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Existing technologies and scientific advancements to decarbonize shipping by retrofitting

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ABSTRACT

The maritime industry is transporting about 90 % of world commerce, contributing to the global greenhouse gas emissions that cause climate change. Increasing pressure on the sector to reduce its carbon footprint requires developing specialized energy-efficient technologies and studying their compatibility with modern safety and sustainability expectations of the waterborne sector. This research supports the United Nations sustainable development goals SDG 7 (Affordable and clean energy) and 13 (Climate Action), and reviews available technologies for shipping decarbonization through design for retrofitting. Promising research areas to improve the energy efficiency of ships could focus on design concepts and methodologies, fluid dynamics, and artificial intelligence. The study suggests that while individual promising decarbonization technologies are available, a comprehensive and coordinated approach is necessary to decarbonize global shipping efficiently. The study identified three promising paths of ship retrofitting to meet the International Maritime Organization decarbonizing objective 2050, aiming at a 70 % reduction of annual greenhouse gas emissions compared to 2008. The first path – using green energy sources (e.g., ammonia, battery, and methanol) – requires scaling up technologies and developing a regulatory framework and control of the lifecycle of the fuel production process. The second path – using ship-based carbon capture technologies, ship design (e.g., hull retrofitting, air lubrication, and wind-assisted propulsion), and operation solutions (e.g., weather routing and logistics planning) – requires building more CO_2 storage and control of the lifecycle of liquified CO_2. The third path – using biodiesel as a fuel in combination with ship design and operation solutions – requires extending feedstock for biodiesel production.

Abbreviations			
		SBCC	Ship-based carbon capture
GHG	Greenhouse gas	ALS	Air lubrication systems
IMO	International Maritime Organization	CFD	Computational fluid dynamics
LNG	Liquefied natural gas	BDR	Bubble drag reduction
EEDI	Energy efficiency design index	ALDR	Air layer drag reduction
MDO	Marine diesel oil	PCDR	Partial cavity drag reduction
WASP	Wind-assisted ship propulsion	AI	Artificial intelligence

1. Introduction

According to Fig. 1, based on data from the National Oceanic and Atmospheric Administration [1], the climate temperature has increased to more than 1° above pre-industrial levels in recent years. This raised significant concerns in the international community. About two hundred countries signed the Paris Agreement to reduce future greenhouse gas (GHG) emissions to keep the global average temperature below 2 °C

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above pre-industrial levels. Transport of goods and people accounts for up to 25 % of total world energy consumption [2], making it one of the largest sources of CO_2 emissions, about 3 % of which belongs to maritime transport [3]. Although shipping is considered the most energy-efficient mode of transportation, the amount of cargo transported by sea and corresponding emissions are constantly growing. The International Maritime Organization (IMO) reports [4] a 9.6 % increase in GHG emissions from ships from 2012 to 2018. Furthermore, the future CO_2 emissions from ships in 2050 are expected to reach up to 130 % of their value in 2008 without preventive actions.

In recent years, the IMO has put significant efforts into developing regulations that may prevent air pollution from ships. The most important of these measures are presented in Fig. 2. The early actions (Tier I-III [5,6]) were adopted within the context of the MARPOL Annex VI regulatory framework. They aimed to enable the greening of ship designs by introducing specific limits for NOx, SOx, and particulate matter emissions from ships of 400 gross tonnage or larger. Reducing these emissions became a priority because of their direct harmful impact on the health of humans and animals, soil, and broader ecosystems, particularly in specialized sensitive emission control areas. Tier I-III regulations significantly contributed to the development and spreading of the use of eco-efficient technologies on ships. Exhaust treatment using SOx scrubbers, selective catalytic reduction, and switching to distillate fuel are proven to be the most efficient and commercially viable for retrofitting and newbuilt Tier I-III compliant ships [7]. The introduction of these new regulations significantly advanced the application of liquefied natural gas (LNG) as fuel and hence resulted in an increased number of LNG-fuelled and dual-fuelled ships. Implementation of Tier I-III regulations resulted in a drastic decrease in NOx and SOx emissions in emission control areas, e.g., 88 % less ship-originated SOx emissions in the Baltic Sea [5].

The success of Tier I-III regulations motivated IMO to take further action and prevent air pollution from ships by reducing CO_2 emissions, which can be seen in Fig. 2. The first step was adopting the energy efficiency design index (EEDI [8]) for newbuild ships. At its outset, this design index aimed to decarbonize ships at the design stage. Today, the EEDI regulation provides specific guidelines on how to estimate in a simplified manner the future CO_2 emission from a specific ship per unit of transported cargo. The estimated value must be less than the defined reference value, considering the size and type of a ship.

Moreover, the regulations are tightened in time, with new EEDI phases taking effect, like EEDI 1–3 and EEDI phase 3 in Fig. 2. These phases require new ships to have 10 %, 20 %, and 30 % less emissions than reference values. EEDI regulations are not prescriptive, i.e., the designer can decide which design measures to apply to reduce CO_2 emissions. Notwithstanding this, the EEDI raised some criticism regarding its practical relevance, especially considering that regulations are based on limiting the installed engine power, which may not generally be equal to minimizing CO_2 emissions [9].

In some cases, limiting the installed power may jeopardize the safety of some ships designed with a significant power margin to operate safely in rare but dangerous conditions, e.g., storms or complex ice [7,10]. It is noted that the power margin does not usually increase CO_2 emissions because such ships operate on a partial load most of the time [11]. As a result, the need to amend EEDI to account for realistic operation conditions during vessel lifecycle has been researched and is highlighted in key papers [12,13]. The topic is even more relevant, especially considering that the present EEDI formulation and measurements from sea trials underestimate the effects of technologies used to reduce carbon emissions and their influence on logistics [14]. An operational energy efficiency existing ship index [15] – similar to EEDI but calculated for existing ships – was introduced in 2021 to motivate shipowners for retrofitting.

The early mandatory operational measures of IMO to reduce CO_2 emissions include the energy efficiency operational indicator [16] and the ship energy efficiency management plan [17] –an index to calculate the operational energy efficiency of a ship and a ship-specific plan for her improvement. A significant further action from the IMO was to adopt the mandatory data collection system [18]. This requires ships of 5000 GT and above to record and report their actual fuel consumption. The information from the data collection system of all relevant ships is combined into the IMO ship fuel consumption database, thus providing important material to develop future efficient means for decarbonization by, e.g., using data-driven analysis. An improved and mandatory version of the energy efficiency operational indicator, namely the carbon intensity indicator [15], is calculated based on the information from the data collection systems. Although the operational IMO measures for decarbonizing shipping are comprehensive, there is some lack of consistency relative to corresponding design measures. In other words, when the adopted formulations and equations are considered, ships optimized for decarbonizing according to IMO design requirements and ships optimized for IMO operational requirements are different.

To support the intentions of the Paris Agreement and the United Nations sustainable development goals SDG 7 (Affordable and clean energy) and SDG 13 (Climate Action), in 2018, IMO adopted the initial IMO strategy for the reduction of GHG emissions ([19–22]) (Fig. 2, Strategy GHG and revised Strategy GHG 2) – a policy framework documenting the decarbonization objectives for the shipping industry. Objective 1 of this strategy suggests a 40 % reduction of CO_2 emissions and a 20 % reduction of annual GHG emissions per transport work by

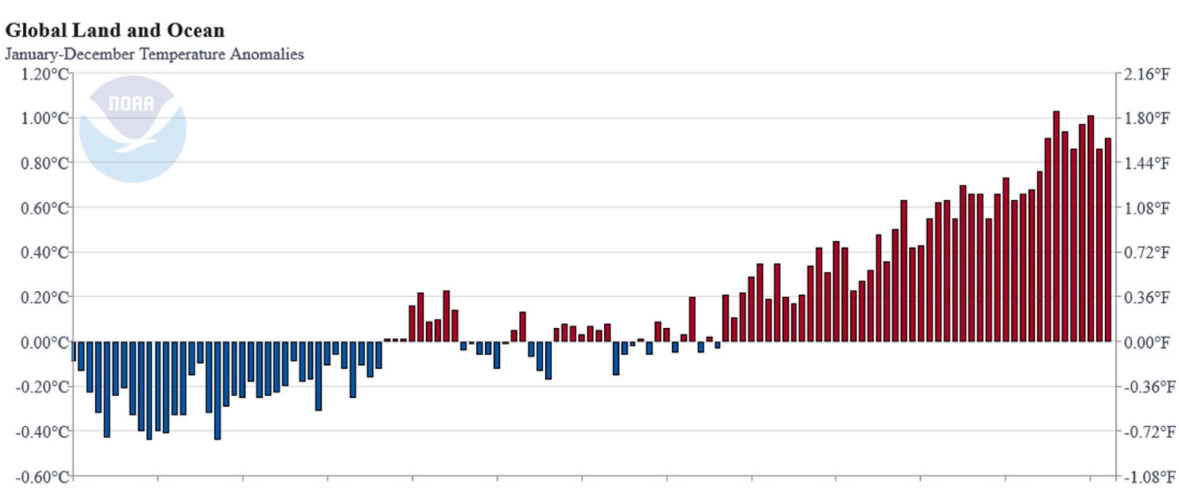

Fig. 1. January–December Temperature Anomalies compared to the pre-industrial long-term average [1].

