where T represents the lifespan of the product*''. Transportation of 1 t cargo over 1 km (tkm) was identified as the second most commonly used functional unit. This functional unit is exclusively used in comparative/non-comparative LCAs of ships. Other functional units used in comparative/non-comparative LCAs of ships are one average year of transport service and the transportation of a specific amount of cargo over a specific distance through one year.

A functional unit based on a unit of power system was found to be often used in LCAs of power system configurations. This functional unit is equivalent to a unit of ship but referred to the lifespan of the power system. Other LCAs of power system configurations use a functional unit based on engine work output (i.e., 1 kWh work output).

As observed, a functional unit based on a unit of ship was found to be used for a variety of goals in addition to comparative/non-comparative LCA of ships, such as LCAs of hull material options, LCAs of ship end-of-life strategies, LCAs of hull maintenance strategies, and LCAs of shipbuilding methods. The study that addresses a comparative assessment of ballast water treatment system uses as functional unit the yearly mass of ballast water treated, while the study that evaluates an inland marine transportation company uses as functional unit the yearly operation of the company.

Figure 21. Choice of functional unit in the reviewed studies on LCA related to ships according to the goal of the study.



Source: IMDEA, 2022.

3.2.1.3 System boundary

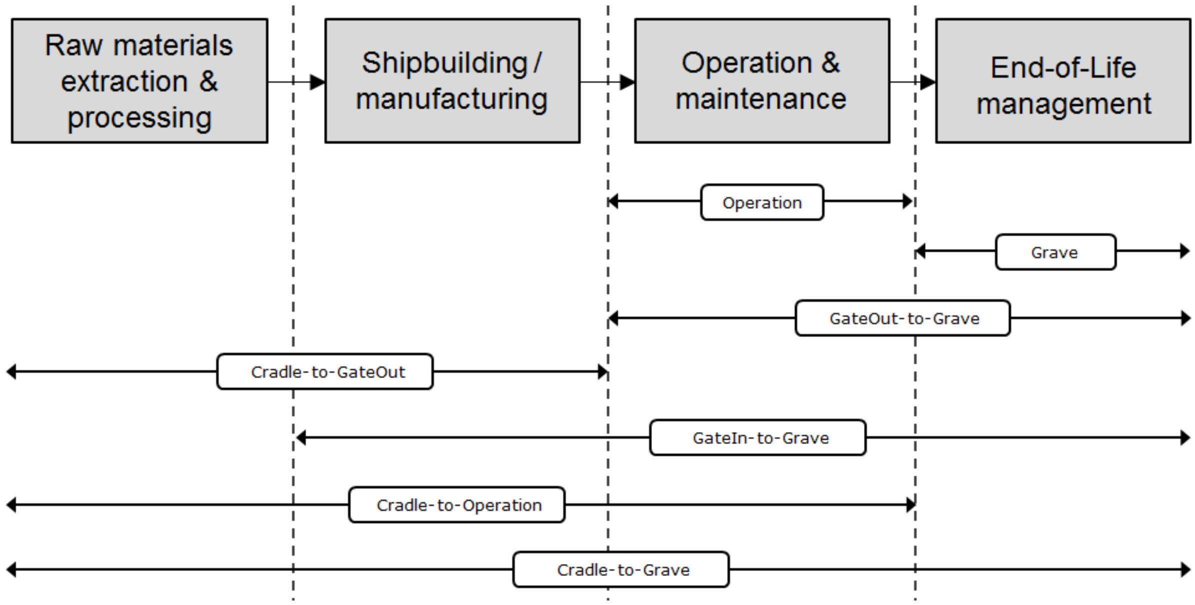
The definition of the system boundary varies with the goal and scope of the study. The complete system boundary of a ship system, so-called Cradle-to-Grave, would involve four main life cycle stages (Figure 22):

- Raw materials extraction.
- Shipbuilding or manufacturing (for studies that assess specific parts of a ship, e.g. manufacturing of the power system).
- Operation & maintenance.
- End-of-life management.

It should be noted that, depending on the goal of the study, the four stages might refer to different products such as the whole ship, the power system or the hull. For example, #7 compares two designs for a bulk carrier. The system boundary involves the following life cycle stages: extraction of raw materials and fabrication of the steel used in the ship, shipbuilding, ship operation & maintenance (plus fuel supply), and ship end-of-life. In contrast, #21 evaluates a hybrid power system based on solar energy for a Ro-Ro ship and the system boundary involves extraction of raw materials, manufacturing of the power system, operation & maintenance of the power system, and end-of-life of the power system.

In addition to the goal, the system boundary settings vary due to different scopes in terms of the number and type of the life cycle stages included. Up to seven system boundary settings were identified in the reviewed studies (Figure 22). For example, #4 performs the LCA of a bulk carrier and includes only the extraction of raw materials and shipbuilding, thus excluding the operation and the end-of-life stages. This setting was so-called Cradle-to-GateOut (the GateOut term refers to the ship exiting the building stage). A GateIn-to-Grave setting was defined for studies that include the shipbuilding/manufacturing stage but not the extraction of raw materials (#12, #15). The GateOut-to-Grave setting refers to studies that include the operation and the end-of-life stages, but exclude the extraction of raw materials and the shipbuilding/manufacturing stages. For example, #2 compares power system configurations for a tugboat, including the operation and the end-of-life of the power system, but excluding the extraction of the raw materials and the manufacturing of the power system.

Figure 22. System boundary settings in the reviewed studies on LCA related to ships.



Source: IMDEA, 2022.

Figure 23 shows the number of studies under each goal category broken down by system boundary settings, also showing the breakdown for the complete sample. About 60% of the studies (27 studies out of 45) were found to involve a Cradle-to-Grave scope. In fact, the Cradle-to-Grave scope was identified as the most used one within each goal category. About 48% of the LCAs of ships, 50% of the LCAs of power system configurations, and 100% of the LCAs of hull material options involve a Cradle-to-Grave scope. Furthermore, two of the three LCAs of ship end-of-life strategies follow a Cradle-to-Grave scope. The second most commonly applied system boundary setting is Cradle-to-Operation, which excludes only the end-of-life stage (20% of the studies, 9 studies out of 45). This setting was found in 33% of the LCAs of ships and 20% of the LCAs of power system configurations. It is remarkable that 30% of the studies that involve a Cradle-to-X scope specify that the raw materials considered are limited to the steel, thus disregarding other materials.

Shipbuilding was found to be included in about 67% of the studies (30 studies out of 45). In particular, about 90% of the LCAs of ships, 100% of the LCAs of hull material options, and 67% of the LCAs of hull maintenance strategies include shipbuilding. The two studies on LCA of shipbuilding methods and LCA of a maritime transportation company also include shipbuilding. On the other hand, only one study on LCA of power system configurations includes shipbuilding. With limited exceptions (e.g., #4 and #35), the studies do not provide detailed information on the shipbuilding stage. Instead, the information provided is generally restricted to the amounts of steel and electricity required (e.g., #1).

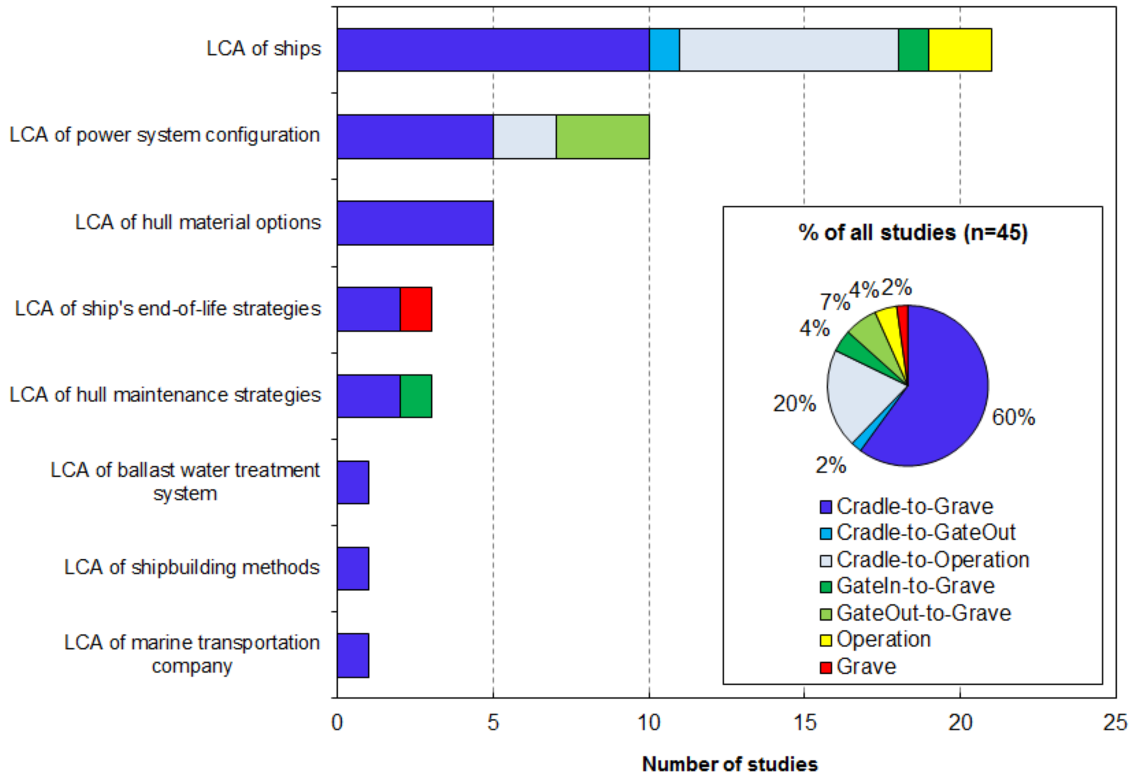
About 50% of the LCAs of power system configurations specify the manufacturing of the power system (5 studies out of 10). Three studies (#20, #21, #23; all involving the same authors) provide detailed information on the manufacturing of the main and auxiliary engines in terms of the materials considered. The other two studies (#42, #44) address the manufacturing of the auxiliary engine (solid oxide fuel cell and molten carbon fuel cell, respectively).

About 91% of the studies (41 studies out of 45) were found to include the use/combustion of fuel (either through ship operation or through power system operation). However, only 56% of these studies (23 studies out of 41) specify the inclusion of the life cycle environmental impacts associated with fuel supply.

Regarding end-of-life management, 27% of the studies omit this stage. Favi et al. (2017) offer two reasons to exclude end-of-life: (i) the end-of-life of a ship (or specific parts of the ship) is not borne by the shipyard, and (ii) there is a lack of established end-of-life strategies and market. Schmidt and Watson (2013) also highlight that the actual ship disposal/recycling is not known, and actual data are very difficult to obtain. The end-of-life of cargo carriers usually takes place in underdeveloped countries such as India or Bangladesh where safety and environmental regulation is lacking (Choi et al. 2016). The potential toxic and social impact of this stage for both workers and the environment remains so far unexplored from a life cycle perspective.

Overall, a lack of homogeneous and/or consolidated system boundary settings was found even among studies with the same goal (e.g., comparative/non-comparative LCA of ships or power system configurations). Furthermore, there is a significant lack of transparency in reporting the definition of the system boundary.

Figure 23. Choices of system boundary settings in the reviewed studies on LCA related to ships.



Source: IMDEA, 2022.

3.2.1.4 Technical choices

3.2.1.4.1 Type of ship

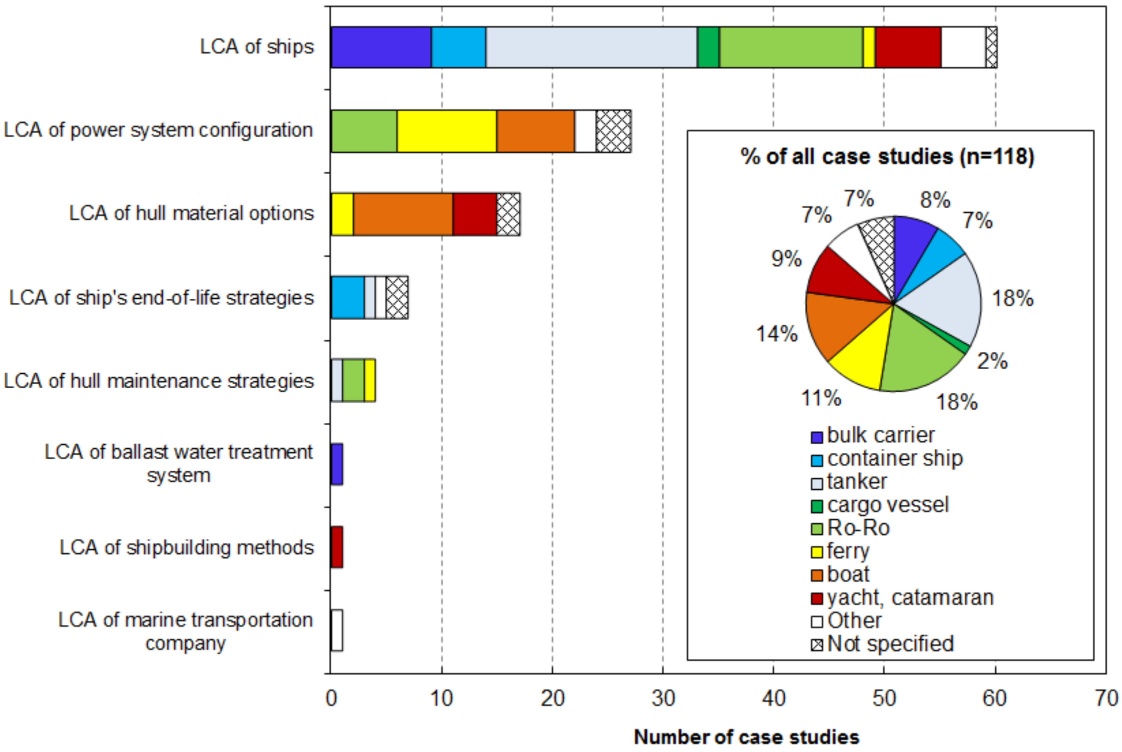
Figure 24 shows the number of case studies under each goal category broken down by the type of ship considered, also showing the breakdown for the whole set of case studies. It should be noted that, depending on the goal and scope of the study, the activities associated with the building of the ship may or may not be included. Nevertheless, an underlying type of ship is always considered whatever the goal and scope. For example, #2 compares a range of power system configurations in terms of the number and power of the main engines for a tugboat.

The trend in Figure 24 indicates that the comparative/non-comparative LCAs of ships evaluate mainly big cargo ships –such as tankers (19 case studies), bulk carriers (9 case studies), and container ships (5 case studies)–, Ro-Ro ships (13 case studies), and yachts/catamarans (6 case studies). It should be noted that the case studies involving Ro-Ro ships come from a single reference (#3). The ships assessed in the highest number of different studies were found to be tankers (6 studies: #10, #15, #27, #28, #29, #39), bulk carriers (5 studies: #1, #4, #7, #18, #41), and container ships (4 studies: #6, #10, #25, #34). This finding suggests an interest in evaluating or comparing the life cycle environmental performance of big cargo ships.

The LCAs of power system configurations were found to involve mainly ferries (9 case studies), boats (7 case studies), and Ro-Ro ships (6 case studies). For example, #5 compares a diesel and a hybrid (diesel plus photovoltaics) power system for a ferry, #21 evaluates a hybrid (diesel plus photovoltaics) power system for a Ro-Ro ship, and #2 compares a range of power system configurations in terms of the number and power of the main engines for a tugboat. With regard to the comparative LCAs of hull material, which have a similar scope than LCAs of ships, these involve boats (9 case studies), yachts/catamarans (4 case studies), and ferries (2 case studies).

Omitting distortion sources (viz., study #3 on Ro-Ro ships), the most commonly considered type of ship was found to be tankers (18% of the case studies). Big cargo ships (tankers, bulk carriers, container ships, and cargo vessels) are considered in about 35% of all studies, while relatively smaller ships (Ro-Ro, boats, and ferries) are considered in 52% of all case studies. The label "Other" in Figure 24 includes barges (defined in one case study in #32), naval ships (defined in one case study in #19), passenger vessels (defined in one case study in #43), and a whole company fleet of barges and boats as defined in #40. A significant number of case studies (8 case studies) do not specify the type of ship considered.

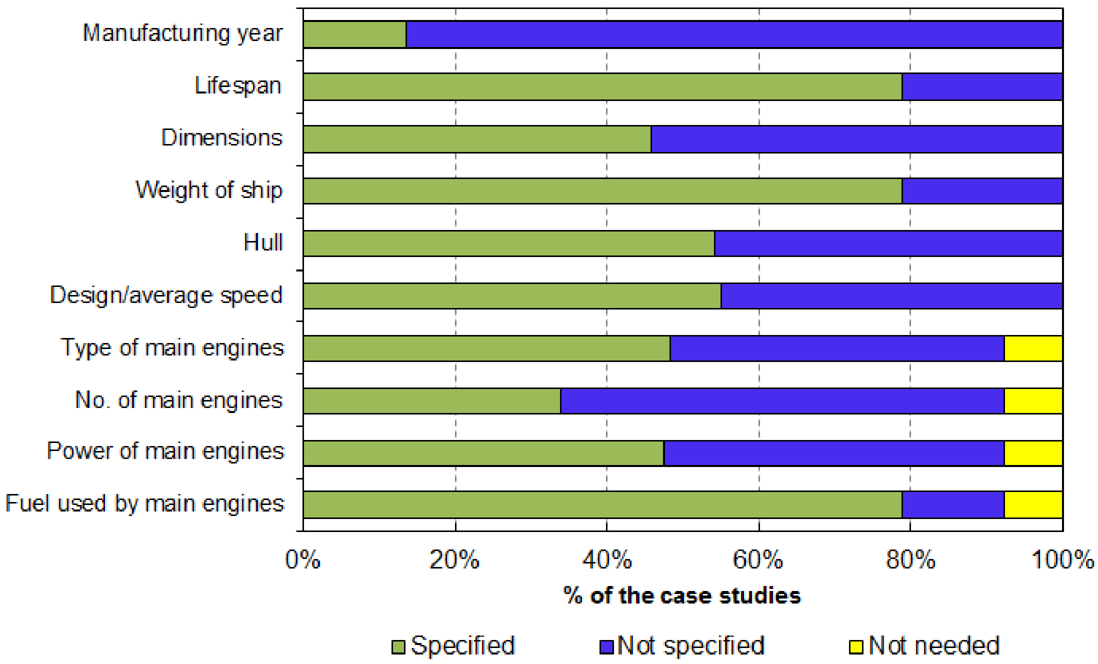
Figure 24. Choice of ship in the reviewed case studies on LCA related to ships.



Source: IMDEA, 2022.

Figure 25 shows the degree of technical information about the ship as provided in the reviewed case studies. In this regard, a significant degree of underspecification was found. The label "Not needed" means that the information is not relevant to the goal and scope of the study. For example, #42 and #44 assess the life cycle environmental performance of the power system but focusing exclusively on the auxiliary engines. In consequence, information on the on-board main engines is not relevant. As observed, most of the studies provide the lifespan and the weight of the ship. The most common lifespan ranges from 20 to 30 years. Regarding the weight of the ship, it was found that the reviewed studies provide up to five weight measures (alone or a combination of them): lightship weight (weight of the ship as designed), gross tonnage, deadweight (measure of how much weight a ship can carry), payload (maximum cargo weight that a ship can carry), and displacement (weight of the ship based on the volume of water displaced). A significant percentage of the case studies also provide the dimensions, hull material (further investigated in Section 3.1.4.2), and design/average speed of the ship. The most commonly reported dimensions measures are breadth, depth, and draft. The most commonly used unit for speed is knots, although km/h is also used in several case studies. Finally, the most commonly reported technical information about the main engines is the type of fuel used (further investigated in Section 3.1.4.4), followed by the type of engines and the total power (further details on power system in Section 3.1.4.3).

