A critical review and normalization of the life cycle assessment outcomes in the naval sector. Articles description

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ARTICLE INFO

Handling Editor: Kathleen Aviso

ABSTRACT

Most of the actual industrial research efforts are aimed at reducing environmental burdens associated with human activities in the context of sustainable development. This trend has become increasingly prevalent in the naval transportation sector shown by a growing number of scientific publications dealing with life cycle assessments of maritime-related activities. However, the life cycle assessment framework provides practitioners with a variety of alternatives for conducting the analyses, giving room for defining key factors, such as functional units, system boundaries, and impact assessment methods, among others. This lack of standardization resulted in a wide range of assumptions and findings that are seldom comparable. The goal of this review is providing a systematic literature analysis, focusing on the characteristics of life cycle assessments dealing with the environmental impacts of various maritime vessel categories. In the first part, a qualitative analysis of the available scientific literature has been performed, providing a bibliometric analysis and a general overview of the characteristics of the studies (*i.e.*, life cycle impact assessment methodologies, background data, and software tools used). The outcomes of the bibliometric analysis are then summarized and discussed to understand current practices and future trends in this field, providing the basis for the normalization phase of the results. The second section of the paper offers advice for naval practitioners on how to perform results normalization to produce comparable analyses. Two approaches for normalization have been proposed in the frame of this study: an "horizontal" one, which is based on vessel features and allows a comparison among different vessel typologies, and a "vertical" one that enables to fairly compare vessels of the same category to one another. In addition, each section reports the outcomes of greenhouse gas-related impact categories, which have been subjected to the proposed normalization procedure, along with the order of magnitude of the results for each life cycle phase. The overall work provides an overview of LCA impact results as well as a collection of procedures and recommendations for future life cycle assessments based on specific vessel types, in terms of functional unit selection, system boundary definition, impact assessment approach, presentation of the outcomes, and normalization basis.

1. Introduction

This review examines the scientific literature dealing with specific vessel categories, in order to serve as a reference for practitioners investigating the environmental performance of peculiar vessels. The analysed publications have been gathered by vessel categories, allowing the reader to focus on past research dealing with specific vessel groups, with the goal of providing some benchmark values against which future investigations may be compared. As reported by Mio et al. (2022), numerous environmental categories have been employed among the investigated documents, posing a critical issue for a full collection of the outcomes in a single review. In order to improve readability, this review solely reports the results of GreenHouse Gas (GHG)-related impact categories, although the proposed normalization approach may be applied to any impact category. The vessels have been categorized using the Central Product Classification (CPC) codes (Department of Economic and Social Affairs, 2015), which represent specific industrial products within a larger product categorization system that encompasses all commodities and services.

The following sections discuss the common characteristics of life cycle assessment (LCA) works developed for distinct vessel categories, with the goal of addressing the primary issue with life cycle assessments in the naval field, namely, the inconsistent presentation of the outcomes.

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Glossary

ADE	Abiotic Depletion of Elements
AP	Acidification Potential
BAU	Business As Usual
CAD	Computer-Aided Design
CC	Climate Change
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand;
CPC	Central Product Classification
DE	Diesel Electrical
DM	Diesel Mechanical
DWT	DeadWeight Tonnage
EcoCSP	Ecological Constraint Satisfaction Problem
EI99	EcoIndicator 99
EIO	Economic Input-Output
EEZ	Exclusive Economic Zone
EoL:	End of Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
ETP	EcoToxicity Potential
FRC	Fouling Release Coating
GHG	GreenHouse Gas
GMAW	Gas Metal Arc Welding
GT	Gross Tonnage
GTAW	Gas Tungsten Arc Welding
GWP	Global Warming Potential
HCFC	HydroChloroFluoroCarbon
HFO	Heavy Fuel Oil
HTP	Human Toxicity Potential
ILCD	International reference Life Cycle Data system
IPCC	Intergovernmental Panel on Climate Change
IR	Ionizing Radiation
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LES	Lifecycle Emission Share
LNG	Liquefied Natural Gas
LWT	Lightship WeighT
MD	Metal Depletion
MDO	Marine Diesel Oil
METP	Marine EcoToxicity Potential
MEU	Marine EUtrophication
MSETP	Marine Sediment EcoToxicity Potential
N.A.	Not Applicable – Not Available
ODP	Ozone Depletion Potential
PM	Particulate Matter
POCP	Photochemical Ozone Creation Potential
POFP	Photochemical Oxidant Formation Potential
RoPax	Roll-on/roll-off Passenger
RoRo	Roll-on/roll-off
SMAW	Shielded Metal Arc Welding
TETP	Terrestrial EcoToxicity Potential
TEU	Terrestrial EUtrophication
TRACI	Tool for Reduction and Assessment of Chemicals and other environmental Impacts
ULCC	Ultra Large Crude Carrier
VLCC	Very Large Crude Carrier
VOC	Volatile Organic Compound
WTW	Well-To-Wake

Additionally, a ranking system to identify the vessel categories with the lowest environmental impact was suggested. To the best of authors' knowledge, a systematic review of the applications of LCA in the wide range of maritime vessels and ships has not been published yet.

2. Methods

The most ambitious aim of this review is to provide a guideline for future publications related to LCA of ships and maritime systems towards a standard presentation of results, enhancing the repeatability and robustness of the studies. Based on the outcomes of the first part of this review (Mio et al., 2022) and following the recommendations prescribed by ISO 14044 (The International Standards Organisation, 2021), information such as functional unit, system boundary, allocation approach and Life Cycle Impact Assessment (LCIA) methods, among others, needs to be clearly stated. These results are reported and summarized in the first part of the literature review (Mio et al., 2022) and provide the framework for the normalization process. Furthermore, the outcomes should be presented in such a way that the contribution from each stage of the life cycle is explicitly outlined and standardized, to allow for comparison with other studies. In this context, practitioners in the naval sector should perform the normalization step described by the ISO standards (The International Standards Organisation, 2021) using the following approach and reference flows:

● A cradle-to-gate analysis of the vessel itself, until the vessel delivery. System boundary should comprehend extraction, refinement, and transportation of materials and shipbuilding activities. This information provides a deeper insight into the construction materials and shipbuilding practices, whose impacts are usually hidden by the burdensome operation activities. Vessels may involve comparable shipbuilding activities but may require a different amount of materials for construction, *i.e.*, they may display a different lightship weight (LWT). These inequalities prevent a fair comparison among various studies and vessels and it would be complex to highlight the good manufacturing practice, as long as a normalization of the result on a common ground is not pursued. Furthermore, the reference service life may be different between vessels, restraining again the comparability between studies.

In this scenario, practitioners should present the outcomes of this life cycle phase normalized on the lightship weight (LWT) of the vessel on a year-basis, as presented in Eq. (1):

$$Shipbuilding = \frac{Impacts\ of\ shipbuilding\ operations\ and\ construction\ materials}{LWT\ [ton]*lifetime\ [yr]} \tag{1}$$

Benefits and drawbacks of this approach can be summarized as follows:

- o it allows comparing vessels of various categories and sizes. Since this approach exhibits the impacts of shipbuilding activities and construction materials, its application is not restricted to a comparison among vessels of the same category, but can be extended to any generic vessel, allowing a comparison between a massive wooden vessel and a lighter aluminium motor yacht;
- o a mass-based functional unit exhibits the intrinsic impacts of construction materials, promoting the employment of novel greener material alternatives;
- o it enables the comparison of literature data with any future study under identical system boundaries for any vessels' lightship weight;
- o a fair comparison between vessels with different service lifetime can be performed;
- o the main disadvantage is the lack of clarity of the impacts of the vessel construction to the reader. It is common practice to show the

impacts related to the overall shipbuilding phase using the entire vessel as normalization basis, which is rather simple to understand. It is desirable to report both the results normalized on the vessel itself and on the lightship weight and lifetime;
- o shipyards are usually able to supply specific documents such as lightship weight document, engines datasheets and Computer-Aided Design (CAD) models, where information for compiling life cycle inventory can be retrieved (Favi et al., 2018a);
- o when only the majority of the vessel's mass, at least the hull and superstructures, is included within the system boundary, the LWT and lifetime normalization may still be valid. However, when the system boundary excludes the heaviest structures of the vessel, this normalization basis appears inadequate and the weight of the product system under investigation should be used. For instance, the weight of the engines (in [ton]) should be utilized as the normalization basis when the power system is the only part of the vessel included within the system boundary.

● Two methods can be used to normalize the operational phase's impact indicators separately from those of the other life cycle phases: (i) a "vertical" normalization carried out by following the vessel function and allowing a comparison of vessels belonging to the same category, and (ii) a "horizontal" normalization carried out by following the vessel features, allowing a comparison of different vessels regardless of their functions. Knowing that the operational phase is the most burdensome life cycle phase of a vessel, many authors focused their studies on identifying the best alternatives in terms of fuel choice, engine technology, fuels supply chain, and so on. Thus, the assessment of life cycle impacts using the normalization basis adopted for the operational phase, can be generally used as the most representative of the life cycle's overall impacts, at least for climate change-related issues. Concerning the vertical normalization, the different purposes of marine vessels (transportation of a person, shipping of cargo, fishing, provision of services to other vessels, leisure, etc.) require a specific definition of the function of the product system, determining the normalization of the results on different bases. The recommended vertical normalization bases for the operational activities of each vessel category are reported in Table 1. The descriptions of the rationale behind each normalization basis can be found in the sections dedicated to peculiar vessel categories.

The development of a given normalization basis for each vessel type brings the following consequences:

- o each normalized indicator depicts the environmental performance of the product system for each unique vessel function, making it easy to comprehend;
- o within the specific vessel category, comparability on the vessel peculiar function is guaranteed;
- o the usage of the normalized indicator is suitable for LCA studies where only the operational phase is considered within the system boundary, *e.g.*, life cycle analysis of a product transported by cargo vessel;
- o a comparison between the operational activities of vessels belonging to the same category is allowed.

Concerning the horizontal normalization, the different features/parameters of a vessel (size, weight, dimensions, power, etc.) can be used to overcome the rigid ship-type scheme. The recommended horizontal normalization basis for the operational activities based on vessel features/parameters is reported in Eq. (9).

$$Efficiency\ Ratio = \frac{\frac{Impacts\ of\ shipbuilding\ activities\ and\ construction\ materials}{Impacts\ of\ operational\ phase}}{\frac{Engine\ Power\ [kW]}{LWT\ [ton]}} \tag{9}$$

The engine power [kW] to lightship weight (LWT in [ton]) ratio is used as an indicator of vessel design efficiency, and it can be used to normalize the ratio of emissions throughout shipbuilding and navigation, regardless of ship category. The Efficiency Ratio enables a comparison between the operational activities of vessels belonging to any vessel category.

Table 1
CPC codes of the vessel types analysed in this review along with the proposed operational phase normalization.

Vessel type	CPC code	Operational phase[a]	Equation
Cruise and ferry boats	49311	$Operation = \frac{Impacts\ of\ operational\ phase}{passengers[\#]*distance[km]*trips[\#]}$	(2)
Tankers	49312	$Operation = \frac{Impacts\ of\ operational\ phase}{cargo[ton]*distance[km]*trips[\#]}$	(3)
LNG carriers	49313	$Operation = \frac{Impacts\ of\ operational\ phase}{cargo[ton]*distance[km]*trips[\#]}$	(4)
Cargo vessel	49314	$Operation = \frac{Impacts\ of\ operational\ phase}{cargo[ton]*distance[km]*trips[\#]}$	(5)
Fishing vessels	49315	$Operation = \frac{Impacts\ of\ operational\ phase}{landing[ton]*distance[km]*trips[\#]}$	(6)
Tug boats	49316	$Operation = \frac{Impacts\ of\ operational\ phase}{cargo[ton]*distance[km]*trips[\#]}$	(7)
Pleasure and sporting boats	494	$Operation = \frac{Impacts\ of\ operational\ phase}{passengers[\#]*time[hr]}$	(8)

[a] [#] stands for dimensionless quantities.

● An indicator focused on maintenance routine should be added when these activities are within the system boundary. Maintenance procedure usually includes activities such as equipment substitution or repainting, which are usually proportional to the vessel's dimension. Therefore, the presentation of the impact scores based on the lightship weight (LWT) and service lifetime is suggested, as reported in Eq. (10):

$$Maintenance = \frac{Impacts\ of\ maintenance\ activities\ and\ materials}{LWT\ [ton]*lifetime[yr]} \tag{10}$$

The introduction of this normalization basis guarantees several benefits:

- o it allows the comparison of similar maintenance activities, even if they have been performed on different size vessel, *e.g.*, the usage of diverse paints and coatings from distinct LCAs;
- o a mass-based functional unit exhibits the intrinsic impacts of maintenance materials and operations, promoting the employment of less burdensome alternatives;
- o it enables the comparison of literature data with any future study under identical system boundaries for any vessels' lightship weight;
- o a fair comparison between maintenance activities of vessels with different service lifetime can be performed;
- o since this method shows the effects of maintenance operations and materials, it may be applied to any vessel, not only those in the same category;
- o the main disadvantage is the lack of clarity of the impacts of the vessel maintenance to the reader. It is common practice to show the impacts of the maintenance activities over the entire lifetime, which is rather simple to understand. It is desirable to report both the results normalized on the vessel itself and on the lightship weight and lifetime;

● An analogous normalization procedure should be used for the end-of-life impact scores. Compiling life cycle inventories for the end-of-life scenarios is challenging, since the disposal of vessels is usually uncertain. When this life cycle phase is within the system boundary of the vessel under study (cradle-to-grave approach), the end-of-life treatment impacts should be normalized on a lightship weight and lifetime bases, as shown in Eq. (11):

$$EoL = \frac{Impacts\ of\ disposal\ treatments}{LWT\ [ton]*lifetime[yr]} \tag{11}$$

The advantages and drawbacks of this approach are equivalent to the ones reported for the maintenance normalization basis.

3. Normalized LCA outcomes from the literature review

This section aims at presenting the LCA outcomes of the studies dealing with maritime vessels available in the scientific literature by applying the normalization procedures previously defined. The normalized results can serve as benchmarks for each vessel group (vertical normalization, presented in section 3.1.), as well as for the comparison of vessels regardless of the function/purpose (horizontal normalization, presented in section 3.2). The last part of this section (section 3.3) refers to the LCA results of studies carried out to investigate vessel-related activities.

3.1. Vertical normalization based on vessel function

The results presented hereafter provide a comparison of LCA analysis based on the function provided by the specific vessel category. The vertical normalization, performed at vessel type, leads to two crucial outcomes: (i) identify the emerging trend and sustainable design solutions developed for specific vessel group, and (ii) provide some benchmark values for practitioners in this field.

3.1.1. Cruise and ferry boats

Cruise ships and ferry boats have been grouped together due to their common purpose of transporting passengers from one location to another. The cruise ships are designed to carry passengers travelling roundtrip for pleasure and stopping at different ports, while ferry boats are used for the transport of both persons and vehicles from point A to point B. They are both classified under CPC code 49311: *"Cruise ships, excursion boats and similar vessels, principally designed for the transport of persons; ferry boats of all kinds"*.

Since the main purpose of this critical review is providing a standardization basis on a reference unit to normalize the environmental impacts of the operational phase for different vessel types, the normalization basis needs to involve the inclusion of three factors: the number of passengers transported each trip (which is unitless and represented using symbol [#]), the weighted average trip distance expressed in kilometres [km] and the number of trips [#] performed during the timespan under investigation, as shown in Eq.(2) of Table 1. The procedure to be followed to obtain a correct normalization is detailed in the Supplementary Materials.

