

SHIP DESIGN AND TECHNOLOGIES TO REDUCE ENVIRONMENTAL IMPACT





About Us

Clear Seas is a Canadian not-for-profit organization that provides independent fact-based information to enable governments, industry, and the public to make informed decisions on marine shipping issues. We work to build awareness and trust so that all people can feel a part of the marine sector. Our vision is a sustainable marine shipping sector that is safe, vibrant, and inclusive, both now and for future generations.

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Executive Summary

Marine shipping provides critical social and economic services, but as ships grow in size and numbers, concern is rising around the potential negative environmental impacts they can create. Whether it is through normal operations or accidents, vessels can produce harmful air emissions and chemical, physical and acoustic discharges into the sea, disrupting the sensitive and highly valued ecosystems through which they transit. In the quest to achieve zero-impact shipping, all impacts must be considered.

Technology offers many pathways to reducing the environmental impacts of vessels. However, ships are complex systems, and all of the technologies have to work well together, be safely operated, and support economic and operational goals. With an ever wider array of technologies on offer and a complicated and highly constrained vessel design space, deciding when and how to innovate with technologies for improving vessel environmental performance is not a simple task.

The research identified 28 impact reduction technologies currently being deployed or under development in new build and retrofit projects. The technologies came from the following areas:

- Hydrodynamic Improvements (7)
- Aerodynamic Improvements (1)
- Outfitting Improvements (7)
- Propulsion Improvements (9)
- Operational Improvements (4)

These technologies were found to have the potential to influence the following areas of environmental impact from shipping:

- GHG Emissions & Air Pollution
- Noise & Vibration and Physical Disturbance
- Water Pollution from Vessel Discharges
- Introduction of Invasive Species

The research identified that the vast majority of technologies were oriented towards GHG emissions and air pollution reduction with less of a focus on the other three areas. This is likely due to the strong focus on regulatory compliance for air pollution and on operating cost reduction through fuel efficiency.

Ship design is traditionally an iterative process, evolving through a spiral approach. Decisions are revisited and refined as the design matures, ensuring alignment with operational, regulatory, and budgetary requirements. The owner, designer, and shipyard actively participate in this iterative process, contributing at different phases to ensure the final vessel meets all objectives. Selecting technologies depends on the unique circumstances and stakeholders involved in each case. Analysis of the design process for new and retrofit ship projects conducted as part of this research revealed the emphasis placed on cost and regulatory compliance in the decision-making processes. Environmental impact reduction was found to be a secondary consideration unless it was contained in current regulations.

Decision support tools were found to have certain advantages when used to support the decision-making processes related to the implementation of impact-reduction technologies. Their strength lies in dealing with uncertainties, avoiding decision errors, assessing trade-offs, providing traceability, accommodating shifting regulations, and accounting for interactions between technologies. However, the research uncovered that formal decision support tools are not commonly used by designers and decision makers.

This report provides a consolidated exploration of existing practices of decision-making by naval architects, ship builders, and ship owners as they select technologies that reduce environmental impacts. It serves as a valuable resource for those looking to understand how the uptake of impact reducing technologies could be increased, and the catalogue of impact reduction technologies will serve as a valuable reference.

Acronyms and Abbreviations

AER	Annual Efficiency Ratio
AI	Artificial Intelligence
B.C.	British Columbia
BWMS	Ballast Water Management Systems
CCG	Canadian Coast Guard
CFD	Computational Fluid Dynamics
CH ₄	Methane
CII	Carbon Intensity Indicator
CO ₂	Carbon dioxide
CO ₂ eq	CO ₂ equivalent
dB	Decibel
DFO	Fisheries and Oceans Canada
DP	Dynamic positioning
ECAs	Emission Control Areas
ECCC	Environment and Climate Change Canada
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Indicator
EGCS	Exhaust Gas Cleaning Systems
EGR	Exhaust Gas Recirculation System
EMSA	European Maritime Safety Agency
EPA	United States Environmental Protection Agency
ESG	Environmental, Social and Governance
ESI	Environmental Ship Index
ETS	Emissions Trading System
EU	European Union
GFS	GHG Fuel Standard
GHG	Greenhouse Gas
GIS	Geographic Information System
HEPA	High-Efficiency Particulate Air
HFO	Heavy Fuel Oil
HVAC	Heating, Ventilation, and Air Conditioning
IMO	International Maritime Organization
JIT	Just-in-Time
km	Kilometres
km ²	Square kilometres
L	Litre
LED	Light emitting diode
LNG	Liquefied natural gas
m	Metre
m ³	Cubic metres
MEPC	Marine Environment Protection Committee
MMON	Marine Mammal Observation Network
MPAs	Marine Protected Areas
N ₂ O	Nitrous oxide