Figure 25. Technical information about the ship as provided in the reviewed case studies.

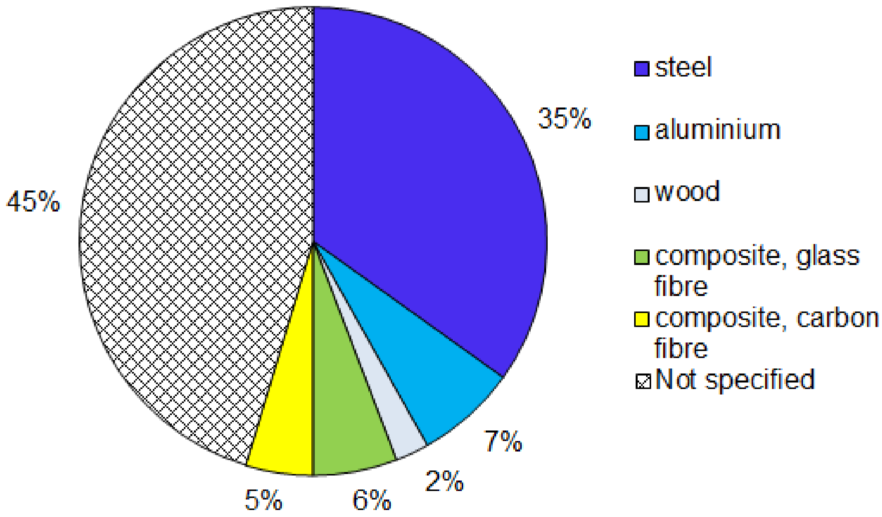


Source: IMDEA, 2022.

3.2.1.4.2 Hull material

The hull material is particularly relevant to studies that involve shipbuilding or hull manufacturing due to the potential environmental impacts associated with raw materials. Shipbuilding or hull manufacturing is included in 31 studies, in which 86 original case studies were identified. Figure 26 shows the number of case studies that involve shipbuilding or hull manufacture broken down by the material of the hull. A very significant percentage of the studies (45%) do not specify the material of the hull. When specified, the most common hull material was found to be steel. To a lesser extent, aluminium was found in six case studies involving yachts (#8, #13), boats (#23, #24), and ferries (#36). Wood was identified in two case studies defined in #24 for a boat. Composites based on glass fibres were found in five case studies on yachts (#8, #17) and boats (#23, #24), and composites based on carbon fibres in four case studies on boats (#23) and ferries (#35).

Figure 26. Choice of hull material in the case studies that involve shipbuilding or hull manufacturing.



Source: IMDEA, 2022.

3.2.1.4.3 Power system

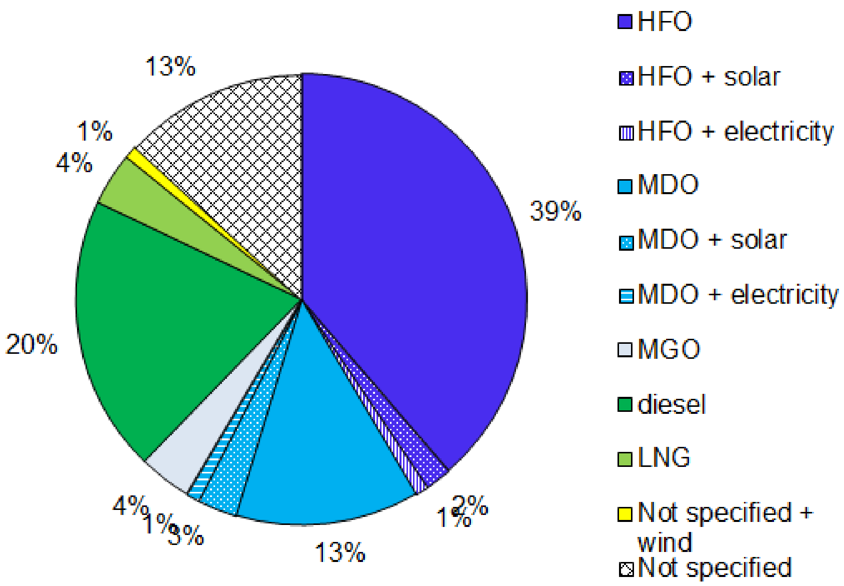
As observed in Figure 25, about half of the reviewed case studies provide information on the type of main engine. A range of nomenclatures and degree of details were found, which hampers a systematic assessment of the information. Overall, diesel engines were found to be the most commonly reported engine in the reviewed case studies. A number of studies specify the type of engine based on the fuel used (i.e., diesel engine –e.g., #5, #24, #33, #32–), while other studies provide the brand and the model of the engine (e.g., MAN B&W 7S50 MC-C 2-stroke in #4, Caterpillar C32 in #8 and #13, STX-MAN B&W 6S60MC 2 stroke in #28, and Wartsila Sulzer RTA96-C 14 in #34). Gas and steam turbines are each reported in two case studies defined in #10 and #37, respectively. Finally, hybrid configurations were found in eight case studies. Five case studies involve diesel engines along with a photovoltaic system, while three case studies involve diesel engines along with lithium-ion batteries.

3.2.1.4.4 Type of fuel

The combustion of the fuel in the main engines is included in 39 studies, in which 106 original case studies were identified. Figure 27 shows the number of case studies that involve fuel combustion in the main engines broken down by the used fuel. All these case studies were found to involve a fossil fuel. Heavy fuel oil (HFO) was identified as the most common choice (about 42% of the case studies), followed by diesel (about 20% of the case studies), and marine diesel oil (MDO, about 17% of the case studies). Liquefied natural gas (LNG) is considered in a relatively small number of case studies (about 4% of the case studies). A significant percentage of the case studies (13%) do not specify the fuel used.

It is remarkable that the eight case studies that involve hybrid configurations use fossil fuels supported by alternative energy sources. HFO and MDO in combination with solar energy were found in two case studies each (#5 and #20 for HFO, and #21 and #22 for MDO). These case studies involve the retrofit of power systems with on-board photovoltaic systems. For example, #5 assesses the installation of a photovoltaic system in order to obtain propulsion power in a short-route ferry. #21 assesses the retrofit of a power system on-board a Ro-Ro ship. After the retrofit, the power is delivered by the diesel engines (MDO combustion) augmented by energy from the photovoltaic and lithium-ion battery systems. #9 presents a case study in which the main diesel engines are complemented with lithium-ion batteries.

Figure 27. Choice of fuel in the case studies that involve fuel combustion through ship operation or power system operation.



Source: IMDEA, 2022.

3.2.1.4.5 End-of-life management

Twenty-three studies, in which 62 original case studies were identified, involve the end-of-life of the ship. Table 5 presents the choice of the end-of-life setting in the reviewed studies. The settings in Table 5 refer to what the authors report as included within the end-of-life stage. Up to 10 ship end-of-life settings were found. Most of the case studies were found to set the end-of-life of the ship as dismantling followed by materials recycling. Several variations of this setting were found. For example, some case studies add landfilling. #15 includes the dismantling of the ship but not the recycling of the materials. In contrast, #30 excludes the dismantling and includes only the recycling of materials. Emerging hull materials such as composites provide opportunities for more advanced ship end-of-life strategies such as pyrolysis (#23). However, #17 argues that this would be an expensive option and therefore considers the disposal in landfill of a composite yacht. As a particularity, one case study defined in #19 addresses the beaching of the ship, i.e. the transportation of the ship to southern Asia where it is hauled onto the beach and then dismantled.

Table 5. Choice of the ship end-of-life setting in the reviewed case studies.

End-of-life setting	**No. original case studies (no. studies)**
Dismantling	13 (1)
Beaching + dismantling	1 (1)
Landfilling	1 (1)
Pyrolysis + incineration	4 (1)
Recycling	3 (3)
Recycling + incineration + landfilling	1 (1)

Dismantling + recycling	17 (12)
Dismantling + recycling + landfilling	7 (2)
Dismantling + recycling + incineration + landfilling	6 (2)
Reuse + recycling	1 (1)
Not specified	8 (2)

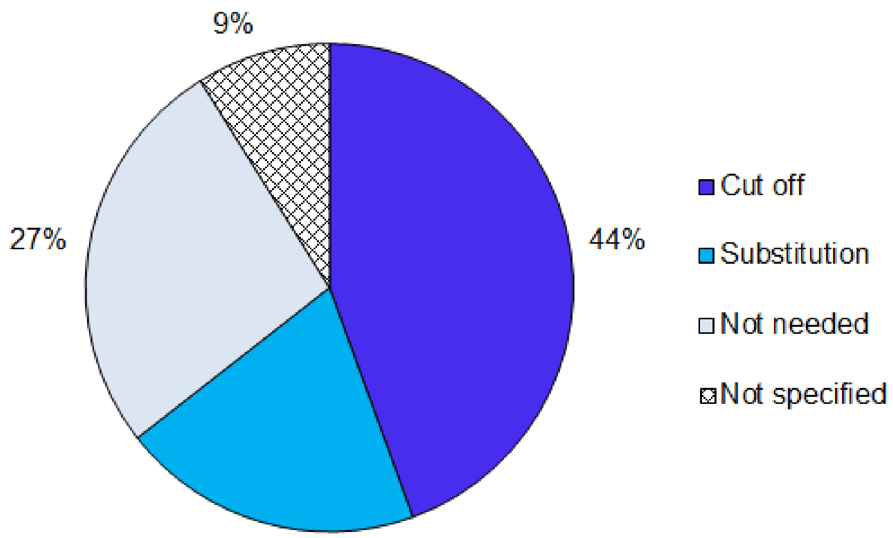
Source: IMDEA, 2022.

3.2.1.5 Multifunctionality

The reviewed LCA studies are affected by multifunctionality in the end-of-life stage due to materials recycling and/or energy recovery. Figure 28 shows the multifunctionality approaches applied in the reviewed studies. About 27% of all studies (12 studies out of 45) are not affected by this multifunctionality because the end-of-life stage is not included within the scope of the analysis. For the rest of the studies, about 44% apply the cut-off approach (remarkably, 36% of the studies do not specify this choice but it was deduced). According to the cut-off approach, any material and/or energy co-product derived from the end-of-life would be burden-free (Schrijvers, Loubet, and Sonnemann 2016). Substitution is used in 20% of the studies (7% of the studies do not specify this choice but it was deduced). According to the substitution approach, the system under study is credited with the potential environmental benefits derived from recovering materials and/or energy in the end-of-life stage. Finally, about 9% of the studies do not specify the multifunctionality approach applied and it could not be deduced.

It should be noted that the entire life cycle of a ship or a specific part of a ship might be affected by multifunctionality in a number of upstream stages. For example, if the ship is fuelled with oil-based fuels, multifunctionality arises in the refinery stage. However, the analyst does not generally address directly this kind of multifunctionality situations, but they are embedded in the used LCA databases.

Figure 28. Choice of end-of-life allocation rule in the reviewed LCA studies related to ships (% of studies, n=45).



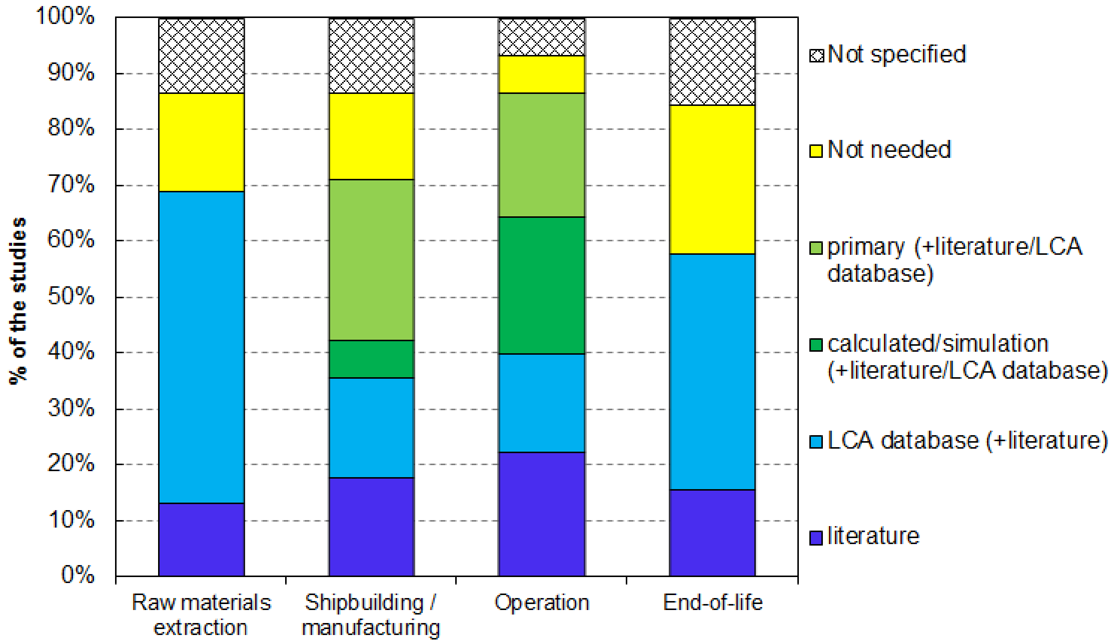
Source: IMDEA, 2022.

3.2.1.6 Life cycle inventory

Figure 29 shows the sources of the inventory data used in the main life cycle stages, namely raw materials extraction, shipbuilding/manufacturing, operation & maintenance, and end-of-life. The sources were obtained from each study based on what the authors reported. The label "primary" means data obtained from industry and/or at the laboratory level. The label "Not needed" means that the life cycle stage is not included in the system boundary of the study (or the study does not specify its inclusion).

The main data sources of raw materials extraction and end-of-life are LCA databases and literature. The most cited LCA databases in the reviewed studies were found to be ecoinvent and GaBi. Other cited LCA databases are FORWAST (environmental input-output database) and GREET. For the shipbuilding or manufacturing stage, a significant number of studies indicate primary data sources. For example, #15 uses data on energy consumption for shipbuilding from site interviews with a Chinese shipbuilding company. #21 uses data on manufacturing of the power system from various sources including industrial members involved in a project. #24 uses data on the building of a boat with different hull materials from the boatyard.

Figure 29. Use of life cycle inventory data sources at different stages in the reviewed studies on LCA related to ships.

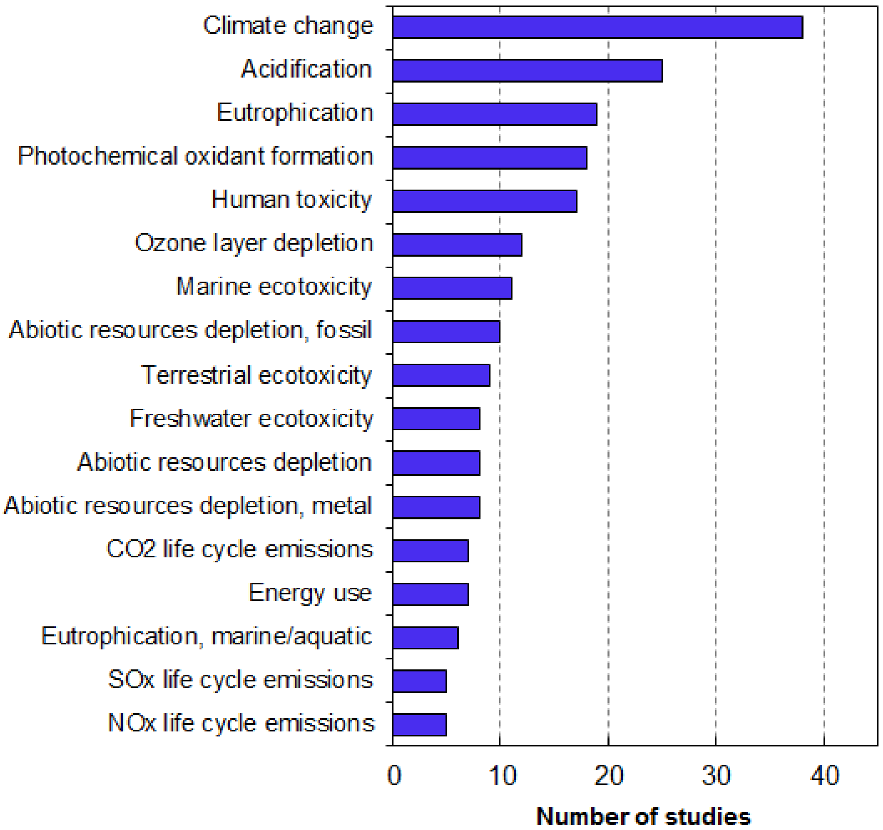


Source: IMDEA, 2022.

3.2.1.7 Life cycle impact assessment

Figure 30 shows the impact categories most commonly assessed in the reviewed studies. This set of categories covers about 84% of the total number of category occurrences. Climate change was found to be the most common impact category (38 studies). Furthermore, a number of studies involve the assessment of CO_2 life cycle emissions with no further impact assessment (7 studies). The other impact category that is assessed in more than 50% of the studies is acidification (25 studies). Eutrophication, photochemical oxidation formation, human toxicity, ozone layer depletion, marine ecotoxicity, and fossil resources depletion are all addressed in 10 or more studies. Several studies assess SO_x (5 studies) and NO_x (5 studies) life cycle emissions with no further impact assessment. Finally, although this review is limited to environmental LCA, about 29% of all studies include costs analysis in addition to environmental analysis.

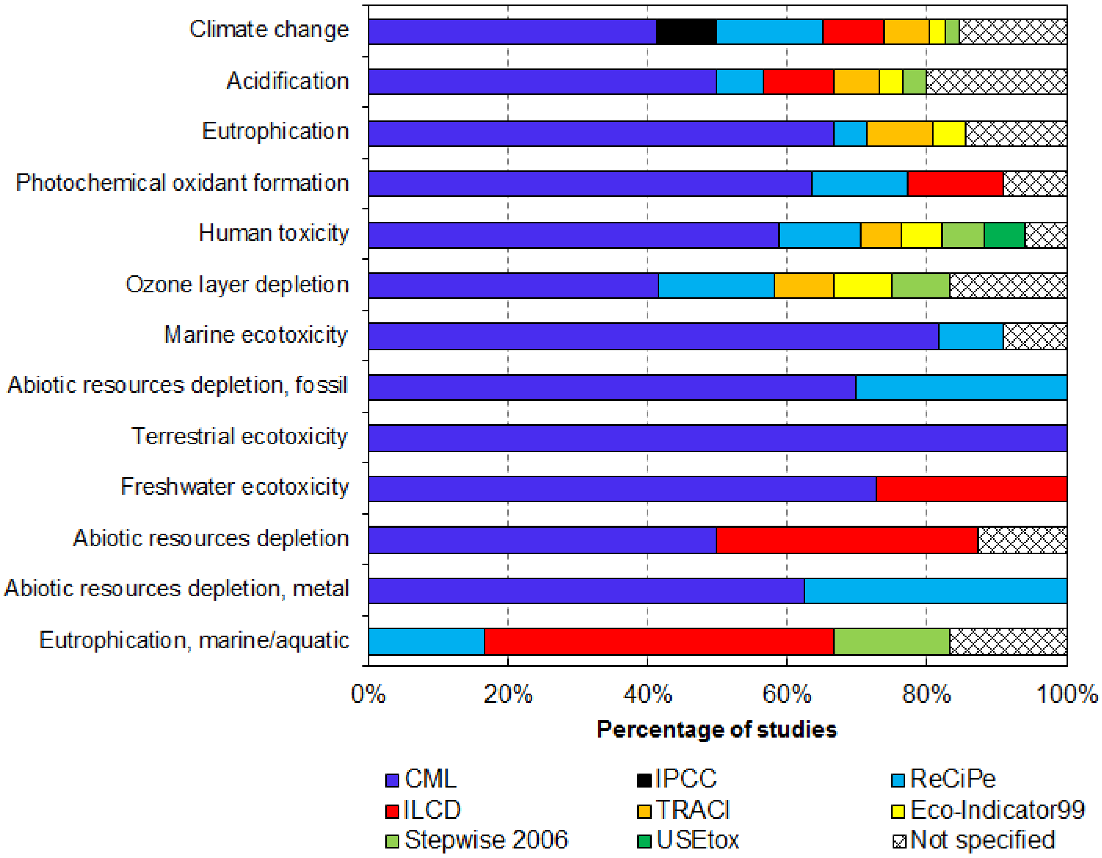
Figure 30. Choice of impact categories in the reviewed studies on LCA related to ships.