The eight peer-reviewed publications available for this vessel category were examined, following a temporal sequence. The publications dealing with Well-To-Wake (WTW) analysis, *i.e.*, including exclusively the life cycle of the fuel within the system boundary, based on the operational profiles of ferry boats were excluded. Tchertchian et al. (2013) employed optimization techniques such as Pareto, Design of Experiment and Constraint Satisfaction Problems in combination with LCA. Their aim was to identify the environmentally optimized configuration during the conceptual design phase of an aluminium ferry boat in terms of both structural and propulsion systems. In this paper, the minimization of the CML-IA and EI99 impact categories was the designed target of the optimization algorithms used to define the product system with the lowest overall environmental burdens. Unfortunately, the presented results provide qualitative information only, preventing the comparison with other literature values. As a general trend, the operational phase exhibits the worst environmental footprint. The authors further extend their work on a following publication (Tchertchian et al., 2016) where they deepened the definition of the functions provided by product systems, discerning between the essential functions and the negotiable services. Each alternative design simultaneously affects various vessel functions, leading to an unavoidable trade-off among optimum performances within each non-essential function constraints, which was bounded between minimum and maximum limits. The proposed Ecological Constraint Satisfaction Problem (EcoCSP) allows defining both suitable combinations of available technologies and the functional mix that significantly reduces the environmental impacts related to vessel construction and operation. Indeed, LCA is not only employed as a comparison tool, but also as an eco-design technique, using "*2400 passengers transported a day*" as a functional unit. Furthermore, the scores of environmental impact categories belonging to CML-IA method and EI99 are presented for the entire life cycle, excluding the end-of-life. Average values among the alternative designs have been taken as benchmarks and normalization has been applied on total transported passengers during the boat daily routine (2300–2400) and distance travelled by each person (13.89 km), using the information provided on both papers of the research group (Tchertchian et al., 2013, 2016). The features of the analysed vessels are reported in Table 2, while the CML-GWP impact category score is reported in Fig. 1 and Table S1 of the Supplementary Materials.

Blanco-Davis et al. (2014) assessed the retrofit potential environmental impacts of a ferry using the LCA methodology, as shown in Table 2. Their scope was to highlight the benefits of the switch from conventional antifouling coating to a Fouling Release Coating (FRC) system based on a silicone elastomer technology. The functional unit inferred from the interpretation of the paper is "*the vessel construction, maintenance, operation and disposal over the lifetime of 25 years*". Two case studies have been developed, distinguished by a regular maintenance of the conventional antifouling coating or a switch to the FRC system after half of vessel lifespan, which leads to a lower fuel consumption for the remaining operational activities. Due to the comparative purpose of this study, shipbuilding materials and activities encompass only the essential elements of the vessel, *i.e.*, hull, accommodation and main machinery. Fuel consumption is modelled considering an average speed of 25 knots, as the vessel's operational profile follows a regular sailing schedule on long trips. The assessment makes use of the GWP impact category within CML-IA method, splitting the overall environmental burden into the contributions from shipbuilding, maintenance, operation and disposal. The environmental impacts for shipbuilding, maintenance and end-of-life phases have been normalized (using Eq. (1), Eq. (10), and Eq. (11), respectively) for a comparison with other works in the same field, as reported in Fig. 1 and Table S1 of Supplementary Material. However, since the passenger capacity is not defined, the results of the operational phase are unsuitable for normalization over the total number of passengers transported and the distance travelled by each one. From an environmental and economic standpoint, antifouling coating replacement outperforms the standard antifouling technology.

A comparative life cycle study among several boat construction materials has been carried out by Pommier et al. (2016), whose assessment analysed the usage of aluminium, composite material, local (French) or African wood for the hull of a small passenger ferry travelling within Archachon Bay, as reported in Table 2. Data have been retrieved within ecoinvent database and completed with information obtained from a local boatyard, Environmental Product Declarations (EPDs) and a private database, using a cradle-to-grave approach. Even though the authors chose the function of the ferry as functional unit ("*transportation of 60 passengers and 20 bikes for 30 years*"), they removed the contribution of the fuel consumption from the presented results, aiming at better highlighting the impacts of each construction material life cycle. A more suitable simplified functional unit would have been *“the construction, maintenance and disposal of the hull of a ferry boat transferring 60 passengers and 20 bikes for 30 years”*. This is a typical case when the usage of the impacts normalization on the lightship weight and expected lifetime is beneficial in order to standardize the results and perform a fair comparison. In fact, a normalization of the outcomes based on the varied lifespan and lightship weight of the boats would have changed the results, boosting the performances of aluminium hulls over composite hulls for all impact categories and even reducing the impacts for wood hulls. These results are mainly driven by the different lifetime of the vessels, which should be accounted for an equal comparison, as a longer vessel lifespan distributes the shipbuilding impacts over a longer timespan). In the original paper the maintenance activities have been accounted for 30 years only, therefore this comparison still needs to be improved, although the impacts generated by maintenance activities are usually negligible in comparison with shipbuilding ones. The authors incorporated the lifetimes into the solutions; nevertheless, it is unclear how the various lifetimes affected the outcomes. The normalized results confirmed and reinforced the authors’ conclusions, suggesting a higher employment of wood for boat hull construction from an environmental viewpoint, particularly for impacts related to Climate Change (CC). The original and normalized scores for CC impact category are reported in Table S1 of Supplementary Materials and graphically in Fig. 1.

Wang et al. (2018a) used GaBi database in combination with four impact categories, *i.e.,* GWP, Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP), to assess the environmental and economic impacts of installing and operating a short-route hybrid ferry power system, applying a life cycle approach to optimize the operational activities. Furthermore, the authors developed three built-in models for fuels (Marine Diesel Oil - MDO and Heavy Fuel Oil - HFO), transportation (fuel consumption and emission released due to specific transportation distance by 3.3-ton payload lorry) and scrapping (energy required by scrapping processes of different materials). Several operational profiles, maintenance without materials, scrapping phase, and the production and installation of the main engines and batteries all fell inside the system boundary, ensuring a cradle-to-grave approach. Different propulsion systems were studied, covering a wide variety of potential configurations. The same research group published a more extensive analysis on the same product system in another paper (Jeong et al., 2018). In this work, the authors developed a modular framework for identifying the best ship design among various choices regarding cost and environmental impacts in the long-run. Each module dealt with a specific ship structure on a single life cycle stage. The composition of various models gave rise to several product systems, which have been compared to identify the optimal solution using a dedicated tool (LabVIEW). In this paper, the presentation of the authors’ methodology was followed by two case studies, one of which focused on the cradle-to-grave LCA of different engines construction, installation and operation on a Ro-Pax ferry, as reported in Table 2. The propulsion alternatives comprehended diesel mechanical (DM), diesel electrical (DE) and hybrid installations, which have been investigated through sensitivity analyses using various LCIA methods (CML-IA and 2010, TRACI and ReCiPe) and electricity sources for battery charging. The system boundaries were restricted to the engines only, therefore the results are not suitable for a comparison with other LCA studies on ferry vessels. In general, the hybrid system was the most environmentally friendly on the impact categories calculated (GWP, AP, EP, POCP) and the operational phase revealed as the most burdensome life cycle phase. Moreover, sensitivity analyses displayed lower emissions and costs when the battery usage was maximum, showing a fruitful relationship between the adoption of the hybrid solution and the reduction in cost and emissions. The results of the paper along with normalized values are reported in Table S1 of Supplementary Material and graphically in Fig. 1. Since the system boundary includes the power system only, the normalization is based on the weight of the engines, *i.e.,* 3.2 ton for a diesel electrical and 4 ton for a diesel mechanical, and the

Table 2
Cruise and Ferry Boats’ features of the available LCA studies.

Type	Passenger ferry	Passenger ferry	RoPax Ship	Ferry boat	MV Hallaig RoPax Ferry	Cruise ferry
Source	Tchertchian et al. (2013)	Tchertchian et al. (2016)	Blanco-Davis et al. (2014)	Pommier et al. (2016)	(Jeong et al., 2018; Wang et al., 2018a, 2018b)	Cucinotta et al. (2021)
Production site	N.A.	N.A.	N.A.	France	UK	Denmark
Production year	N.A.	N.A.	2001	2012	2012	2012
Operation location	France	France	Atlantic Ocean	France	UK	Norway
Estimated lifetime [year]	20	20	25	30–100	30	25
Service speed [knots]	12	12	25	N.A.	9	20.5
Mass Displacement [ton]	N.A.	25.5–27.8	20,150	20.5–23.4	235	15,199–15,309
Deadweight (DWT) [ton]	N.A.	9.4–11.5	6515	1.6–4.5	135	3,551
Lightship weight (LWT) [ton]	20–40	16.1–16.7	13,635	16–21.7	100	11,648–11,758
Main engine power [kW] [b]	2x(150–350)DM[a] 2x(20–150)DE[a]	2x(70–80)DM[a] 2x(22–24)DE[a]	4x12,000 DM[a]	N.A.	2x450 DM[a] 3x360 DE[a]	4x5,600 DM[a] 4x5,250 LNG[a]
Auxiliary engine power [kW]	40–250	10	N.A.	N.A.	N.A.	N.A.
Fuel type	Diesel/Elec	Diesel/Elec	HFO	Diesel/Elec	MDO/Elec	HFO or LNG
Passenger capacity	96	100	N.A.	60	150	1,500
Single trips	24/day	23-24/day	150/yr	N.A.	6260/yr	175/yr
Average distance travelled by passenger [km]	13.89	13.89	1037.12	N.A.	5.1	1,426

[a] DM = Diesel Mechanical, DE = Diesel Electrical, LNG = Liquefied Natural Gas.

[b] If more than one engine was present, the number of engines was specified, along with the specific engines power.

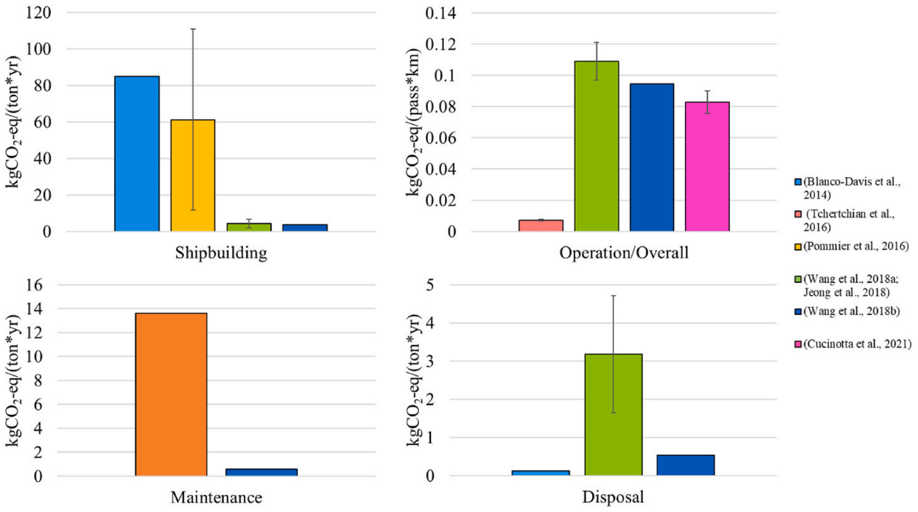

Fig. 1. GHG-related normalized scores for Cruise and Ferry Boats. Error bars are reported when multiple outcomes, e.g., sensitivity analyses or different vessel configurations, have been evaluated by the original authors.

weight of the batteries (3.5 ton). The last paper of this research group (Wang et al., 2018b) extended the application of the LCA to investigate the economic and environmental assessment of the ship hull maintenance, providing a useful tool to determine an optimal maintenance strategy for ship operators. According to the authors, a poorly maintained hull surface could increase hull resistance and hence fuel consumption. Based on the ship's lifespan, their LCA model included four stages: shipbuilding (hull construction and machinery installation), operation (service activity and fuel consumption), five ship hull-specific maintenance plans, and scrapping through steel recycling and disposal. The results showed that, although the operators adopted a five-year re-coating interval, the re-coating time should be reduced to once a year, resulting in decreased fuel use and emissions. Among the available impact categories, the carbon footprint (assessed using different LCIA methods such as CML-IA, ReCiPe, TRACI and ILCD), was chosen to represent the environmental burdens. Although the functional unit was not clearly defined, a short-distance ferry that frequently travels across Scotland was chosen as the subject of the case study. Thus, it is possible to consider as a functional unit, "*the construction, operation, maintenance, and scrapping of a short route ferry with a lifespan of 30 years*". For the estimation of the steel weight required for the ship hull construction and the wet surface area for the quantity of anti-fouling coating, primary data were calculated using ad-hoc equations, using Gabi as secondary data source. The LCA analysis was coupled with life cycle cost assessment to support the decision-making process of the ship owner. Since the scores calculated using the different LCIA methods are mostly equivalent and the results for each life cycle phase are not appreciable due to their different order of magnitude, the outcomes of the assessment have been reported in terms of inventory data (CO_2 emissions) in Table S1 of the Supplementary Material and graphically in Fig. 1.

In their study, Cucinotta et al. (2021) performed a comparative LCA of two propulsion systems on a cruise ferry, *i.e.*, a standard Diesel machinery system and Liquefied Natural Gas (LNG) one, as shown in Table 2. The two configurations have been analysed using the impact categories belonging to ILCD 2018 method in a cradle-to-grave perspective, including shipbuilding materials and activities (in terms of hull, outfitting and machinery), operational phase for 25 years on a regular route and dismantling of the vessels. During end-of-life activities, all the recyclable materials are partially or entirely reused or refurbished, while non-recyclable materials are landfilled. The maintenance phase has not been considered as it is generally less burdensome in comparison to the other phases and it does not vary between vessel configurations. The ecoinvent European market data has been used to describe the fuels supply chain. Both ecoinvent data uncertainty and final result sensitivity have been performed. The former exploited the ecoinvent data quality system, while the latter dealt with variations in fuel consumptions and steel loss during the shipbuilding activities. Since the variation of propulsion has not significant influence on the overall vessel configuration, the functional unit chosen is "*one ship during its lifetime*". As a general result, the LNG propulsion achieved better performance among the majority of impact categories. In particular, LNG-fuelled ship exhibits better results on resource depletion and, generally, on human health, which is strongly influenced by HFO extraction, refining and combustion. However, climate change score is strongly influenced by the processes of natural gas liquefaction, transport and evaporation (due to compression, refrigeration, emission of Volatile Organic Compounds - VOC and methane leakage) as well as by the phenomenon of methane slip, which increase the CO_2-equivalent effect. Moreover, the authors identified a critical activity releasing massive methane emission, *i.e.*, the five-year dry-docking operations when the LNG fuel tanks must be completely emptied, gas freed and filled with air. The most burdensome life cycle phase is the operational one, while the contribution from shipbuilding is more relevant for the LNG ship than for the diesel one, particularly for human health issues. The LNG Otto cycle engines revealed as a valid alternative in terms of emission reduction, as long as methane leakage and liquefaction energy consumption are below a certain limit. As a consequence, LNG-fuelled ship shifts the impact generation on the methane supply chain, delocalizing the emission that used to be mostly produced during fuel combustion. Moreover, a relevant reduction of the emission of SOx, NOx and Particulate Matter (PM) can be achieved, allowing the navigation within the Emission Control Areas set up by the International Maritime Organization. The original and normalized results of the assessment are shown in Table S1 of Supplementary Material and graphically in Fig. 1 for GHG-related impact categories.