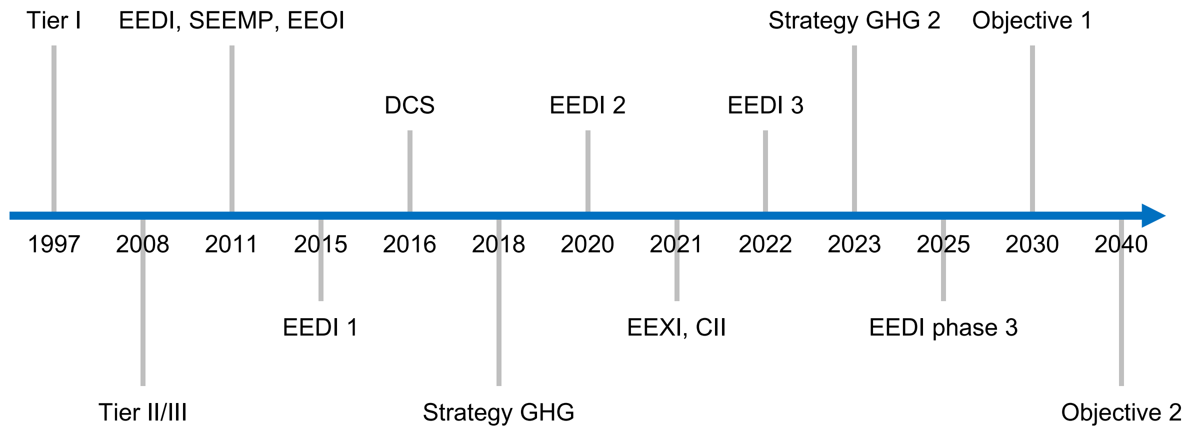

Fig. 2. Important IMO regulations to prevent air pollution from ships

2030 compared to 2008. Objective 2 recommends a 70 % reduction of annual GHG emissions per transport work by 2040 compared to 2008.

The IMO decarbonizing strategy is ambitious and needs immediate actions to meet the objectives. A straightforward solution – a requirement of zero emissions for all newbuilt ships and a complete replacing the existing fleet – is complicated for two practical reasons: (i) the necessary technologies and related infrastructure are not mature enough for a full-scale commercial rollout, and (ii) existing fleet and ships under construction may not be scrapped at once without a global economic and social collapse. The most realistic policy is to promote the rapid development and testing of zero-emission and energy-efficient technologies for newly built ships and to retrofit the existing fleet. According to Ref. [23], half of the existing ships must be retrofitted by 2050 to meet the IMO decarbonizing strategy goals, comprising about 29000 vessels of 300 GT or above as of January 2022 [24]. Such significant retrofitting efforts require tight collaboration between science, the shipping industry, and the government to be successful.

An example of promising collaboration for decarbonizing shipping is the aims of the GettingToZero coalition [25] initiative supported by approximately two hundred private and state-owned companies managed by the Global Maritime Forum. Driven by the need to adapt to the rapidly changing regulations and their potential consequences, e.g., the risk of owning unprofitable ships in the future or eventually being pulled out of the market, the coalition aims to lead a new technological revolution in shipping to prevent climate change. The activity of the coalition includes supporting commercially viable zero-emission shipping by developing, testing, and scaling up the new green technologies for different types of ships and operating conditions. The changing business environment provides an opportunity for redistribution of the market [26], thus making the activity of the coalition highly beneficial and future-proof. Active involvement of the industrial stakeholders at the early stages of the development of new decarbonizing technologies gives them significant reputational benefits, which may allow them to influence the content of future policies and regulations. An example of such collaboration towards retrofitting is the RETROFIT55 Horizons Europe consortium which involves fourteen partners from seven EU member states, Australia and the United Kingdom [27]. Direct participation of experienced technical experts from research and practice in developing the regulations benefits the entire society, resulting in high-quality regulations and their predictability for the industry, and helps avoid unnecessary drawbacks [9,28].

The meticulous selection of a specific technology to reduce air pollution for a ship is of outmost importance, as investing in suboptimal technology may result in significant economic and environmental loss. The existing experience of addressing Tier I-III regulations by the shipping industry provides many valuable lessons that may help manage future decarbonization transitions and targets. After the adoption of the Tier I-III regulations, LNG was widely advertised by scientists and politicians as the most advanced and green fuel of the future [29], while exhaust treatment (e.g., using scrubbers) was deemed a secondary opportunistic measure for retrofitting old ships [29]. However, exhaust treatment was later practically proven the most efficient and commercially viable solution to comply with the Tier I-III regulations [30]. A potential advantage of LNG over exhaust treatment is to reduce CO_2 emissions by 25–30 % compared to oil-based fuels, which are not considered by Tier I-III regulations. Moreover, the ability of LNG fuel to reduce GHG emissions is widely questioned due to the risk of methane slip, which in some cases can nullify the corresponding limited benefits [31]. It is noted that using dual-fuel engines has proven practically successful in addressing Tier I-III regulations [32].

A feature of addressing Tier I-III regulations by the shipping industry has been the utilization of reactive measures that ignore incoming CO_2 emissions regulations, although the issue of climate change has been known since 1908 [33]. This practice resulted in retrofitting and re-retrofitting five-fifteen-year-old ships designed for Tier I-III regulations. Such a lack of forecasting capabilities comes with a high cost for the industry and society, as retrofitting a ship is expensive and triggers additional GHG emissions. Therefore, proactive consideration of potential changes in ship design and operation regulations during the lifecycle of an asset is of utmost importance for planning decarbonization options.

Based on this overview, it is recommended to consider the lifecycle dynamics of GHG emissions [34], respective costs, and changes in regulations when selecting the right decarbonization option for a ship [35]. Furthermore, GHG emissions and costs must be studied from end-to-end to account for energy source specifics, ship design qualities, operational practices, and available infrastructure [36] for the production, distribution, storage, and bunkering of zero-emission fuels. Significant prospects are related to the promotion of adaptable and flexible ship designs. Such designs should utilize multi-fuel options and modular retrofitting [37]. Considering that shipping should align with the highest standards of eco-efficiency, safety, and commercial viability, it is favorable to develop, test, and scale up novel zero-emission and energy efficiency technologies [38,39] that does not require artificial underpowering of ships or introducing emission trading schemes. This study overviews such innovative and advanced technologies applicable to the retrofitting of ships.

There are many studies on the applications of specific decarbonizing technologies for newly built ships, but the literature on applications for ship retrofitting is limited. The existing state of the art provides a fragmented picture, overlooking systemic and temporal aspects. In contrast, this study provides a holistic analysis of existing scientific and professional literature on design, operation, and fundamental elements of technologies applicable to shipping decarbonization by retrofitting, albeit considering lifecycle aspects.

The literature review includes existing limited studies on applications of decarbonization technologies for retrofitting and relevant studies on other technologies that can be potentially applied to retrofitting. The studies are selected from different disciplines and sources to provide a diverse and interdisciplinary perspective. This allowed us to identify three promising paths to meet the decarbonizing objectives of the IMO. The recommendations can be helpful for academics, ship designers, policymakers, and decision-makers in maritime business. We also emphasized another issue, typically overlooked in the existing literature namely the importance of considering the decarbonizing uncertainty alongside maximum decarbonizing efficiency, usually estimated under idealized conditions.

Fig. 3 shows the map of the most frequent terms used in the titles and abstracts of the reviewed literature. Analysis of connections revealed that the terms may be divided into two main clusters. The first cluster includes general-level terms, e.g., emission, impact, and climate change, which are typical for practical and policy-related articles. The second cluster includes technical terms, e.g., model, approach, and performance, which are typical of specialized engineering articles. Insights from both practical and technical domains provide valuable information for a comprehensive overview.

This study contributes to the improvement of the energy efficiency and decarbonization of maritime transportation, supporting the United Nations sustainable development goals SDG 7 (Affordable and clean energy) and SDG 13 (Climate Action). The remainder of the study is organized as follows. Section 1 outlines available technologies (including alternative energy technologies) that may be used to decarbonize ships by retrofitting. Specific ship design solutions are summarized in Section 2, and operational practices in Section 3. Section 4 outlines emerging directions of theoretical research that have the potential to contribute to decarbonization objectives. Conclusions are given in Section 5.

2. Retrofitting a ship for alternative energy sources

One of the most straightforward ways to decarbonize an existing ship is by retrofitting green energy sources [40]. Following the review of published literature, Table 1 summarises alternative energy sources according to their relative volumetric energy density, the cost of retrofitting, the potential for GHG emissions reduction, energy source allocation benefits (primary or secondary), ship types, and public perception. The volumetric energy density and cost of retrofitting are provided as a % of marine diesel oil (MDO) volumetric density and the market value of a non-retrofitted ship, respectively.

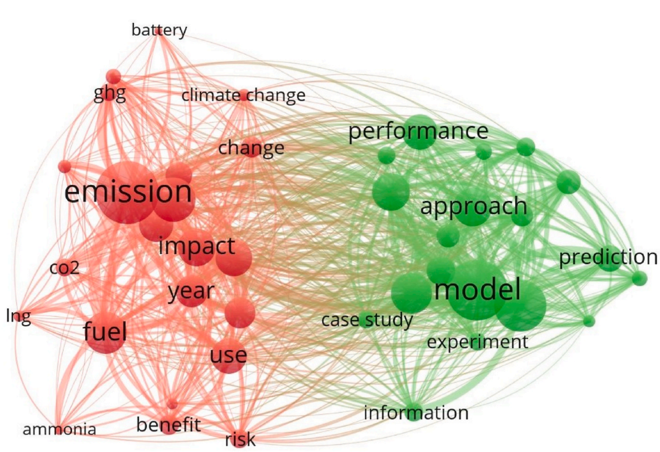

Fig. 3. A map of the most frequent terms used in the titles and abstracts of the reviewed literature. The red word cloud is related to practical and policy-related articles, and the green cloud is related to technical articles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

According to Table 1, retrofitting for nuclear power is challenging, considering the negative public attitude, the high initial investments, and the reduced lifecycle of existing ships. However, the economic advantages of nuclear power pay off in time ([41,42]). Fig. 4 illustrates the ranges for retrofitting costs and corresponding potential GHG reduction for other energy sources. The popularity of LNG as climate-friendly fuel has significantly declined in the past years due to the limited decarbonizing efficiency and the risk of methane slip neutralizing the benefits of retrofitting [31]. Biogas – a greener version of LNG – has higher decarbonizing potential because it may be emission neutral as its carbon originates from plants, but the corresponding methane slip risk is still high. Moreover, the competition for the necessary feedstock is expected to be high among the producers of green fuels [43].