Source: IMDEA, 2022.

Figure 31 shows the choice regarding the impact assessment methods. It should be noted that a number of studies use several methods to assess an impact category (e.g., CML and ReCiPe for freshwater ecotoxicity). The studies presenting the results for several impact assessment methods were counted as many times as needed in Figure 31. CML is visibly the most popular method for all impact categories with the exception of marine eutrophication. ReCiPe is also commonly used for many of the impact categories. Even though the Intergovernmental Panel on Climate Change (IPCC) method alone was not found to be a common choice among the reviewed studies (8% of the total occurrences regarding climate change impact assessment methods), it should be noted that impact assessment methods such as CML and ReCiPe actually involve the use of IPCC characterisation factors. The group of ILCD methods, recommended by the European Commission within the European context (European Commission 2011a; Fazio et al. 2018), is scarcely used. A significant percentage of studies do not specify the method used to evaluate climate change, acidification, eutrophication, ozone layer depletion, and marine eutrophication.

Figure 31. Choice of life cycle impact assessment method in the reviewed studies on LCA related to ships.



Source: IMDEA, 2022.

Normalisation and weighting of life cycle environmental impacts is presented in 11% and 16% of all studies, respectively. From the 5 studies (#4, #16, #17, #23, #44) that present normalised life cycle environmental impacts, only 2 studies (#17 and #44) additionally present weighted results. Most of the studies only present either the normalised or the weighted impacts. The normalisation methods used involve CML 2001 (#4, #17), CML baseline 2000 (#23), and ReCiPe (#16). The weighted methods used involve CML 2001 (#1, #7, #17), IMPACT 2002+ (#35), ReCiPe (#35), and EcoIndicator99 (#36). Furthermore, about 33% of all studies do not need normalisation or weighting since they address only one impact category.

3.2.1.8 Sensitivity and uncertainty

About 38% of the studies (17 studies out of 45) perform a sensitivity analysis. A variety of aspects were found to be covered by sensitivity analysis. Four studies (#20, #21, #35, #44) assess the influence of the end-of-life strategy on the LCA results. For example, #20 and #21 investigate the sensitivity of the life cycle environmental performance of a power system on-board a Ro-Ro ship to the shares of recycling, incineration, and landfilling. Furthermore, #7 assesses by sensitivity analysis the influence of maximising the recycling or landfilling of the carbon fibre contained in the hull of a ferry. Four studies (#4, #21, #22, #35) assess the influence of the rate of fuel consumption. Three studies (#9, #15, #28) evaluate the influence of ship speed on its life cycle environmental performance. Two studies (#4, #7) address the environmental influence of electricity consumption and the weight of ship components. For example, #7 evaluates the sensitivity of the life cycle environmental performance of two bulk carriers to the electricity consumed for shipbuilding and to the proportion of steel over other raw materials. Other parameters assessed by sensitivity analysis in the reviewed studies are the annual operation days and the sunny hours per day (#5) and the engine load (#44).

Only one study (#3) performs parameter uncertainty analysis by error propagation methods (Monte Carlo simulation).

3.2.2 Gaps and trends

The reviewed ship-related LCA studies cover a variety of goals and scopes. Fundamental aspects of the LCA methodology are often not clearly defined in the studies, which makes the interpretation of the results challenging. In particular, a significant lack of transparency in reporting the definition of the system boundary was found.

Based on the meta-analysis, the following trends were identified:

- The application of LCA to ship systems as identified in this review involves many goals. Apart from the non-comparative or comparative LCA of ships, other goals are the comparison of power system configurations, hull materials, end-of-life strategies, and hull maintenance strategies.
- The functional unit is usually based on the lifespan of the product assessed (e.g., the ship or the power system).
- The reviewed comparative/non-comparative LCAs of ships show an interest towards big cargo ships such as tankers, bulk carriers and container ships.
  - Climate change is by far the most assessed impact category followed by acidification.
- CML is the most popular life cycle impact assessment method in this field.

Furthermore, the following gaps and underdeveloped topics were identified:

- Lack of homogeneous and consolidated system boundaries settings.
- Lack of transparency in reporting the definition of the system boundary and underspecification of technical information on the system assessed.
- Lack of homogeneous and consolidated rules to address end-of-life multifunctionality.
- The potential impact of the end-of-life stage in underdeveloped countries remains so far unexplored.

3.2.3 Quantitative assessment of life cycle environmental impacts

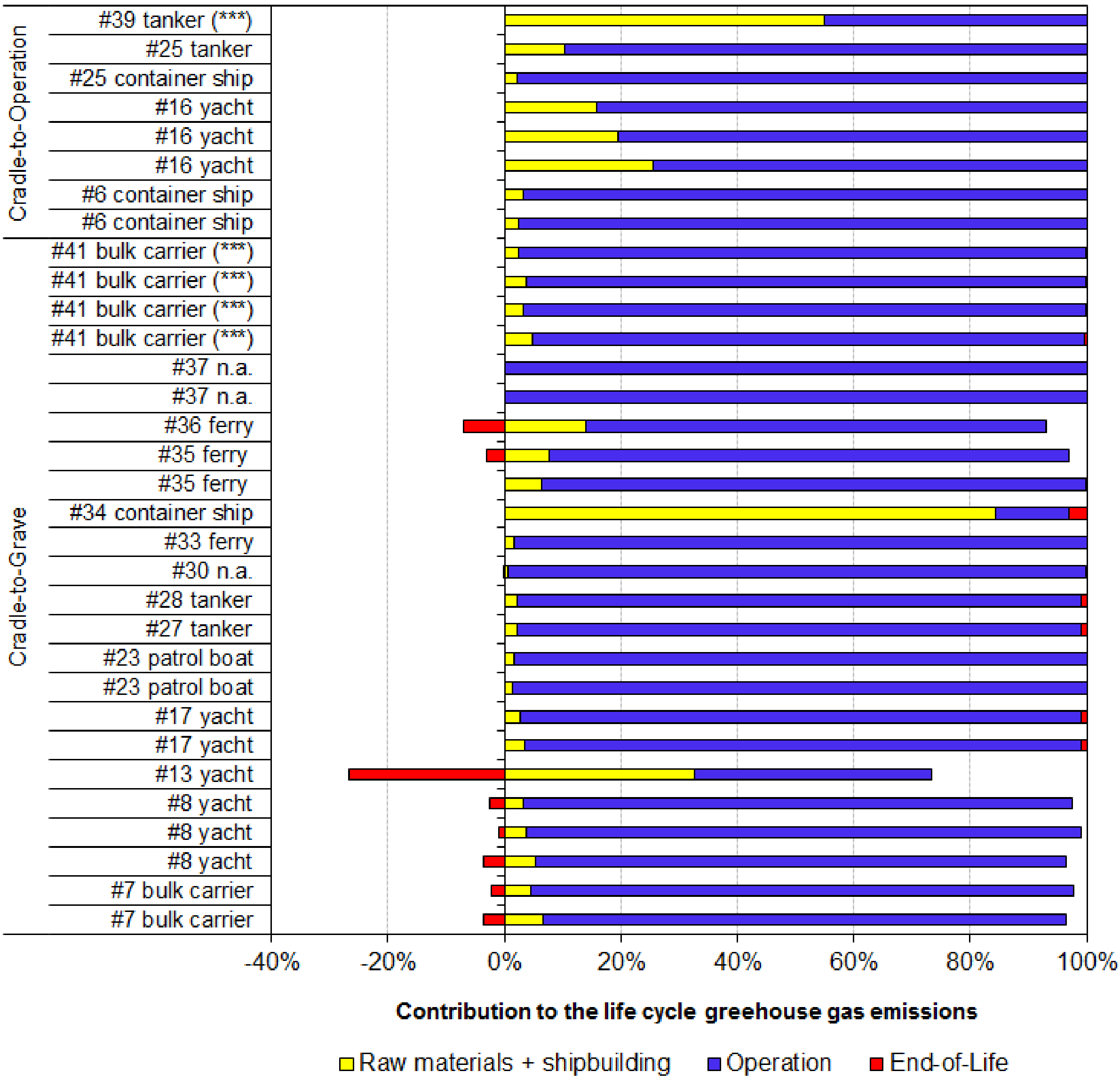
The heterogeneity of the reviewed LCA studies of ships in terms of goal and scope, especially regarding the system boundary settings, hampers a systematic quantitative assessment of the LCA results. Notwithstanding, a contribution assessment restricted to a limited number of studies that are relatively homogeneous in terms of scope was performed. In particular, the assessment focuses on evaluating the contribution of three main life cycle stages (raw materials extraction & shipbuilding, operation, and end-of-life management) to the life cycle GHG emissions of ships. Therefore, the studies selected for the assessment involve a Cradle-to-Operation or a Cradle-to-Grave assessment of a ship. The inclusion/exclusion of the end-of-life stage was not set as a selection criterion since the influence of this stage on the life cycle GHG emissions of ships was found to be generally negligible. Furthermore, the climate change impact based on a 100-year timeframe and life cycle CO_2 emissions were assessed since the occurrence of the other impact categories is not enough to provide a relevant number of case studies.

Data was retrieved for 32 case studies based on 18 studies. Eight case studies correspond to a Cradle-to-Operation scope, while the remaining 24 have a Cradle-to-Grave scope. Figure 32 shows the contribution of the main life cycle stages to the GHG emissions of ships. The results are split between studies that involve a Cradle-to-Operation scope and studies that involve a Cradle-to-Grave scope. Furthermore, the code of the study along with the type of ship assessed are indicated.

The operation stage was generally found to be the largest source of GHG emissions in the life cycle of a ship. The average contribution of operation to the life cycle GHG emissions was found to be 88%, with a median of

95%. It should be noted that all the case studies involve fossil fuels. The contribution of raw materials extraction and processing and shipbuilding is generally reduced, with an average of 11% and a median of 4%. Furthermore, the contribution of the end-of-life stage is generally negligible. Overall, these findings indicate that the combustion of fuel during ship operation is the most important life cycle stage from a climate change perspective.

Figure 32. Analysis of the life cycle stage contribution to the climate change impact of ships. (***) indicates that the study assesses only life cycle emissions CO_2.



Source: IMDEA, 2022.

3.3 LCA of fuel supply chains for maritime applications

This section reviews LCA studies of maritime fuel supply chains. The sample includes 26 studies in which 189 original case studies were identified. Table 6 gathers the LCA studies included in the review. It should be noted that many LCA studies of fuels for road and air transportation have been published over the last decades (Kolosz et al. 2020; Liu et al. 2018). While the first stages of the fuel supply chain such as the extraction/production of the feedstock are generally translatable to the maritime sector, that is not the case for the last stages, namely fuel distribution and fuel use/combustion. On the one hand, the storage of the fuels at ports and their dispensing are different from that associated with road or air transportation. On the other hand, marine engines are designed for fuels with different properties (e.g., higher viscosity). In other words, process conditions change and so will do the life cycle environmental performance of the fuel supply chain. Therefore, this review was restricted to LCA studies that explicitly address maritime fuels.

Table 6. List of the reviewed studies on LCA of maritime fuel supply chains.

ID	Reference	Scope	No. original case studies	Fuel(s) assessed
#1	(Seithe et al. 2020)	Well-to-Propeller	4	HFO, LNG
#2	(Pavlenko et al. 2020)	Well-to-Propeller	4	HFO, MGO, IFO, LNG
#3	(thinkstep 2019)	Well-to-Propeller	6	HFO, MGO, IFO, LNG
#4	(El-Houjeiri et al. 2019)	Well-to-Propeller	9	HFO, MGO, LNG
#5	(Hwang et al. 2019)	Well-to-Propeller	4	MGO, LNG
#6	(Kesieme et al. 2019)	Well-to-Tank	4	biodiesel, SVO
#7	(Sharafian, Blomerus, and Mérida 2019)	Well-to-Propeller	4	HFO, LNG
#8	(Tanzer et al. 2019)	Well-to-Propeller	33	biodiesel
#9	(Winebrake et al. 2019)	Well-to-Propeller	5	MDO, LNG, methanol
#10	(Gilbert et al. 2018)	Well-to-Propeller	12	HFO, MDO, LNG, biodiesel, methanol, hydrogen, biomethane, SVO
#11	(Bicer and Dincer, 2018b)	Well-to-Propeller	5	HFO, ammonia, hydrogen
#12	(Bicer and Dincer, 2018a)	Well-to-Propeller	7	HFO, ammonia, hydrogen
#13	(Corbett and Winebrake 2018)	Well-to-Propeller	12	methanol
#14	(Hua, Wu, and Chen 2017)	Well-to-Propeller	6	HFO, LNG
#15	(Schönsteiner, Massier, and Hamacher 2016)	Well-to-Propeller	5	HFO, MGO, LNG, biodiesel, hydrogen
#16	(Thomson, Corbett, and Winebrake 2015)	Well-to-Propeller	9	LNG
#17	(S. Brynolf et al. 2014)	Well-to-Propeller	4	HFO, MGO, LNG
#18	(Selma Brynolf, Fridell, and Andersson 2014)	Well-to-Propeller	5	HFO, LNG, methanol, biogas
#19	(Bengtsson, Fridell, and Andersson 2014)	Well-to-Propeller	7	HFO, MGO, LNG, biodiesel, biogas

#20	(Lowell et al. 2013)	Well-to-Propeller	8	LNG
#21	(Bengtsson, Fridell, and Andersson 2012)	Well-to-Propeller	7	HFO, MGO, LNG, biodiesel, biogas, biomethane
#22	(Verbeek et al. 2011)	Well-to-Propeller	6	HFO, MDO, diesel, LNG
#23	(Petzold et al. 2011)	Well-to-Propeller	4	HFO, MGO, biodiesel
#24	(Bengtsson, Andersson, and Fridell 2011)	Well-to-Propeller	8	HFO, MGO, LNG, synthetic diesel
#25	(Corbett and Winebrake 2008)	Well-to-Propeller	5	IFO, MGO, MDO
#26	(Winebrake, Corbett, and Meyer 2007)	Well-to-Propeller	6	HFO, synthetic diesel, biodiesel, CNG

Source: IMDEA, 2022.

3.3.1 Methodological and technical features

3.3.1.1 Goal and scope

All the reviewed studies involve a comparative LCA of maritime fuel supply chains. For the purpose of this review, each variation in technical aspects (fuel, feedstock, fuel processing technology, and bunkering operation) and/or location (feedstock origin, fuel processing location, and fuel consumption location) was considered to define a new fuel supply chain (i.e., an original case study). On the other hand, it should be noted that variations in the type of ship or engine considered for the fuel use/combustion stage do not define a new fuel supply chain.

Fuel, feedstock, and location were found to be the variables most often used to define new supply chains (Table 7). For example, #21 compares six maritime fuels, namely HFO, marine gas oil (MGO), LNG, biodiesel, biogas, and biomethane. The authors define two biodiesel supply chains depending on whether the feedstock is rapeseed or forest residues. As well, #5 compares HFO and LNG and for each fuel the authors define two supply chains depending on whether the feedstock comes from Qatar or the U.S. (crude oil) or from Saudi Arabia or the U.S. (natural gas). Two studies compared a range of supply chains for the same fuel: #16 focuses on LNG supply chains by varying feedstock origin (U.S., Qatar, Norway, Russia, and Libya), while #13 focuses on methanol supply chains by varying both feedstock (natural gas, forest residues, landfill gas, and coal) and feedstock origin (natural gas from North America or the global average). Only one study (#8) compares several fuel processing technologies when defining new fuel supply chains, namely gasification, pyrolysis, and hydrothermal liquefaction for synthetic biodiesel production. Overall, these findings highlight a particular interest in evaluating the life cycle environmental performance of a range of fuel supply chain configurations.

It is remarkable that a non-negligible number of studies evaluate the fuel use/combustion stage under different assumptions on the type of ship (7 studies) and/or engine (6 studies). For example, #12 compares three fuels, namely HFO, ammonia, and hydrogen, and for each fuel the combustion in both a tanker and a container ship is evaluated. As well, #7 compares HFO and LNG considering two engines for HFO (slow-speed diesel engine and medium/high-speed diesel engine) and four engines for LNG (spark-ignition engine, low-pressure dual-fuel medium-speed engine, low-pressure dual-fuel slow-speed engine, and high-pressure dual-fuel slow-speed engine). The evaluation of different engines occurs in studies that involve LNG, highlighting a concern on methane slip from LNG engines (Pavlenko et al. 2020).

Table 7. List of variables that define new maritime fuel supply chains in the reviewed studies.

Variable changed	No. studies (no. original case studies)	ID (no. original case studies)
Fuel	5 (24)	#2 (4), #3 (6), #15 (5), #17 (4), #25 (5)
Fuel + feedstock	7 (41)	#11 (5), #12 (7), #18 (5), #19 (7), #21 (7), #23 (4), #26 (6)
Fuel + location	5 (28)	#5 (4), #7 (4), #14 (6), #22 (6), #24 (8)
Fuel + feedstock + location	5 (34)	#1 (4), #4 (9), #6 (4), #9 (5), #10 (12)
Feedstock + location	2 (21)	#13 (12), #16 (9)
Feedstock + fuel production technology + location	1 (33)	#8 (33)
Feedstock + location + bunkering operation	1 (8)	#20 (8)

Source: IMDEA, 2022.

The modelling approach adopted (attributional/consequential) was found to be explicitly specified in only five studies out 26. For the rest of the studies, the modelling approach could be generally deduced from the type of data used (average data, no marginal suppliers identified). In this regard, the attributional LCA was found to be followed in approximately 92% of the studies. Only two studies specify that a consequential LCA was followed (#21 and #24). However, the actual application of a consequential approach in these studies could not be confirmed based on the information provided in the documents (regarding e.g. data used).