It is essential to keep in mind that, notwithstanding the normalization procedure, the outcomes are hardly comparable, due to different functional units (entire vessel, hull or engines only), system boundary (exclusion of raw materials, transports between life cycle phases), allocation not clearly defined, or aggregation of the outcomes in a single score. In general, shipbuilding activities related to vessels' structures manufacturing generate GHG emission in the order of 10^1-10^2 $kgCO_2$-eq normalized on LWT and lifetime, while operational activities emit 10^{-2}-10^{-1} $kgCO_2$-eq for each passenger transported for 1 km. The former is mostly influenced by the materials used in hull construction, whilst the latter is highly variable owing to the length of trips and the vessel's passenger capacity.

3.1.2. *Tankers*

Tanker vessels are mainly used in the oil industry to carry either crude oil from oil fields to refineries or petroleum products such as gasoline, diesel fuel, fuel oil, or petrochemical feedstock from refineries to distribution centres. Major types of tankships include the oil tanker, the chemical tanker, and gas carrier, which are gathered under 49312 CPC code. Tankers vary in size from small coastal vessels about 60 m (200 feet) long, carrying from 1500 to 2000 DWT, up to huge vessels that reach lengths of more than 400 m (1300 feet), carrying as much as 550,000 DWT. In addition to tankers that navigate on the ocean or the sea, there are also specialized inland-waterway tankers that travel on rivers and canals and have an average cargo capacity of up to a few thousand tons.

In order to obtain a standard reference unit to normalize the environmental impacts of the operational phase for different vessel types, three parameters are recommended for this purpose: the cargo capacity [ton], the covered distance of single trips expressed in kilometres [km] and the number of full trips (unitless [#]) performed during the timespan under investigation, as shown in Eq.(3) of Table 1. It is worth noticing that cargo capacity is commonly expressed using the deadweight tonnage (DWT), even though the payload capacity is a more accurate parameter than DWT. However, payload capacity is not always available and it does not differ too much from the DWT, which is then recommended. The procedure to be followed to obtain a correct normalization is detailed in the Supplementary Materials.

The main focus of the available scientific literature dealing with LCA studies on tankers refers to the air emission (*i.e.*, GHG) of the extraction, processing and combustion of traditional or alternative marine fuels. The operating phase of tanker vessels, which is covered in six published publications about tanker vessels themselves (Bicer and Dincer, 2018a, 2018b; Chatzinikolaou and Ventikos, 2015; Kjær et al., 2015; Nian and Yuan, 2017; Quang et al., 2021), shows the greatest impact because it involves burning engine fuel to move cargo from one location to another. As a frequent result, using alternative fuels to MDO and HFO (such as LNG) appears to be helpful in lowering GHG emissions, leading to a more sustainable approach in this field. So far, no comparison of different tankships has been published, nor has a benchmark for this CPC category been established for further research and decision-making strategies.

The study published by Kjær et al. (2015) adopted the environmental input-output model to investigate how LCA and life cycle costing (LCC) can be integrated by using the same financial-inventory data for medium range tankers operating worldwide. Tanker's features are provided in Table 3. System boundaries were defined with a cradle-to-grave perspective, including shipbuilding activities, ship operations, maintenance, and ship scrapping. The functional unit was defined as "*one average year of ship transport service*" and the reference flow was set as "*the total amount of t-km per average year*", expressing the results per t-km. The overall impacts across the whole life cycle can be obtained considering the tanker lifetime of 20 years. The Economic Input-Output (EIO) database from the FORWAST project (Villeneuve, 2007) was combined with primary data from various sources (such as shipyards, literature, and shipping routes) as background information. The results were given in terms of CO_2-eq for the environmental standpoint and USD for the life cycle costing. As shown in Fig. 2 and Table S2 of the Supplementary Material, the results were calculated using the total number of t-km yearly (2.87 billion t-km) and the annual GHG emissions (32 million tonCO_2-eq). The normalization procedure described in this study is not-applicable to the assessment outcomes since no further information about the trips or the distance travelled in a single trip is supplied.

The work proposed by Chatzinikolaou and Ventikos (2015) aims to model the air emissions of an ocean-going ship in a life cycle perspective, creating an adequate and reliable life cycle emissions inventory. A case study referring to a Panamax tanker is reported and the tanker's features are provided in Table 3. System boundaries were defined with a cradle-to-grave perspective, including shipbuilding activities (limited to hull and machinery production), ship operation, maintenance, and ship dismantling. In this case, although the analysis was performed under the LCA framework, the functional unit was not defined since the examination of life cycle impacts of vessel emissions is not included within the scope of this paper. However, the functional unit can be assumed as "*the construction, maintenance, operation and disposal of a tanker for a period of 25 years*". Primary data from different sources (*i.e.*, shipyard, literature, shipping routes) were managed by using ad-hoc equations. Primary data were integrated with background data using EX–TREMIS DB for the estimation of emission factors of CO, PM, and CH_4 for operational phase. The results in terms of air emissions of CO_2 are displayed graphically in Fig. 2 and numerically in Table S2 of Supplementary Material.

The same Panamax tanker with the an analogous operational profile was analysed by Quang et al. (2021). Vessel features described in this work are provided in Table 3. System boundaries were defined with a cradle-to-grave perspective: from raw material extraction stage to the ship's end-of-life (including shipbuilding, ship operation, maintenance, ship's disposal, and material transportation activities). The functional unit was defined as "*one oil tanker with a deadweight of 74,296 ton for the transportation of crude oil by sea over its 25-year lifetime*" and the reference flow is the Panamax oil tanker itself. Primary data from different sources (*i.e.*, shipyard, literature) were integrated with background data from GaBi. Results are displayed following the CML-IA LCIA method, comprehending numerous impact categories. The results of the two works (Chatzinikolaou and Ventikos, 2015; Quang et al., 2021) performed on the same vessel are reported in Fig. 2 and in Table S2 of Supplementary

Table 3
Tankers' features of the available LCA studies.

Type	Medium range tanker	Panamax tanker	Five categories of tankers	Tanker
Source	Kjær et al. (2015)	(Chatzinikolaou and Ventikos, 2015; Quang et al., 2021)	Nian and Yuan (2017)	(Bicer and Dincer, 2018a, 2018b)
Production site	China	South Korea	China	N.A.
Production year	2008	2009	2015	N.A.
Operation location	worldwide	worldwide	worldwide	worldwide
Estimated lifetime [year]	20	25	30	25
Service speed [knots]	14	14	8–15	18
Mass Displacement [ton]	61,000	88,300	N.A.	N.A.
Deadweight (DWT) [ton]	50,000	74,300	85,000–560,000	100,000
Lightship weight (LWT) [ton]	11,000	14,000	N.A.	N.A.
Main engine power [kW] [a]	N.A.	2x12,240	12,200–42,200	15,000
Auxiliary engine power [kW] [a]	N.A.	4x740	2,800–5,800	2,850
Fuel type	MGO, HFO, LSHFO	HFO	IFO	HFO, H2, NH3
Single Trips	N.A.	19-22/year	N.A.	1/lifetime
Average distance travelled by cargo [km]	N.A.	2800 (estimated)	2,380–20,302	3,920,00

[a] If more than one engine was present, the number of engines was specified, along with the specific engines power.

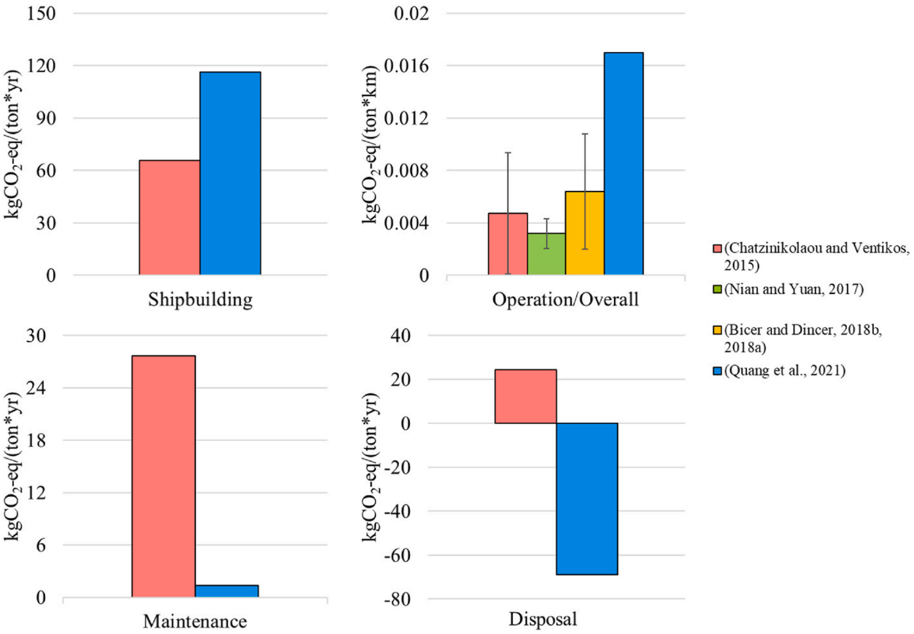

Fig. 2. GHG-related normalized scores for Tankers. Error bars are reported when multiple outcomes, e.g., sensitivity analyses or different vessel configurations, have been evaluated by the original authors.

Material. Due to the use of different units of measure ($kgCO_2$ vs. $kgCO_2$-eq), there is a substantial difference between the works, which reflects the use of CML-IA LCIA method in the evaluation of CML-GWP, comprehending other GHG emissions (*i.e.*, CH_4, HCFC, etc.). Moreover, the work of Quang et al. (2021) adopted a different allocation approach, accounting for environmental benefits from material recycling at the End of Life (EoL) phase, in contrast with the work of Chatzinikolaou and Ventikos (2015).

Referring to the work of Nian and Yuan (2017), the authors' objective was to use an LCA approach to evaluate systems offering services in maritime transportation (i.e., crude oil transport by mean of tankers). The paper investigated eleven oil routes that encompassed five different tanker types: (i) Panamax, (ii) Aframax, (iii) Suezmax, (iv) very large crude carrier – VLCC, and (v) ultra large crude carrier – ULCC (Table 3). System boundaries were defined with a cradle-to-grave perspective, including shipbuilding activities (in terms of energy consumption for one tonne of LWT), ship operation, maintenance, and ship scrapping (materials recycling). Even though the authors suggested creating a new benchmark for maritime energy efficiency improvement and decarbonization based on the physical unit of $kgCO_2$/t-km, the functional unit was not explicitly established within the research. Primary data from different sources (*i.e.*, Chinese shipyard, shipping routes, etc.) were managed by using ad-hoc equations and results are reported in terms of direct CO_2 emissions. The normalization process of the functional unit was performed by considering the overall cargo transported in a round trip by the tanker (considering the DWT) and the overall distance (km) travelled in a year, which has been calculated using the single trip distance times the number of annual trips. The approach is consistent, in its basis, with the one proposed in this review. However, no information is provided regarding trips and the distance covered in empty/full mode (see Fig. 2 and Table S2 of Supplementary Material).

As indicated in Table 3, two articles by Bicer and Dincer (2018a, 2018b) studied the environmental implications of alternative carbon-free fuels (hydrogen and ammonia) vs traditional HFO for the operating activities of a freight vessel and a tanker. The system boundary included the vessel production, operation and maintenance, the lifecycle of the fuels, and the construction, activities and dismantling of two ports. The vessel engines under consideration were dual-fuel engines with hydrogen or ammonia replacing some HFO, either totally or partially (50/50). Green hydrogen produced by water electrolysis and ammonia obtained through the Haber-Bosch process have been employed by both studies. The two works differ in terms of the energy source used to produce the fuels, which is either biomass, geothermal and municipal waste energy (Bicer and Dincer, 2018a) or wind and hydropower (Bicer and Dincer, 2018b). Both studies used "*the transportation of 1 tonne of cargo for* 1 km" as a functional unit to analyse the environmental consequences of shipping activities, allowing for simple comparison with other assessments. Based on trip scenarios, the GREET software was used to calculate power ratings and energy consumption, and the ecoinvent was used to collect life cycle inventory. Although the authors identified the processes that mostly affected each impact category, they did not go into detail regarding the life cycle inventory or how each life cycle stage contributed to the final results. This lack of information makes it very difficult to recreate the product system, should be avoided for the sake of clarity. Among the two authors' publications, twenty-one potential scenarios were studied based on different combinations of fuels and supply chains Due to their greater energy consumption rate per ton-km, transoceanic freight ships exhibited higher impact values than tankers. Hydrogen derived from hydropower, geothermal, and municipal solid waste sources performed best as a standalone fuel, with the lowest environmental impacts for Marine Sediment EcoToxicity Potential (MSETP), Marine EcoToxicity Potential (METP), GWP, AP, Abiotic Depletion of Elements (ADE) and Ozone Depletion Potential (ODP). The use of ammonia as a dual fuel with HFO improves the outcomes by roughly 25–50% in every impact category, whereas the use of hydrogen in conjunction with HFO reduces impacts by about 35–60%. Despite the apparent advantages, some issues with the safe management and storage of hydrogen and ammonia (to a less extent) in sea transport remain. The results have already been normalized by the authors based on the total distance travelled by the ship during its service lifetime (3,920,000 km) and the deadweight of the freight ship of 100,000 ton. However, since tankers are commonly used to carry cargo on outward routes only, it is recommended using a normalization process based on the distance covered by the vessel while executing its cargo-carrying duty, which is half of the total distance given. The original outcomes for GHG-related impacts are reported in Table S2 of Supplementary Material, along with the normalized ones, which are also showed graphically in Fig. 2.

It is essential to keep in mind that, notwithstanding the normalization procedure, the outcomes are hardly comparable, due to different functional units (entire vessel, hull or engines only), system boundary (exclusion of raw materials, transports of life cycle phases), allocation not clearly defined, or aggregation of the outcomes in a single score. As general outcome for tankers, the shipbuilding activities related to the main structures (*i.e.,* hulls and machinery) generate GHG emission in the order of 10^1-10^2 kgCO_2-eq, normalized on LWT and lifetime. For this kind of vessel, the main material used for hull construction is carbon steel and the variability of results based on LWT is limited. On the other hand, operational activities are responsible of approx. 10^{-2}-10^{-3} kgCO_2-eq for each ton of fuel transported for 1 km. The operational phase is mainly affected by the distance covered during a trip and the possibility to carry fuels during the return trip, too. The end-of-life phase shows high variability (in a range 10^{-1}-10^2 kgCO_2-eq normalized on LWT and lifetime) due to different allocation approaches.

The outcomes of LCA studies dealing with tankers exhibit how the use phase is responsible of the highest impact along the overall life cycle. In particular, the operational phase accounts for 79% (Kjær et al., 2015), 96% (Chatzinikolaou and Ventikos, 2015), 91% (Nian and Yuan, 2017) and 99% (Quang et al., 2021) of the overall GHG emissions. In terms of impact generation, the operational phase is followed by the ship production, the port and transit service, other operational activities (loading/unloading) and the maintenance activities. Results are in accordance with the other studies previously discussed, supporting the general outcome in the transportation sector which highlights how the highest impact is generated during the operational phase. However, it is worth noticing that these findings need to be taken with caution, due to inconsistencies among the works regarding allocation approach, system boundary and functional units.