Wind-assisted ship propulsion (WASP) and solar energy are renowned as renewable technologies with low ship retrofit costs. They are recommended as a secondary supporting energy source and energy-saving device and are further considered in Section 1.2.

Hydrogen is considered one of the most competitive fuels for new-built ships primarily because of its high decarbonizing capability. Hydrogen as a fuel is less promising for retrofits due to high initial investments and relatively low volumetric energy density. Moreover, it has a diverse public reputation, with many people concerned about the related explosion risks and its decarbonizing efficiency, which is highly dependable on production processes/measures. However, retrofitting for hydrogen may be promising for deep-sea ferry and cruise ships, especially considering that such specialist ship segments may be sensitive to some drawbacks of batteries (large size and weight) and ammonia (toxicity), as discussed further.

Biofuels have an energy density close to traditional maritime fuels and fit well into the storage systems of a ship, resulting in low-cost retrofitting. However, they may not be as potentially efficient as a standalone measure for preventing climate change as their greener counterparts, and the future competition for the feedstock is expected to be high [43]. Fig. 4 shows that using biofuels (e.g., biodiesel and ethanol) allows vessels to meet the requirements for 2030 (Objective 1, see Introduction) at a relatively low cost. Biofuels are favorable candidates for retrofitting vessels older than ten years as of 2023. This is because their lifecycle will likely end or will be close to its end at the deadline of Objective 2 (see Introduction) in 2040, assuming a thirty-year lifespan of a ship. Considering the maturity of technologies, biofuels may be an efficient intermediary solution for the transition to zero-emission shipping.

Unlike hydrogen and ammonia, methanol is a technologically-ready fuel for application in shipping [71]. The decarbonization efficiency of methanol depends highly on the source used for its production. It ranges from zero-emission green methanol produced from biomass to highly contaminating brown methanol produced from coal. This is about four times less expensive than green methanol [71]. Paper [73] reports a positive public perception of methanol. However, the high cost and demand from different industries for feedstock contribute to the expensive lifecycle of green methanol. The low energy density of methanol requires more than two times higher fuel tank capacity than MDO. This may result in limited transportation performance. Although green methanol is beneficial at present due to available technologies and low retrofitting cost, there are concerns about its future competitiveness, as other alternative energy sources are expected to be more cost-efficient over a ship's lifecycle [71].

Ammonia is one of the most promising candidate fuels for retrofitting because of low GHG emissions and cost of implementation [59], the readiness of the manufacturing technologies used, and the positive perception of the public. It is also considered one of the most cost-efficient options. Notwithstanding this, it is very contagious for human health and nature [104]. Slips of ammonia caused by equipment faults or human error may result in significant GHG emissions. Furthermore, the factual decarbonization efficiency of ammonia is highly dependent on the feedstock and the production technology used

Table 1
Available technologies for decarbonizing existing ships by retrofitting for alternative energy sources.

Energy source	Vol. energy density/vol. energy density of MDO	Cost of retrofitting in % of the market value of a ship	Lifecycle GHG reduction	Role	Primary ship types	Public perception
Hydrogen	0.26 [44]	from 100 to 160 % [45,46]	from 0 to 100 % [47,48]	Primary	Ferry, cruise ship, tugs [49–51]	Diverse ([52–55])
Ammonia	0.31 [44]	from 15 to 50 + % [56,57]	from 0 to 100 % [58,59]	Primary	Tanker, bulker, bunkering ship [49,60]	Positive [55,61, 62]
Battery power	0.1 [44]	from 35 % to 180 % [63–65]	from <0 to 100 % [47,48]	Primary	Ferry, container ship, Ro-ro [49,65–67]	Positive [68–70]
Methanol	0.43 [44]	from 12 to 16 % [57]	from 0 to 95 % [47,71]	Primary	Support vessel, tanker, and tug [49,72]	Positive [73], limited data
Biofuels	0.89 [44]	from 13 to 20 % [74]	From 17 to 59 % [75,76],	Primary	Container ship, Ro-Ro [49]	Diverse [77–79]
WASP	Not applicable	from 3 to 5 % [80,81]	100 %	Secondary	Bulker, cruise ship, ferry container ship [49,82]	Positive [83–85]
Liquified biogas, synthetic methane	0.37 [44]	from 11 to 70 % [86–88]	from 0 to 100 % [89]	Primary	Container ship, bunkering ship [49]	Indifferent [90–92]
Solar energy	Not applicable	from 3 to 5 % [93]	100 %	Secondary	Ferry, Ro-Ro [93,94]	Positive [95–97]
Liquified natural gas	0.37 [44]	from 11 to 70 % [86–88]	25–30 % [29,31]	Primary	LNG carrier [98]	Diverse [99,100]
Nuclear power	10^6 + [101]	From 400 to 500 + % [41]	100 %	Primary	Icebreaker [42]	Negative [36,102, 103]

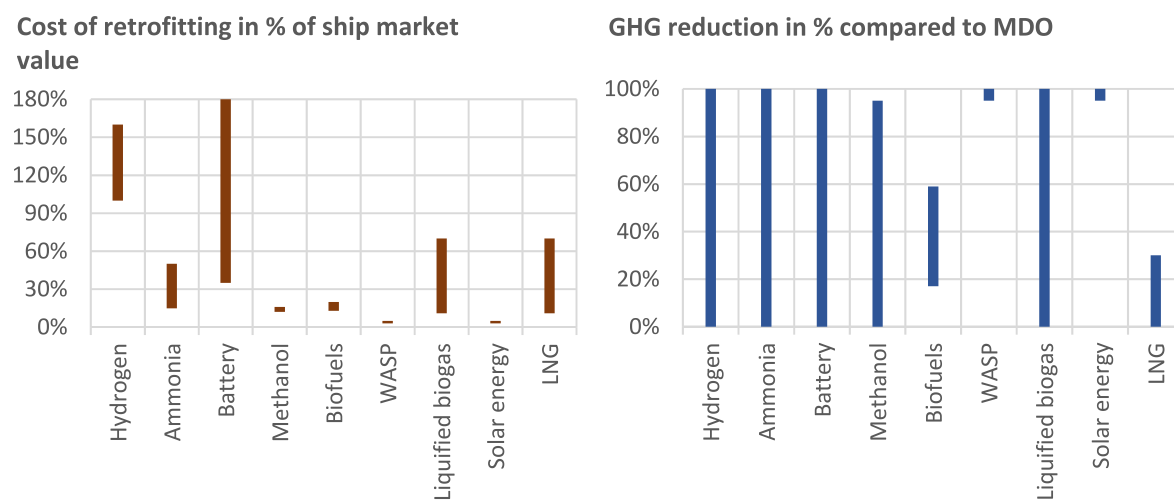

Fig. 4. Ranges of the retrofitting costs and corresponding potential GHG reduction for different energy sources

[60]. Toxicity issues limit its application as fuel to specific types of vessels with a moderate number of persons onboard, e.g., tankers, bulkers, bunkering, and container ships.

Battery-driven electrical propulsion powered from ashore charging stations may be another useful decarbonization option. However, the cost of retrofitting varies significantly, i.e., 35 % of the market value for a short-distance (1.6 n.m.) RoPax ferry [63] to 180 % of the market value for a middle-distance (120 n.m.) Ro-Ro ship. Battery technology is deemed non-toxic and, unlike ammonia, is recommended for passenger ships. An advantage of battery power over some other green fuel alternatives is the minimal GHG slip risk. Nevertheless, how energy for battery powering is produced entails significant uncertainties regarding the practical decarbonizing efficiency of the technology. Safety issues related to battery power, e.g., high risk of explosions and fires, can be mitigated by arranging advanced fire-extinguishing equipment, which requires much space [105]. That factor, together with low energy density, results in the significant volume and weight for the arrangement of batteries, which may hinder the stability, payload, and cargo capacity of the ship. Such constraints limit battery applications to ships operating in developed coastal areas with access to charging facilities and ships requiring low powering, e.g., small and inland vessels [106].

Biofuels, methanol, ammonia, and battery-powering are the most promising options for retrofitting existing ships for a new energy source. However, they all have specific prospects and constraints, making them all relevant for different ship segments, as summarized in Fig. 5. Considering that about 40 % of the world fleet consists of large tankers and bulkers [24], ammonia is likely the most promising future retrofitting option among alternative energy sources [107].