NOAA	National Oceanic and Atmospheric Administration
NO _x	Nitrogen oxides
OCC	Onboard Carbon Capture
OECMs	Other Effective Area-Based Conservation Measures
PBCF	Propeller Boss Cap Fin
PM	Particulate matter
SCR	Selective Catalytic Reduction
SO _x	Sulfur oxides
SPS	Special Purpose Ship
TC	Transport Canada
UBC	University of British Columbia
URN	Underwater Radiated Noise
VFD	Variable Frequency Drive
VOCs	Volatile Organic Compounds
VTC	Variation to Contract
WED	Wake-Equalising Ducts

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1.0 Introduction

1.1 Purpose and Objectives of the Study

There is a growing awareness of the wider effects ships have on the natural environment. Even in normal, safe operation, ships can be a source of harmful air pollution, disturbance to habitats, chemical discharges, greenhouse gas emissions, noise pollution or invasive species transmission. Fortunately, there is a growing array of technologies available to reduce these harmful effects, but it can be challenging to choose which of these technologies to prioritize. Technologies like air cleaning scrubbers or hull surface coatings can have surprising unintended secondary effects. These interactions are complex to understand.

If we are to move towards the goal of a zero-impact ship then a new set of decision support tools is going to be required to help the shipping industry evaluate the impacts and sort through the potential solutions to deploy the most impactful ones. The Pathways to Zero-Impact Shipping project, led by Clear Seas in collaboration with the National Research Council of Canada (NRC) and the University of British Columbia (UBC), aims to develop just such an evaluation framework.

To provide the background to the larger Pathways to Zero-Impact Shipping project, the researchers selected Dillon-ABL to undertake a study to specifically explore and consolidate the existing practices of decision-making by naval architects, ship builders, and ship owners as they select technologies that reduce environmental impacts. This report presents these findings together with a catalogue of existing impact reduction technologies.

The focus of the technologies evaluated in this report is non-fuel-based maritime technologies, excluding alternative marine fuels. This is because the topic of alternative fuels for GHG reduction is already widely researched, but there is far less information available about other impact reduction technologies. Low-carbon fuels being developed are costly, so non-fuel technologies that improve efficiency and reduce the fuel consumption of scarce low-carbon fuels will be even more critical.

The objectives of this study are as follows:

- Identify the different environmental impact-reduction technologies currently being considered in vessel design and develop an inventory of ship impact reduction technologies.
- Provide insight into how decisions are currently being made during vessel design and procurement around vessel technologies that are consequential to environmental performance.

Project outcomes will increase understanding of environmental impact-reduction technologies, help clarify the decision-making context for the selection of these technologies on vessels, and inform the development of the decision support framework developed through the larger Pathways to Zero-Impact Shipping project.

1.2 Approach and Methodology

This study included a desktop review of existing technologies, engagement with subject matter experts, semi-structured interviews with individuals in the ship design industry, and the exploration of several case studies. The approach was divided into the following steps:

Step 1. Technological Review

A desktop literature review of ship impact-reduction technologies was conducted. First, literature was collected by the UBC research team using academic search engines, reference lists from articles, and recommendations from academic journal recommender algorithms. This was then synthesized with existing knowledge at Dillon-ABL to provide an understanding of the current technological landscape and an inventory of key technologies being considered by industry players and in research.

Step 2. Subject Matter Expertise Engagement

The Dillon-ABL team analyzed technology options, drawing on internal expertise in naval engineering, naval architecture, and decarbonization. The team provided insights into the complexities of different impact-reduction technologies and their real-world applications.