3.1.3. *Cargo vessels*

A cargo ship, often known as a freighter, is a merchant ship that transports commodities, minerals, and cargo from one port to another. Cargo vessels are normally custom-built for their purpose, including cranes and other loading and unloading gear, and exist in a variety of sizes and cargo capacity which are often identified by peculiar names (Suezmax, Q-max, Chinamax, Panamax, Seawaymax, etc.). They are generally built of welded steel nowadays, and they typically last 25–30 years before being dismantled, with a few exceptions. They can be classified into various categories based on the sort of cargo they transport. This section deals with the cargo ships classified under the 49314 CPC code "*Other vessels for the transport of goods and other vessels for the transport of both persons and goods*": (i) general freight ships transporting packaged goods such as consumer products and vehicles, (ii) container ships carrying their cargo within truck-size intermodal containers, (iii) dry bulk carriers shipping grain, ore, coal and other pellet-size products in loose form, (iv) Roll-on/roll-off (RoRo) ships transporting wheeled cargo that is driven on and off the ship on its own wheels, such as cars, trucks, semi-trailer vehicles, trailers, and train cars.

Three parameters are required by the normalization approach: (i) the cargo transported by the vessel expressed in tonnage [ton], the weighted average shipping distance of the cargo expressed in kilometres [km] and the number of full trips performed during the considered time span ([#], unitless), as shown in Eq.(5) of Table 1. The procedure to be followed to obtain a correct normalization is detailed in the Supplementary Materials.

Plenty of scientific publications focus their assessment on the operational phase only, including exclusively the fuel supply chain within the system boundary (WTW analyses). These contributions have not been taken into account, resulting in twelve publications analysed in this section.

The first contribution by Gratsos et al. (2010) assessed the carbon footprint of the manufacturing, operation and disassembly of two distinct cargo ship hulls (Panamax and Handymax), each with different corrosion margins and distinctive LWT. A previous work by the same research group (Gratsos and Zachariadis, 2005) indicated that ships built with corrosion allowances suitable for the ship's design lifetime exhibit a reduced total cost, even though they would carry a little less cargo. A comparison based on lifetime CO_2 emission required a reasonable functional unit definition in order to guarantee the same transport service by ships with different expected lifetime (20 and 30 years). Since the various product systems have unequal payloads, different operating days per year and same speed, the authors decided to equalize the annual cargo*distance (ton-km) adjusting the number of available ships in the fleet for a total period of 60 years, which is the least common multiple between the ships lifetimes, in order to define a functional unit. First to introduce the actual capacity utilization of the ship, the authors estimated that the ships transport cargo about 65% of sea time (due to possible route optimization), while 35% of sea time the ships are on ballast. Their findings showed that lighter ships have superior life cycle environmental performance when CO_2 emissions generated from fuel burnt over the ship's lifetime operation are taken into account. However, additional CO_2 emissions are generated due to activities related to steel production (excluding raw materials extraction), shipbuilding activities, maintenance practice, recycling technologies and transport of raw materials. Therefore, in terms of total carbon footprint, more robust ships revealed more environmentally friendly due to larger corrosion margins, which result in fewer steel replacements and idle days. Following the normalization procedure pursued by this review, the DWT (instead of the payload) and a utilization factor of 50% (instead of 65%) have been employed to keep the normalization method consistent, which means that return trips are done on ballast and have the same length as direct journeys.

Ling-Chin and Roskilly published a series of articles dealing with the estimation of the environmental impacts of a hybrid system on-board of a RoRo cargo ship, *i.e.*, a diesel generator (acting as prime movers) assisted by photovoltaic modules, lithium-ion battery systems and a cold-ironing facility. In their first publication (Ling-Chin and Roskilly, 2016a), the authors investigated whether the refitting of the power system on-board of a RoRo cargo ship would be advantageous in terms of resource consumption and environmental burdens. Therefore, they investigated the possibility of replacing a conventional diesel generator with a hybrid system after 10 years of operation of the same RoRo cargo ship travelling on regular routes over a lifespan of 30 years. System boundaries comprehended energy and materials supply, manufacturing of the hybrid system, operational and maintenance activities and recycling processes, which are presented in detail for metallic scraps. The functional unit was defined as *"the operation of the hybrid power system implemented on-board a RoRo cargo ship travelling on regular routes within ECAs over a lifespan of 30 years"*. The characterization of the environmental burdens through impact categories (CML-IA, ILCD, EI99) showed that most of the environmental footprint is generated during operation and end of life phases, in which ecotoxicity potential reveals as the most significant impact. Sensitivity analyses have been employed to double-check the environmental benefits of the retrofit plant, showing a significant reduction in the consumption of marine diesel oil (MDO) and in the scores of CML-GWP, CML-Human Toxicity Potential (HTP), CML-AP, CML-Eutrophication Potential (EP), CML-EcoToxicity Potential (ETP), as a result of increasing the rate of recycling or landfilling at the end of life. The same authors published another extensive work (Ling-Chin and Roskilly, 2016b), providing a detailed inventory of the hybrid system raw materials and manufacturing processes, using technical reports, expert judgement and textbook as sources of information. Even though the power system configurations are different in comparison with the previous work, the system boundaries have not been modified, as well as the functional unit. The authors provided an accurate life cycle inventory, enabling other practitioners to straightforwardly replicate their results using several impact assessment methods (CML-IA, ILCD, EI99). The authors then compared the performance of the hybrid system with a "business as usual" diesel mechanical power system aiming at justifying the environmental benefits of the novel

Table 4
Cargo vessels' features of the available LCA studies.

Type	Panamax bulk carrier	Handymax bulk carrier	Panamax bulk carrier	RoRo Cargo ship		Container vessel	Freight ship	Bulk carrier	Panamax bulk carrier
Source	Gratsos et al. (2010)		(Dong and Cai, 2019, 2020; Quang et al., 2020)	(Ling-Chin and Roskilly, 2016a, 2016c)	(Ling-Chin and Roskilly, 2016b, 2016c)	Gilbert et al. (2017)	(Bicer and Dincer, 2018a, 2018b)	Wang and Zhou (2018)	Tuan and Wei (2019)
Production site	N.A.		Singapore	Denmark		N.A.	N.A.	N.A.	Japan
Production year	N.A.		2004	2004		N.A.	N.A.	N.A.	2004
Operation location	World		World	Europe		N.A.	World	World	World
Estimated lifetime [year]	20–30		20–30	10–30	30	2x26	25	30	25
Service speed [knots]	13.3		13.3	15–17		N.A.	18	N.A.	15.5
Mass Displacement [ton]	84,400	54,600	84,400	22,398		N.A.	N.A.	N.A.	88,248
Deadweight (DWT) [ton]	72,200–73,000	45,900–46,513	72,200–73,000	12,350		N.A.	51,500	157,500	76,300
Lightship weight (LWT) [ton]	11,400–12,200	8,087–8,700	11,400–12,200	10,048		55,000	N.A.	N.A.	11,948
Main engine power [kW] [a]	N.A.		8830	4x5,760	2x5,000 1x4,000 1x3,000 1x2,000 1x1,000	N.A.	37,500	18,660	8830
Auxiliary engine power [kW] [a]	N.A.		N.A.	2x1,563	N.A.	N.A.	8300	N.A.	3x420
Fuel type	HFO		LSHFO	MDO, HFO	MDO	N.A.	HFO, H_2, NH_3	HFO	HFO
Single Trips	1/yr	1/yr	1/yr	300/yr	300/yr	N.A.	1/lifetime	N.A.	N.A.
Average shipping distance [km]	145,248–148,558	146,075–148,972	145,248–148,558	209	209	N.A.	2,000,000	N.A.	N.A.

[a] If more than one engine was present, the number of engines was specified, along with the specific engines power.

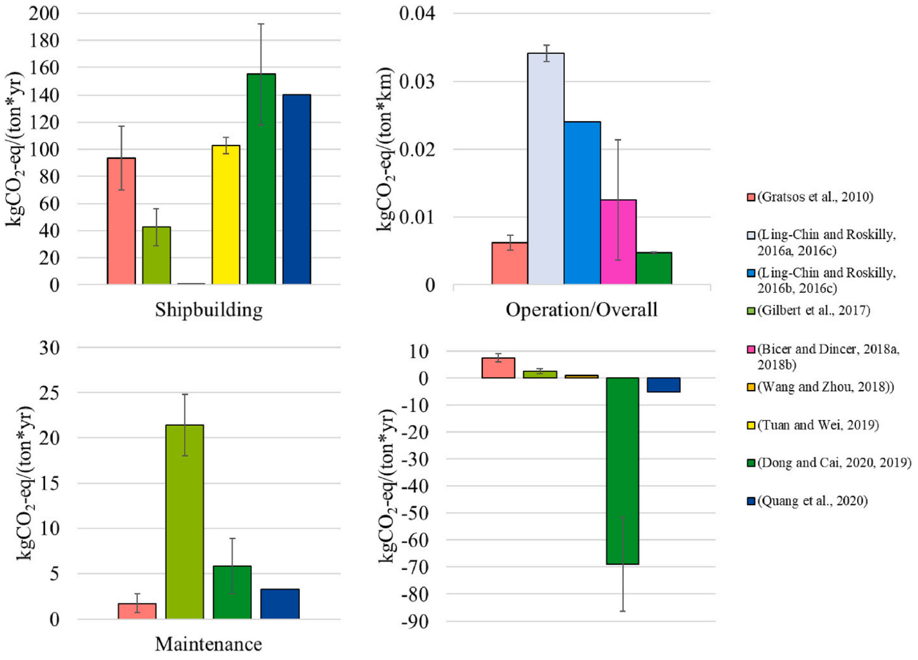

Fig. 3. GHG-related normalized scores for Cargo Vessels. Error bars are reported when multiple outcomes, e.g., sensitivity analyses or different vessel configurations, have been evaluated by the original authors.

technology. It was found that throughout the lifespan, the hybrid system shows a higher environmental footprint in terms of ecotoxicity potential and abiotic depletion of fossil fuels. This is mainly due to the larger amount of metal constituting the hybrid system, whose manufacturing and disposal processes were responsible for the drop of the environmental performances. However, taking all impact categories into account, the hybrid system provided an overall improvement of the environmental performance in comparison with the conventional marine power system. In fact, the reduction by one or less order of magnitude for twenty impact categories is perceived by the authors to prevail on the same magnitude increase for the other six impact categories. The conventional plant, the retrofit plant and a new-build all-electric system have been compared in a following paper by the same authors (Ling-Chin and Roskilly, 2016c). They built up a bottom-up integrated approach to model each power system as a composition of peculiar components, whose life cycle inventory has been studied in detail. Their findings confirmed that environmental footprint on various natural compartments is generally reduced by the installation of the new-build all-electric system when compared to the retrofit system, which in turn exhibits improved performances than conventional systems. Basically, the installation of advanced marine power systems demands more resources for manufacturing and disposal, although consuming less fuel and releasing less emissions during navigation. Since the operational phase is the most burdensome activity throughout the life cycle of the power system, this results in a general reduction in most impact categories at the expense of a few. The information related to the vessels analysed in the works just presented are reported in Table 4, while the outcomes are displayed graphically in Fig. 3 and numerically in Table S4 of Supplementary Material.

The first complete life cycle analysis of a container vessel hull has been published by Gilbert et al. (2017), whose aim was to explore the CO_2 implications of introducing reusing/recycling practice in the shipbuilding sector. The authors defined the functional unit as "*two hulls used for a duration of 26 years each*". Three scenarios have been developed, each one characterized by a different amount of primary steel used for the second hull, *i.e.*, (i) 100% primary metal (Business As Usual - BAU), (ii) 100% secondary metal from previous hull, iii) 50% secondary steel from previous hull and 50% primary metal. System boundaries included exclusively shipbuilding activities related to steel hull manufacturing, such as raw material supply, hull manufacture, ship assembly, maintenance and end-of-life treatment processes. The impact assessment exhibits a CO_2 emission reduction of approximately 29% for a complete reuse of the first hull (scenario (ii)) and a decrease of CO_2 emission of roughly 10% for a 50% reuse of first hull (scenario (iii)), both in comparison with BAU. This is not surprising, as scenarios (ii) and (iii) cut down the usage of burdensome primary metal, yielding substantial savings in terms of CO_2 emissions. Although the potential CO_2 emissions related to maintenance and transportation may increase to enable higher levels of reuse and/or remanufacture, they are likely to be negligible if compared to the primary metal supply required by the BAU scenario. The work's primary shortcomings include the lack of a comprehensive overview provided by well-recognized environmental impact methodologies and the absence of data regarding the ship's operational activities, which precludes comparison with other thorough life cycle assessments available in the literature. Table 4 and Fig. 3 show how the calculated CO_2 emissions were normalized using a LWT of 55000 tons and a lifetime of 52 years to make the results useful for future research.

A following series of publications by Bicer and Dincer (2018a, 2018b) investigated the environmental impacts of alternative carbon-free fuels (hydrogen and ammonia) in comparison with conventional HFO for the operational activities of a freight vessel and a tanker, as shown in Table 4. These works have already been described in section 3.2, where the outcomes related to the LCA of a tanker have been presented. In the freight-related case study, the results have been normalized by the authors based on the total distance travelled by the ship during its service lifetime (2,000,000 km) and the DWT of the freight ship of 40,000 ton. However, since a freight ship usually transports cargo on direct journeys only, a normalization procedure based on the distance travelled by the vessel when performing its function of carrying cargo (which is half of the total distance reported) is recommended. The normalized results for GHG-related impacts are reported graphically in Fig. 3 and numerically in Table S4 of Supplementary Material, along with original scores.

The life cycle assessment of ship engines coupled with a Carbon Capture and Storage (CCS) system to reduce the greenhouse gas emissions from the exhausted gas of a bulk carrier has been carried out by Wang and Zhou (2018). Their goal was to estimate the carbon footprint and the economic implications of introducing a carbon capture and solidification process on-board a bulk carrier, whose characteristics are reported in Table 4. The functional unit is not clearly defined, even though it can be assumed that "*the manufacturing, 30-year operation and disposal of a ship engine coupled with a CCS system on a bulk carrier*" has been used. Limited information is provided for the operational phase (distance travelled, cargo transported, CCS mass and energy balances are missing), scrapping phase (no materials recovery or treatments) or electricity mix. In fact, looking at the flowchart of the product system, electricity for manufacturing and dismantling seems to be totally generated from wind energy, even though the authors did not justify this assumption in the text. Nonetheless, the authors developed various scenarios under different carbon reduction targets and determined a higher profit for lower carbon emission due to saving from carbon credits and trading of the final product, *i.e.*, $CaCO_3$. A further limitation of the work resides on its narrow perspective focused on global warming potential only. Indeed, the inclusion of other impact categories would have depicted a shifting of the environmental burdens from one environmental issue to another, which is a well-known drawback of CCS (Barbera et al., 2022). The GWP results presented in Fig. 3 should be used bearing in mind that raw materials extraction and refinement have not been included within the system boundary. Since the paper deals with power system only, the normalization has been performed on the weight of the engine (36 ton), while information regarding the distance travelled was missing.