3. Ship design for retrofitting

This section presents applications of ship design for retrofitting decarbonization solutions, as shown in Table 2. Retrofitting based on ship design improvements results in a limited but reliable effect achieved by increasing the energy efficiency of ships. One of the most popular options is the so-called local retrofitting options for improved hydrodynamic efficiency applicable to ship hulls and propulsion. Examples are innovative bulbous bow features or small hull appendages (e.g., pre-swirl stators, skegs, underwater stern foils, Gate Rudder System). In many cases, such retrofits are inexpensive, with moderate decarbonization potential of up to about 10 % emission reduction. However, their decarbonizing efficiency per unit of investments is very high. Hydrodynamics-based hull retrofits depend on the operational mode of a ship (speed, loading conditions, and sea states) that, under unfavorable environmental conditions, may lead to higher emissions [108,109]. Hekkenberg and Thill [110] noted that the efficiency of such retrofits is limited if the initial design performance is excellent, which is not often the case. A removable icebreaking bow design concept suitable for hull

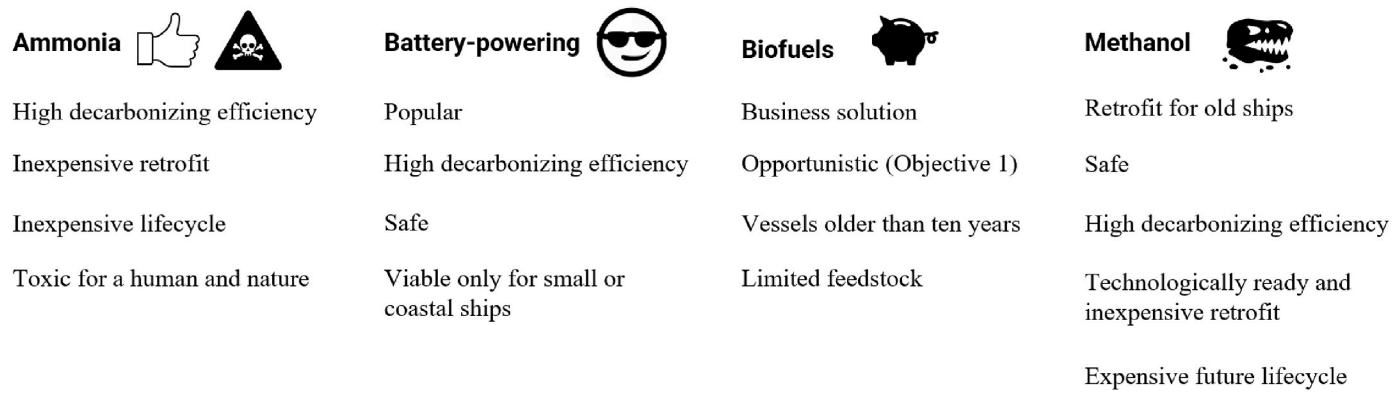

Fig. 5. Features of the most promising energy sources for ship retrofitting

retrofitting in cold regions is proposed by Eronen [111]. The technology provides significant lifecycle GHG emission reduction of up to 20 %.

Another promising measure is improving ship design for retrofitting via the application of WASP. The most promising technologies are Flettner rotors, wing sails, and towing kites [80,112,113]. Wind turbines are considered sub-optimal because of their limited decarbonization efficiency of 1 %–2 % [114]. Flettner rotors may be up to 20 % efficient. However, the public occasionally perceives Flettner rotors as unesthetic [115], a fact that limits their application on some ships, e.g., motor yachts and cruise ships. In such cases, wing sails are usually considered an appropriate option for passenger ships because of their traditionally well-perceived appearance despite their lower decarbonization efficiency. In any case, retrofitting by Flettner rotors and wing sails requires significant deck space [116], and therefore, both technologies are suitable for bulkers, tankers, and general cargo ships while both technologies also have the potential to comply with safe bridge visibility standards [117]. The actual decarbonizing capability of WASP significantly depends on the average lifecycle wind condition on a shipping route, and it may drop to zero if there is no wind. It is noted that the typical retrofitting cost for WASP is higher than the cost of hull retrofitting. Table 2 shows that compared to alternative energy sources (see Section 2) or hull retrofitting, the reported GHG reduction in % for WASP is highly manipulative. WASP provides additional thrust, which is practically non-sensitive to ship speed and depends on wind conditions. Consequently, it shows higher decarbonizing potential for vessels with low fuel consumption, e.g., small vessels operating at low Froude numbers. Moreover, the GHG reduction for WASP is often reported assuming favorable wind conditions, which may mainly be achieved by combining with weather routing.

Air lubrication systems (ALS) aim to reduce the frictional resistance of the hull and corresponding fuel consumption. IMO recommends ALS as an innovative energy efficiency technology [118]. There are different alternative principles of air lubrication, but the pump injecting a layer of air microbubbles between the bottom of a ship and water is proved to be the most commercially viable [119]. Since November 2021, producers of the most popular ALS (Silverstream Technologies) reported eighty-two signed installation contracts [120]. Table 2 shows that shipping companies report about a 5 % reduction in fuel consumption and corresponding GHG emission for diverse operation modes following ALS retrofitting. In those cases, installation costs range from 0.8 to 5 million USD depending on the size of a ship [120,121]. Shipping companies that successfully retrofitted a ship with ALS tend to repeat the retrofit action on their other ships [122]. Some of the producers of ALS technology highlight the feasibility of untypically fast retrofitting operational practices (starting from ten days) [123]. Yet, deep uncertainty is noted about how the decarbonization benefits of ALS are quantified. Some providers propose to measure GHG emissions reductions by comparing the fuel consumption rates of a retrofitted vessel during ALS activation and deactivation modes [124]. Nevertheless, ALS technologies have significant hidden decarbonization potential related to hull biofouling prevention. Some preliminary industrial experiments [124] showed a 50 % reduction in biofouling growth due to operating ALS, which effect may outperform savings from the direct frictional resistance reduction. Hence, there is no known published research on the ALS impact on biofouling, which is identified as a significant research gap and promising research direction.

One of the most promising retrofitting technologies for decarbonization is ship-based carbon capture (SBCC) [142,143]. The technology satisfies the requirements for reaching IMO decarbonization Objectives 1 and 2 and may compete with alternative fuels in terms of efficiency [144]. SBCC utilizes exhaust gas treatment by capturing CO_2 in the post-combustion phase, thus allowing vessels to operate with conventional fuels [144]. Fig. 6 shows that after capturing, CO_2 is liquified and stored in a ship tank before its transfer for further storage in specialized port facilities, or it may be sold to other industries. The SBCC technology is mature [144,145] and is currently pilot-tested on ships [146–148]. Although achievable carbon capture is about 90–99 %, the maximum decarbonizing capability of SBCC is from 75 to 85 %, as some energy is required for CO_2 liquefaction. The carbon capture rate can be reduced, if necessary, thus resulting in less installation and operation costs. Whereas the CO_2 emission lifecycle for a ship with SBCC is more transparent than for alternative fuels, some studies point out the need to extend the capacity of available CO_2 storage facilities and to refrain from selling liquified CO_2 due to the high probability of its further misusing resulting in emissions migrating from shipping to other industries [145]. According to estimates by the Oil and Gas Climate Initiative [145], the cost of a Suezmax tanker retrofitting for SBCC is about 13.2 million USD for a 50 % carbon capture rate and about 20 million USD for a 90 % carbon capture rate. These values account for about 16.5 % and 25 % of the cost of a corresponding newbuilt ship. Feenestra et al. [142] calculated that the cost of SBCC installation on a general cargo ship of 8000 DWT could account for more than 3 million USD or about 30 % of newbuilt ship cost. The operating cost of CO_2 capture is uncertain and is evaluated at 105 USD to 175 USD per tonne of CO_2. This indicates that SBCC may outperform alternative energy technologies in terms of cost efficiency [142,144,149]. The SBCC role in future shipping seems to be significantly underestimated, considering its competitive advantages. It has a high potential to outperform the majority of well-advertised decarbonization solutions.

Biofouling of the immersed hull increases hydrodynamic resistance. According to Schultz ([150–152]), even a slight biofouling layer produces significant resistance and increases fuel consumption. The economic impact can become considerable depending on the extent of the biofouling [153]. In addition to economic effects, hulls with biofouling form a vector for the spread of alien species alongside ballast waters [154]. Therefore, biofouling management produces immediate economic and environmental benefits [155]. According to empirical data, Adland et al. [147] report that biofouling management may reduce the

Table 2
Applications of ship-design-based retrofitting technologies for hull and propulsion.

Source	Ship type	Retrofitting option	Installation cost	Lifecycle GHG reduction
Prins et al. [125], Voermans [126]	Bulker	Hull: pre-swirl stator	Insignificant [127]	up to 10 %
Sasaki et al. [128]	Container ship	Hull: Gate Rudder System	From 0.065 to 0.3 million USD [129]	from 5 to 14 %
Chun et al. [130]	U.S. navy auxiliary and amphibious ships	Hull: bulbous bow	From 1.7 to 2.6 million USD, amended for 2023 [131]	up to 4 %
Szelangiewicz et al. [132], Pérez-Arribas et al. [133]	Fishing vessel	Hull: bulbous bow	Insignificant	up to 10 %
Hou et al. [134]	Guided-missile destroyers	Hull: underwater stern foil	Approx. from 0.2 to 0.6 million USD	up to 10 %
Brenner et al. [108]	Motor yacht	Hull: bulbous bow and skeg	Not specified	up to 16 %
Eronen [111]	Tug	Hull: removable bow	8.3 million USD, about 30 % of newbuilt ship cost	up to 20 %
Zhang et al. [135], Nelissen et al. [114], Lindstad et al. [82],	Bulker from 60000 to 90000 DWT	WASP: Flettner Rotors	2.2 million USD [135]	from 4 % to 17 %, depending on wind conditions
Pearson [116]	Chemical tanker 15000 DWT	WASP: Flettner Rotors	Not reported	up to 10 %
Vahs [136]	General cargo, 4250 DWT	WASP: Flettner Rotors	0.54 million USD	from 10 % to 20 %, depending on ship speed
Beluga Fleet Management [137], Nelissen et al. [114]	Bulker 60000 DWT	WASP: towing kite	2.4 million USD [135]	from 1 % to 12 %, depending on wind conditions
Shukla and Ghosh [138]	LPG carrier, 17500 DWT	WASP: wing sails	Not reported	up to 8.3 %
Nelissen et al. [114]	Bulker from 7000 to 90000 DWT	WASP: wing sails	Not reported	from 5 to 18 %
Silberschmidt et al. [119]	Chemical tanker, 40000 DWT	ALS	about 0.8 million [120]	up to 4.3 % [119,139]
Clean Shipping International [122]	Cruise ship, length 330 m	ALS	Not reported	up to 5 % [122]
Houlder [121]	Ore carrier, 325000 DWT	ALS	5 million USD [140]	from 5 to 8 % [121]
Snyder [139]	LNG carrier, 70000 m^3	ALS	Not reported	up to 6.7 % [139]
Snyder [139]	General cargo, 2300 DWT	ALS	Not reported	up to 12 % [139]
Mandra [141]	Ro-Ro, length 238 m	ALS	Not reported	up to 5.1 % [141]

average fuel consumption from 9 % to 17 %.