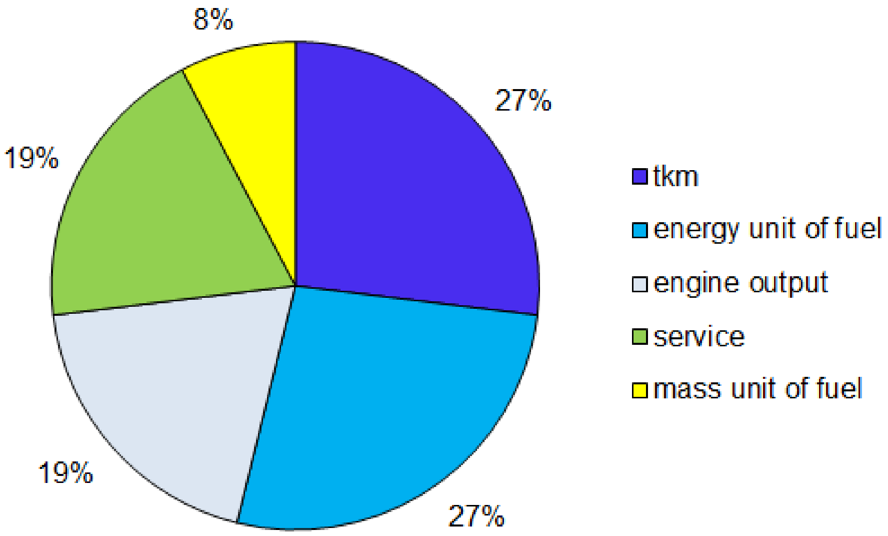
3.3.1.2 Functional unit

The functional unit is generally specified or alternatively can be deduced from the units used in the presentation of the results. Figure 33 illustrates the nature of the functional unit chosen. The choice of the functional unit was found to be similarly distributed between tkm (transportation of 1 t cargo over 1 km, 27% of the studies), energy unit of fuel (1 MJ or 1 GJ of fuel energy content, 27% of the studies), engine work output (1 kWh work output, 19% of the studies), and service provided (1 trip or service time, 19% of the studies). Furthermore, a small percentage of the studies use a mass of fuel as the functional unit (1 kg or 1 tonne of fuel, 8% of the studies).

The choice of the functional unit can strongly affect the outcomes of the LCA study. Sharafian et al. (2019) argue that a functional unit based on energy unit of fuel is not a valid assumption in most cases since it does not capture the potential effect of the engine efficiency on the life cycle emissions. This is particularly relevant from a comparison perspective. Emissions from fuel combustion depend on the composition of the fuel but also on the engine efficiency. The lower the engine efficiency, the more the MJ of fuel needed to have a certain mechanical work output. In this regard, Sharafian et al. (2019) propose the use of the engine work output as the functional unit. However, Lowell et al. (2013) justify the use of a functional unit based on energy unit of fuel due to the negligible difference (up to 2%) between the efficiency of gas and diesel engines.

In addition to the engine efficiency, the functional unit should be able to capture any change in fuel storage requirements which, in turn, reduces the cargo space (S. Brynolf et al. 2014). That is the case of LNG and methanol fuels, which have increased storage requirements compared to conventional oil-based fuels. For example, Seithe et al. (2020) assume that the use of LNG decreases the cargo capacity by 1.8% for a container ship and by 4% for a ferry. In this regard, a tkm based functional unit is the most suitable for fuels that involve changes in the cargo space. However, some authors consider complex to model mass-distance (tkm) functional unit due to the availability and consistency of field measurements of emissions from ships (El-Houjeiri et al. 2019).

Figure 33. Choice of functional unit in the reviewed studies on LCA of maritime fuel supply chains (% of studies, n=26).

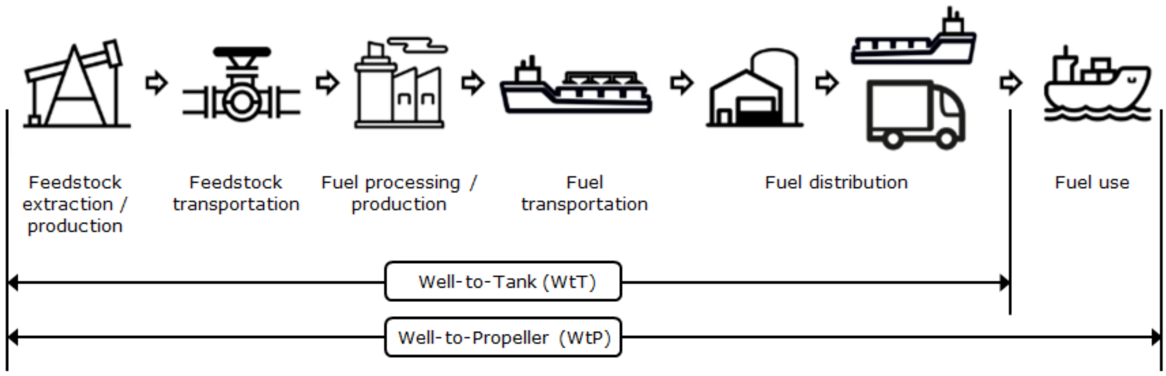


Source: IMDEA, 2022.

3.3.1.3 System boundary

The majority of the studies were found to involve a Well-to-Propeller scope. Only one study (#6) involves a Well-to-Tank scope. Well-to-Tank covers from feedstock production/extraction to fuel transportation and distribution and excludes fuel use/combustion (Figure 34). Well-to-Propeller covers the full life cycle from feedstock production/extraction to fuel use/combustion. No study used alternative system boundary such as Gate-to-Gate.

Figure 34. System boundary of a generic maritime fuel supply chain according to the Well-to-Tank and Well-to-Propeller scopes.

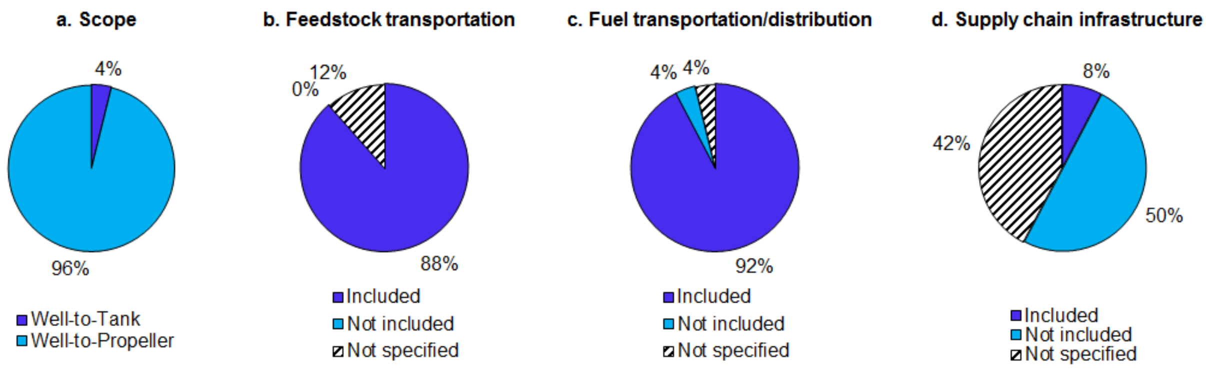


Source: IMDEA, 2022. Adapted from Hwang et al. (2019)

All but one of the reviewed studies include the life cycle environmental impacts associated with the main stages of the fuel supply chain, namely feedstock extraction/production, fuel processing, and fuel use/combustion. Furthermore, about 88% and 92% of the studies specify the inclusion of feedstock and fuel transportation, respectively (Figure 35b and Figure 35c). However, only 8% of the studies explicitly specify the inclusion of supply chain infrastructure such as wells for exploration, processing facilities, and pipelines (#1, #14). About 50% of the studies explicitly specify the exclusion of supply chain infrastructure (13 studies), whereas the remaining 42% of the studies does not specify this aspect (Figure 35d). The studies #11 and #12 represent a singularity in this regard since they include the construction, operation, and end-of-life of port facilities as well as the life cycle stages of the ship.

The exclusion of capital goods (i.e., infrastructure, machinery, and equipment) in LCA studies is usually justified by the negligible contribution to the final outcomes. However, it should be noted that conventional oil-based fuels such as MDO and MGO can use the existing infrastructure for HFO with small modifications, while larger infrastructural changes are needed for other fuels such as LNG or methanol (Bengtsson et al. 2012). These changes may affect the life cycle environmental performance of the fuel supply chain.

Figure 35. Choices of system boundary settings in the reviewed studies on LCA of maritime fuel supply chains (% of studies, n=26).



Source: IMDEA, 2022.

3.3.1.4 Technical choices

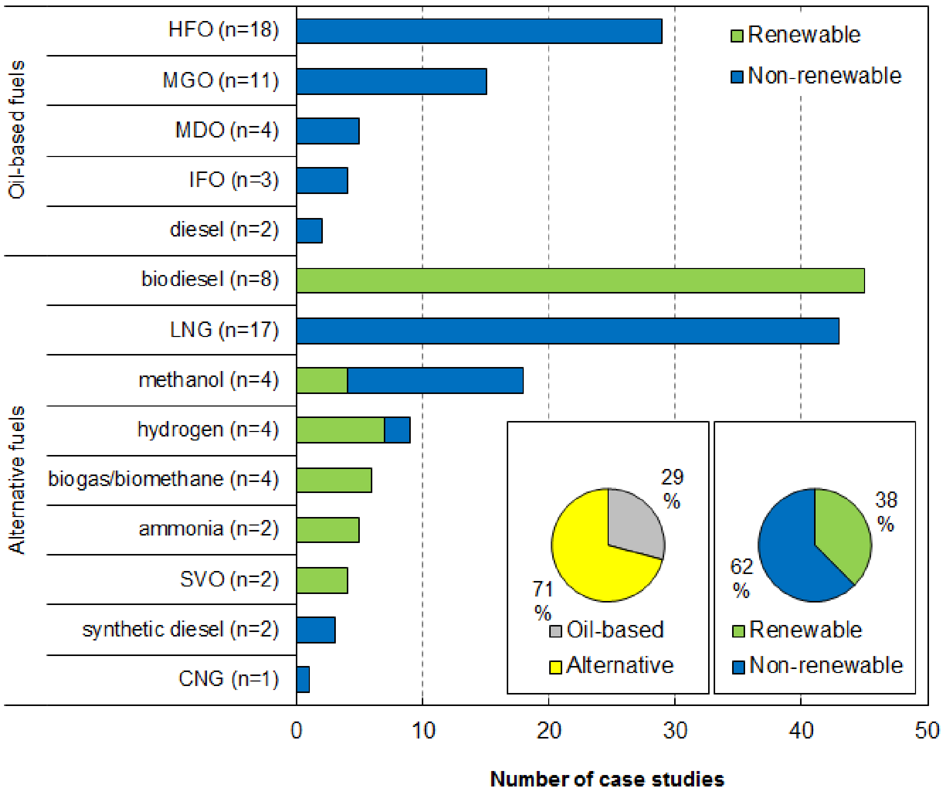
3.3.1.4.1 Fuels

The fuels assessed in the reviewed case studies range from oil-based conventional fuels such as HFO, MGO, and MDO to alternative non-renewable fuels such as LNG and synthetic diesel and alternative renewable fuels such as biodiesel and biogas/biomethane. Figure 36 shows the number of case studies broken down by fuels, also showing if these are oil-based or alternative fuels and renewable or non-renewable. The trend in Figure 36 shows that biodiesel is the most assessed fuel (45 case studies). However, a distortion is introduced by the definition of 33 case studies in a single reference (#8). Skipping the contribution of biodiesel, the most assessed fuels are LNG (43 case studies from 17 studies) and HFO (29 case studies from 18 studies). The high occurrence of HFO is closely linked to the fact that all the studies are comparative and HFO is usually selected as the benchmark. Besides biodiesel, LNG, and HFO, methanol (18 case studies) and MGO (15 case studies) are the most commonly assessed fuels. However, methanol only involves four studies with one of them (#13) defining 12 methanol supply chains. Furthermore, only four case studies out of 18 on methanol are based on renewable sources. Hydrogen, liquefied biogas/biomethane, ammonia, straight vegetable oil (SVO), synthetic diesel, and compressed natural gas (CNG) complete the variety of fuels found.

About 29% of all case studies (55 case studies) were found to involve an oil-based fuel, while 71% (134 case studies) involve an alternative fuel. However, a significant percentage of non-renewable fuels was observed (62%, 134 case studies), mainly because LNG arises as one of the most assessed alternative fuels.

Furthermore, other alternative fuels such as methanol and hydrogen can be based on non-renewable feedstocks. The proportion of renewable-based fuels would be even less if the 33 case studies of renewable-based biodiesel defined in #8 were omitted.

Figure 36. Choice of fuel in the reviewed case studies on LCA of maritime fuel supply chains. The number "n" after each fuel name refers to the number of studies that include the fuel.

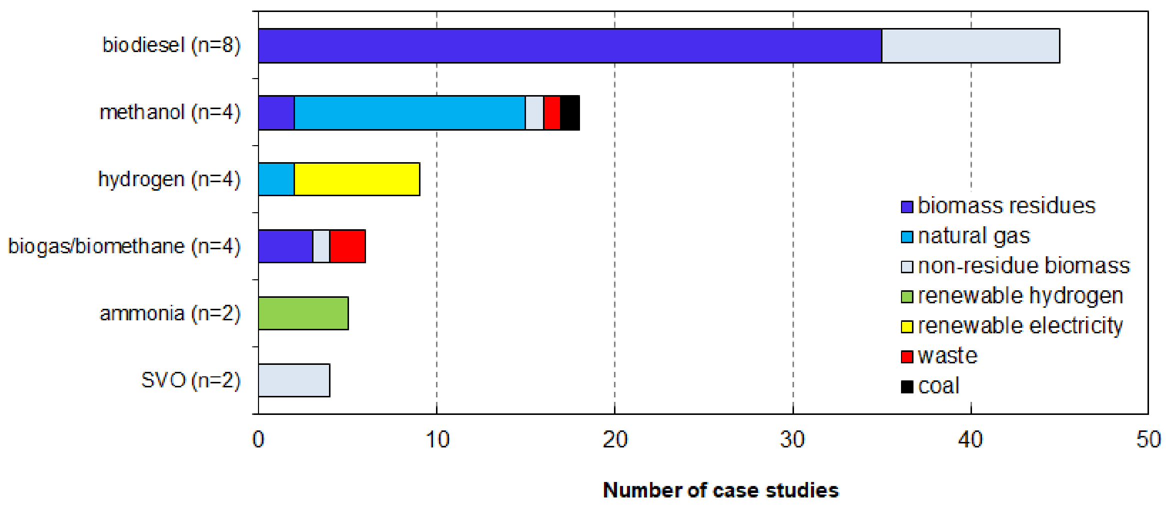


Source: IMDEA, 2022.

3.3.1.4.2 Feedstock

As highlighted in Section 4.1.1, the feedstock is a variable often used to define new fuel supply chains. This applies particularly to specific alternative fuels such as biodiesel and methanol, in contrast to oil-based fuels (based on crude oil) and LNG, synthetic diesel, and CNG (based on natural gas). Therefore, Figure 37 shows the number of case studies broken down by the feedstock considered for a set of alternative fuels. Again, a distortion is introduced in the case of biodiesel due to the definition of 33 case studies in one single reference (#8). This study compares nine biomass residues for biodiesel production: residues from eucalyptus, pine, corn, rice, wheat, sugarcane, sorghum, spruce, and barley. The other feedstock investigated for biodiesel production are non-residue biomass ones: rapeseed (4 case studies), soybean (4 case studies), and oil palms (2 case studies). The most common feedstock for methanol production in the reviewed case studies is natural gas (13 case studies). Only one study includes biomass-based methanol (willow, #18) and another one coal-based methanol (#13). For the rest of the fuels the number of occurrences was found to be relatively small, which hampers any trend analysis. Hydrogen is based on water electrolysis with renewable electricity in seven case studies (electricity based on biomass, wind, photovoltaics, hydropower, geothermal power, and municipal solid waste) and on natural gas reforming in two case studies. Liquefied biogas/biomethane is based on biomass residues (3 case studies), waste (2 case studies), and biomass (1 case study). Ammonia, presented in two studies from the same authors (#11, #12), is based on renewable hydrogen.

Figure 37. Choice of feedstock in the reviewed case studies on LCA of maritime fuel supply chains (number of case studies). The number “n” after each fuel name refers to the number of studies that include the fuel.



Source: IMDEA, 2022.

With regard to the supply chain of natural gas-based fuels, the general location of the wells (onshore or offshore) and the type (conventional or shale gas) directly influence the life cycle environmental impacts (Lowell et al. 2013). For example, shale gas wells tend to have higher GHG emissions compared with conventional wells due to high methane leakage. Natural gas is used as feedstock in 62 case studies: 43 on LNG, 13 on methanol, 3 on synthetic diesel, 2 on hydrogen, and 1 on CNG. Table 8 shows these 62 case studies broken down by the location and type of natural gas extraction wells. A significant percentage of case studies (44%, 27 case studies) do not specify the location and type of the wells investigated.

Table 8. Choice of location and type of natural gas extraction wells in the reviewed case studies that include natural gas as a feedstock (% of case studies, n=62).

		Type of well			
		Conventional	**Shale**	**Mix**	**Unspecified**
Location of well	**Onshore**	10%	0%	0%	0%
	Offshore	6%	0%	0%	3%
	Mix	6%	0%	2%	0%
	Unspecified	16%	3%	10%	44%

Source: IMDEA, 2022.

3.3.1.4.3 Fuel processing/production technology

Overall, the details provided on the fuel processing/production technology in the reviewed studies are scarce. The conventional oil-based fuels (i.e., HFO, MGO, MDO, intermediate fuel oil (IFO), and diesel) are all based on crude oil refining. LNG is produced by liquefaction. The liquefaction step is generally the largest energy consumer in the LNG supply chain. The scale influences the energy efficiency of liquefaction: the larger the liquefaction facility, the higher the efficiency (Lowell et al. 2013). This variation in the energy efficiency according to the scale influences the life cycle environmental performance of the supply chain and therefore should be considered in the LCA. However, the majority of the case studies on LNG (74%, 32 case studies) do not specify any technical consideration about liquefaction. The two case studies defined in #7 specify the use of an industrial gas turbine with no information on the scale of the plant. The most detailed study in this regard is #20, which compares LNG supply chains based on considerations on the scale of the liquefaction plant. The authors assume a 10% and 20% energy penalty for large and small liquefaction plants, respectively.

Six biodiesel production technologies were found in the reviewed case studies. Gasification (followed by Fischer-Tropsch synthesis, 13 case studies), pyrolysis (11 case studies), and hydrothermal liquefaction (11 case studies) were found to be the most recurrent technologies, which is conditioned by the definition of 33 case studies in #8. Transesterification and hydrogenation of biomass feedstocks (7 and 1 case studies, respectively) complete the list of biodiesel production technologies found.

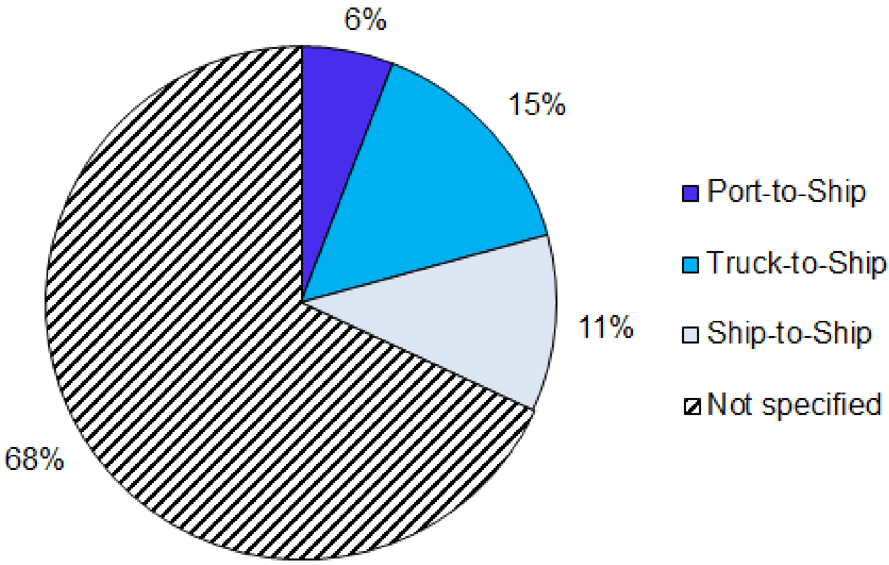
Methanol is produced either by direct reforming of natural gas (13 case studies out of 18) or by reforming of syngas from gasification (5 case studies out of 18). As a particularity, in #13 the authors investigate different technology configurations depending on whether gasification is designed to generate additional electricity or steam for export.