Step 3. Focused Interviews

In consultation with the Dillon-ABL team, the UBC research team conducted targeted interviews with specific individuals from various organizations, both private and public, within the ship-design industry. The aim of the interviews was to gain deeper insights into the implementation and decision-making processes related to impact-reduction technologies. The insights gleaned from these interviews were then analyzed to explore, confirm and adapt existing perceptions arising from literature review and judgments of the Dillon-ABL team regarding how decisions are typically made around the adoption of impact-reduction technologies.

Step 4. Validation

Interview data were validated and complemented by the Dillon-ABL team through dialogue with members of their professional networks. This involved reaching out to key stakeholders, industry experts, and relevant organizations to validate the findings, gather supplementary data, and ensure the robustness and credibility of the findings.

2.0 Environmental Impacts of Marine Shipping

Environmental impacts of marine shipping can be physical, chemical, biological or acoustic. This section explores these impacts as informed by the literature review and insights gleaned from expert interviews. These environmental impacts are the problems that need to be solved by the technologies catalogued in the section that follows this one.

2.1 Greenhouse Gas Emissions and Air Pollution

Atmospheric emissions from the ship engine include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), nitrogen oxides (NO_x), particulate matter (PM), black carbon, volatile organic compounds (VOCs), ozone-depleting substances and sulfur oxides (SO_x) (Walker et al., 2019; Transport Canada, 2010). These pollutants have consequential impacts on the environment, including on human health. For example, NO_x contributes to the formation of ground-level ozone (or smog) when reacting with volatile organic compounds (VOCs) in the presence of sunlight (Transport Canada, 2010). It is also implicated in the formation of acid rain and nutrient loading which can cause algal blooms (de Vries, 2021). SO_x can travel hundreds of kilometres inland, contributing to the development of health harming PM and ecologically destructive acid rain (EPA 2023 a,b). Ground-level ozone is harmful to humans, contributing to premature deaths and lost productivity (Health Canada, 2021). It is also known to impact ecosystems by reducing primary productivity and CO₂ uptake and inducing premature senescence in plants (ECCC, 2011). Air pollution has been highlighted as a paramount concern by industry members who focus on impact-reducing technologies, with the reduction of GHG emissions being identified as a top priority among interview participants in this study.

Greenhouse gases (CO₂, CH₄, N₂O) exhibit varying global warming potentials and atmospheric lifespans. As these gases accumulate in the atmosphere, they increase atmospheric warming through the so-called greenhouse effect. Black carbon contained in ship exhaust further exacerbates this effect. CO₂ is released in large quantities as a result of fuel combustion in marine engines. In 2018, global marine shipping emissions represented 1,056 Mt of CO₂ emissions (Deng & Mi 2023) or 2.9% of global anthropogenic CO₂ emissions (European Commission, n.d.). Methane slip, or the release of unburned methane that has not fully combusted in the ship's engine, is associated with the use of liquefied natural gas (LNG) fuels in the marine shipping industry.

Emissions of atmospheric pollutants and GHGs depend on the type of fuel, engine, treatment considerations, and engine efficiency of vessels (Walker et al., 2019). Between 2012 and 2018, it is estimated that CO₂ emissions from marine shipping grew by 11% and methane emissions by 145%, due to the increased use of LNG as a marine fuel. These emissions are predicted to increase by 16% from 2018 to 2030, and 50% by 2050 without additional policy efforts (The International Council on Clean Transportation, n.d.).

2.2 Anthropogenic Noise and Vibrations

Commercial marine shipping is a source of anthropogenic underwater noise (URN) and its contribution to URN have been increasing in recent years. Noise is mainly generated by propeller cavitation and onboard machinery (Transport Canada, 2020). Marine vessels generate low-frequency sounds that efficiently travel in deep water marine environments. URN can overlap with frequencies used by marine mammals to communicate, navigate, feed and reproduce. The interference of URN with mammal communication poses a recognized threat to several species (Transport Canada, 2020). Anthropogenic noise and vibrations emerged as a key concern among multiple participants interviewed to inform this report. However, the significance of this impact appears to vary depending on the industry or region, particularly in areas where URN has been observed to adversely affect marine life, such as the Southern Resident Killer Whale population in British Columbia, Canada.