A comprehensive biofouling management strategy is partly a ship-specific, regional, and global issue: The marine environment, sea temperature, salinity, available sunlight, seasonal ice conditions, operational profile, idle periods (in ports or anchorage areas), and selected coatings of immersed hull structures affect the rate of formation of fouling ([154,156,157]). Restrictions on permitted surface treatment agents and hull cleaning methods vary geographically [158]. However, there are often gaps in terms of understanding the importance of effective biofouling management. The spreading rate varies notably in immersed hull structures [159]. The biofouling rate increases rapidly in structures just below the sea level, but a flat bottom protected from sunlight gets fouled much more slowly. The differences can be considerable depending on the region of operation. Ship-specific niche areas, such as suction ducts or seawater wells, are often difficult to clean [160].

Selecting a treatment method is an important decision in biofouling management. Coating types can be roughly divided into three main categories: antifouling, foul release, and hard coatings [154]. Anti-fouling coatings contain chemicals such as biocides that limit the growth of organisms [161]. However, biocides, e.g., organic tin and copper compounds dissolved in seawater, can cause water and seabed sediment pollution, which is why the composition and application of anti-fouling coatings in various marine areas are regulated [162]. Foul-release coatings are non-biocidal type agents, whereby organisms attached to the hull are detached mechanically when the ship moves through the water [163]. At best, this solution makes regular hull cleaning unnecessary, but in practice, especially with an outdated coating, detachment often does not happen ideally. Hard coat-type coatings are often used in ships whose hulls may be exposed to intense mechanical stress due to, for example, operating in ice conditions. Hard-coated hulls get biofouling quickly, while the biofouling management must be based on regular cleanings, especially during ice-free seasons. In ice operations, the hulls are cleaned effectively during hull-ice interaction. According to Floerl et al. [164], the coverage of biofouling must also be considered, resulting in additional power loss depending on its extent: absent (0 %), light (1–5%), considerable (6–15 %), extensive (16–40 %) or very heavy (41–100 %). Table 3 describes a classification of biofouling types, the corresponding definition, and the rating of the Naval Ships' Technical Manual (NSTM) [165]. The same table includes estimates of the increase in the power demand and in-water hull cleaning (IWC) mitigating measures.

Prevention is often the most economical way of operating in-water hull cleanings: A regularly cleaned hull usually contains only soft organisms such as algae and is quicker to clean, keeping cleaning costs significantly lower than hull structures full of hard-shelled organisms such as barnacles. Removing hard-shelled organisms can also damage the coating surface, making it a better platform for future biofouling growth. However, in-water cleaning can also promote the spread of organisms, especially without collecting cleaning waste [167]. Additional challenges arise because the relevant regulations vary widely from state to state.

4. The impact of retrofitting on ship operations

The overall sustainability potential of a ship at the design stage is demonstrated only if sustainable engineering systems and associated operational practices apply. The availability of trustworthy Decision Support System technology has a prominent role to play in this area. Examples are weather routing systems [168–172], systems for planning shipping logistics [173–175], and simulators [176–178]. More recently, great prospects have been attributed to the positive outcomes of developing energy-efficient port infrastructure [179].

Weather routing in spatial (where) and time (when) domains account for concurrent environmental conditions (e.g., wind, waves, currents) and weather extremes, e.g., ice routing in polar weather conditions [180–182]. A weather routing tool consists of a mathematical

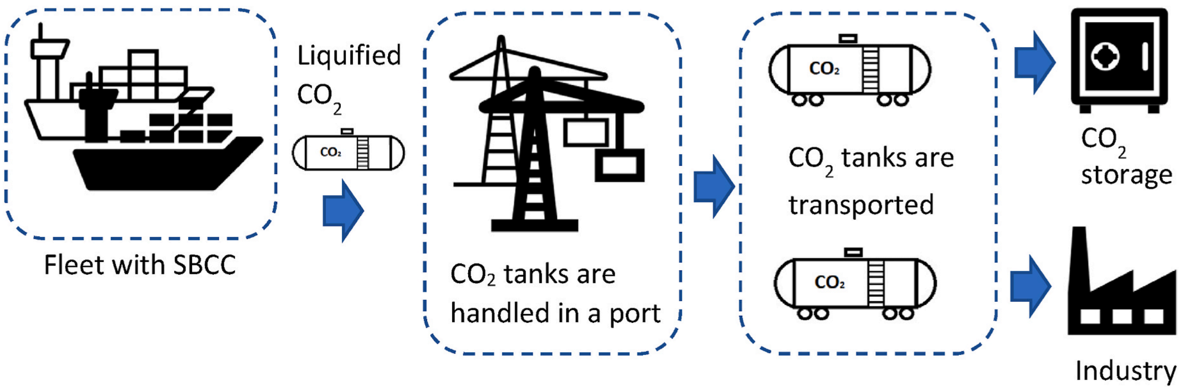

Fig. 6. Ship-Based Carbon Capture and related logistics

Table 3
Types of biofoulings, a corresponding increase in the power demand, and mitigating measures.

Parameter	Description						Source
Fouling type	No fouling	Microfouling	Moderate macrofouling (soft)	Moderate macrofouling (hard)		Heavy macrofouling (hard)	[165]
NSTM rating	0	10–20	30	40–60	70–80	90–100	
NSTM definition	Hydraulically smooth surface	Deteriorated coating or slight slime	Heavy slime	Small calcareous fouling or weed	Medium calcareous fouling	Heavy calcareous fouling	
Increase in power at 15 kn (%)	0	11	21	35	54	86	[152]
IWC	No measures	Proactive IWC (soft brushes)	IWC (soft brushes)	Reactive IWC (metal brushes)			[166]

optimization algorithm (e.g., heuristics [183], metaheuristics [184], deterministic global optimization [169,180]) and a ship performance model, which estimates key performance indicators. Shallow water regions constrain the feasible routes to avoid ship grounding. A* [161] is the most popular optimization algorithm for weather routing. The typical routing key performance indicators are fuel consumption, voyage time, and voyage cost, usually defined by considering the design qualities of a specific ship in different weather conditions. Routes and speeds optimized for different key performance indicators may be very different. For example, a solution minimizing fuel consumption may utilize slow steaming, which increases voyage time.

The decarbonizing efficiency of routing significantly depends on the quality of weather data, i.e., how well the data correspond to the actual weather conditions along a specific shipping route [168,185]. Inaccurate data may result in less efficient routes than the shortest route paved without optimization. For ideal cases assuming that the weather data are 100 % accurate, research papers report 4 %–11 % reduced CO_2 emissions [183,184,186,187]. Unlike many promising technologies in decarbonizing shipping, weather routing is actively used in the shipping industry and is provided as a subscription-based service. Wärtsilä Navi-Planner [188] – one of the most popular weather routing tools – reports up to 5–7% reduced fuel consumption in realistic sailing conditions. Another promising weather routing tool – NAPA voyage optimization for reducing ship emissions and enhancing safety [189].

WASP-assisted weather routing aims for a trade-off between maximizing wind against hydrodynamic added resistance. Bentin et al. [187] demonstrated more than 14 % additional fuel savings because of WASP-oriented weather routing. Such benefits imply extending voyage time for one day for a 17000 DWT multipurpose vessel on a line between Wilhelmshaven (Germany) and Baltimore (USA). In another study [190], WASP-oriented weather routing demonstrated about 4.5 % fuel savings and insignificant changes in voyage time for a Very Large Crude Carrier on a line between the East China Sea and the Strait of Hormuz in the Middle East.

Logistics planning and maritime transport systems simulation tools may further improve the sustainability of ships by optimizing their operations [175]. Johnson and Styhre [174] demonstrated that decreasing non-productive time in port provides more opportunities for slow steaming with the same delivery schedule, saving more than 8 % of the fuel consumption of a ship due to reduced speed and lower total energy demand while berthed. Power management systems can improve the energy efficiency of a ship by up to 10 percent by optimizing loading distribution between engines, generators, or batteries for different power demands [191–193]. Agent-based decision-support tools for the simulation of polar maritime transport systems may allow for optimizing icebreaker assistance to reduce CO_2 emissions by more than 7 % [173,260].

5. Key emerging maritime engineering science perspectives

5.1. The case of air lubrication systems

As discussed in Section 3, ALS is used because air/gas injection helps to improve energy efficiency by controlling the drag coefficient of the hull bottom surface of a ship. The technology applies in low to moderate sea states. In rough seas, waves can affect ship dynamics, safety, and efficiency by causing large motions and wave loads (e.g., slamming). Experimental and computational fluid dynamics (CFD) are the preferred methods to test and optimize ALS ship operations. Early studies focused on fluid flow physics to understand how air bubbles are generated and to analyze their influence on the skin friction coefficient. Research in this area introduced dimensionless quantities that may be used to understand the effects of air/gas injection on ship resistance.