Tuan and Wei (2019) performed a detailed cradle-to-gate assessment of the production of a Panamax bulk carrier (see Table 4), choosing the functional unit accordingly, *i.e.*, "*the construction of one Panamax bulk carrier for the transportation of coal from Australia to Japan over a 25-year life cycle*". System boundary included material extraction and production, ship hull and machinery construction, sea trials and transportations between the activities. The inventory of each activity is well-described, showing formulas, calculation principles, parameters values and inventory obtained. Secondary data have been retrieved within the GaBi database, while CML-IA environmental impact method has been used. The results highlighted a dominant contribution of raw material extraction and refinement phase, as it generates most of the burdens among all the impact categories (87–100%). Shipbuilding emerged as the second most burdensome activity (2.26–10.50%), followed by sea trials, machinery production and transportation. Sensitivity analyses have been performed aiming at evaluating the effect of assumptions and calculation principles on the impact category scores. The final results, as expected, are heavily influenced by the hull weight, which comprises the majority of the ship's steel. Based on these findings, the authors extended their work on another publication (Dong and Cai, 2019), which deals with the eco-design of a Panamax bulk carrier comparing different lightship weights. This work extends the previous publication of Gratsos et al. (2010) introducing the raw materials extraction processes taken from GaBi as well as the holistic approach provided by the CML-IA LCIA method. The outcomes of Gratsos et al.'s assessment indicates that, for a given mass displacement, a lighter vessel maximizes its payload by cutting down the lightship weight. On the other hand, a heavier ship resulting from an increase of the hull thickness guarantees lower steel maintenance replacement and larger corrosion margins. The authors' study compares the environmental performances of these two ship design concepts by using an attributional LCA method, aiming at providing assistance to naval architects during the ship design stage. The functional unit adopted was "*the transport of one ton of bulk cargo over a distance of one km by sea during T years of service (20 or 30 years)*", which enables a comparison with other works in the field. System boundaries included the entire life cycle of the ships, pursuing a cradle-to-grave perspective. Materials and energy balances are well-described for each activity throughout the whole life cycle of the ship, as well as limitations and assumptions, which are further investigated using sensitivity analyses. Their results indicate that the lighter solution would emit more than double VOC, whereas slightly reducing NOx and SOx emissions in comparison with heavier ships. Concerning CML-IA environmental indicators, in general they are marginally increased by heavier ships (0.6–2.15%). However, this design yields a decisive improvement in terms of ADE (38.69%), Terrestrial EcoToxicity Potential-TETP (3.60–7.09%), ODP (21.29–21.58%), and METP (18.29–19.74%), justifying the authors' claim of better environmental performance for more massive ships. Their findings relied on a drop of maintenance material replacements, energy consumption, and emissions from the life cycle of the heavier ship, excluding the operational phase. This paper might be used as a benchmark for future studies on cargo vessels, thanks to the adoption of a suitable functional unit, the quality of the information provided and the assumptions transparency, which have been investigated through sensitivity analyses. In this review, the score normalization step employed the peculiar payloads of the vessels (70, 700–71,500 ton) instead of the DWT, due to the essential role of this parameter to distinguish the different vessel features in this work. This research group further examined the environmental performance of a Panamax bulk carrier from an energy efficiency viewpoint (Dong and Cai, 2020). Energy efficiency technologies, such as air-lubrication systems or installation of solar panels, may decisively decrease life cycle emissions of ships, since the operational phase is commonly the most burdensome life cycle phase. However, the installation of additional systems raises the lightship weight, increasing the emissions from production and maintenance phases, while reducing the vessel payload. Numerous scenarios have been developed by the authors, using CML-IA method to evaluate both fuels savings (0–20%) and LWT increment (0–20%) simultaneously, avoiding the introduction of any specific energy optimization technology. The functional unit is "*the transport of one ton of bulk cargo over one km by sea over a 20-year service life*", whereas the system boundaries include raw material extraction and production, shipbuilding activities, operation and maintenance. The assessment's main conclusions are dual: a significant reduction of environmental impacts (except ADE) is gained by fuel savings, while several scenarios are more burdensome than the base case due to the increase in the lightship weight. A cradle-to-grave study published by the same research group concluded the series of group's publications presenting a Korean bulk carrier LCA (Quang et al., 2020) from different perspectives. The vessel under study was the same as in Gratsos et al.'s work (Gratsos et al., 2010), where more detailed information about assumptions and data source can be retrieved. The focus of this study is on GHG emissions only, limiting the analysis on GWP impact category of CML-IA. Since the work lacks information for reproducibility of the results (*e.g.*, supply chains of materials, electricity mix, detailed inventory), the GWP result is not free of criticism. In accordance with other works, the operational phase is revealed as the most burdensome activity.

It is essential to keep in mind that, notwithstanding the normalization procedure, the outcomes are hardly comparable, due to different functional units (entire vessel, hull or engines only), system boundary (exclusion of raw materials, transports of life cycle phases), allocation not clearly defined, or aggregation of the outcomes in a single score. Shipbuilding activities that involve the construction of vessel structures produce GHG emissions in the range of 10^1-10^2 $kgCO_2$-eq, based on LWT and lifespan. For each ton of cargo moved for 1 km, operational activities produce 10^{-3}-10^{-2} $kgCO_2$-eq, which is aligned with ecoinvent documentation. The former is mostly driven by the material (steel) used in freight vessel construction, whereas the latter is primarily influenced by the large amount of transportable cargo and the ships' high utilization.

3.1.4. Fishing vessels

A fishing vessel is a boat or ship employed for catching fish and other seafood generally from wild fisheries for commercial profit. On an estimate, the number of total fishing vessels in the world in the year 2016 was about 4.6 million, mostly operating in Asiatic regions. Fishing boats are grouped under 49315 CPC code and are usually classified using the size of the vessel, expressed in Gross Tonnage (GT) or length. This strictly statistical subdivision is in practical applications often replaced by a simplified form in which "large", "medium sized" and "small" vessels are distinguished. This above subdivision corresponds approximately to the area of operation of the vessel: large fishing vessels operate principally in open seas, medium sized vessels in the Exclusive Economic Zone (EEZ) marine areas and small decked vessels are predominantly used in coastal and sheltered marine and brackish waters. Another categorization is based on the type of fishing activity and processing carried out by the vessel, including trawlers (the ones that pull trawler nets against the ocean water) and non-trawling vessels (the ones that still use a net but the net is fixed and the fish swim to the net and get themselves caught).

In order to obtain a standard reference unit to normalize the environmental impacts of the operational phase for fishing vessels, three parameters are recommended for this purpose: the quantity of landing [ton], the covered distance expressed in kilometres [km] and the number of trips (unitless [#]) performed in the analysed timespan, as shown in Eq.(6) of Table 1. The procedure to be followed to obtain a correct normalization is detailed in the Supplementary Materials.

Despite the large variety of sizes and types, the available literature refers to LCA studies of fishery activities in different geographical areas (*i.e.*, Mediterranean Sea, Baltic and North Sea). Among the five published documents related to fishing vessels, three of them take into account trawlers, while only two refer to a coastal purse-seining fleet. Unlike other vessel categories, the majority of LCA studies dealing with fishing operations do not focus on a single vessel (i.e., a specific case study), but rather a fleet of vessels. (Abdou et al., 2018, 2020; González-García et al., 2015; Ramos et al., 2011). This outcome reflects the fact that fishing vessels used in a geographical area are about the same size and use approximately the same level of technology. Thus, it is interesting to investigate the forecasting of more efficient solutions to allow a correct management and strategic planning of fishing activities.

All the papers adopted approximately the same functional unit, *i.e.*, "*1 ton of landed round fish/landed seafood in one year of operation*" (Abdou et al., 2018, 2020; González-García et al., 2015; Ramos et al., 2011; Ziegler et al., 2018). The operational phase is the most burdensome activity for this type of vessel due to the fuel combustion which is necessary to reach the fishing site, perform the fishing activities and then process the collected fishes, *i.e.*, making ice to preserve the catches. Most of these works dealt with the prospect of processing fishes at on-shore facilities, so reducing fuel consumption and utilizing more sustainable energy from the power grid. This sort of information may be used by producers to optimize production, and it can also be utilized by enterprises further downstream in the value chain to adapt their sourcing strategy. Increased knowledge of this variability might be utilized to enhance the fisheries management system by, for example, creating the most resource-efficient geographical and temporal limits for fisheries and the allocation of fishing rights. A common aspect among the analysed publications is related to the first step of the LCA methodology (goal and scope definition), *i.e.,* a cut-off mass allocation method with a cradle-to-gate perspective including shipbuilding activity, ship operations, and maintenance. End-of-life was neglected in all research works due to uncertainty and lack of available data. Shipbuilding activity included materials used for hull, fishing gear, engines, as well as paint and anti-fouling production which are also required during maintenance operations. Ship operations included diesel consumption, marine lubricant oil, net replacement, and ice consumption. Emissions to water, air and soil were also included within the system boundaries. Primary life cycle inventory (LCI) data from different sources were integrated with background data (*e.g.*, ecoinvent database) and LCIA results were reported mainly following CML-IA baseline and ReCiPe midpoints indicators. Concerning primary data, specific maritime registers/organizations were contacted as well as surveys were performed involving skippers and fishermen. Landings, vessel characteristics (beam, GT, etc.), fishing operations, and fishing areas were the most relevant data obtained from the register. Gathered data included vessels' operational details (*e.g.*, fuel consumption, number of fishing trips, and number of days at sea) and information about vessel construction (*e.g.*, the material used for construction, paint and antifouling paint quantities, dimensions of vessels, life span). Fishing vessels' features are provided in Table 5.

The results of LCA studies exhibit how the fishing vessel use phase is responsible of the highest impact along the overall life cycle. The two works of Abdou et al. (2020, 2018) show that more than 96% of the overall impacts for the majority of the environmental categories (CML-ADE, CML-ODP, CML-GWP, CML-EP, and Cumulative Energy Demand-CED) are caused by (i) fuel and lubricating oil production, and (ii) seafood production. On the other hand, the trawler and trawling net manufacturing contributed most to toxicity-related impact categories. The same trend is shown by Ziegler et al. (2018), who found that fuel production and combustion dominated all conventional LCA impact categories, such as ILCD-CC, ILCD-AP, ILCD-Marine Eutrophication (MEU), ILCD-PM, ILCD-POCP, and ILCD-Terrestrial Eutrophication (TEU), with the exception of toxicity-related impacts dominated by the manufacture of materials for fishing vessels and gear. Again, in the work of Ramos et al. (2011), vessel operations were the major sources of environmental impacts related to fishery, considering all the conventional impact categories assessed, except for ODP and ADE. Diesel consumption was discovered to be the primary contributor to

Table 5
Fishing vessels' features of the available LCA studies.

Type	Basque coastal purse-seining fleet	Norwegian demersal trawler	Wooden trawlers	Portuguese purse-seining fleet
Source	Ramos et al. (2011)	Ziegler et al. (2018)	(Abdou et al., 2018, 2020)	González-García et al. (2015)
Production site	N.A.	N.A.	N.A.	N.A.
Production year	N.A.	N.A.	N.A.	N.A.
Operation location	Gulf of Biscay (Atlantic Sea)	Norwegian and Barents Sea	Gulf of Gabes (Mediterranean Sea)	Spanish and Portuguese coast (Atlantic Ocean)
Estimated lifetime [year]	N.A.	30	40	40
Number of vessels (fleet)	226	Single vessel	184	20
Length [m]	N.A.	N.A.	22–25	20
Mass Displacement [ton]	N.A.	N.A.	N.A.	N.A.
Deadweight (DWT) [ton]	N.A.	N.A.	N.A.	N.A.
Lightship weight (LWT) [ton]	N.A.	N.A.	105–115	N.A.
Main engine power [kW]	N.A.	N.A.	N.A.	N.A.
Auxiliary engine power [kW]	N.A.	N.A.	N.A.	N.A.
Single trips	N.A.	20/year	13-25/year	N.A.
Fuel type	N.A.	N.A.	N.A.	N.A.
Average fishing trip distance [km]	N.A.	N.A.	N.A.	N.A.
Landing per year [ton/yr]	5000	6200	6300	1000

environmental effect within vessel operations for all impact categories, with the exception of METP, where the greatest burden was brought on by antifouling emissions to the ocean. The net production and transportation subsystem also appeared as an important contributor in ADE and GWP categories. Other relevant activities generating environmental impacts were the ice production system and, to a lesser extent, operations related to the construction and maintenance of the vessels (antifouling and steel production). Concerning the work of González-García et al. (2015), results are reported in terms of [kgCO$_2$-eq/ton of landing] by using the ReCiPe midpoint LCIA method. Only a general overview of the LCA impact is reported, neglecting the splitting into shipbuilding, operations and end-of-life, even though the results are consistent with the findings of previous studies. The final goal claimed by this work is to estimate the environmental burdens related to operational inefficiencies, as well as to define target performance threshold for optimizing vessel operations. Even though it can be challenging to pinpoint the causes of inefficiency because fishing activity is so unpredictable, the main source of uncertainty appears to be related to operational and behavioral variations among skippers, while other crucial factors like the characteristics of the vessels did not correlate with the inefficiency values.

A summary of features of the analysed vessels are reported in Table 5. It is worth noticing that, due to lack of information (*e.g.,* average fishing trip distance), it is not possible to perform the normalization procedure, neither report GHG-related results specific for each life cycle phase. The employment of different materials in shipbuilding and the geographical areas where fishing activities are carried out require a normalizing process to compare different fleets, which would be beneficial in comparing single fishing vessels. Nonetheless, the original scores are reported in Table S3 of Supplementary Material.

3.1.5. Pleasure and sporting boats

Pleasure and sporting boats (also known as recreational crafts) are sorted into numerous main categories and subcategories, depending on their intended use and their size. They are all identified under CPC code 494, which comprehends sailboats, inflatable boats, motor crafts under 6 m, motor yachts under 24 m and motor superyachts over 24 m. Their purpose is generally a recreational use for sport or pleasure, including vessel categories such as (i) paddlesports boats (canoes, kayaks, rowing shells) for sports and recreational activities; (ii) dinghies (usually under 16 ft, 5 m) used for transfers from larger boats, powered by sail, small engines, or muscle power; (iii) runabouts (15–25 ft, 5–8 m) powerboats with either outboard, sterndrive, or inboard engines commonly used for pleasure activities like fishing, racing, boating or as a transfer service from larger vessels; (iv) daysailers sailboats (14–25 ft, 4–8 m) sometimes equipped with sleeping accommodation and a small auxiliary engine; (v) cruisers (25–65 ft, 8–20 m), *i.e.*, powerboats with cabins for accommodation; (vi) cruising and racing sailboats (25–65 ft, 8–20 m) which are sailboats with auxiliary engines and suitable for longer journeys.

With the aim of providing a benchmark to future investigations in this vessel category, the usage of a normalization basis that requires the inclusion of two parameters is recommended: the number of passengers transported ([# unitless) and the average time [hr] spent on the boat offshore, as shown in Eq.(8) of Table 1. The procedure to be followed to obtain a correct normalization is detailed in the Supplementary Materials.

The rather small dimensions of these vessels allow various production materials using several manufacturing processes. Thus, most of the available literature deals with comparative LCA studies among suitable hull materials or hull manufacturing processes. Among the six published documents, three distinct papers focused on the hull production and disposal (Burman et al., 2014; Cucinotta et al., 2017; Önal and Neşer, 2018), while the other three from the same working group encompassed the entire vessel into the system boundaries (Favi et al., 2017, 2018a, 2018b).