Hydrogen is produced by reforming of natural gas in two cases studies defined in #10. In other seven case studies defined in #10, #11, #12, and #15 hydrogen is produced by electrolysis using renewable electricity. Liquefied biogas/biomethane is produced by gasification followed by methanation and liquefaction (3 case studies) or by anaerobic digestion followed by liquefaction (3 case studies). Ammonia is assessed in 5 case studies from 2 studies published by the same authors (#11, #12), who assume the Haber-Bosch process based on hydrogen produced by electrolysis with renewable electricity. Synthetic diesel is produced by the Fischer-Tropsch synthesis after natural gas reforming (3 case studies). SVO is produced by extraction and refining of rapeseed (2 case studies) or soybean (2 case studies).

3.3.1.4.4 Bunkering operation

Bunkering operation refers to the dispensing of the fuel to the ship that will use it and can be Port-to-Ship, Truck-to-Ship, or Ship-to-Ship (thinkstep 2019). Ship-to-Ship is seen as the most common and promising pathway (Schönsteiner et al. 2016; thinkstep 2019). Figure 38 shows the number of case studies broken down by the choice regarding bunkering operation. The majority of the case studies (128 case studies) do not specify any information related to bunkering operation. For the rest of the case studies, the choice is similarly distributed between Truck-to-Ship (28 case studies) and Ship-to-Ship (21 case studies). A minor number of case studies consider Port-to-Ship bunkering (11 case studies).

Figure 38. Choice of bunkering operation in the reviewed case studies on LCA of maritime fuel supply chains (% of case studies, n=189).

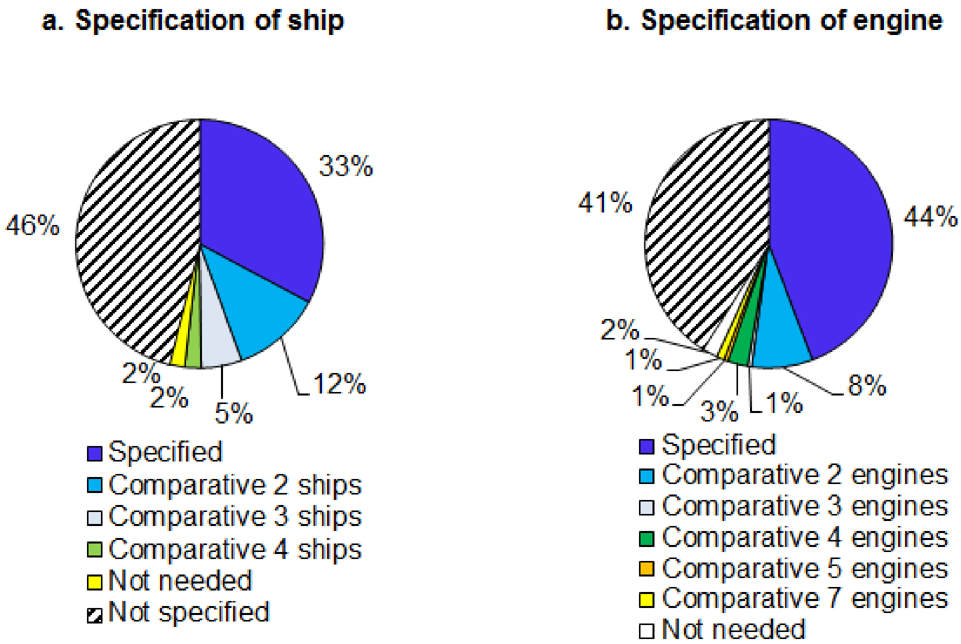


Source: IMDEA, 2022.

3.3.1.4.5 Type of ship and engine

As mentioned in Section 4.1.1, a non-negligible number of studies evaluate the fuel use/combustion stage under different types of ship and/or engine. Figure 39a and Figure 39b show the number of case studies broken down by the degree of specification of the type of ship and engine, respectively. About 46% of the case studies do not specify the type of ship considered, while 19% of the case studies evaluate the fuel use/combustion stage under two or more types of ship. With regard to the specification of the type of engine, about 41% of the case studies do not provide information in this regard. The evaluation of the fuel use/combustion stage under two or more types of engine occurs in 13% of the case studies. Up to five and seven types of engine are compared in some of the case studies defined in #3.

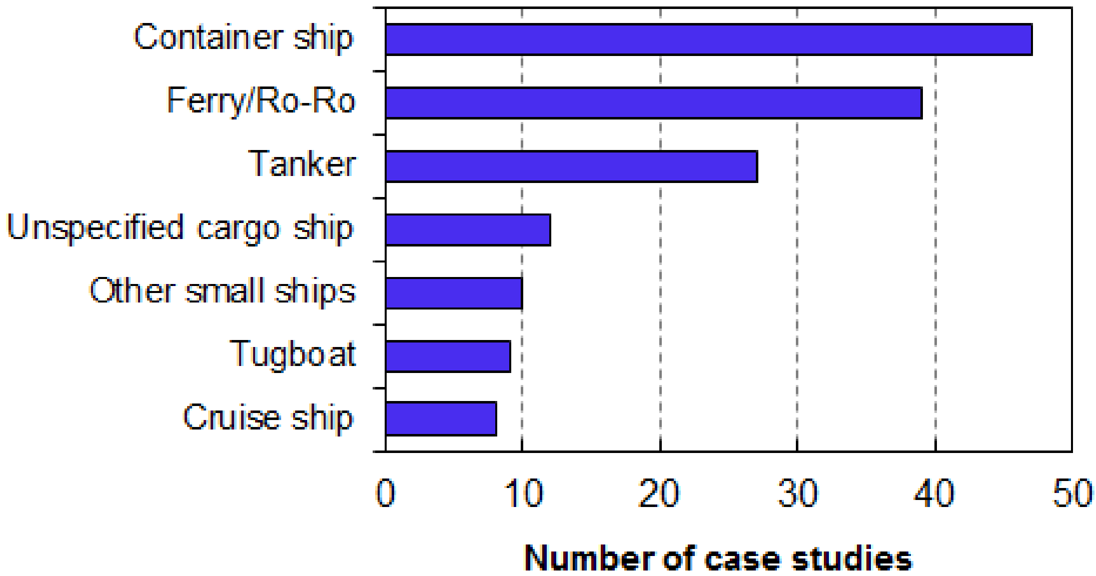
Figure 39. Specification of the type of ship an engine evaluated (% of case studies. n=189).



Source: IMDEA, 2022.

Figure 40 shows the choice of the type of ship in the reviewed case studies. Case studies evaluated under two or more types of ship were counted as many times as needed according to the number of ship types. As observed, container ships were found to be the most common choice (47 case studies) followed by ferry/Ro-Ro ships (39 case studies) and tankers (27 case studies). Overall, big cargo ships arose as the most common choice (total of 86 case studies).

Figure 40. Choice of type of ship in the reviewed case studies on LCA of maritime fuel supply chains.



Source: IMDEA, 2022.

With regard to the choice of the type of engine, the interest in evaluating different engines was found to be linked to their methane slip behaviour, which affects the environmental performance of LNG supply chains (Pavlenko et al. 2020). Methane slip refers to unburned methane mainly due to incomplete combustion. In this regard, Table 9 summarises the types of engine as provided in different studies on LNG along with the reported methane slip. As observed, a range of nomenclatures and degree of details were found. Dual-fuel (2-stroke, 4-stroke or unspecified) and spark ignition engines were identified as the most recurrent. Only one study (#3) evaluates gas turbines. According to the data provided in #3, gas turbines have the lowest methane slip when compared to dual-fuel and spark ignition engines. Among dual-fuel engines, 2-stroke engines have lower methane slip than 4-stroke engines. Furthermore, high-pressure injection is associated with a lower methane slip (Pavlenko et al. 2020; Seithe et al. 2020; Sharafian et al. 2019)

Table 9. Types of engine considered in different LCA studies on LNG for shipping. The methane slip is reported in brackets.

ID	Type of engine (methane slip)
#1	• Dual-fuel 2-stroke (0.1%) • Dual-fuel 4-stroke (2 – 3%)
#2	• Low-pressure injection dual-fuel, 4-stroke, medium-speed (5.5 g CH_4 kWh^{-1}) • Low-pressure injection dual-fuel, 2-stroke, slow-speed (2.5 g CH_4 kWh^{-1}) • High-pressure injection dual fuel, 2-stroke, slow-speed (0.2 g CH_4 kWh^{-1})
#3	• Dual-fuel, slow-speed 2-stroke diesel (0.1% of LNG) • Dual-fuel, slow-speed 2-stroke Otto (1.5% of LNG) • Dual-fuel, medium-speed 4-stroke Otto (2.5% of LNG) • Spark ignited, medium-speed 4-stroke Otto (1.3% of LNG) • Spark ignited, high-speed 4-stroke Otto (1.7% of LNG) • Gas turbine simple cycle (0.4% of LNG) • Gas turbine combined cycle (0.03% of LNG)
#4	• Dual-fuel engine (7 – 36 g CH_4 kWh^{-1})
#5	• Slow-speed 2-stroke diesel (Not specified)
#7	• Low-pressure dual-fuel, medium-speed (6.9 g CH_4 kWh^{-1}) • Low-pressure dual-fuel, slow-speed (3.3 g CH_4 kWh^{-1}) • High-pressure dual-fuel, slow-speed (0.01 g CH_4 kWh^{-1}) • Lean-burn spark-ignition engine (4.1 g CH_4 kWh^{-1})
#9	• Lean-burn spark-ignition engine (Not specified) • Low-pressure dual-fuel (Not specified)
#10	• Spark ignition engine (Not specified)
#14	• MAN 6L70MC C7 diesel engine (Not specified) • MAN 20V 28/33D diesel engine (Not specified)
#16	• Compression-ignition gas engine (Not specified) • Spark ignition medium-speed (Not specified) • Compression-ignition low-speed (Not specified)
#17	• Dual-fuel engine (3% weight) • Spark-ignition engine (4.4% weight)

#18	• Dual fuel engine (4% weight)
#21	• Dual fuel engine (Not specified)
#23	• Single-cylinder test engine (Not specified)
#24	• Spark-ignition engine (Not specified)
#25	• Slow-speed 2-stroke (Not specified)

Source: IMDEA, 2022.

3.3.1.4.6 Air pollution control system

The use of air pollution control (APC) systems such as scrubbers or selective catalytic reduction (SCR) was found in 11 case studies (about 6% of all case studies). HFO or MGO coupled with APC was found in eight case studies, synthetic diesel coupled with APC was found in one case study, and the remaining two case studies focus on biodiesel coupled with APC. #17 defines a case study where HFO combustion is followed by both a scrubber and SCR. The use of a scrubber after HFO/MGO combustion is assessed in #2, #3, and #24. The use of SCR after HFO/MGO combustion is assessed in #17, #21, and #24. Finally, #21 and #24 present case studies where the combustion of biodiesel and synthetic diesel is followed by SCR.

3.3.1.5 Multifunctionality

Maritime fuel supply chains are affected by multifunctionality in different life cycle stages due to multiple co-products. The distribution of the environmental burdens between the co-products is required. Table 10 summarises the multifunctionality situations identified in the reviewed studies along with the multifunctionality approach applied.

Table 10. Multifunctionality situations in different life cycle stages of maritime fuel supply chains.

Multifunctionality issue	**Fuel(s) affected**	**Life cycle stage**	**No. of studies affected**	**Multifunctionality approach**
Crude oil refining	HFO, MGO, MDO, IFO, diesel	Fuel processing/production	21	Subdivision (1), energy allocation (8), mass allocation (1), normalisation (1), not specified (10)
Electricity co-production	Biodiesel, methanol, biogas/biomethane	Fuel processing/production	5	Substitution (3), energy allocation (2),
Heat co-production	Biodiesel, methanol, biogas/biomethane	Fuel processing/production	2	Energy allocation (1), substitution (1)
Biomass residues harvesting	Biodiesel	Feedstock extraction/production	2	Economic allocation (1), not specified (1)
Glycerine/meal co-production	Biodiesel	Fuel processing/production	5	Energy allocation (2), economic/mass allocation (1), not specified (2)
Waste management	Methanol, biogas, biomethane	Feedstock extraction/production	3	Substitution (1), not specified (2)

Source: IMDEA, 2022.

Oil-based fuel supply chains are affected by multifunctionality in the refinery stage. Twenty-one studies out of 26 are affected by this multifunctionality. A significant number of the studies (10 studies) do not specify the applied allocation rule. The studies that specify the allocation rule were found to apply mainly energy allocation (8 case studies). Only one study (#4) applies mass allocation, justified by the fact that an energy allocation provides a preferential treatment towards heavier products because of their lower energy content. Furthermore, one study (#15) specifies that allocation was avoided by splitting the original processes into mono-functional sub-processes. An alternative allocation rule, called normalisation, was found in #22. In this study, the authors establish the energy consumption and emissions of the most complex refinery product, namely EN590 diesel, as the reference. Subsequently, the emissions of the other products are calculated based on the percentage of energy consumed by these products with regard to the reference.

In some cases, multifunctionality may occur due to the co-production of electricity in fuel processing/production technologies such as gasification or pyrolysis. Such a multifunctionality situation is specified in five studies. Three studies (#8, #13, #15) apply the substitution approach and the other two (#19, #21) apply energy allocation. In addition to electricity, heat (or steam) can also be a co-product of fuel processing. Heat co-production is specified in two studies: one applies energy allocation (#19) and the other substitution (#13, for steam).

Biodiesel based on biomass residues derived from crops is affected by multifunctionality in the feedstock harvesting stage. More specifically, burdens should be allocated between the biomass crop and the residue (Tanzer et al. 2019). This multifunctionality occurs in two studies (#8, #19), but only #8 specifies the application of economic allocation.

Transesterification is also a multifunctional process due to the co-production of glycerine and meal in addition to biodiesel (Kesieme et al. 2019). This multifunctionality occurs in five studies. Two studies apply energy allocation (#19, #21), one study (#6) applies both economic and mass allocation, and the two remaining studies do not specify the applied allocation rule.

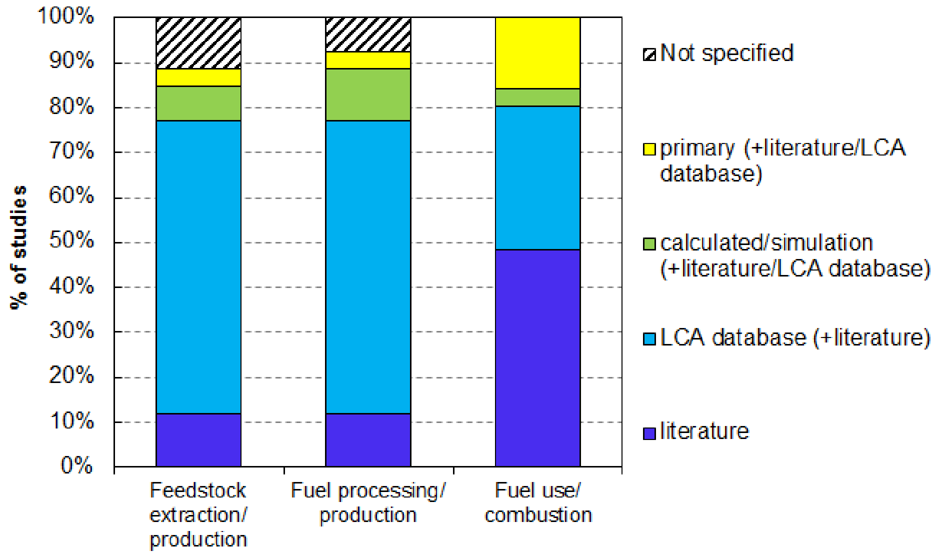
Finally, a particularity in terms of allocation may arise when using waste feedstocks. Three studies use waste feedstocks: #10 uses animal waste (mixed with agricultural waste) for biogas/biomethane production, #21 uses manure and municipal solid waste (mixed with agricultural waste) for biogas/biomethane production, and #13 uses landfill gas for methanol production. One may want to account for the environmental savings of deriving waste from the conventional treatment (e.g., landfilling or incineration) towards fuel production. In this regard, the substitution approach can be applied so that the fuel production system is credited for the potential environmental impacts of the avoided treatment option (Laurent et al. 2014). This approach is followed in #13, which assumes that the utilisation of landfill gas for methanol production prevents its emission to the atmosphere. Therefore, the methanol is credited for these avoided emissions. The other two studies involving waste feedstocks do not provide information in this regard.

3.3.1.6 Life cycle inventory analysis

Life cycle inventory data sources were collected for the main life cycle stages, namely feedstock extraction/production, fuel processing/production, and fuel use/combustion (Figure 41). It should be noted that the used sources were obtained from each study based on what the authors reported. LCA databases either alone or in combination with literature are highly used for the feedstock extraction/production or fuel processing/production stages. The most cited LCA databases in the reviewed studies are GREET, ecoinvent, and ELCD. Other cited LCA databases are GaBi, Agri-footprint, CPM, and GEMIS. Literature is highly used for the fuel use/combustion stage. It should be noted that the label ''literature'' includes reports as well. In this regard, several studies cite the Third IMO Greenhouse Gas Study 2014 as the source of fuel combustion emission factors.

Life cycle inventory data from simulation and/or calculation as well as primary data (i.e. based on direct measurements in plants on both industrial and laboratory scale) are scarcely used in the reviewed studies. Only one study (#3) specifies the use of primary data for all the three stages. The primary data comes from the industrial partners involved in the project. In the case of the fuel use/combustion stage, four studies specify the use of primary data. In addition to the aforementioned study, #23 derives emissions factors for biodiesel combustion from laboratory experiments.

Figure 41. Use of life cycle inventory data sources at different stages in the reviewed studies on LCA of maritime fuel supply chains.

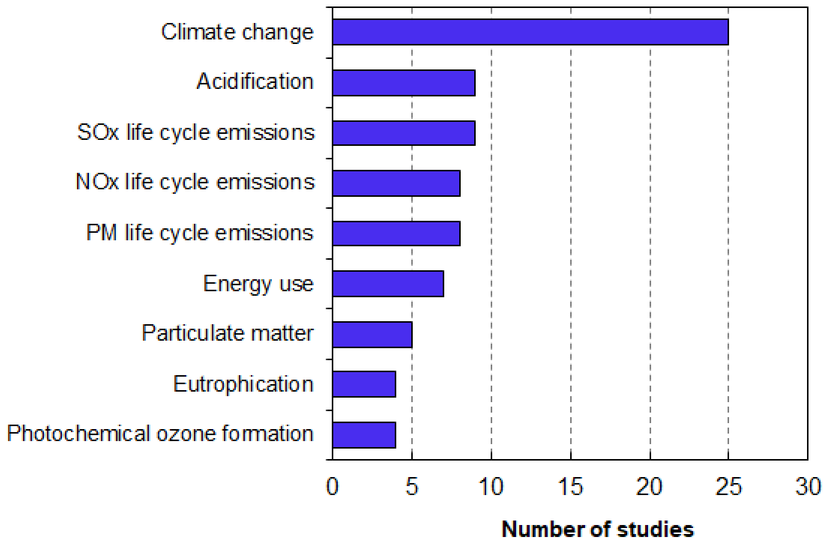


Source: IMDEA, 2022.