The first experimental fluid dynamics research on ALS was conducted by McCormick and Bhattacharya [194], who studied the effects of gas injection on a plate towed in water. They demonstrated the drag coefficient reduction at lower towing speed, called the bubble drag reduction (BDR, Fig. 7e). This discovery has raised the interest of other researchers in ALS technology, who studied during the 1970s the effect of gas injection on the drag coefficient of a pipe [195,196] (e.g., in Fig. 7b), a plate placed in a water tank [196,197], and a lower wall of the water tunnel [197]. The studies introduced the dimensionless

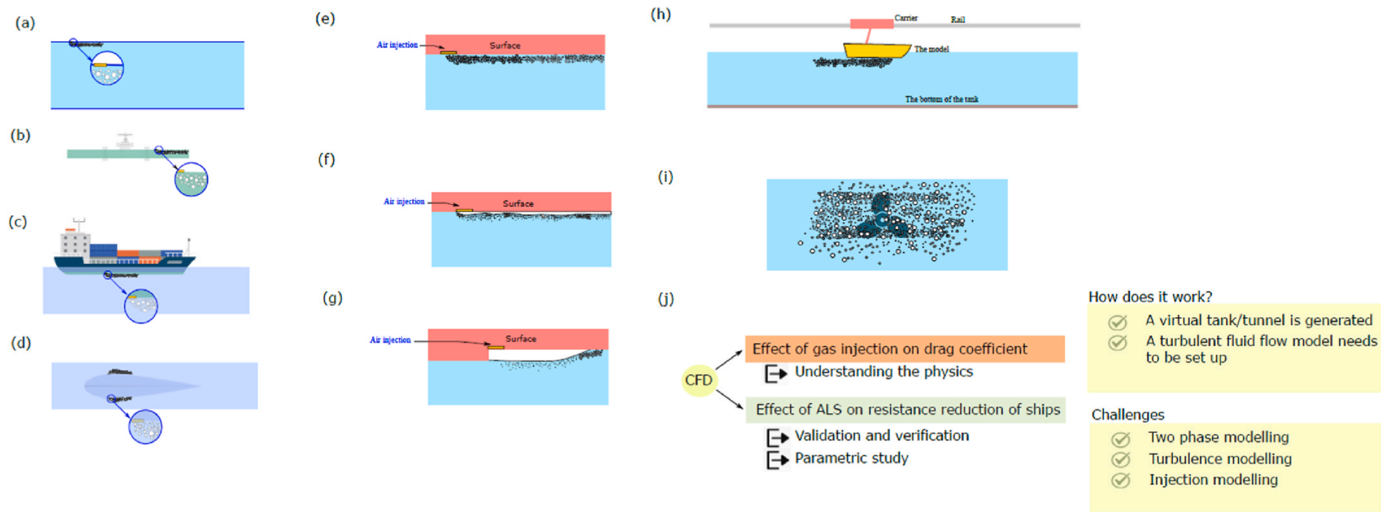

Fig. 7. Fluid dynamics and its application in retrofitting by ALS. Panels (a–d) show different applications of air injections. Panels (e–g) respectively show BDR, ALDR, and PCDR. Panels (h) and (i) display the related towing tank test of a ship with ALS and open-water tests in an aerated sea. Panel (j) shows a general view of the application of CFD in modeling ALS.

volumetric flow rates of the gas, helping to understand the physics of the problem better.

Later, in the mid-1980s, the dimensionless airflow parameter was introduced, and drag reduction was thought to be a function of this parameter [198]. The wind tunnel experiments were conducted to study the impact of gas injection on the drag coefficient (e.g., in Fig. 7a–d), [199,200]. Buoyancy can affect the resulting drag reduction, and thus, it is vital to formulate the drag coefficients of lower and upper walls separately. In the experiments, injected gas with a very high rate was seen to lead to an air layer under the surface known as air layer drag reduction (ALDR, Fig. 7f). The gas reduction under a step design creates a cavity that can significantly decrease the frictional drag. This mechanism is known as partial cavity drag reduction (PCDR, Fig. 7g). In general, the drag reduction of the plate and other flat surfaces equipped with gas injection has been reported to be reduced by 80 % in most studies [201].

The air injection effects on ships and the total resistance reduction are measured via tests in towing tanks where a ship is equipped with an ALS (e.g., in Refs. [202–204], Fig. 7h). To date, the resistance reduction of the ship in tank tests is usually reported from 5 % to 15 % [205]. Different towing tank tests over the last two decades have studied the effects of BDR, ALDR, and PCDR on ship resistance.

Modern research focuses on (1) the drag coefficient reduction of plates as a function of airflow parameters and (2) the resistance reduction of ships. For the development of a better hydrodynamic tool for predicting the effects of ALS on the decarbonization of ships, laboratory tests can be done to provide the followings.

1) A general criterion for choosing the best gas injection (BDR, ALDR, or PCDR). Recommendations are provided based on the flow speed [206], but using a dimensionless form better helps engineers decide on the proper system. This may require more systematic towing tank tests for different gas injection methods.
2) Integration of dimensionless data of frictional drag reduction of the plate (pure fluid dynamics) into ship resistance calculations. Since the towing tank tests have been accelerated over the last decade, steps should be taken to implement the data found for frictional coefficients of plates subjected to gas injection into resistance calculation. That can help us build simpler mathematical equations for estimating the effects of ALS on ship resistance.
3) Studies should consider that bubbles left behind aerated surface may affect the propeller performance [207,208] (Fig. 7i). Testing of the open propellers in an aerated tank and self-propulsion of ship models equipped with ALS is recommended to identify the effect of ALS on the performance of a propeller. That may lead to a better design of a potential retrofitting system.

Simulation studies looking into the effects of ALS on ship resistance have been accelerated over recent years. CFD can be used to numerically simulate BDR, ALDR, and PCDR problems. They can be implemented to study the fundamentals of the problem (frictional drag reduction of the plate) or resistance reduction of the ship equipped with the ALS. Fluid equations must be solved using a numerical technique, and two phases (air and water) must be considered. Thus, a volume fraction model or an Euler-Euler two-fluid model can be used to simulate the problem [209]. There are two challenges to the application of CFD for studying ALS. The first challenge is modeling the bubble injection, which can be done either by numerical injection of air from inlets or using a population-balance method [210,211]. The other challenge is to model the turbulent fluid motion near the wall (Fig. 7j). This can be done by using direct numerical simulations [212], solving Reynolds averaged Navier Stokes Equations [208], or large eddy simulation [213], which can provide systematic numerical experiments (e.g., in Refs. [214,215]). However, while it is essential to do so, a deep verification and validation study of these technologies is still lacking in the literature. It is promising for future studies to develop proper setups for full-scale numerical simulations of different ALS, which may help engineers choose the proper ALS that can be used for retrofitting.

5.2. The use of artificial intelligence for shipping decarbonization

This section examines the existing artificial intelligence (AI) technologies for decarbonizing maritime transportation, explicitly focusing on ship design and operational strategies. The review evaluates the advancements in AI-driven technologies that contribute to reducing greenhouse gas emissions and enhancing environmental sustainability.

Naval architects typically employ regression analyses to predict ship performance. The analysis is based on existing hull forms or empirical formulae [216,217]. However, this approach has limitations as it only considers a few primary parameters and often doesn't account for complex factors like non-linear hull surfaces. As the design progresses and optimization becomes crucial, designers heavily rely on their experience [218].

AI technologies may be leveraged to optimize ship design by utilizing advanced algorithms and machine learning methods ([219–222]). These technologies analyze vast amounts of data and identify design modifications that result in improved hydrodynamics and reduced resistance. By employing AI algorithms, naval architects and engineers can achieve designs that minimize energy consumption and, consequently, decrease emissions (e.g., Refs. [223–225]). Recently, Khan et al. [223] utilized a dataset of 52,591 physically validated ship designs, including container ships, tankers, bulk carriers, tugboats, and crew supply vessels, to train ShipHullGAN, a deep convolutional generative model. The trained model enables ship hull generation and optimization, as depicted in Fig. 8. Additionally, Ao et al. [224] developed an AI-based deep-learning neural network to predict ship-hull resistance in real-time during the initial design phase. The model exhibited accurate resistance prediction with an average error below 4 % and facilitated real-time performance assessment without pre-processing. These advancements mark significant progress towards AI-aided design in naval architecture.

AI techniques have emerged as crucial tools for reducing resistance in ship design, particularly at the preliminary design stage ([225–227]). This is because they leverage historical performance data and computational models to evaluate the impact of different design parameters on hull form and appendages design that ultimately have the potential to minimize resistance ([228,229]). Advanced optimization algorithms can identify optimal design configurations that strike a balance between operational requirements and environmental sustainability ([224,230]). AI algorithms have successfully optimized ship propulsion systems to reduce emissions ([231–233]). Using AI algorithms and machine learning techniques enables efficient exploration of the design space [232], more accurate fuel consumption prediction [234], and intelligent voyage planning algorithms [235], as depicted in Fig. 9.

Intelligent fuel consumption prediction is another crucial area. AI can generate accurate fuel consumption predictions by leveraging historical data and advanced machine learning algorithms. This allows ship operators to optimize their fuel usage, leading to reductions in emissions and cost savings. Several review papers have extensively discussed the potential application of machine learning and deep learning methods in predicting ship fuel consumption ([218,236,237]). These papers have identified three main clusters of algorithms commonly used in this domain, namely: (i) supervised machine learning methods, (ii) unsupervised machine learning methods, and (iii) deep learning methods. Supervised machine learning methods encompass a range of techniques, including multiple regression [238], random forest [239], least absolute shrinkage and selection operator regression [240], support vector regression [241], extreme gradient boosting [242], and decision trees [243]. Unsupervised machine learning methods involve Gaussian process regression [244] and Gaussian mixture models [245]. Deep learning methods consist of artificial neural networks [246], long short-term memory networks [247], and gated recurrent units [248]. So far, these methods have been employed to predict ship fuel consumption for various types of ships, utilizing diverse data sources and their combinations, such as voyage reports, Automatic Identification Systems, meteorological, and sensor data [249]. These diverse data sources provide valuable information that enables accurate predictions and enhances understanding of operational influences on fuel consumption in maritime operations. Additionally, Intelligent weather routing algorithms incorporating AI consider factors such as weather conditions, traffic congestion, and fuel consumption [250]. These algorithms determine the most efficient routes and operating strategies [251].