The available research on this vessel category focuses mainly on studying various materials and hull fabrication procedures. The first investigation was published by Burman et al. (2014), who compared various materials for the hull production of a patrol craft, excluding from the system boundaries the shared elements among boat alternatives. Although the vessel under examination is not a pleasure boat, its structural characteristics, lifetime, and yearly fuel use are typical of a motor yacht. The authors chose "*one high-speed patrol craft (TTRB-2000) hull during 25 years of service*" as a functional unit and employed CML-IA method for the life cycle impact assessment phase. As a shared outcome with other studies, the use-phase unveiled as the greatest source of environmental burden for the majority of impact categories. The features of the patrol craft are shown in Table 6. While the lack of information regarding the passenger capacity hinders the normalization of the usage phase, the mass of the hulls, *i.e.,* between 4.4 and 8.7 tons, has been normalized as reported in Table S5 of the Supplementary Material for GHG-related impacts and graphically in Fig. 4.

The study of Cucinotta et at. (2017) dealt with the comparison among different manufacturing processes for the production of the hull of a pleasure yacht, which is commonly made of a composite sandwich of glass fibre and polyester or epoxy resins. Two manufacturing processes were considered, *i.e.,* hand lay-up and vacuum infusion, characterized by different amounts of wastes and different weight of the final structure. In fact, vacuum infusion allows a higher glass fibre content, meaning that a lighter infused sandwich provides the same mechanical

Table 6
Pleasure vessels' features of the available LCA studies.

Type	TTRB-2000 Patrol Craft	Motor Yacht	"Supercoronero" Yacht	Superyachts	Weekender Boat
Source	Burman et al. (2014)	Cucinotta et al. (2017)	(Favi et al., 2017, 2018b)	Favi et al. (2018a)	Önal and Neşer (2018)
Production site	Sweden	Italy	Italy	Italy	Turkey
Production year	N.A.	2006	2016	N.A.	N.A.
Operation location	Sweden	Mediterranean Area	World	Mediterranean Area	Mediterranean Area
Estimated lifetime [year]	25	25	20	20	10
Maximum speed [knots]	33	33	15	15–38	N.A.
Mass Displacement [ton]	27.4–33.6	34.284	432	N.A.	N.A.
Deadweight (DWT) [ton]	N.A.	3	42	N.A.	N.A.
Lightship weight (LWT) [ton]	4.4–8.7 (Hull)	28.150–31.284	390	230–390	4
Main engine power [kW] [a]	N.A.	2x820	2x1,081	2x1,081 2x1,045 4x1,939	N.A.
Auxiliary engine power [kW] [a]	N.A.	16	2x125	2x125, 1x55 2x100 2x80	N.A.
Fuel type	MDO	MDO	MDO	MDO	N.A.
Passenger capacity	N.A.	6	10	10	N.A.
Average offshore period [hr/yr]	1000	200–500	500-1500	500	N.A.

[a] If more than one engine was present, the number of engines was specified, along with the specific engines power.

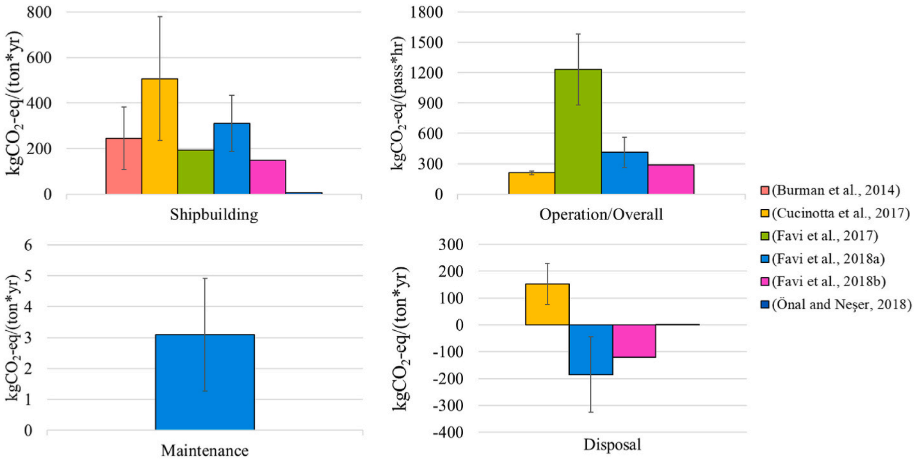

Fig. 4. GHG-related normalized scores for Pleasure and Sporting Boats. Error bars are reported when multiple outcomes, e.g., sensitivity analyses or different vessel configurations, have been evaluated by the original authors.

properties as a heavier one produced by hand lay-up technique. The system boundary comprehended the hull production from cradle-to-grave, with different use-phase and disposal scenarios. The functional unit, despite not clearly stated by the authors, appeared to be *"the hull manufacturing and usage for 25 years of service"*. Raw materials, production processes and end-of-life activities were related to the hull only, while the operational phase and fuel consumption were calculated on the mass displacement of the boats. This study, which was a comparative life cycle assessment of hull manufacturing methods, ignored common materials and structures of the two vessels, as their impacts on the final results were equal. The outcomes of the study demonstrated an overall improvement of environmental performances for vacuum infusion, particularly for low usage scenario. The vessel details are shown in Table 6, while the original and normalized results for GHG-related impacts (based on the LWT of the vessel, to allow comparability with other works in this vessels category) are reported in Table S5 of Supplementary Material and graphically in Fig. 4.

In the first paper of the group, Favi et al. (2017) employed CAD tool and shipyard information retrieved within lightship weight document to obtain a detailed LCI for a pleasure yacht construction. In order to ease data acquisition by manufacturers, vessel materials were sorted by functional groups, providing a benchmark for future application. Both LCA and LCC were evaluated, focusing mostly on shipbuilding activities which have been detailed using primary data. System boundary endorsed a cradle-to-gate perspective with various use phase scenarios, exhibiting greater impacts from fuel (MDO) combustion during the operating phase, regardless of the scenarios. The authors adopted "*the maritime operational activities and the transportation of persons and goods by sea for a period of 20 years*" as a functional unit, claiming that could be elected as a benchmark for different vessel categories. Although a unique functional unit for the maritime sector would be practical, it would allow unfair comparison between vessels with different purposes, *e.g.*, a comparison between a cargo vessel and a kayak for transportation. In fact, the horizontal normalization defined in section 3.2 only provides an overview of the design efficiency of the vessel compared to the actual one, failing to account for the unique function offered by each vessel category. Several operating phase scenarios have been studied, considering different annual usage of the superyacht (from 500 to 1500 h/year), which have been compared using ReCiPe midpoint indicators. The outcomes shed light on the great influence of the operating phase, as different operating scenarios strongly affect the final results, *i.e.*, for the longest usage the GHG emissions almost doubles. In another paper dealing with the same vessel (Favi et al., 2018b), the authors investigated different shipbuilding techniques (laser cutting, Shielded Metal Arc Welding - SMAW, Gas Tungsten Arc Welding - GTAW and infusion) and materials for hull and hatches, including carbon steel, aluminium and carbon fibre composite. The LCIA results showed that aluminium hulls had better environmental performance (particularly in terms of ecotoxicity and metal depletion), with marginal gains when carbon fiber composite hatches were used. The vessel details are reported in Table 6, while the normalized results are shown in Fig. 4. The authors further extended their previous works through a collaboration with several Italian shipyards in order to provide an LCA/LCC tool for calculation of pleasure yachts' environmental footprint (Favi et al., 2018a). The proposed methodology recommended the utilization of a singular functional unit, similar to the previous one, which could be adapted to every vessel category: "*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 vessel (commonly 20–25 years). This definition broadens the system boundaries endorsing a cradle-to-grave perspective, where operational and end-of-life scenarios are employed to model the impact of the ship after the production phase. Although this functional unit looks practical and easy to implement, the development of a specific functional unit for each peculiar vessel type may prevent an unfair comparison between vessels belonging to different categories, as previously stressed. Nevertheless, the authors presented a detailed and valuable guideline for LCA practitioners in the maritime sector, splitting the vessel into its constitutive functional systems and specifying the data source for compiling a reliable life cycle inventory. A comparative cradle-to-grave LCA on three pleasure boats is used to support this guideline, and the results are shown in Table 6. These results are consistent with the general pattern of locating the greatest impacts during the operational phase. The impact assessment has been performed using midpoint ReCiPe method in combination with Cumulative Energy Demand (CED), even though the authors report the results for Climate Change (tCO_2-eq) only. The results gained by Favi et al. (2018a) are reported in Table S5 of Supplementary Material, along with the normalized scores obtained through the normalization procedure. The most burdensome operational phase is exhibited by the aluminium yacht (P140), followed by the steel/-aluminium vessel (C136) and the glass-fibre one (CNR43). Apart from the operating phase, the shipbuilding operations produce equivalent outcomes. When comparing the end-of-life benefits of the different vessels, CNR43 has the lowest benefit since polymer-based materials are primarily landfilled, whereas metal-based yachts have higher benefits because of their high recycling rates (Fig. 4).

Focusing on different shipbuilding techniques and various recycling practices, Önal and Neşer (2018) analysed the manufacturing and EoL phases of a glass-reinforced polyester vessel hull of a recreational boat. The functional unit was defined as *"the complete life cycle of 11 m long*

Table 7
Other vessels' features of the available LCA studies.

Type	Tugboat	"Salvation 21" Tugboat	Re-liquefaction systems applied to LNG carrier
Source	Jeong et al. (2018)	Wang et al. (2020)	Park et al. (2020)
Production site	N.A.	N.A.	China
Production year	N.A.	N.A.	N.A.
Operation location	South Korea	South Korea	USA and South Korea
Estimated lifetime [year]	30	30	25
Service speed [knots]	N.A.	N.A.	N.A.
Mass Displacement [ton]	2270	N.A.	N.A.
Deadweight (DWT) [ton]	N.A.	156	115,541
Lightship weight (LWT) [ton]	N.A.	N.A.	N.A.
Main engine power [kW] [a]	2x4,500 4x2,200	2x1,518 3x1,062 2x1,062 4x761 3x761	2x18,200
Auxiliary engine power [kW]	N.A.	N.A.	N.A.
Fuel type	MDO	HFO	HFO
Single Trips	N.A.	N.A.	155/lifetime
Average distance travelled by cargo [km]	N.A.	N.A.	27,000 (estimated)

[a] If more than one engine was present, the number of engines was specified, along with the specific engines power.

GRP boat hull; produced in Izmir (Turkey), excluding operation stage of the boat and recycled in a Turkish state-of-the-art recycling system". Primary data was collected from interviews and site visits at the shipyard, while secondary data was retrieved within ecoinvent database. The LCIA calculations have been performed on SimaPro using CML-IA baseline impact categories. The results for composite hulls show that vacuum infusion has a slightly larger environmental impact (approx. 2.5%) than hand lay-up due to its higher energy consumption, but there is also a lower chance of occupational health problems, thanks to the usage of a lower amount raw materials in a closed mould. The findings of Cucinotta et al. (2017), which revealed that vacuum infusion performed better in every impact category, are in conflict with Onal's findings. Even though Cucinotta's study appears to be more accurate as a result of a deeper analysis of the manufacturing processes, more investigation is still required to fully comprehend this topic. With the exception of TETP, Photochemical Oxidant Formation Potential (POFP), and AP, the comparison of the disposal scenarios suggests that mechanical recycling, followed by the granule extrusion method, has lower environmental burdens. Among the end-of-life alternatives, landfill shows the highest environmental impacts, while composite recycling showed the best performance. However, even if the process of recycling for composites hull seems beneficial in terms of environmental impacts, its technological feasibility is still an unresolved issue.

It is essential to keep in mind that, notwithstanding the normalization procedure, the outcomes are hardly comparable, due to different functional units (entire vessel, hull or engines only), system boundary (exclusion of raw materials, transports of life cycle phases), allocation not clearly defined, or aggregation of the outcomes in a single score. Shipbuilding activities involving the construction of vessels' structures produce GHG emissions in the range of 10^2 $kgCO_2$-eq normalized on LWT and lifespan, which are coherent with the emissions related to the shipbuilding of other vessel types using the same construction material. For each passenger carried for 1 h, 10^2-10^3 $kgCO_2$-eq are emitted by operating activities. These outcomes, averaged among various works and strongly dependent on estimated operational profiles, exhibit the impact of leisure activities of motor yachts, which usually have low passenger capacity and high fuel consumption.

3.1.6. *Other vessels categories and naval systems*

Following the LCA principles, research was done on additional vessel classifications that weren't included in the earlier parts. These analyses, though, are constrained and isolated. For example, only two publication from the same research group dealt with tugboats' characteristics (Jeong et al., 2018; Wang et al., 2020), both focusing on optimizing the power system and its application offshore. A tugboat, often known as a tug, is a nautical vehicle that pushes or pulls other vessels using direct contact or a tow line. Tugs usually tow ships that can't move on their own, including barges, damaged ships, log rafts, or oil platforms. Tugs are powerful and durable for their size, and they are designed based on the environment they operate in, such as ocean-going tugs, icebreakers or salvage tugs.

As previously reported, Jeong et al. (2018) developed a comprehensive tool for determining the optimum ship design among numerous options in terms of long-term cost and environmental implications. The characteristics of the tugboat under investigation are reported in Table 7. Two different power system designs and flexible engine operating scenarios were examined, with one of the setups resulting in less engine running hours since the burden was spread more evenly across the engines. A slower pace would be desirable in terms of cost-benefit analysis and environmental effects, according to various speeds that have been assumed. These conclusions are helpful for different operating procedures. Using Eq.(7) of Table 1, the data were normalized using the weights of the engines under investigation, 102 and 36 ton for the basic case and alternate option, respectively. The results are shown in Table 7.

The life cycle performance of a tugboat (Table 7) was evaluated by Wang et al. (2020), who carefully compared various propulsion system configurations and chose the best system with the lowest emissions release, costs, and hazard implications. The authors employed a self-developed software (ShipLCA) as a decision-making tool to help identifying the optimal setup in terms of selecting engines, configuring systems or using different electricity sources. Results are expressed in terms of GWP and AP by adopting CML-IA as LCIA method, while the functional unit was defined, as "*the quantified ship performance during its service*". This choice was done by the authors to allow the end-users to set up an assessment based on a different objective. Primary data related to engine consumption during operational activities and fuel supply chain scenarios were coupled with background data retrieved from the Gabi database. The findings are consistent with LCA studies conducted on other vessel categories, as the ship operation exhibits the highest share of environmental impacts, both in terms of GWP and AP. The use phase accounts for approximately 90% for the GWP and about 98% for the AP in relation to the total impact, regardless of the engine technology. It is worth highlighting that the shipbuilding and end-of-life phases were considered only for the engine module, and not for the entire ship. Although the operating phase emissions are well described by the developed tool, the results reported within the paper for the shipbuilding and decommissioning phases are not consistent between the two calculation methods. (GaBi tool and ShipLCA). Because no additional information was provided to fill this gap, and no data about shipbuilding or decommissioning was provided, it is difficult to determine the cause of this mismatch.

Park et al. (2020) evaluated the environmental benefits of the LNG partial re-liquefaction system applied to LNG carriers by comparing five different combination/configuration of LNG re-liquefaction systems. An LNG carrier is a tank ship designed for transporting liquefied natural gas (LNG) and it might be thought of as a peculiar kind of tanker. Since the gas is transported in liquid phase, pressures much greater than atmospheric one and/or very low temperatures are required. Therefore, LNG carriers can be classified as (i) fully pressurized, (ii) semi-pressurized and refrigerated, and (iii) fully refrigerated. Looking at the work of

Table 8
Vessels' features of the available LCA studies for horizontal normalization.