3.3.1.7 Life cycle impact assessment

Figure 42 shows the impact categories that cover about 85% of the total number of category occurrences in the studies reviewed. Climate change is visibly the most common impact category. Twenty-five out of 26 studies assess the climate change impact. It should be noted that one study (#25) involves the assessment of CO_2 life cycle emissions with no further impact assessment. Acidification and SO_x life cycle emissions are addressed in nine studies each, while NO_x and PM life cycle emissions are addressed in eight studies each. As observed, a significant number of studies assess life cycle emissions of local pollutants (SO_x, NO_x, PM) with no further impact assessment. This trend may reflect the importance given to shipping as an important source of these local pollutants. However, thinkstep (2019) argue that adding all air pollutants along the fuel supply chains in different locations may give wrong conclusions of air quality impacts, especially for coastal areas, harbours and ECAs. Since most of the studies focus only on the climate change impact or on the climate change impact and the life cycle emissions of local pollutants, normalisation and weighting are often disregarded. It is remarkable that about 12% of the studies include costs analysis in addition to environmental analysis.

Figure 42. Choice of impact categories in the reviewed studies on LCA of maritime fuel supply chains.

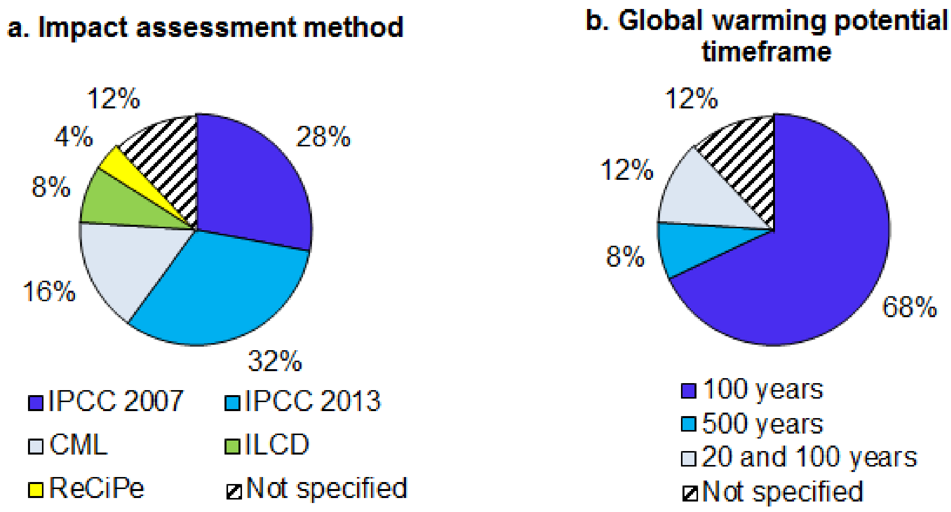


Source: IMDEA, 2022.

Regarding the climate change impact category, Figure 43 shows the number of studies broken down by the choice regarding the impact assessment method and the global warming potential (GWP) timeframe. IPCC methods were found to be the most common choice. The choice is similarly distributed between IPCC 2007 and IPCC 2013. Other used methods are CML, ILCD, and ReCiPe. It should be noted that these methods usually apply IPCC characterisation factors. Three studies do not specify clearly the method used to evaluate climate change.

The GWP timeframe can significantly affect the outcomes of the LCA study. In this regard, 17 studies (68% of total) assumed the standard 100-year timeframe, two studies, carried out by the same authors (#11, #12), assume a 500-year timeframe, and three studies (#2, #4, #9) evaluate both 20- and 100-year timeframe. Three studies do not specify clearly the GWP timeframe. It should be noted that these statistics do not include sensitivity analysis. The GWP timeframe can play a key role when assessing LNG due to methane leakage/slip (Pavlenko et al. 2020). The use of a 20-year timeframe (vs the standard 100 years) increases the impact on global warming since the GWP of methane for 100 years is lower compared to 20 years. Pavlenko et al. (2020) conclude that under 20-year GWP there is no climate benefit from using LNG compared to HFO or MGO.

Figure 43. Choice of climate change impact assessment method and global warming potential timeframe in the reviewed studies on LCA of maritime fuel supply chains (% of studies, n=25).

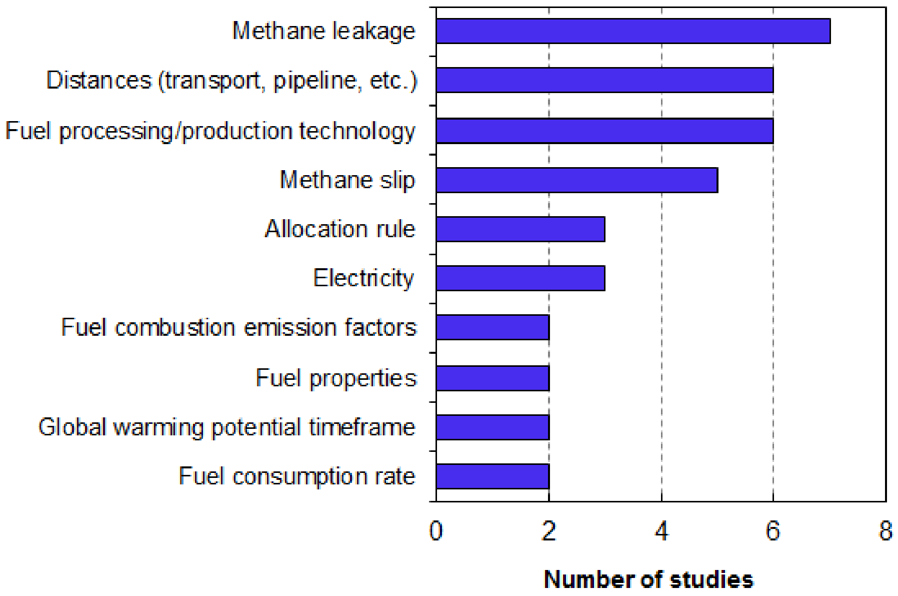


Source: IMDEA, 2022.

3.3.1.8 Sensitivity and uncertainty

About 65% of all studies (17 studies out of 26) were found to perform a sensitivity analysis. Figure 44 shows the parameters/choices subject to sensitivity analysis in more than one study. The parameter most commonly assessed through sensitivity analysis is the methane leakage related to natural gas feedstock (7 studies). Furthermore, the sensitivity to the methane slip from the engine is also assessed by five studies. Overall, Lowell et al. (2013) state that the life cycle GHG emissions of LNG fuel supply chains can be reduced by between 10% and 16% by implementing best practices in controlling methane leaks throughout the fuel cycle. The influence of the performance of fuel processing technology on the LCA results was assessed through sensitivity analysis in six studies. These analyses include changes in refining efficiency (#1, #25), liquefaction performance (#1, #7, #10, #18), methanol production performance (#18), and biogas upgrading performance (#10). The sensitivity to parameters related to transportation such as feedstock or fuel transportation distances by road or ship and pipeline length is also addressed in six studies. Only one study (#3) performs parameter uncertainty analysis by error propagation methods (Monte Carlo simulation).

Figure 44. Choice of parameters for sensitivity analysis in the reviewed studies on LCA of maritime fuel supply chains.



Source: IMDEA, 2022.

3.3.2 Gaps and trends

The reviewed LCA studies of maritime fuel supply chains are concluded to be homogeneous in terms of goal and scope definition. More specifically, the majority of the studies compare the life cycle environmental performance of maritime fuel supply chains covering a Well-to-Propeller scope and including the most important stages in the supply chain, namely feedstock extraction/production, fuel processing/production, and fuel use/combustion. The LCA methodology is usually well reported and assumptions are easily interpretable.

Based on the meta-analysis study, the following trends were identified:

- The interest of authors is placed not only in the comparison of fuels, but also in the comparison of supply chains configurations. Feedstock and location are the variables most often used to define new fuel supply chain configurations.
- The majority of the studies follow a Well-to-Propeller system boundary, i.e. covering the full life cycle from feedstock production/extraction to fuel use/combustion. The life cycle environmental impacts related to ship's life cycle stages such as shipbuilding or engine manufacturing are generally excluded.
- The majority of the case studies address alternative fuels in opposition to oil-based fuels. However, the percentage of case studies of non-renewable fuels is superior to renewable fuels. Omitting distortion sources (viz., study #8 on biodiesel), the most assessed fuels are LNG and HFO; both non-renewable fuels. The occurrence of MGO, a non-renewable fuel, and non-renewable methanol is also relevant. Within renewable fuels, the most assessed is biodiesel.
- The consideration of different types of engine for the fuel use/combustion stage is a recurrent topic for LNG evaluation due to different methane slip.
- Methane leakage is the most addressed parameter through sensitivity analysis followed by transportation distances, fuel processing/production technology parameters, and methane slip from the engine.
- A combination of LCA databases and literature is the most recurrent source of life cycle inventory data.
- Climate change is by far the most assessed impact category. An interest in SO_x, NO_x, and PM life cycle emissions was also observed.

Furthermore, the following gaps and underdeveloped topics were identified:

- Lack of a homogeneous and consolidated functional unit.
- Reduced number of case studies on alternative renewable-based fuels.
- Reduced number of case studies comparing different fuel processing/production technologies.
- Reduced number of case studies on air pollution control systems such as scrubbers and selective catalytic reduction.
- The supply chain infrastructure is not usually included within the system boundary.
- Generally, scarce information is provided with regard to the source of the natural gas used for LNG production.
- The use of primary life cycle inventory data is scarce and generally restricted to the fuel use/combustion stage.
- Little attention is generally paid to impact categories other than global warming.
- Lack of uncertainty analysis (probabilistic modelling) and prospective assessment.

3.3.3 Quantitative assessment of life cycle environmental impacts

The homogeneity of the reviewed LCA studies of maritime fuel supply chains in terms of goal and scope allows a joint quantitative assessment of the LCA results. This quantitative assessment was restricted to studies that involve a Well-to-Propeller scope. Furthermore, only the climate change impact based on 100-year timeframe was statistically assessed since the occurrence of the other impact categories is not enough to provide a relevant number of data points for a statistical analysis. In any case, Section 4.3.4 includes an additional discussion on the results for other impact categories.

Results for climate change impact based on the 100-year timeframe were collected from 20 LCA studies. The total number of data points collected is 203. It should be noted that a variation in the type of ship or engine was considered as a new data point for the purpose of this analysis since the climate change impact would be affected by such a consideration. This explains why the number of data points is higher than the number of original case studies (189). Harmonisation of methodological choices for robust comparison was not pursued in this study. Therefore, the raw data as provided in the original case studies were used to perform the quantitative assessment. However, whenever possible, the functional unit was converted to 1 GJ of fuel energy content in order to allow comparisons. In this regard, data points referred to 1 kWh engine work output in the original study were recalculated per 1 GJ of fuel energy content. This functional unit conversion was performed whenever the engine efficiency was reported in the original study.

Table 11 summarises the number of data points for each fuel and functional unit (functional unit conversion as aforementioned). The number of studies associated with the data points is indicated in brackets. A relatively relevant number of data points (> 10) were obtained for LNG, biodiesel, HFO, MGO, and methanol. Furthermore, the majority of the data points were provided (or successfully converted) per 1 GJ of fuel energy content. The highest diversity, in terms of the number of original studies providing data points, was observed for LNG (16 studies) and HFO (15 studies). Therefore, the most representative statistical results will be obtained for these fuels. Biodiesel and methanol have a relatively high number of data points, 45 and 18 respectively, but provided by a reduced number of studies, seven and four, respectively. Therefore, the statistical results for biodiesel and methanol, as well as for the rest of the fuels, should be interpreted with caution, bearing in mind the low degree of representativeness.

Table 11. Number of data points of climate change impact (100-year timeframe) per fuel and functional unit obtained from the reviewed case studies. The number of studies associated with the data points is included in brackets.

Fuel	1 GJ of fuel energy content	1 kWh of engine work output	tkm	service	Total
LNG	39 (10)	4 (2)	5 (4)	0 (-)	48 (16)
Biodiesel	39 (5)	2 (1)	2 (1)	2 (1)	45 (7)
HFO	24 (9)	4 (2)	6 (4)	2 (1)	36 (15)
MGO	15 (6)	3 (1)	4 (3)	0 (-)	22 (10)
Methanol	15 (2)	1 (1)	2 (1)	0 (-)	18 (4)
IFO	7 (2)	0 (-)	0 (-)	0 (-)	7 (2)
Biogas/biomethane	2 (1)	1 (1)	3 (2)	0 (-)	6 (4)
Synthetic diesel	1 (1)	0 (-)	2 (1)	2 (1)	5 (2)
Diesel	2 (2)	0 (-)	0 (-)	2 (1)	4 (2)
Hydrogen	1 (1)	3 (1)	0 (-)	0 (-)	4 (2)
MDO	2 (2)	1 (1)	0 (-)	0 (-)	3 (3)
CNG	1 (1)	0 (-)	0 (-)	2 (1)	3 (1)
SVO	0 (-)	2 (1)	0 (-)	0 (-)	2 (1)

Source: IMDEA, 2022.

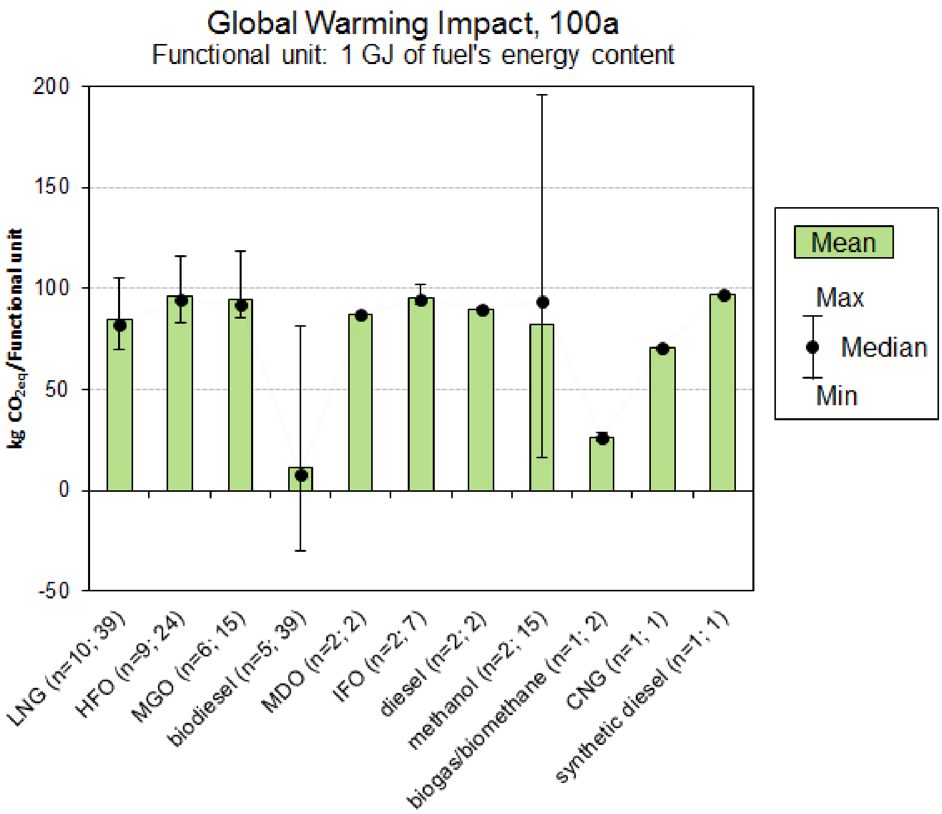
3.3.3.1 Statistical analysis of the climate change impact of maritime fuel supply chains

This section presents a statistical analysis of the life cycle climate change impact (100-year timeframe) of maritime fuel supply chains. Figure 45 shows the analysis for the functional unit of 1 GJ of fuel energy content. This functional unit groups the highest number of data points. Fuels in Figure 45 are ordered from highest to lowest diversity in terms of the number of studies associated with the data points.

Overall, the life cycle climate change impact of LNG was found to be in the range of the impact of oil-based fuels. The median life cycle climate change impact of LNG, based on 39 data points retrieved from 10 studies, is 82 kg $CO_{2\ eq}$ GJ^{-1}; data points range from 70 to 105 kg $CO_{2\ eq}$ GJ^{-1} fuel. The median value obtained for HFO is 96 kg $CO_{2\ eq}$ GJ^{-1} fuel, with data points ranging from 83 to 116 kg $CO_{2\ eq}$ GJ^{-1} fuel, while the median value for MGO is 92 kg $CO_{2\ eq}$ GJ^{-1} fuel, with data points ranging from 85 to 118 kg $CO_{2\ eq}$ GJ^{-1} fuel. The results obtained for the other oil-based fuels (MDO, IFO, and diesel) and synthetic diesel fall within the range 87 – 102 kg $CO_{2\ eq}$ GJ^{-1} fuel (although based on a reduced number of data points). It should be noted that the median and mean values are very similar. The potential life cycle climate change benefit of LNG over HFO is further investigated in Section 4.3.2.

For the rest of the fuels, the number of data points is reduced and, consequently, the relevance of the statistical analysis of the life cycle impacts is limited. The life cycle climate change impact of biodiesel ranges between -30 and 81 kg $CO_{2\ eq}$ GJ^{-1} fuel with a median of 8 kg $CO_{2\ eq}$ GJ^{-1} fuel. The highest impact was observed for a case study on soybean-based biodiesel defined in #26. This case study assumes that biogenic CO_2 from fuel combustion has an unfavourable impact on climate change, while the accounting of the CO_2 uptake during feedstock growth remains unclear. The rest of case studies assume that biogenic CO_2 has a net zero impact on climate change due to its biogenic origin (Tanzer et al. 2019). Furthermore, a negative (i.e., favourable) climate change impact was obtained in several case studies based on forest residues defined in #8 due to the avoided impact associated with electricity co-production.

Figure 45. Statistical analysis of the life cycle climate change impact (100-year timeframe) of maritime fuel supply chains per 1 GJ of fuel energy content. The numbers after each fuel name refer to the number of studies associated with the data points and the number of data points, respectively.



Source: IMDEA, 2022.