AI-based predictive maintenance techniques utilize machine

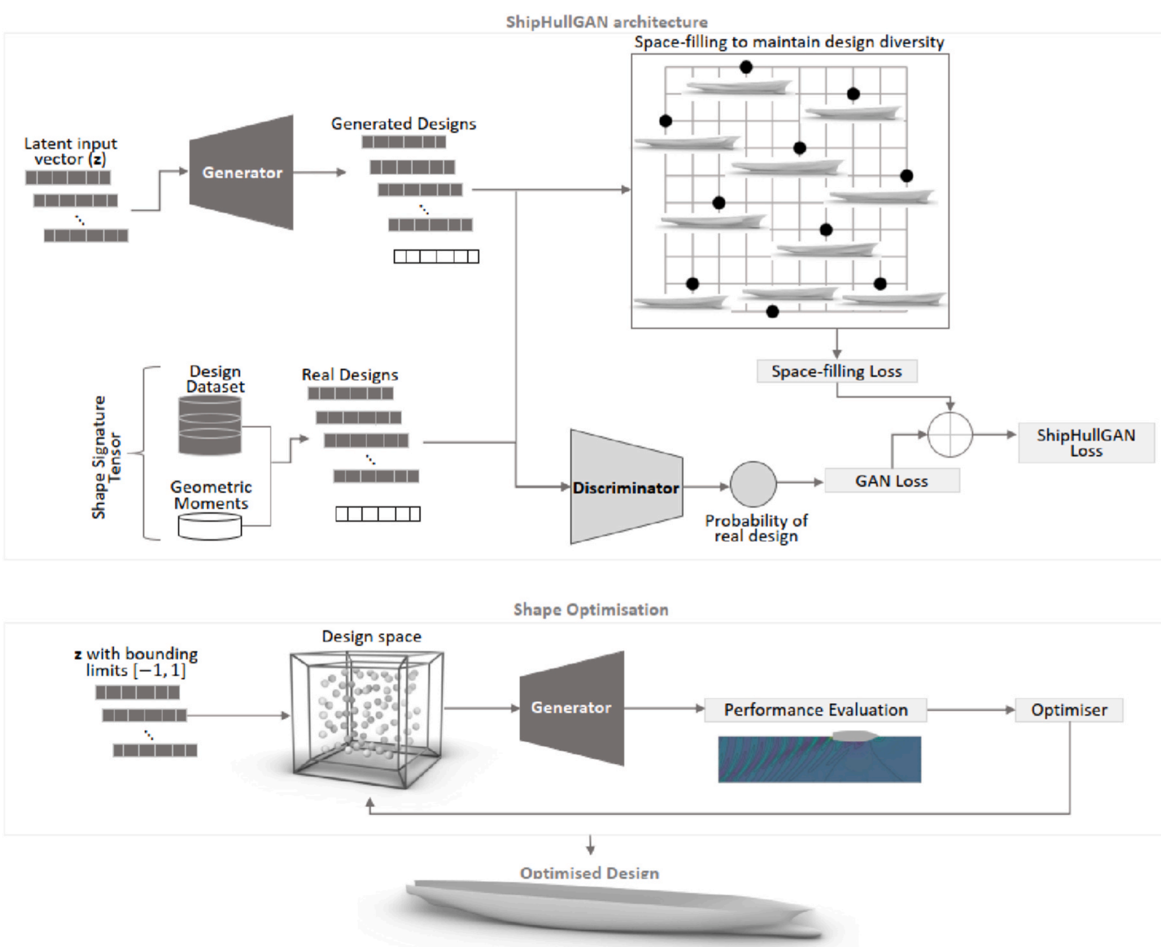

Fig. 8. AI-based ship hull design and optimization [223].

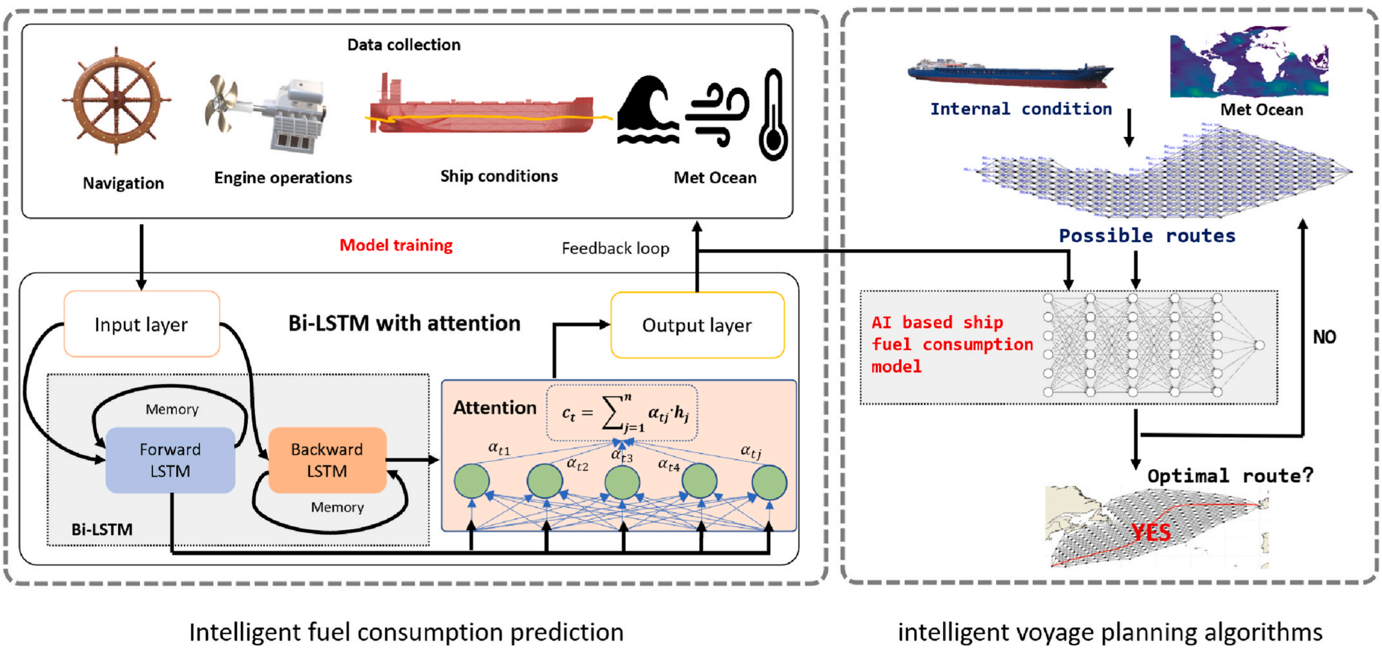

Fig. 9. AI-based tool for the decarbonizing of ship operation

learning algorithms and real-time sensor data to identify potential machinery failures in advance [252,253]. By detecting early signs of equipment malfunction, ship operators can proactively schedule maintenance, avoid costly breakdowns, and optimize maintenance activities to minimize emissions and maximize efficiency. Energy management and optimization strategies leveraging AI are crucial for decarbonizing ship operations. AI algorithms analyze real-time power generation, distribution, and consumption data to optimize energy usage. This includes load balancing, optimizing power generation sources, and implementing energy-efficient technologies [192].

Present constraints of AI must be managed to bolster its utilization for maritime decarbonization. They include the limited availability of high-quality/standardized maritime data [254], the absence of policy guidelines and regulations ([255,256]), limited onboard computing capacities, and some ethical, privacy, and security considerations. Biases inherited from training data can result in discriminatory or unfair outcomes, necessitating measures to ensure fairness and mitigate biases. Transparent and accountable AI decision-making processes are essential to avoid opaque outcomes, and explainable AI techniques can provide insights into the decision-making process [257]. The integration of AI should consider the collaboration between human operators, physics models, and AI systems.

6. Discussion

The implementation of green technologies on newbuilt ships is not enough to attain ambitious climate action goals (e.g., IMO Objectives and the United Nations sustainable development goals SDG 7 and SDG 13), as existing ships will account for a significant part of maritime shipping for a long time. The intelligent selection of ship retrofitting options defines the environmental efficiency of a ship because not all retrofitting options are suitable for any ship type and are compatible with each other. Accordingly, this study discussed emerging retrofitting options for green ship design and operations. Fig. 10 compares ship retrofitting options in terms of efficiency and decarbonization uncertainty. Decarbonization uncertainty defines how precise the efficiency of retrofitting measures is. The same figure compares estimates of this study with IMO estimates [258]. For most solutions, the success of a decarbonization measure significantly depends on how energy-efficient the initial point is to be compared with. For example, hull retrofitting a poorly designed ship reduces more emissions than the hydrodynamically sound one. IMO, estimates are more optimistic in most cases, which could be attributed to the sources analyzed in this study (Tables 1–3, Section 4).

Fig. 10 identifies three equally promising paths for ship retrofitting that meet IMO 2050 decarbonization objectives (i.e., 70 % reduction of GHG emissions compared to 2008). **Path 1 – “popular”** – uses only “zero-emission” energy sources (e.g., ammonia, battery, and methanol) with maximum decarbonizing efficiency from 95 % to 100 %. The main limitation of Path 1 is a high level of decarbonizing uncertainty because CO_2 emissions significantly depend on the lifecycle of the energy unit. The way energy is produced is not well captured by IMO regulations. For example, grey ammonia and grey methanol may be produced from natural gas, while a battery may be powered by a coal power plant. Whereas all of them theoretically meet the IMO 2050 objectives, there is a high risk of migration of CO_2 emissions from the shipping industry to the energy production part of the supply chain. The primary mitigation measure is building transparency on the energy source background and supporting traceability of CO_2 emissions through a comprehensive regulatory framework, certification, and strict control. Although “zero-emission technologies” will be more affordable when technologies are more mature and scaled up, Path 1 is expected to have an expensive ship lifecycle compared to its counterparts. Improving energy efficiency by applying ship design and operation solutions is also relevant for Path 1 to provide its technical viability. This is because green fuels have a low energy density, which may require much space for fuel tanks, which reduces the payload and capacity of a ship and decreases its lifecycle performance.