Category	Authors	LWT [ton]	Power [kW]	Power/LWT ratio [kW/ton]	GWP shipbuilding [kg CO_2-eq]	GWP operation [kg CO_2-eq]	LES [% kg CO_2-eq]	Efficiency Ratio [%kg CO_2-eq/kW/ton]
Pleasure - C136	Favi et al. (2018a)	390	2467	6.33	1.76E+06	2.97E+07	5.93E-02	9.37E-03
Pleasure - CNR 43		280	2290	8.18	1.04E+06	2.65E+07	3.92E-02	4.80E-03
Pleasure - P140		230	7916	34.42	2.00E+06	5.63E+07	3.55E-02	1.03E-03
Pleasure - Infusion	Cucinotta et al. (2017)	28	1640	58.26	1.66E+05	5.72E+06	2.91E-02	4.99E-04
Pleasure - Hand Lay-up		31	1640	52.42	6.09E+05	1.71E+07	3.56E-02	6.78E-04
Ferry -Reference	Blanco-Davis et al. (2014)	13,635	48,000	3.52	2.89E+07	1.83E+09	1.58E-02	4.49E-03
Ferry - with coating		13,635	48,000	3.52	2.89E+07	1.69E+09	1.71E-02	4.86E-03
Tanker 1	Chatzinikolaou et al. (2015)	13,925	14,520	1.04	2.29E+07	1.07E+09	2.14E-02	2.05E-02
Tanker 2	Quang et al. (2021)	13,925	14,520	1.04	3.62E+07	1.77E+09	2.05E-02	1.96E-02
Cargo 1	Dong et al. (2019)	11,400	8830	0.77	4.37E+07	6.08E+08	7.19E-02	9.28E-02
Cargo 2		12,200	8830	0.72	4.39E+07	9.33E+08	4.70E-02	6.49E-02
Cargo 3		11,400	8830	0.77	4.37E+07	5.77E+08	7.58E-02	9.79E-02
Cargo 4		12,200	8830	0.72	4.39E+07	8.85E+08	4.96E-02	6.85E-02
Cargo 5	Quang et al. (2020)	11,400	8830	0.77	4.79E+07	9.60E+08	4.99E-02	6.44E-02

Park et al. (2020), the authors performed LCA analysis to evaluate the environmental benefits of a LNG partial re-liquefaction system applied to LNG carriers by comparing five different combination/configuration of LNG re-liquefaction systems (Table 7). Since the analysis is focused at the operations on-board of the vessel, materials and manufacturing of the vessel itself were neglected, as well as the vessel decommissioning. Results are expressed in terms of GWP, AP, POCP and PM2.5 by adopting CML-IA as LCIA method. In this case the functional unit was set as "*a system capable of re-liquefying* 4000 kg *of the BOG (Boil Off Gas) in an hour for 25 years*" for a comparison purpose. Primary data related to re-liquefying systems were estimated on the basis of data from manufacturers and coupled with background data retrieved from the Gabi database. The results revealed that the use phase is the most burdensome, accounting for around 98% for the GWP indicator (88% refers to the re-liquefaction process while 11% to the fuel production). It is worth noting that the manufacturing and scrapping phases are solely concerned with the re-liquefying system, ignoring the ship's other components. There is a disparity between the five systems studied, which reflects variances in fuel use during the operational phase. The outcomes of the LCA study (only GWP) are reported in Table S6 of Supplementary Material.

Two works (Andersson and Winnes, 2011; Jang et al., 2020) focused on the operational profile of maritime vessels using an exhaust gas cleaning system (commonly called scrubber system) installed on-board of the vessel to remove SOx and particulate matter (PM) emitted by conventional engines. The two papers examined the trade-off between the benefits received from the deployment of a scrubber system throughout the course of a ship's entire life cycle and the drawbacks produced by its fabrication and installation. In the work of Andersson and Winnes (2011), the LCA performances of the installation and usage of various scrubber systems on-board of a RoPax vessel (called Stena Britannica) was assessed. On the other hand, the research of Jang et al. (2020) focused on scrubber systems used by generic Ro-Ro vessels and offered a decision-making tool for the design of a scrubber system in the early stages of design (considering vessel size, engine power and service lifetime). The results of these works are expressed using the most common LCIA indicators (*i.e.*, GWP, EP, AP and HTP) following the CML-IA method. Despite the analysis was performed on the same system the results are significantly different: in the work of Andersson and Winnes (2011), an open loop scrubber system is preferred since less materials and components are required compared to a closed loop scrubber system. This result is in contrast with the outcome of Jang et al. (2020) study, where closed-loop scrubbers show better performance than open-loop scrubbers in terms of GWP and AP, whereas the opposite

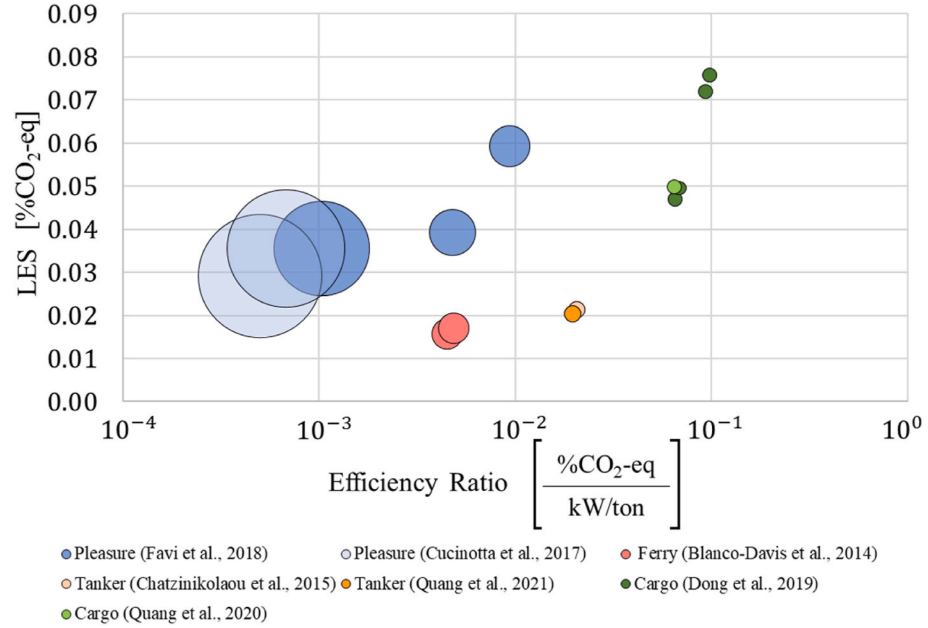

Fig. 5. Horizontal normalization and comparison among different vessel typologies for GHG-related impact categories.

trend is found for EP. However, two parameters result dominant on the holistic environmental impacts of SOx scrubber systems: the power and the year (age) of operation. As a common outcome, even if scrubber systems contributed to the AP reduction, they were shown to exacerbate other environmental impacts such as GWP and EP.

As a conclusion, for other types of vessels which have a peculiar operational profile and purpose, the focus of the LCA analysis was not the entire vessel, but rather the equipment and the emissions related to the activity that is taking place on-board. The usage phase is the most significant among the other phases in the LCA, which is carried out taking into consideration the whole life cycle of the ship or naval system under study *(i.e.,* equipment manufacturing, installation and decommissioning). Finding a functional unit to standardize the LCA analysis and enable comparisons between various works is challenging for these vessel categories.

3.2. *Horizontal normalization based on vessel features*

The following findings are the result of a normalization of LCA outcomes based on the primary vessel characteristics (i.e., weight and power). The horizontal normalization, carried out independently from the vessel categories, allows for comparison of LCA outcomes, offering an overview of distinct ship category clusters and an associated index for assessing their efficiency. Due to a scarcity of data reported in the referenced papers, only a subset of vessels was examined in this horizontal normalization. Vessels features of the considered works are reported in Table 8 and the horizontal normalization was performed using Eq. (9) previously defined. The comparison was done taking into account four vessel categories: (i) pleasure and sporting boats, (ii) ferries, (iii) tankers, and (iv) cargo. For other vessel's categories, data for the horizontal normalization were not available.

In the case of pleasure and sporting boats, the paper published by Favi et al. (2018a) assessed three motor yacht, whose Power/LWT ratio ranges from 6.33 to and 34.42 kW/ton, while Cucinotta et al. (2017), employed two different manufacturing processes for the construction of the same hull, leading to different lightship weights (28–31 ton). Considering that the yacht's installed engines were of equal power, the Power/LWT ratios are 58.26 kW/ton for the yacht manufactured with infusion process, and 52.42 kW/ton for the yacht manufactured with hand lay-up process. The research published by Blanco-Davis et al. (2014) deals with two ferry configurations: (i) one that serves as a benchmark, and (ii) one that has a fouling release coating applied, with an identical Power/LWT ratio of 3.52 kW/ton. In the case of tankers, Chatzinikolaou et al. (2015) and Quang et al. (2021) took into account the same vessel with a power/weight ratio of 1.04 kW/ton. Due to the fact that the same type of vessel was analysed with small differences in terms of GWP, the horizontal normalization shows very similar results. Two publications fell into the cargo vessel category. The work of Dong et al. (2019) takes into account four configurations of two vessels with identical engine power, one of which was also considered in the work of Quang et al. (2020). In the case of cargo vessels, the power/weight ratio is ranging from 0.72 to 0.77 kW/ton.

An overview of the results obtained for the horizontal normalization is presented in Fig. 5. The size of the bubbles represents the vessel design efficiency (power/weight ratio) and it is calculated as the ratio between the main engine power [kW] over the lightship weight [ton]. The larger the bubble, the higher the ratio, indicating that the engines are over-designed to increase navigation speed. In Fig. 5, the Y-axis represents the Lifecycle Emission Share (LES), and the X-axis shows the Efficiency Ratio. The LES is calculated dividing the "Impacts of shipbuilding operations and construction materials" by the "Impacts of operational phase". This index indicates the share of environmental impacts generated during shipbuilding activities in comparison to the navigation/use phase, which is typically the most critical phase in terms of GHG emissions. The meaning of the LES reflects the efficiency of the vessel during the operational phase in terms of emissions, therefore, the increase of the LES is achieved by reducing the emissions during the operational phase, keeping the emissions during the shipbuilding operations constant. The higher LES, the lower the relevance of the operational phase in terms of environmental burden. The Efficiency Ratio, which expresses the normalization of the lifecycle emissions in relation to the vessel features, is derived by dividing the LES by the power/weight ratio. The bigger this index, the most efficient is the vessel (low power/weight ratio and low impacts related to the operational phase) meaning that the engineering design of the vessel was properly done.

Based on the aforementioned parameters, it is possible to clearly identify four areas of the graph that characterize each analysed vessel category (Fig. 5). The pleasure boats are located in the central-left area of the graph. They are characterized by a high power/weight ratio (big size of the bubbles) due to the fact that the engines are usually oversized in relation to the lightship weight. Indeed, the choice of installed power for this type of vessel is not based on the engineering optimization but rather on producing high performance vessels. Although their specific emissions are significant (due to oversized engines), their modest utilization counterbalance their poor environmental performances, narrowing the potential gap between their LES and that of more efficient vessels. For this type of vessel, the Efficiency Ratio ranges from 10^{-4} to 10^{-2} indicating unequivocally that it is the most critical category in terms of environmental impacts. Cargo vessels, on the other hand, are positioned in the upper-right corner of the graph due to their low power/weight ratio (small size of the bubbles), high LES, and high Efficiency Ratio. Commonly, their engines are sized to minimize fuel consumption throughout the operational period (for cost minimization), but the environmental impacts related to the use phase is significantly more relevant than the shipbuilding ones, owing to long navigation periods. Cargo vessels have one of the highest Efficiency Ratios among all vessel categories, with a magnitude of 10^{-1} ranking them among the most efficient in terms of environmental performance. Similar behaviour is noticed for the tankers, with a comparable value of the power/weight ratio (small size of the bubbles) but a lower value of the LES. In this case, they are mostly positioned in the central part of the graph, leading this vessel category close to the cargos for what concern the environmental performance (e.g., the Efficiency Ratio is between 10^{-2} and 10^{-1}). Ferries are characterized by a quite relevant power/weight ratio (the size of the bubbles is between the tankers and the pleasure boats) while the LES is the lowest among the vessel categories. This is likely caused by the use-phase emissions, which are more significant because of the large number of manoeuvring operations at the port and the higher speed required during navigation. Due to these factors, the environmental consequences associated with shipbuilding activities are less significant than those associated with the operation phase, placing this vessel category within the central-bottom portion of the graph. For this vessel category, the Efficiency Ratio is between 10^{-3} and 10^{-2}, making ferries one of the most impactful categories after pleasure boats.

3.3. *Publications on vessel-related activities*

Several activities are associated with maritime vessels and they were analysed independently from the vessel categories. Based on the review of the literature, a possible classification of these activities is proposed: (i) shipyard manufacturing and maintenance activity, (ii) port activity, and (iii) ship breaking activity.

Concerning the shipyard manufacturing activity, two works of Favi et al. (2019b, 2019a), described an ISO-compliant procedure to perform a LCA analysis of complex welded structures (*i.e.*, the ship hull) by using engineering design documentation, reducing the uncertainty related to primary data. The functional unit was defined as "*the manufacturing, use, and disposal of a welded structure able to guarantee the engineering requirements (according to a specific standard) in terms of strain, stress, and corrosion allowance over the expected lifetime of T-years*". The functional unit refers to a specific lifetime, and T represents the lifespan of the product specified at the beginning of the project. Primary data was collected from engineering design documentation (*i.e.*, CAD model, welding procedure specifications, etc.), while secondary data was retrieved within ecoinvent database. ReCiPe impact assessment method (both midpoint and endpoint impact categories) was coupled with the CED method for the LCIA. The data collecting and management for large and complex welded structures were the two works' main objectives. The first one was mainly focused on the analysis of products/structures manufactured with metal arc welding technology (Favi et al., 2019a), while the second one provided also a tool for the welding technologies comparison (Favi et al., 2019b). The comparison of welding technologies shows how there is not an optimal solution for the development of welded structures, such as ship hulls. Indeed, the GMAW (Gas Metal Arc Welding) process exhibits the least environmental burden for most of the environmental indicators compared with other processes, but it performs quite badly in terms of human toxicity, which is directly connected with fume emissions. The LCA comparison of welding processes allowed the authors to define several design actions aiming at reducing the environmental impacts related to the manufacturing of welded structures, among which a possible measure to control the impact of filler material is the adoption of a different bevel geometry (*i.e.*, narrow bevels) that minimizes the amount of filler material. According to an analysis of the structures manufactured with metal arc welding technology, carbon steel seems to be the most suitable material for the construction of ship hulls, being aluminium more impactful for most of the environmental indicators, except for ODP, Metal Depletion (MD), Ionizing Radiation (IR), and HTP. From the environmental perspective, the authors claimed that the adoption of carbon steel is a preferable solution if the analysis is limited to the shipbuilding activities.