A study conducted between 2015 and 2018 in the Strait of Georgia off Canada's Pacific Coast showed that container ships (> 200 m long), bulkers (> 200 m long), ferries, tankers and bulkers (< 200 m long) were the five loudest vessel classes for which measured average radiated noise levels ranged between 189.7 dB for container ships (> 200 m long) and 185.9 dB for bulkers (< 200 m long) (Port of Vancouver, 2019). Noise levels are also dependent on the vessel speed, vessel design, and propeller and hull maintenance (IMO, 2013b). It has been noted that absolute volume should not be the sole consideration when evaluating the impacts from URN, and that the consistency of traffic noise over time, even at lower levels, should also be examined. Noise is particularly a chronic issue in coastal areas near shipping lanes, ferry routes and ports, while critical habitat of whales overlaps with major shipping routes (Breeze et al., 2022). Noise impacts on marine mammals are difficult to assess and depend on many variables including salinity, type of noise, conditions at the ocean floor, temperature, vulnerability of species, and the depth of water (Bradley & Stern, 2008).

2.3 Operational and Accidental Discharges

Marine shipping can cause both accidental and operational discharges into the marine environment. Accidental discharges may occur due to unintended incidents such as spills or leaks, while operational discharges are regularly produced during routine activities. These discharges encompass a wide range of substances, including but not limited to: fuels, lubricants, chemicals, and waste products. The pose environmental risks and necessitating effective management strategies. Specific examples of operational and accidental discharges include:

2.3.1 Ballast Water and Invasive Species Transmission

Water is held in the ballast tanks holds of vessels and routinely pumped into surrounding waters to provide stability in response to changing cargo weights or sea conditions. Because ballast water can contain and transfer marine species, microbes and many other elements, its release can contribute to the introduction of harmful invasive species. Marine shipping vessels globally transfer approximately 3-5 billion tonnes of ballast water annually (Walker et al., 2019). While all ships are required to implement a Ballast Water Management Plan (MEPC.50(31), ballast water continues to introduce aquatic invasive species (Walker et al., 2019).

2.3.2 Greywater and Blackwater

Greywater is wastewater from various activities, including showers, galleys, laundry, and cleaning activities onboard. Greywater may contain a wide range of contaminants such as pharmaceuticals, detergents, food particles, bacteria, and microplastics among others, all of which can impact water

quality and increase nutrient loads in receiving waters, creating a health hazard for humans and marine life (Nuka Research and Planning Group, 2019; Vard Marine Inc., 2019). Cargo vessels produce approximately 125 L of greywater per person, per day, while cruise ships produce more than double that amount due to the relatively large number of passengers and crew onboard (Vard Marine Inc., 2019).

Sewage, also known as black water, includes human body wastes and associated components from septic systems such as toilet water and sewage sludge. Blackwater is composed primarily of water, but also includes contaminants such as solids, nutrients, pathogens, organic chemicals, metals, oil and grease, and plastic (Clear Seas).

2.3.3 Scrubber Washwater

Scrubber wash water is produced by exhaust gas cleaning systems commonly known as scrubbers. Scrubbers remove SO_x from ship exhausts when heavy fuel oil (HFO) is burned, allowing vessel operators to meet regulated SO_x limits without resorting to higher priced fuels. Wash-water is a highly contaminated and acidic by-product of the scrubber process, which is frequently released directly into the ocean. Pollutants present in wash water are detrimental to aquatic life and can have localized acidifying consequences. While some types of scrubbers (closed-loop and hybrid scrubbers) can capture the wash water for storage and disposal on land, most vessels with scrubbers discharge directly to the surrounding waters. Moreover, even closed-loop technologies release some wash-water, which can contain high concentrations of contaminants (Clear Seas).