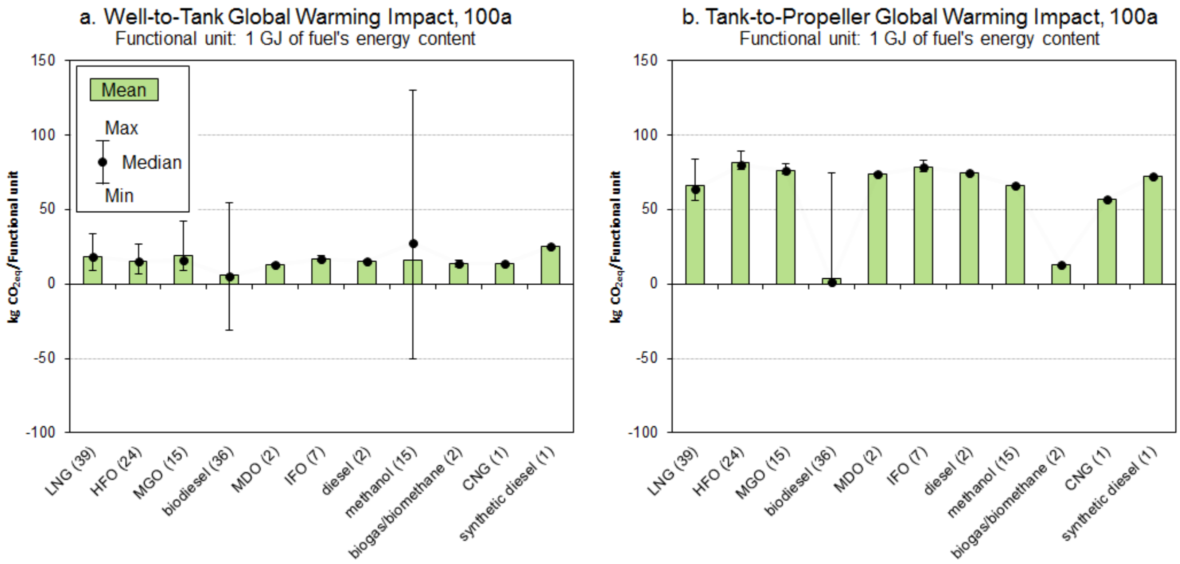
The life cycle climate change impact of methanol ranges between 16 and 196 kg $CO_{2\ eq}$ GJ^{-1} fuel. The large variability is primarily due to the feedstock used. The highest impact corresponds to methanol production through gasification of coal (196 kg $CO_{2\ eq}$ GJ^{-1} fuel). Methanol production through natural gas reforming also provides a relatively high impact (average of 95 kg $CO_{2\ eq}$ GJ^{-1} fuel). A particularity arises in #13, which evaluates an alternative natural gas flow, namely surplus natural gas that would be flared otherwise. The authors assume that, since the natural gas is no longer flared but used for methanol production, the methanol is credited for the avoided environmental burdens. This results in a minimum life cycle climate change impact of 16 kg $CO_{2\ eq}$ GJ^{-1} fuel. With regard to biomass-based methanol, both #9 and #13 report 71 kg $CO_{2\ eq}$ GJ^{-1} fuel for methanol production through gasification of forest residues. However, it is unclear how the biogenic CO_2 was accounted for. For example, #9 assumes that the emission of biogenic CO_2 from fuel combustion has an unfavourable impact on climate change. In contrast, the assumptions about CO_2 uptake during feedstock growth are not detailed.

Figure 46 splits the life cycle climate change impact of each fuel between Well-to-Tank (from fuel extraction/production to fuel distribution) and Tank-to-Propeller (fuel use/combustion). This analysis was performed for the case studies that provide separate results for the two stages. The life cycle climate change impact of LNG, oil-based fuels, CNG, and synthetic diesel is primarily concentrated in the Tank-to-Propeller stage, i.e. the combustion of the fuel. The median Well-to-Tank and Tank-to-Propeller impacts of LNG are 19 and 64 kg $CO_{2\ eq}$ GJ^{-1} fuel, respectively. In the case of HFO and MGO, these values are 15 and 80 kg $CO_{2\ eq}$ GJ^{-1} fuel and 16 and 76 kg $CO_{2\ eq}$ GJ^{-1} fuel, respectively.

The median life cycle climate change impact of biodiesel is mainly concentrated in the Well-to-Tank stage. The median Well-to-Tank impact is 6 kg $CO_{2\ eq}$ GJ^{-1} fuel, while the median Tank-to-Propeller impact is 1 kg $CO_{2\ eq}$ GJ^{-1} fuel. However, the life cycle climate change impact of biodiesel involves high uncertainty due to authors' assumptions on biogenic CO_2 accounting and multifunctionality. In this regard, the Well-to-Tank impact can become negative if assuming electricity co-production, while the Tank-to-Propeller impact can become significant if assuming that the biogenic CO_2 has an unfavourable impact on climate change.

The median life cycle climate change impact of methanol is concentrated in the Tank-to-Propeller stage due to the high number of case studies on natural gas-based methanol. The median Well-to-Tank impact is 28 kg $CO_{2\ eq}$ GJ^{-1} fuel, while the median Tank-to-Propeller impact is 66 kg $CO_{2\ eq}$ GJ^{-1} fuel.

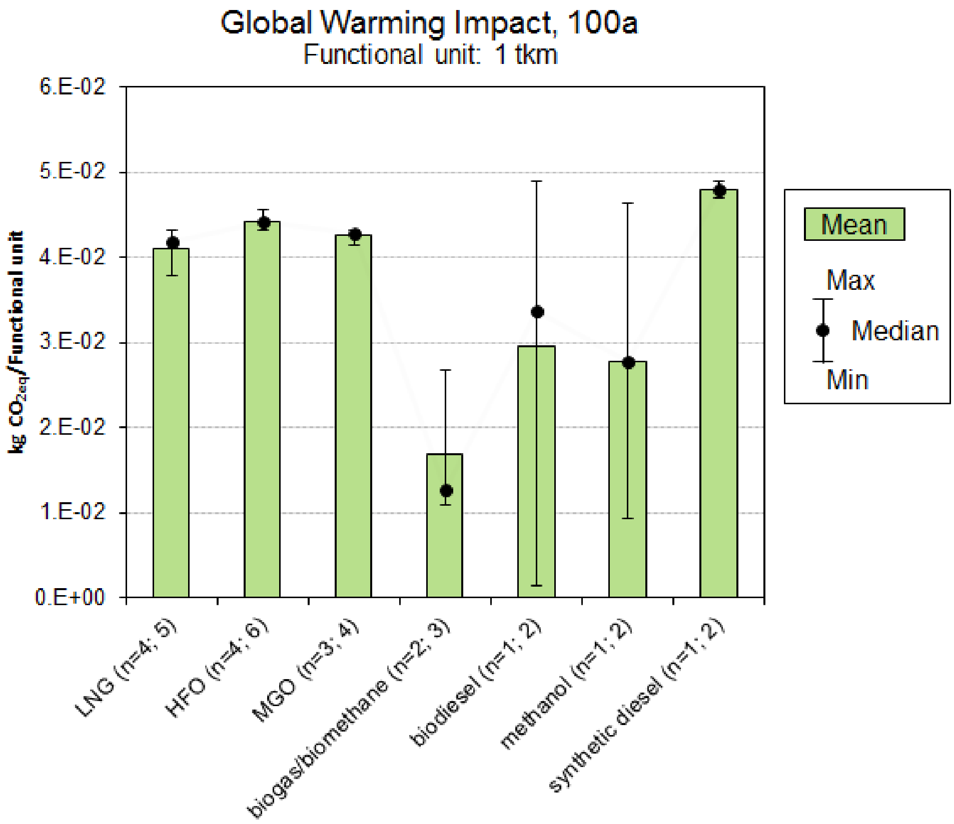
Figure 46. Split between Well-to-Tank and Tank-to-Propeller of the life cycle climate change impact (100-year timeframe) of maritime fuel supply chains per 1 GJ of fuel energy content. The numbers after each fuel name refer to the number of data points.



Source: IMDEA, 2022.

Finally, Figure 47 shows the statistical analysis of the life cycle climate change impact (100-year timeframe) of maritime fuel supply chains per tkm. The number of data points available for this functional unit is reduced. The median life cycle climate change impact of LNG, based on five data points retrieved from four studies, is 0.041 kg $CO_{2\ eq}$ tkm^{-1}, with data points ranging from 0.038 to 0.043 kg $CO_{2\ eq}$ tkm^{-1}. The median value for HFO is 0.044 kg $CO_{2\ eq}$ tkm^{-1}, within data points the range 0.043 – 0.046 kg $CO_{2\ eq}$ tkm^{-1}, and for MGO is 0.043 kg $CO_{2\ eq}$ tkm^{-1}, within data points in the range 0.041 – 0.043 kg $CO_{2\ eq}$ tkm^{-1}.

Figure 47. Statistical analysis of the life cycle climate change impact (100-year timeframe) of maritime fuel supply chains per 1 tkm. The numbers after each fuel name refer to the number of studies associated with the data points and the number of data points, respectively.



Source: IMDEA, 2022.

3.3.3.2 Climate benefits of LNG over HFO

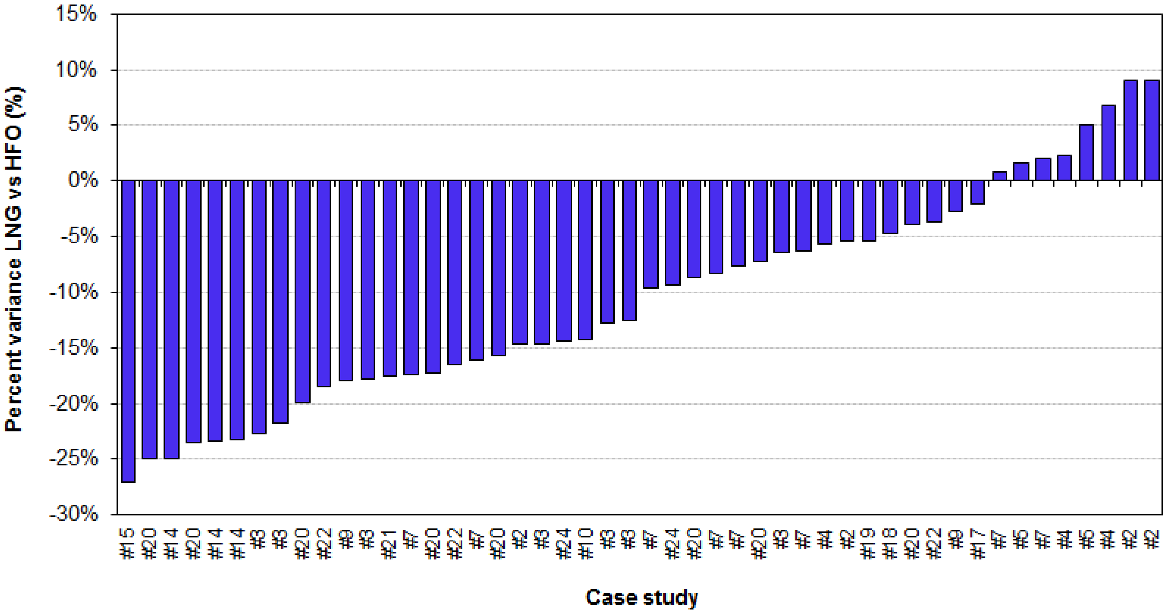
LNG and HFO are the fuels with the highest number of data points and source diversity. This is motivated in part by the interest in LNG as an alternative to HFO in order to reduce GHG emissions from shipping. In this regard, Figure 48 presents an analysis of the life cycle climate change impact (100-year timeframe) of LNG in comparison with HFO. More specifically, Figure 48 shows the percent variance of each data point on LNG with respect to the average value obtained for HFO:

$$Percent\ variance\ (\%) = \frac{I_{LNG,i} - Ia_{HFO}}{Ia_{HFO}} \cdot 100$$

where $I_{LNG,i}$ is each data point i on the life cycle climate change impact of LNG and Ia_{HFO} is the average life cycle climate change impact of HFO. The average impact of HFO for each functional unit is: 96 kg $CO_{2\ eq}$ GJ^{-1} fuel, 0.685 kg $CO_{2\ eq}$ kWh^{-1} engine work output, and 0.044 kg $CO_{2\ eq}$ tkm^{-1}.

About 83% of the case studies were found to show a reduced life cycle climate change impact of LNG compared to HFO. The average reduction is 11%, while the maximum reduction is 27%. On the other hand, a maximum increase of 9% was found.

Figure 48. Percent variance of the life cycle climate change impact (100-year timeframe) of LNG with respect to HFO.



Source: IMDEA, 2022.

The GWP timeframe can play a key role when assessing the life cycle climate benefits of LNG over HFO or other oil-based fuels (Pavlenko et al. 2020). Two studies (#2, #4) compare LNG and HFO under both 20- and 100-year GWP timeframes (Table 12). Both studies show a slightly decreased life cycle climate change impact for LNG compared to HFO under a 100-year timeframe following the trend in Figure 48. However, when assuming a 20-year timeframe, HFO outperforms LNG. As observed, the GWP timeframe has a negligible influence on the life cycle climate change impact of HFO, but largely influences the life cycle climate change impact of LNG primarily due to methane leakage through the supply chain and methane slip from the engine.

Table 12. Life cycle climate change impact of LNG and HFO under 100- and 20-year global warming potential timeframe retrieved from two studies. Minimum-mean-maximum values reported in the original references are indicated.

ID	**Functional unit**	**100-year timeframe GWP** (kg $CO_{2\ eq}$/functional unit)		**20-year timeframe GWP** (kg $CO_{2\ eq}$/functional unit)	
		LNG	**HFO**	**LNG**	**HFO**
#2	1 GJ of fuel energy content	82 – **96** – 105	96 – **100** – 105	99 – **136** – 156	98 – **105** – 111
#4	1 kWh engine work output	0.646 – **0.692** – 0.731	0.700 – **0.703** – 0.708	0.802 – **0.893** – 0.977	0.733 – **0.738** – 0.748

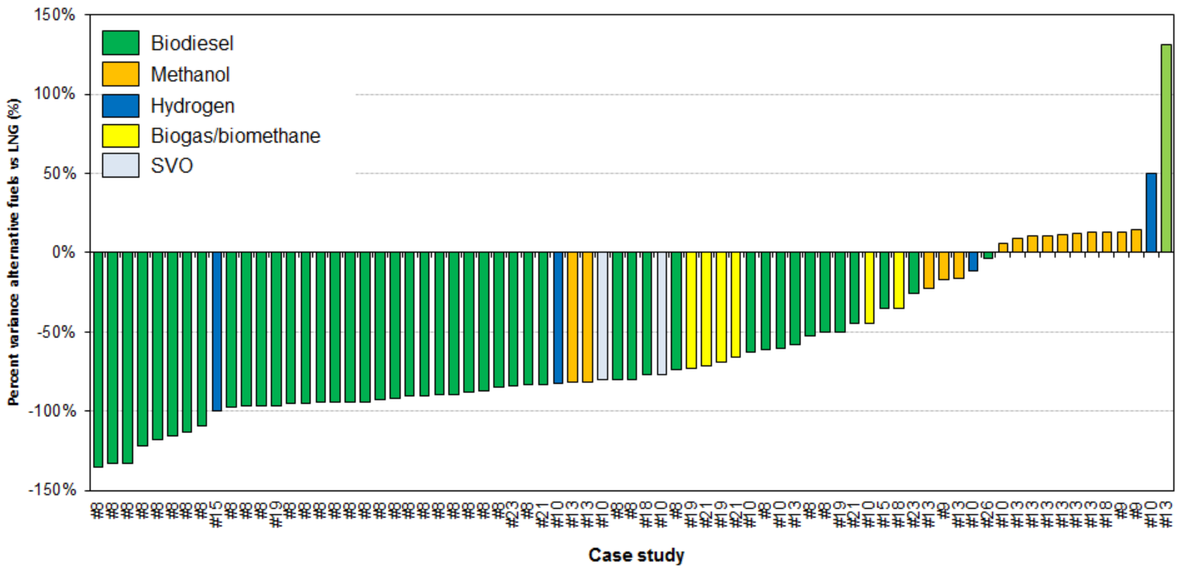
Source: IMDEA, 2022.

3.3.3.3 Alternative fuels

Apart from LNG, other alternative fuels assessed in the reviewed studies are biodiesel, methanol, hydrogen, biogas/biomethane, and SVO. The life cycle climate change impact of these fuels was compared against LNG following the approach used in the previous section. Thus, Figure 49 presents the percent variance of each data point on these alternative fuels with respect to the average impact of LNG. The average impact of LNG for each functional unit is: 85 kg $CO_{2\ eq}$ GJ^{-1} fuel, 0.666 kg $CO_{2\ eq}$ kWh^{-1} engine work output, and 0.041 kg $CO_{2\ eq}$ tkm^{-1}. The results presented in Figure 49 should be interpreted with caution due to the reduced representativeness of the data (i.e. the data points are concentrated in a reduced number of studies). Furthermore, as shown in Section 4.3.1, the climate change impact of alternative fuels such as biodiesel and methanol are subject to large uncertainty associated with authors' assumptions.

Overall, the alternative fuels show a reduced life cycle climate change impact compared to LNG. The data points that reflect an increased impact corresponds to natural gas-based methanol, natural gas-based hydrogen, and coal-based methanol.

Figure 49. Percent variance of the life cycle climate change impact (100-year timeframe) of alternative fuels with respect to LNG.



Source: IMDEA, 2022.

3.3.3.4 Other life cycle impacts

The statistic assessment of the life cycle environmental impacts of maritime fuel supply chains was restricted to the climate change impact due to data availability. However, other impacts such as acidification and emissions such as SO_x, NO_x, and PM are of particular relevance to the shipping sector. This section discusses the most relevant observations within the reviewed case studies for these other impacts.

LNG arises as the most promising alternative to reduce the relatively high emission levels of SO_x, NO_x, and PM associated with HFO. In this regard, the life cycle SO_x emissions of LNG are significantly lower compared to HFO. The life cycle SO_x emissions reported in #6 range between 26 and 80 g SO_x GJ^{-1} LNG and between 1,444 and 1,547 g SO_x GJ^{-1} HFO. Similarly, #14 reports a range between 1.96 and 2.37 g SO_x GJ^{-1} LNG and between 1,221 and 1,223 g SO_x GJ^{-1} HFO. The lower emission levels of SO_x contribute to reducing the acidification impact of LNG compared to HFO, as found in #17, #19, and #24. LNG largely outperforms HFO also in terms of life cycle PM emissions. The life cycle PM_{10} emissions reported in #6 range between $4.40 \cdot 10^{-3}$ and $8.20 \cdot 10^{-3}$ kg PM_{10} GJ^{-1} LNG and between $1.94 \cdot 10^{-1}$ and $2.05 \cdot 10^{-1}$ kg PM_{10} GJ^{-1}HFO. As observed, the difference in the life cycle SO_x and PM emissions between LNG and HFO is of several orders of magnitude. With regard to the life cycle emissions of NO_x, the potential benefit of LNG over HFO is less clear. For example, #6 reports a range from 209 to 1,311 g NO_x GJ^{-1} LNG and from 1,058 to 1,665 g GJ^{-1} NO_x HFO. In the case of #14, the reported ranges are 1,413 – 1,419 g NO_x GJ^{-1} LNG and 2,389 – 2,390 g GJ^{-1} NO_x HFO.

In terms of energy use, #15 found that HFO, MGO, and LNG have a similar cumulative energy demand: 1.09 GJ GJ^{-1} HFO, 1.12 GJ GJ^{-1} HFO, and 1.16 GJ GJ^{-1} LNG. Furthermore, the cumulative energy demand of alternative fuels such as biodiesel and renewable hydrogen increases up to 2.31 GJ GJ^{-1} biodiesel and 2.02 GJ GJ^{-1} hydrogen. This trend is also found in #21, which reports the primary energy use for HFO (1.189 GJ GJ^{-1}), LNG (1.162 GJ GJ^{-1}), biodiesel (2.391 GJ GJ^{-1}), and biogas (2.911 GJ GJ^{-1}). Alternatively, #18 calculates the total extracted energy required per tkm. The results show the same trend, with HFO ($5.42 \cdot 10^{-4}$ GJ tkm^{-1}) and LNG ($5.90 \cdot 10^{-4}$ GJ tkm^{-1}) demanding a considerably lower amount of energy in comparison with alternative renewable fuels such as liquefied biogas ($1.01 \cdot 10^{-3}$ GJ tkm^{-1}) and biomass-based methanol ($1.17 \cdot 10^{-3}$ GJ tkm^{-1}).

3.4 Conclusions

This report addresses a meta-study to catalogue the available LCA literature on maritime systems, identifying the soundness of the studies, and performing a gap and trend analysis of both methodological and technical features. After an exhaustive screening of the scientific literature, involving more than 800 documents, two categories of studies on maritime systems were identified: 45 studies that apply LCA to ships, and 26 studies that apply LCA to maritime fuel supply chains.