Path 2 – “pragmatic” – uses a combination of ship-based carbon capture technologies, ship design, and operation solutions. It has a low level of decarbonizing uncertainty and a maximum decarbonizing efficiency of about 95 %, considering energy losses for capturing. The main limitations of Path 2 are limited capacities for CO_2 storage and lack of transparency of future CO_2 emissions if liquified CO_2 is sold to the industry. The main mitigation measures are building more CO_2 storage and avoiding selling CO_2 to the industry. If liquified CO_2 is sold to the industry, strict regulatory framework and control steps are necessary to prevent the misuse of CO_2. The ship lifecycle cost of Path 2 is moderate and holds an intermediate position between Path 1 and Path 3. Based on experience from the oil and gas industry, the public perception of ship-

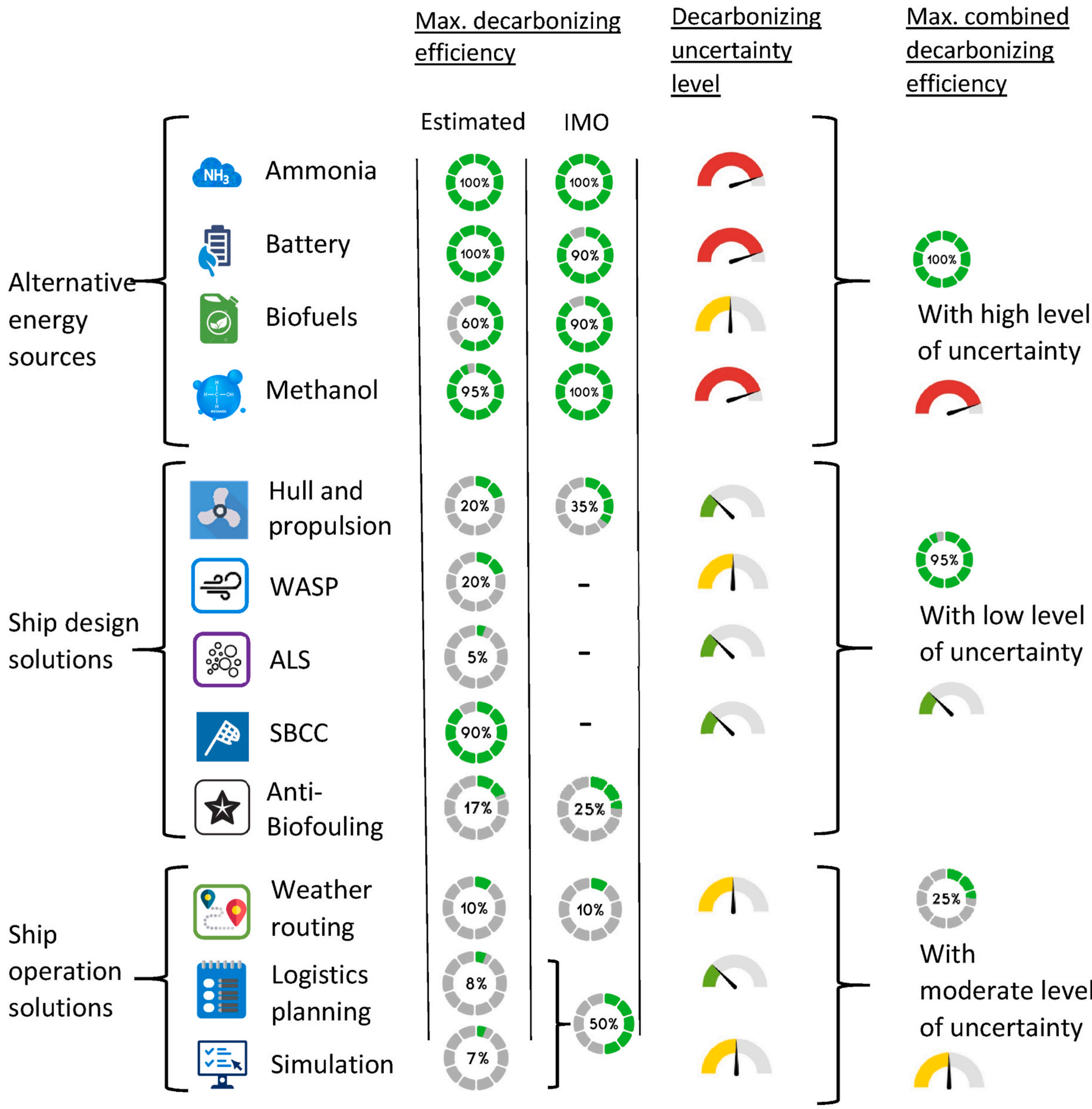

Fig. 10. Comparison of ship retrofitting options in terms of decarbonizing efficiency and its uncertainty

based carbon capture may be diverse.

Path 3 – "limited resources" – uses biodiesel as a fuel in combination with ship design and operation solutions. It has a moderate level of decarbonizing uncertainty with a maximum decarbonizing efficiency of about 85 %. The ship lifecycle of Path 3 is the most commercially viable, with insignificant retrofitting required for the existing ships and moderate fuel cost. The main limitation of Path 3 is the limited feedstock for biodiesel production. The latter hinders it from holding the top position, and currently, there are no effective mitigation steps to neutralize this limitation.

Advances in fluid dynamics can improve ship efficiency via the introduction of ALS. The lack of studies on the ALS impact on biofouling is identified as a significant research gap and promising research direction for shipping decarbonization. In the future, AI can help optimize the utilization of alternative fuels, improve energy efficiency, and facilitate the development of innovative propulsion systems for greener maritime transportation [259]. Furthermore, there is a significant potential for applying AI to optimize maritime transport systems as a part of resilient supply chains [261].

Naturally, this study has some limitations. Existing studies on decarbonizing shipping by retrofitting are limited, requiring us to use sources on general decarbonizing technologies and interpret them in the retrofitting context. Future research should focus on the efficiency gains versus the decarbonization potential of various technologies. For example, specific case studies or the collection of empirical data on the application of technologies for decarbonizing shipping by retrofitting could be very useful [262,263]. The proposed Path 1 includes using battery power as one of the possible decarbonizing alternatives, which requires a stable supply of electricity from renewable energy sources [264]. It is promising to study the supply and demand of renewable energy for future global shipping, considering the needs of the competing industries, e.g., different modes of transportation.

The diverse sources explored throughout this research allowed us to provide an interdisciplinary perspective. However, some of them contain information that is not proven. Although the identified need to account for the decarbonizing uncertainty is significant, our study assesses it qualitatively rather than quantitatively. Developing an approach for quantitative assessment of decarbonizing uncertainty with a transparent methodology is recommended.

This study accounted for essential regulations regarding ship emissions. However, the development of future regulations and their impact are hard to predict in detail. They may significantly affect the quality of the recommended measures. It is promising to develop new IMO regulations for certification and control of the lifecycle of the fuel production process, considering the experience of other industries. For example, in the cocoa industry, there is an international standard for sustainable cocoa bean production and traceability [265], which could be used as a reference.

New technologies for decarbonizing shipping emerge often, and some promising ones might be overlooked. Furthermore, existing decarbonizing technologies might be in different stages of their development. This means that some technologies might be evaluated as the most promising compared to others but may reach their full technological potential very soon without prospects for further significant improvement. The other less developed technologies might have a longer part of the lifecycle ahead, showing their true potential in time. Thus, such a comparison might wrongly attribute the developed technologies to being more promising in the long term than developing technologies.

7. Conclusions

Decarbonizing existing ships by retrofitting is essential for achieving the UN climate action goals (e.g., the United Nations sustainable development goals SDG 7 and SDG 13). Significant efforts are being put into developing and piloting green technologies, improving their theoretical efficiency and the practical application of emerging technologies such as green fuels, WASP, carbon capture and storage, ALS, and AI methods. The decarbonizing effect of different technologies applied simultaneously is not a simple sum but the result of complex interactions. The technology solution paths suggested by this study are inevitably subject to limitations and uncertainties. Hence, solutions should account for ship segment specifics and market fundamentals. A comprehensive and coordinated approach will be necessary to achieve emissions reductions to meet global climate targets. This study identified three promising paths to decarbonize global shipping by retrofitting, which allow for near zero-emission operation of ships, meeting IMO 2050 decarbonization objectives. Consideration of the identified opportunities by engineers in the design of transport and energy systems, policymakers, and businesses can result in better decarbonization.

The first path – using green fuels (e.g., ammonia, battery, and methanol) – is the most popular, although relatively expensive. It has an exceptional decarbonizing potential, which may be uncovered by making the production of fuels and battery energy more transparent – only this way can we avoid the migration of CO_2 emissions between different industries. The second path – using ship-based carbon capture, ship design (e.g., hull retrofitting, air lubrication, and wind-assisted propulsion), and operation solutions (e.g., weather routing and logistics planning) – has a moderate cost and high decarbonizing potential but requires sustainable handling of the liquified CO_2. The third path – using biodiesel with ship design and operation solutions – has high decarbonizing efficiency with low-cost retrofitting and lifecycle, but the feedstock for biodiesel production is currently limited because of competition from different industries.

Limitations of the present study are caused by the lack of literature on decarbonizing shipping by retrofitting, the unclear reliability of some sources, the lack of quantitative assessment of the decarbonizing uncertainty, the emergence of unknown future regulations, and the unknown decarbonization potential of emerging technologies.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, '*Existing technologies and scientific advancements to decarbonize shipping by retrofitting*'.

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Data availability

The dataset generated during this study is available in Zenodo and can be accessed via the persistent identifier https://doi.org/10.5281/zenodo.14749923. This dataset is made available under the license : Creative Commons Attribution 4.0 International License (CC-BY 4.0). For additional inquiries regarding the dataset, please contact the corresponding author.

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