2.3.4 Solid Waste

It is estimated that more than 636,000 tonnes of marine debris enter the sea from ships each year, with cruise vessels being the greatest source of waste (Dabrowska et al., 2021). Ship-generated solid waste can be associated with lost cargo, litter, and discarded or lost deck debris and can include glass, metal, plastic, organic waste and paper, some of which may be hazardous to marine life (Walker et al., 2021). Of these solid wastes, plastics pose a significant threat to marine life, from plankton to large mammals, and can remain in the marine environment for years where they are unlikely to biodegrade (Jambeck, 2018; IMO, n.d.). Plastics can accidentally be ingested by marine species (e.g., birds, fish, cetaceans), where they obstruct the species' digestive system, leading to malnutrition and/or lethal effects due to physical harm or poisoning. Marine species can also become trapped in plastic items (IMO, n.d.). Bacteria, algae, and other types of invasive species are also able to attach and grow on plastics drifting across the globe, becoming vectors of disease or invasive species once in foreign environments (Jambeck, 2018). Solid waste (i.e., garbage, overboard disposal, recycling) was identified in interviews as a relevant environmental impact that deserves more attention.

2.3.5 Bilge Water and Oily Waste

Oily waste generated by ships in their operations may include propeller shaft oil, cargo residues, and bilge water (Walker et al., 2019; Clear Seas, n.d.). Bilge water contains a mixture of oil, sludge, chemicals, detergents, and other pollutants from ship operations.

2.4 Biophysical Impacts

Whales are the species most frequently impacted by ship-strikes. The risk of a fatal collision considerably increases with the size and the speed of the vessel but is also dependent on the species time spent at or near the surface, behaviour at the surface, hearing capabilities, and behavioural response to vessels

(Schoeman et al., 2020). Along the Atlantic coastline of the United States and Canada and the Gulf of Mexico, a total of 37 whales were reported injured following collisions with marine vessels from 2010 to 2017, but this number is likely low because of unreported death and injuries (National Marine Fisheries Services, n.d.).

Between 2017 and 2024, just over one-third (15 out of 41) of endangered North Atlantic right whale recorded deaths were attributed to vessel collisions (NOAA, 2025). The number of deaths for other smaller marine mammal or turtle species are even more likely to be underestimated as they are less likely to be noticed by mariners and the dead animals are less likely to be recovered on beaches (National Marine Fisheries Services, n.d.). The impact of collision-related mortality on species populations is not well understood (Schoeman et al., 2020), but they are likely to severely limit the recovery of the North Atlantic right whale population, one of the whale species the most vulnerable to and most affected by reported ship strikes (MMON et al., 2022; Walker et al., 2019).

3.0 Ship Impact Reduction Technologies

Cette section présente un catalogue des technologies de réduction des impacts environnementaux des navires pouvant s'appliquer aux navires neufs et aux navires déjà en service. Ce résumé s'appuie sur l'expertise de Dillon-ABL et de spécialistes externes qui ont apporté leur expérience dans ce domaine lors de consultations ou d'entretiens. Nous répertorions d'abord les technologies connues, suivies d'un tableau indiquant les impacts environnementaux sur lesquels elles agissent.

3.1 Available Impact Reduction Technologies

Technologies are grouped into six different categories and are briefly described as follows:

- a. **Hydrodynamic Improvements:** These technologies prioritize enhancing the ship's performance in water by refining the efficiency of its underwater hull and appendages.
- b. **Aerodynamic Improvements:** These technologies focus on minimizing the ship's air resistance and optimizing its behavior in windy conditions.
- c. **Outfitting Improvements:** This category encompasses energy-efficient technologies and materials aimed at reducing the ship's hotel power consumption and enhancing its overall sustainability.
- d. **Mechanical Improvements:** These are improvements to the mechanical systems of the ships such as generators, engines, and motors. Because the main engines and generators are the bigger power consumers on the ship, there are high potential gains in efficiency and reduction in emissions. They can even include replacing conventional propulsion with wind propulsion.
- e. **Operational Improvements:** This category addresses strategies pertaining to navigation, big data and analytics, route planning, and operational practices aimed at reducing the ship's overall environmental footprint.