Despite the fact that port operations are an integral part of a vessel's operating activities, they are rarely included within the life cycle of vessels. For this reason, port activities are commonly analysed using a different functional unit, which is not strictly related to the vessel itself. In terms of port activities, the work of Zuin et al. (2009) analysed the ship waste streams in a specific location (the Port of Koper, Slovenia), attempting to quantify the impacts of cargo vessel-generated waste in order to identify the critical procedures. The functional unit was defined as *"the average annual amount of cargo-generated waste collected and managed in Luka Koper in 2007 (i.e., 2200 tonnes/year of cargo)"*. Both primary data collected directly from the port and secondary data retrieved by the ecoinvent database were used in the analysis. EI99 impact assessment method was used as LCIA method, including both midpoint and endpoint indicators. To increase the awareness of decision-makers, environmental concerns resulting from ship waste management and disposal beyond the port region (e.g., landfill, incinerator, etc.) were also assessed. The waste streams analysed in this work included mixed solid waste, biodegradable waste (*i.e.*, kitchen waste), wastewater (*i.e.,* oily bilge waters), and other residues. Based on LCA outcomes, sea ports produce large amounts of oily and solid waste, as well as chemical hazardous residues, that require a sustainable disposal practice. To promote a more sustainable management of port waste, the legislative framework created in this context specifies the minimal standards for waste disposal. There is a need to stimulate more measures focused at increasing the reduction, recycling, and reuse of ship-generated waste. Indeed, the assessment results showed that producing secondary fuels during the waste treatment phase provides for a partial reduction in impacts by limiting the depletion of fossil resources, such as natural gas and coal, as well as air emissions. The analysis also showed that the final treatment of ship garbage, specifically landfill disposal, was responsible for the majority of all environmental problems. Another work related to the port activity was performed by Dvarioniene et al. (2013) with a specific focus at the oil waste management from ship engine bilge entering in the Klaipeda Sea Port, Lithuania. A life cycle assessment was performed to evaluate the environmental impacts caused by the ship-generated waste management, focusing on oily waters. The functional unit was defined as *"ship-generated waste, focusing on oily waters, of the port of Klaipeda in 2007 and 2008"*. Oil water management for all stages of the life cycle was equalized to CO_2 gas effect expressed as $kgCO_2$-eq, according to IPCC indicator. The analysis estimated that oil waste constitutes the majority of the whole collected waste amount. The prospect of using engine bilge water as a source of thermal energy by combustion is a viable method for reducing greenhouse gas emissions connected to engine bilge water. A suitable improvement towards this direction is represented by the usage of the generated thermal energy to cover the engine bilge water treatment process, reducing the carbon footprint by 60%.

Shipbreaking (or dismantling) is a crucial process that enables the replacement of out-of-date ships and the recycling or reuse of up to 95% of their materials, modernizing global shipping commerce. Ocean-going ships are usually sent for dismantling after serving the global shipping fleet for 20–30 years. Bangladesh is dominating global shipbreaking processing with more than 2,300,000 LWT processed in 2009 (Sujauddin et al., 2015). Several works have been published in relation to the shipbreaking segment, utilizing an LCA approach to address the environmental issues associated with the shipbreaking activities (Choi et al., 2016; Ko and Gantner, 2016; Önal et al., 2020; Rahman et al., 2016). Choi et al. (2016) analysed the ship disposal management options with economic cost-benefit features and life cycle thinking approach, while Rahman et al. (2016) proposed an LCA analysis to compare rebar production in Bangladesh using secondary steel scraps recovered from ship recycling, reaching equivalent conclusions. Focusing on the work of Choi et al. (2016), current scenarios for end-of-life ship management were addressed both in terms of economic feasibility and environmental impacts. Although recycling is the most frequent technique of end-of-life ship management, other options were studied, including (i) dry-dock ship breaking, (ii) beaching, and (iii) reefing. The functional unit was defined as *"the lightship weight (LWT) of the recycled ship"* considered for each disposal scenario. Primary data were collected directly from the ship breaking yards and recycling facilities when available, while secondary data were retrieved within the ecoinvent database. To assist the economic evaluation from a sustainability standpoint, a cost-benefit analysis was integrated into the life cycle study. Even though ship recycling appears to be the most ecologically beneficial choice according to the TRACI midpoint impact assessment method, it only delivers a marginal economic gain. Standard ship breaking techniques prevent the release of harmful contaminants into the environment while also reducing the demand for numerous virgin materials. However, when compared to recovered materials from dry-dock ship breaking process, recovered materials from beaching did not show significantly greater environmental impacts. This is primarily due to a lack of data and great uncertainty in estimating the environmental impact of ship recycling using beaching methods. Limited information prevented a numerical study of the reefing alternative, and only a review of the literature was conducted to address the key environmental problems of this process. The environmental implications of rebar manufacturing from recovered metal, produced from ship recycled iron scraps, were investigated in the work of Rahman et al. (2016). The functional unit was defined as "*one ton of rebar produced at a manufacturing facility*". Primary data were gathered through direct interviews with local workers and managers at ship breaking sites, while secondary data were retrieved from the ecoinvent database. IPCC 2013 100a and IMPACT 2002 were employed as LCIA methods to include both midpoints and endpoints perspectives. According to the LCA results, the environmental benefits (up to one order of magnitude per indicator) are evident when compared to manufacturing processes utilizing raw materials, even though the recycling of steel from ship waste is still hazardous and harmful from a social perspective. In summary, the most critical phase of the ship recycling process involves rerolling, followed by in-yard processing and ship cutting. The authors claimed that using rebar made from ship recycling scraps saved 16,492 MJ worth of resources and avoided 1965 $kgCO_2$-eq emissions per ton of final product.

In their publication, Ko and Gantner (2016) used LCA for the quantification of the environmental impacts of a vessel, coupling this result with economic benefit of each phase of the vessel life cycle. The goal of this study was to determine the added value of ship operations (*i.e.*, shipbuilding, operations, and shipbreaking) in various geographical areas. The authors underlined that ship owners benefit the most during the vessel use phase, whereas environmental burdens per unit of added value are significantly higher for Asian ship builders and wreckers. The analysis was conducted using the functional unit of "*one ship with a light displacement tonnage (LDT) of 4108.4 over the lifetime of 25 years*". GaBi software was used for both computational analysis and background data. Two impact categories were chosen to display the environmental results, *i.e.*, CC base on ReCiPe and HTP-non cancer based on USEtox method. Unfortunately, the LCA results were not reported within the paper, but only aggregated results.

Following their first publication dealing with yachts, the second work of Önal et al. (2020) focused on the end of life of steel hull boats, using a functional unit of "*a ship of its kind built in the Tuzla Shipyards Zone, Istanbul, Turkey, and recycled in the Aliağa Ship Recycling Zone, İzmir, Turkey during 2008–2018*". SimaPro was used for the computational analysis and CML-IA method was adopted for LCIA. The shipbuilding phase for the steel hull gained higher environmental impacts when compared to material recycling processes. It is worth noticing that the system boundaries of the ship recycling process do not include the benefits related to the recycled material. Moreover, boats with complex shapes (fishing boats, yachts and sailboats) generates a higher environmental impact than ships with more regular shapes such as barge, tanker, bulk carrier, passenger and service boats. Thus, designing an easy-to-dismantle ship in terms of energy (for all the shipbreaking activities) and materials results in eco-friendly shipbuilding and ship recycling. In conclusion, shipbreaking is a crucial stage in the life cycle of a vessel and must be taken into account for a cradle-to-grave approach. Even if the impacts related to this phase are not negligible, shipbreaking activities are critical to manage due to the long lifespan of a vessel and the uncertainty related to the vessel's end-of-life.

4. Conclusion

In this review, the scientific literature concerning LCA studies applied to the naval sector has been investigated using two perspectives: in the first section, a bibliometric analysis and the main trends of the research were analysed (Mio et al., 2022), while in the second section, a quantitative analysis and normalization of the LCA outcomes were undertaken.

The second part of this review focused on the quantitative analysis of the outcomes of the scientific literature dealing with LCA studies applied to the naval sector. Before delving into the descriptions of the assessments, the introduction of the normalization stage outlined in the ISO standard has been carried out, and a list of suggestions for naval practitioners has been compiled. The first recommendation prescribed to disaggregate the overall life cycle impacts of the vessel into the impacts specific for each life cycle phase (i.e., shipbuilding, operation, maintenance and disposal). A peculiar normalization basis has been suggested for each life cycle phase, aiming at producing consistent results among different studies, allowing future comparisons. Shipbuilding, manufacturing and disposal impacts should be normalized on lightship weight and lifetime of the vessel, allowing for comparisons focused on construction materials and good manufacturing practices rather than ship size. The results presented hereafter provide a comparison of LCA analysis.

Operational phase impacts (as well as overall life cycle ones) may be normalized using a vertical or a horizontal approach. The former is based on the function provided by each specific vessel group and allows to identify the emerging trend and some benchmark values for practitioners dealing with peculiar vessel categories. The latter provide the Efficiency Ratio, which enables a comparison between the operational activities of vessels belonging to any vessel category. This enables the adoption of engineering eco-design actions to promote cleaner ship development and use.

The 47 articles, selected using the procedure reported in the first part of this review (Mio et al., 2022), have been classified according to vessel types (using CPC codes), reporting a description of the assessments and the results of GHG-related impact categories, which have been subjected to the proposed normalization procedures.

It is possible to establish some benchmark values for each stage of the vessels lifecycle in relation to the vessel category by looking at the results of the vertical normalization. Indeed, without normalization, the identification of average scores for each lifecycle phase is quite challenging, as the outcomes are hardly comparable due to different functional units, system boundaries and allocation models. Taking into account the outcomes from the publications dealing with hulls or entire vessels, the shipbuilding GHG-related impacts can be compared in terms of shipbuilding materials (*i.e.,* steel, aluminium, wood and composite material), as shown in Fig. 6. It appears clear how steel-made vessels gained better average performance in comparison with vessels built using other materials. The assessments dealing with large ships (cruise, tanker, and cargo) are driving this general trend, as there is a benefit associated to economies of scale, the use of diverse materials is impractical and more assumptions must be made during the life cycle inventory gathering process, which may lead to an underestimation of the emissions. When steel is used for smaller vessels (*e.g.,* pleasure boats), the shipbuilding specific impact increases. The assessment of various shipbuilding materials within the same study was limited to smaller vessels, typically pleasure boats or small ferries. As expected, wooden boats generate the lowest GHG-emissions. They are usually followed by composite materials, depending on the materials used in their production and the shipbuilding technique (hand lay-up or vacuum infusion) adopted. Additional research is still needed to fully understand which manufacturing practice performed better, although vacuum infusion appears to be the most promising. When compared to other materials, aluminium performed the worst, making it the most burdensome material for shipbuilding. This is primarily owing to the

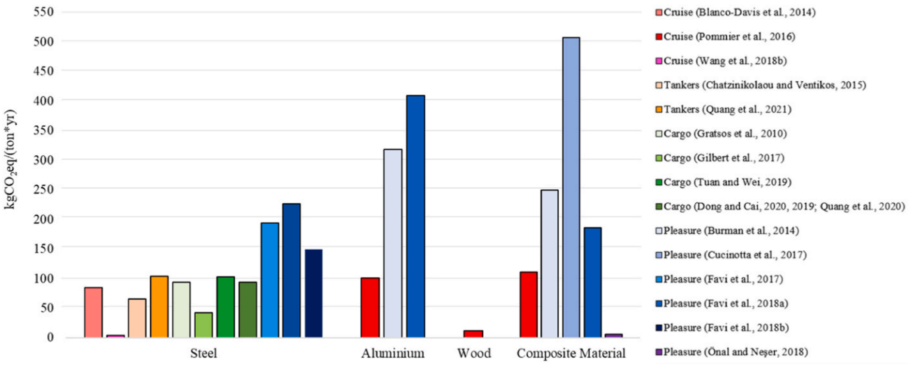

Fig. 6. GHG-related normalized scores for several vessels' construction materials.

Table 9

GHG-related emission ranges for the publications within each vessel category.

Vessel type	CPC code	Operational phase GHG-related score (Vertical normalization)	Unit	Efficiency Ratio (Horizontal normalization)	Unit
Cruise and ferry boats	49311	$10^{-2} - 10^{-1}$	$\frac{kgCO_2eq}{pass*km}$	$10^{-3} - 10^{-2}$	$\frac{\% \ kgCO_2eq}{\frac{kW}{ton}}$
Tankers	49312	$10^{-3} - 10^{-2}$	$\frac{kgCO_2eq}{ton*km}$	$10^{-2} - 10^{-1}$	
Cargo vessels	49314	$10^{-3} - 10^{-2}$	$\frac{kgCO_2eq}{ton*km}$	10^{-1}	
Pleasure and sporting boats	494	$10^{2} - 10^{3}$	$\frac{kgCO_2eq}{pass*hr}$	$10^{-4} - 10^{-2}$	

carbon footprint of raw aluminium, which requires a significant amount of energy for extraction and purification. In this regard, the use of secondary aluminium would have significantly reduced the vessel's environmental impact, as documented in another publication (Mio et al., 2021).

The benchmark values for the vertical normalization and the horizontal normalization of GHG-related impact categories are both presented in Table 9. Using vertical normalization, the operating phase impacts are not comparable across vessel classifications since they must be tailored to the purpose of each vessel. It is clear that a benchmark can be set for each vessel type when the user is considering the operational phase. For instance, a magnitude of 10^{-2}-10^{-1} $\frac{kgCO_2eq}{pass*km}$ is observed for cruise and ferry boats. On the other hand, a magnitude of 10^{-3}-10^{-2} $\frac{kgCO_2eq}{ton*km}$ is observed for tankers and cargo vessels, while a magnitude of 10^{2}-10^{3} $\frac{kgCO_2eq}{pass*hr}$ is observed for pleasure and sporting boats. These benchmark values can be adopted to investigate novel technologies and alternative fuels that allow reducing the environmental load of vessels based on their purpose.

The index developed for the horizontal normalization (Efficiency Ratio), clearly rates the cargo vessels as the most efficient ships in terms of environmental load for the operational phase providing a benchmark of 10^{-1} $\frac{\% \ kgCO_2eq}{\frac{kW}{ton}}$ which can serve as a reference to develop other type of vessels with significant improvements towards a higher environmental sustainability. The construction of recreational and sports boats demonstrates the necessity for greater care in their conception and design. In particular, the use of very powerful engines in comparison to the weight of the vessel leads to higher inefficiency during navigation, which, from a life cycle perspective, greatly increases the incidence of the operational phase.

To sum up, despite previous attempts, the scientific literature still lacks a normalization method for measuring the environmental performance of shipbuilding activities that covers all manufacturing and maintenance procedures aside from welding. In general, the environmental impacts related to raw materials used for hull and machinery constructions have been included within LCA studies, along with the related manufacturing processes (*i.e.*, cutting, bending, welding). This approach left the maintenance practices, which are quite relevant in shipyards activities, still affected by a higher degree of uncertainty. The maritime sector's vessel disposal processes are still fairly unknown or uncertain. The life cycle assessments utilizing a cradle-to-grave perspective lack homogeneity in allocation models, preventing a meaningful comparison of the outcomes.

This critical analysis contributes to the body of literature by collecting representative LCA publications in the naval industry for various vessel categories. This review identifies which naval vessels have been considered in previous LCA studies, reports the development and the assumptions of each work, collects the outcomes for GHG-related impacts, and offers some recommendations for future life cycle assessments in terms of functional unit selection, system boundaries, LCA approach, and results normalization and presentation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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