The reviewed studies on LCA related to ships cover a variety of goals. Besides comparative and non-comparative LCAs of ships, other goals found were the assessment of power system configurations, hull materials, ship end-of-life strategies, and hull maintenance strategies. Certainly, this variety is aligned with the objective of promoting sustainability in the shipping sector through a broad range of technical, strategic measures. It was found that even LCA studies with a similar goal (e.g., comparative LCAs of power system configurations) are generally heterogeneous in terms of the number and type of life cycle stages assessed (i.e., the scope). A slight prevalence of the Cradle-to-Grave scope was detected, although the Cradle-to-Operation and Gate-to-Grave scopes were also found to be common. Furthermore, differences in the definition of specific life cycle stages were observed (e.g., the raw materials considered are limited to steel in a number of studies). In addition to the heterogeneous scope, it was found that fundamental aspects of the LCA methodology (e.g., functional unit and end-of-life multifunctionality approach) are usually not clearly defined. Overall, these features make the interpretation of the results challenging.

The reviewed studies on LCA of maritime fuel supply chains were found to be homogeneous in terms of goal and scope. Most of the studies compare the life cycle environmental performance of maritime fuel supply chains covering a Well-to-Propeller scope, i.e. from feedstock extraction/production to fuel use/combustion. The functional unit is similarly distributed between tkm, energy unit of fuel, engine work output, and service provided. Therefore, a lack of a consolidated functional unit was observed. Omitting distortion sources, the most assessed fuel was found to be LNG, while the number of case studies on alternative renewable fuels was found reduced. Furthermore, little attention is generally paid to impact categories other than climate change. Overall, the LCA methodology is usually well reported and assumptions are easily interpretable.

A joint quantitative assessment of the LCA results was performed whenever possible and appropriate. An analysis of the contribution of the main ship life cycle stages (raw materials extraction and shipbuilding, operation, and end-of-life) to the life cycle GHG emissions was performed. The operation stage was found to be the largest source of GHG emissions in the life cycle of ships. This finding highlights the importance of promoting alternative clean fuels. In this regard, it was found that the supply chain of LNG generally shows a reduced life cycle climate change impact compared to HFO. Furthermore, LNG also shows a significant reduction in the life cycle SO_x and particulate matter emissions. On the other hand, alternative renewable fuels such as biodiesel, methanol, hydrogen, and biogas/biomethane show a reduced life cycle climate change impact compared to LNG.

Overall, the reviewed studies on LCA related to ships indicate the need for further harmonisation and consolidation of methodological choices. In contrast, the reviewed LCA studies of maritime fuel supply chains generally involve similar and well-defined methodological choices, which is linked to the large literature and guidelines available on LCA of transportation fuels. In this sense, the application of LCA to ships or specific parts of a ship could become more robust as the literature in this specific field grows. The development of guidelines and recommendations would also contribute to this purpose, with current attempts showing limited scope and consistency. The trends and gaps discussed throughout this report could serve as a starting point for the definition of future recommendations in LCA of maritime systems.

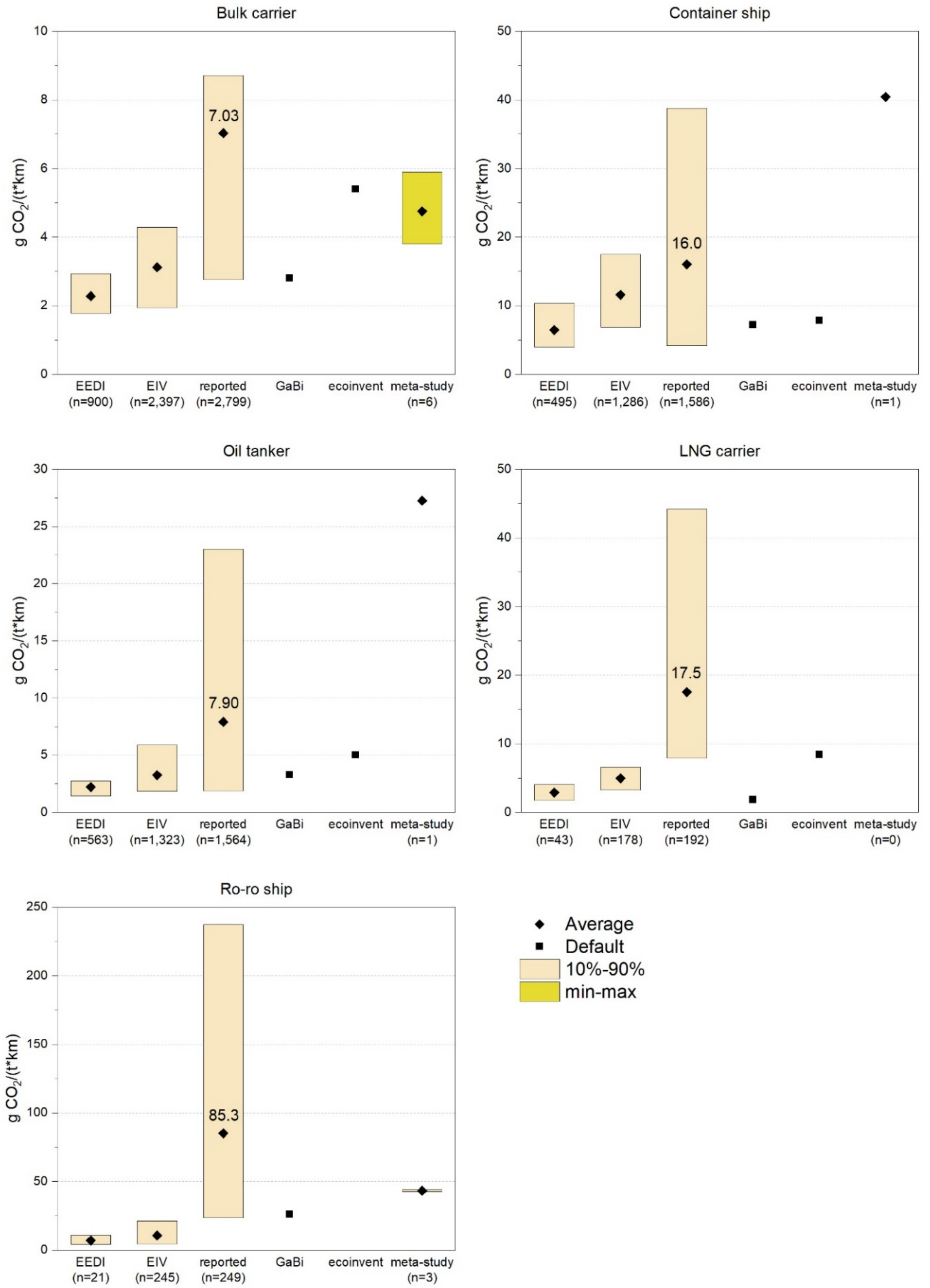
4 Implications for LCA of shipping

The European Commission considers LCA as the best available framework to assess the potential environmental impacts of products and activities (S. Sala et al. 2021). Transport by ship is part of the life cycle of most products, from the supply of fuels and raw materials used all over Europe to the delivery by sea of final goods. Compared to other means of transportation, ships are regarded as less damaging for the climate due to the lower emissions per tonne-km transported. However, as the LCA meta-analysis in chapter 3 pointed out, there is not a large body of research regarding the life cycle environmental impacts of ships. Moreover, most of the available LCA studies rely on secondary data or calculations to assess the potential impacts during operations (see Figure 29 and Figure 41). Secondary data for shipping are also used for LCAs of products different from ships including the transportation stage in their assessment (e.g., the LCA of bananas sold in Europe). Secondary data are typically sourced from LCA databases. This section tries to compare the default emissions per tonne-km transported in two widely used LCA databases (i.e., ecoinvent and GaBi) to the results of the THETIS-MRV data analysis (chapter 2) and of the LCA meta-study (chapter 3). While this section tries to jointly address some aspects from Sections 2 and 3, we acknowledge that such an attempt is highly conditioned by the different nature of the studies involved in each of these sections. For instance, the number of data points retrieved from the review in the previous section is very low compared to the sample handled in Section 2, which is further stressed when enlarging the comparison with reference systems from well-established databases such as ecoinvent and GaBi. Thus, the outcomes of this section should be carefully understood under these terms.

In Figure 50 the results of the comparison between LCA databases, the THETIS-MRV data analysis, and the LCA meta-study are presented. The comparison is limited to the CO_2 emissions during the operation stage of the ships (excluding therefore other greenhouse gases) and to the ship categories available in ecoinvent v3.6 (Wernet et al. 2016) and GaBi v10 (Sphera Solutions GmbH 2021): bulk carrier, container ships, oil tankers, LNG tankers, and ro-ro ships. Few of the studies available in the literature reported their results only in CO_2 equivalents (Bengtsson et al. 2014; Selma Brynolf et al. 2014; Nahlik et al. 2016); for those cases, the CO_2 equivalents results are used for the comparison. The same filters used in chapter 2 for the THETIS-MRV data analysis are applied for the comparison. In addition, only ships that reported both the efficiency index (either EEDI or EIV) and the emissions per transport work (i.e., per tonne-km) are included in the comparison. The number of data points considered for the comparison are reported on the x-axes in Figure 50. Average emission values reported in Figure 50 differ from the ones reported in chapter 2 (Figure 9) because the results were converted from nautical miles to kilometres, in line with the LCA databases. Both GaBi and ecoinvent rely on the IMO work to estimate the emissions per transport work for the different ship categories: the discrete values of fuel consumption reported on the Third IMO GHG study (IMO 2015) are averaged and adjusted to include the empty return of the ship after delivery (Notten et al. 2018). The final default values could be further adapted by the database users if more detailed information regarding the ships employed for transportation (e.g., deadweight, capacity utilisation factor, speed) is available. However, this is rarely the case and, therefore, default values are typically employed.

Default values from ecoinvent appear to be higher than the ones from GaBi for all ship categories available on the two databases. GaBi values are more aligned to the EEDI/EIV values than to the average emission per transport work found in the MRV-THETIS database or in the reviewed LCA studies. It is worth reminding that the EEDI/EIV indices are meant to indicate the design efficiency of the ship at the start of its life (under specific conditions), and may not represent its actual performance. This could be due for instance to performance losses due to fouling and a deterioration of the hull's surface and machineries, or to a lower capacity utilization. Moreover, emissions at ports are excluded from the index; although they typically represent a small share of a ship's overall emissions, these emissions should be accounted for when a life cycle approach is adopted. Although being higher than GaBi's values, ecoinvent default shipping emissions are significantly lower than the ones defined using the 2019 dataset of MRV-THETIS: from 14% lower for bulk carriers to 56% for LNG carriers. The difference might be explained by an overestimation in the IMO reports used by LCA databases of the average cargo mass transported (IMO 2020). As for the scientific literature (i.e., "meta-study" bar in Figure 50), very few studies have been found expressing the results in CO_2 emissions per transport work. Furthermore, it should be noted that the attempt of comparing the results of the literature meta-study with the THETIS-MRV data is highly conditioned by the different nature of the data. The most represented category, with 6 data points, is bulk carriers; for such category, emissions per transport work are in line with the default values available on ecoinvent. On the other hand, the only available study for container ships and oil carriers (Nahlik et al. 2016) show emissions per tonne-km much higher than the ones available on LCA databases. Curiously, these emissions are also higher than 90% of the data points available on the THETIS-MRV database. This could be only partially ascribed to the inclusion of other greenhouse gases (e.g., methane) in the use phase emissions of the study from Nahlik et al. (2016). In fact, other greenhouse gases than CO_2 play a minor role in the global warming potential of the use phase of ships fuelled by non-LNG fuels. However, not enough information is available in the study to explain the main reason for the discrepancies. The lack of detailed inventories is a long-standing issue in LCA that the meta-analysis of the literature has further evidenced.

Figure 50. Comparison of the CO_2 emissions per transport work (g CO_2/t*km) available in the THETIS-MRV database (EEDI, EIV, and annual average reported for 2019) with the default values available in LCA databases (GaBi and ecoinvent) and the average values found in the meta-study of the LCA literature. The shaded bar indicates the range of the 10-90 percentile with the exception of data coming from the literature analysis, where it indicates maximum and minimum.



Source: JRC, 2022.

5 Conclusions

Reducing and, eventually, zeroing the greenhouse gas emissions from the maritime sector is a global and EU priority. This report aims to provide support to policymakers, researchers, and the maritime industry to reach this goal while avoiding unintended consequences.

Two main analyses have been provided in this paper:

- First, the greenhouse gas emissions of ships transiting EU ports in 2019, publicly available within the **MRV-THETIS database**, have been examined to benchmark the CO_2 emissions of the different ship categories;

- Second, a **meta-study of available scientific literature on the life cycle assessment of maritime systems** has been performed to identify gaps and trends. Using a full life cycle approach to face the challenge of emission reduction is fundamental to have a complete picture of the environmental impact caused by the maritime sector and to avoid potential burden shifting.

Specific conclusions for the two analyses are presented respectively in Sections 2.3 and 3.4. In Chapter 4, results from both analyses have been compared to the default emission values per transport work of ships (i.e., CO2 emissions per tonne-km transported) in two widely used LCA databases: ecoinvent and GaBi. In this final chapter the main results from both sections are used to provide recommendations for future research and policy actions.

The analysis of the data collected through the THETIS database highlights that the majority of GHG are emitted during travel, while just a minority of the emissions are associated with ships at berth (Figure 7). Fuel use related emissions can therefore be singled out as main contributors in terms of GHG from shipping activities, in line with previous research (Winnes, Styhre, and Fridell 2015). *Reducing overall emissions (not just CO_2) at berth can be beneficial for improving overall local air-quality, but should not be considered the number one priority for decreasing GHG emissions coming from the shipping sector.*

Using field data coming from the THETIS database also help in clarifying that it is different to single out main emitters among the ship categories considered. As can be seen in Figure 4 and Figure 5, ships having average higher emissions per ship (e.g., passenger ships, ro-pax ships), account for a minor fraction of the total GHG emissions (Figure 4); while categories such as container ships, bulk carriers and oil tankers, although having lower average emissions per ship, they cover a much larger fraction of total emissions (Figure 4) compared to ship categories with average higher emissions per ship. These differences suggest that different strategies could be employed for reducing GHG emissions in the shipping sector depending on the type of ship considered. For example, when considering a ship belonging to a ship class with relatively high average emissions per ship and contributing to a smaller fraction of total shipping emissions, adopting measures able to drastically reduce ship emissions (e.g.: using alternative fuels) can be considered a more effective measure for achieving overall decarbonisation in the maritime sector. The opposite is true for ship categories with average low emissions, but high fractions of overall maritime emissions. In this case, even measures with a limited impact on single ship emissions would guarantee a much larger effect on total maritime emissions. Nevertheless, a combination of all mitigation measures will likely be necessary to fully reach the carbon neutrality of the maritime sector.

LNG is the alternative fuel investigated the most in literature, but LCA results are subject to a high level of uncertainty. To improve the robustness of the results, more studies on the emissions on-board and on the methane slippage in the upstream processes are required (Balcombe et al. 2021). Nevertheless, it is important to underline that LNG cannot be the solution to a full decarbonisation of the maritime sector. As a recent investigation pointed out (Schuller et al. 2021), *replacing traditional fuels with LNG could reduce the operation emissions up to only 21%. This is not nearly enough to reach the IMO 50% greenhouse gas reduction target by 2050.* More research is therefore necessary on the use of alternative fuels generating zero emissions during the use phase, such as hydrogen or ammonia. For these fuels, particular attention should be devoted to the emissions arising from production and delivery. While the potential reduction in GHG emission in the near future due to a lower demand for fossil fuels was investigated by the IMO, the potential impact from the supply chain of green fuels was not included in their assessment (IMO 2020).

The meta-analysis of LCA literature relevant for shipping clearly indicated that more field data on the use of alternative fuels and on life cycle stages different from operation, should be covered by additional LCA studies. *Although fuel consumption results to be the main source of the potential global warming impact for shipping in the LCA studies analysed in chapter 3* (the few exceptions depicted in Figure 32 seem to be the result of erroneous assumptions, such as extremely high greenhouse gas emissions from steel manufacture (Zhao et al. 2011)), *shipbuilding activities and end-of-life stage are not extensively covered in the surveyed* *literature.* Since these life cycle stages will become more and more relevant in comparison to the operation phase as greener fuels are employed, more LCA studies covering ship production and end-of-life stage are necessary. The end-of-life stage is particularly important for 'environmental-impact leakage' outside EU territory considering that the vast majority of EU-nation-owned ships are scrapped in countries outside the EU with lax environmental regulations (Wan et al. 2021). Even if the meta-analysis showed that the end-of-life is not the most impactful stage in terms of GHG emissions, improved waste management would reduce the demand for virgin materials and the environmental and health risks associated with ship-scrappage in low-income countries, such as the release of toxic and ozone-depleting substances (Singh et al. 2020).

The meta-study revealed the urgent need for a standardized LCA methodology for shipping. A standardized methodology would allow for the comparison of (future) LCA studies, currently hampered by conflicting methodological assumptions. Moreover, it could push towards more holistic assessments: shifting the focus from the global warming impact of the use phase of ships to the overall environmental impacts generated by the life cycle of a ship.

Results from the analyses outlined in Chapters 2 and 3 have been compared to the default emission values per transport work of ships available in ecoinvent v3.6 and GaBi v10. The comparison (chapter 4) showed that the default values in these databases likely underestimate the CO_2 emissions arising from ships. *The difference between the average emissions per transport work in the THETIS-MRV database and the design performance indices (i.e., EEDI and EIV) was even more striking, indicating that real-world emissions are likely driven more by the way a ship is operated than the way the ship is designed.* Given the large variability in the results per transport work and the lack of robust scientific literature on ships' emissions per transport work (indicated by the number of data points of the "meta-study" bar of Figure 50), *we recommend LCA practitioner to perform a sensitivity analysis whenever detailed information regarding shipping is not available.* Using the average emission values reported by ships under the Regulation (EU) 2015/757 (i.e., "reported" bar in Figure 50) would likely provide more realistic results than efficiency indices or current default CO_2 values in LCA databases. It is worth acknowledging here the new operational carbon intensity (CII) indicator that the IMO will require to document to ships above 5,000 gross tonnage from 2023 (IMO 2021). By documenting the emissions per transport work, this new index could provide new primary data for LCA practitioners. Moreover, the goal of progressively reducing the emissions per transport work goes in the same direction advocated by this report. Nevertheless, we want to stress the importance of introducing a life cycle approach in the environmental mitigation measures to avoid any burden shifting. More research is needed and methodological guidance is necessary to include in the LCAs environmental impacts currently under-investigated, such as the GHG emissions from trawling (E. Sala et al. 2021), the spread of invasive species (Sardain, Sardain, and Leung 2019), pollution from bilge (Jägerbrand et al. 2019) and plastic (Li, Tse, and Fok 2016), or the impacts from noise (Erbe et al. 2019). A more robust and complete delineation of the life cycle environmental footprint of the maritime sector is fundamental to reach the sustainability targets set by the EC.

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List of abbreviations

APC	Air Pollution Control
CNG	Compressed Natural Gas
ECA	Emission Control Area
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IFO	Intermediate Fuel Oil
ILCD	International Reference Life Cycle Data System
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
PM	Particulate Matter
Ro-Ro	Roll-on/Roll-off ships
SCR	Selective Catalytic Reduction
SVO	Straight Vegetable Oil

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