3.1.1 Hydrodynamic Improvements

Hydrodynamic improvements to vessel design are often informed by computational fluid dynamic analysis or tank tests and can result in a significant reduction of emissions over the lifetime of the vessel due to lower resistance and therefore fuel requirements. Existing hull forms can benefit from the greatest improvements through refinement of the bow sections which can yield up to a 7% reduction in fuel consumption (Tanttari, 2020). Hydrodynamic improvements encompass a wide array of improvements associated not only with the vessel's hull but also with its rudder, propeller, and various other appendages. These enhancements are designed to optimize the vessel's performance in water, reduce drag, enhance maneuverability, and improve overall efficiency.

Hydrodynamic improvements often require little to no additional training, maintenance burdens, or increased workload for crew members. The timely installation of these designs, especially during pre-scheduled dry-docking periods, can reduce costs and interruptions to operations that would otherwise accompany implementation. Synergies with other interventions are available by combining multiple hydrodynamic enhancements to achieve a net benefit, such as pairing azimuth thrusters with enhanced hull design to optimize efficiency.

There are many different types of hydrodynamic improvements, as summarized below.

3.1.1.1 High Efficiency Propellers

Refined blade shapes incorporate foil profiles aimed at minimizing drag and cavitation. Non-uniform chord distribution aids in distributing loads evenly across the blade span, thereby diminishing energy loss due to uneven pressures. Optimization of parameters such as the number of blades, skew, aspect ratio, and blade area ratio contributes to the creation of a highly efficient propeller.

Insights gleaned from the interview process reveal that propeller design innovations have become influential technologies offering favorable returns on investment and significant cost savings. Moreover, it's crucial to acknowledge that advancements in propeller design can also mitigate impacts associated with URN and ship strikes. For instance, design enhancements aimed at reducing cavitation can effectively decrease URN, while positioning the propeller higher on the vessel can lower the risk of ship strikes for marine mammals like whales. It is worth noting that there are various forms of cavitation on propellers, each displaying different cavitation inception speeds (CIS) and subsequent noise characteristics.

Propeller Boss Cap Fins (PBCF): Mounted at the front of the propeller hub, PBCFs modify the water flow entering the propeller, reducing swirl and improving overall efficiency.

Application	Benefits	Challenges
New build and retrofits for larger ships	Enhanced propulsive efficiency	Implementation cost



(Hansen, 2011)

Blade tip rake: Blade tips help mitigate the development of tip vortices, which can cause energy loss and cavitation. They reduce the pressure difference between the blade tips and the surrounding water. Applied to vessels that require precise maneuverability, such as ferries, tugs, and workboats. These devices minimize the energy loss associated with tip vortices during frequent speed changes.

Application	Benefits	Challenges
New build and retrofits for all ships	Enhanced propulsive efficiency, noise reduction	Implementation cost



(Feizi, 2013)

3.1.1.2 Propeller Nozzles & Ducts

There are different types of nozzle and ducts that can be installed around or close to the propeller to minimize turbulence in the water stream to and off the propeller, improving efficiency and ultimately reducing fuel consumption. The following are different available propeller nozzles or ducts that can be adopted by new designs or retrofitted:

Kort nozzles, which are fitted around the propeller, aid in the acceleration of water flow as it exits the propeller. Primarily employed in low-speed and high-load scenarios such as towing, they exhibit reduced efficiency at higher speeds.

Application	Benefits	Challenges
New build, and retrofits for low speed range and high torque application	Enhanced propulsive efficiency	Reduced efficiency at higher speeds, increased weight



(Damen, 2022)

Mewis ducts® are fitted forward of the propeller, around the tail shaft housing. Inside of the duct, there are a number of fins that guide the water towards the propeller. The largest efficiency increase occurs for heavily loaded propellers with speeds of up to 20knts (Mewis and Guiard, 2011).

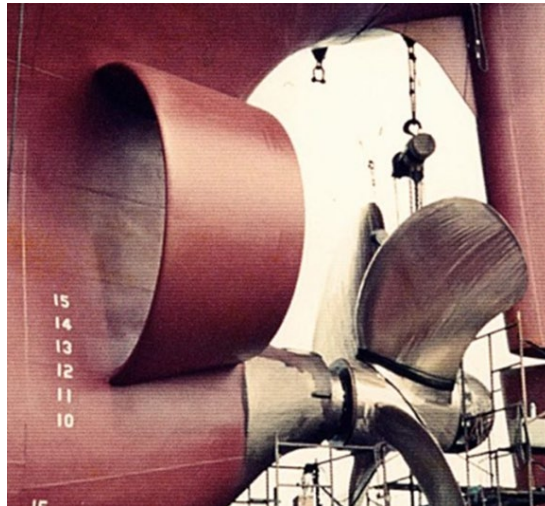
Application	Benefits	Challenges
New build and retrofits, large ships	Enhanced propulsive efficiency, vibration reduction	Implementation cost



(Becker Marine, 2020)

Wake-Equalising Ducts (WEDs) which are fitted ahead to the upper two quadrants of a propeller on ships with high block coefficients. Similarly to the Mewis ducts, the WED's guide the inflow of water to the propeller and prevent turbulent flow.

Application	Benefits	Challenges
New build and retrofits, large ships	Enhanced propulsive efficiency	Implementation cost



(Schneekluth Hydrodynamik, 2019)

3.1.1.3 Fins & Guides

Fins and guides on a ship control water flow for improved maneuverability, stability, and performance. Bilge fins, located on the hull's sides or beneath the waterline, reduce rolling motion and enhance stability by generating lift or resistance. Meanwhile, guides, positioned near the propeller or thrusters, optimize propulsion efficiency by directing water flow towards the propeller (pre-swirl) or recover energy from the slipstream behind the propeller (post-swirl).

The following are different available solutions depending on the location and arrangement of the fins or guides:

Grim Vane Wheel: A rotating large diameter “wheel” located aft of the propeller, with a diameter larger than the propeller, and sectional variation from turbine blade profiles to propeller blade profiles. Generates additional thrust by accelerating the water flow exiting the propeller.

Application	Benefits	Challenges
New build and retrofits, large ships all speeds	Enhanced propulsive efficiency	Implementation cost, maintenance required



(Martinli, 2008)

Pre-swirl stator: Fins fitted forward of the propeller that increase its efficiency by imparting a swirl to the water stream.

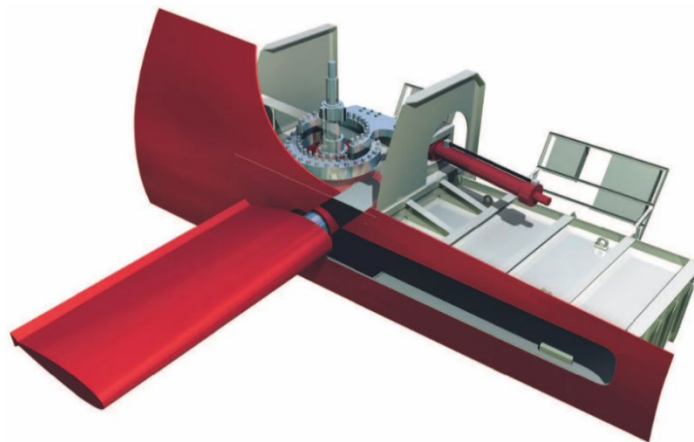
Application	Benefits	Challenges
New build and retrofits, high block coefficient ships	Enhanced propulsive efficiency	Implementation cost



(Waterborne.eu, 2024)

Retractable Bilge fins: Bilge fins are hull appendages that are fitted to the bilge area of the hull and help stabilize the ship against rolling motions. Bilge keels can be passive if they are just fixed in place, or active if the fins rotate as the ship moves. Bilge fins do increase the resistance of the hull, and therefore the fuel consumption. Retractable bilge fins can be retracted within the hull when the sea state does not require roll damping, increasing the efficiency of a ship as compared to one fitted with regular non-retractable fins.

Application	Benefits	Challenges
New build and retrofits, calm seas	Enhanced efficiency	Cost, maintenance, need for space, and complexity



(Wartsila, 2024)

Bow Thruster Grillages: the openings of bow thrusters carry a penalty in overall hull efficiency due to the flow disruption created by the opening. One way to mitigate this disruption is installing grids in the way of the opening. These grids can be just vertical bars or more complex geometries such as the Elogrid solution. The Elogrid aims to increase bow thruster efficiency by streaming the flow to the propeller (Tanttari et al., 2022).

Application	Benefits	Challenges
New build and retrofits	Increase in hull efficiency and thruster efficiency, decrease in vibrations	Cost



(Eliomatic, 2023)

3.1.1.4 Bow Geometry

The bow plays a pivotal role in determining the efficiency of a ship as it directly influences its movement through the water. An effectively designed bow has the potential to decrease water resistance and mitigate drag, thereby enhancing fuel efficiency. Various bow geometries serve distinct purposes, some of which are outlined below:

Bulbous bow: Positioned at the forefront of a ship's hull, the bulbous bow features a protruding, bulb-like structure. This design element creates a distinct wave pattern that interacts with the ship's own wave, minimizing resistance. The efficacy of a bulbous bow is contingent upon the ship's draft, making it most effective for vessels capable of maintaining the intended operational draft.

Originally, bulbous bows were tailored to a ship's predominant operating speed. However, contemporary designs often accommodate a broader spectrum of speeds and loading conditions, sometimes incorporating adjustable or retractable bulb configurations. With the growing emphasis on curbing GHG emissions through practices like slow steaming—reducing vessel speed to decrease fuel consumption and, consequently, emissions—bulbous bows calibrated for specific speeds may necessitate replacement to optimize GHG emission reduction efforts.

Application	Benefits	Challenges
New build, displacement ships with constant draft	Enhanced efficiency	Gains limited to specific draft and speed



(Shipwright.biz, 2014)

Inverted bow: Vertical or inverse bows like the Ulstein X-Bow, Damen Axe-Bow, and Groot Cross-Bow are engineered to optimize performance across various speeds and draughts. By minimizing slamming and pitching, inverted bows enhance seakeeping abilities (vessel's capability to navigate and maintain stability in various sea conditions), thereby allowing for a reduction in sea margin and, consequently, a decrease in overall installed power.

Application	Benefits	Challenges
New build, all ships	Enhanced efficiency, reduction in vibrations in high seas	Implementation cost, impact to ship's arrangement



(Stoichevski, 2014)

Wave-piercing bow: This configuration features an exceptionally slender, almost knife-shaped bow, designed to cut through waves instead of riding over them. It is commonly employed in medium-sized multi-hull ferries.

Application	Benefits	Challenges
New build, high speed multi-hulls	Enhanced handling and comfort	Implementation cost, impact to ship's arrangement, complexity



(incat.com.eu, 2018)

Winged bow: This design incorporates a horizontal extension to the bow, aiding in the reduction of both overall resistance and wave slamming.

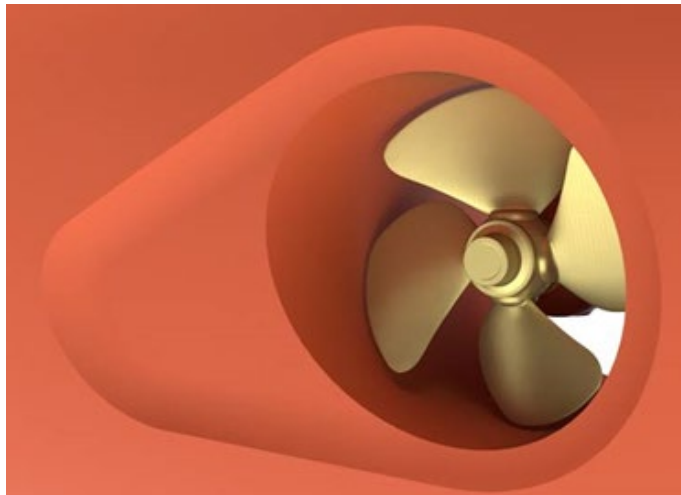
Application	Benefits	Challenges
New build, fine bow forms, limited sea states	Enhanced efficiency and handling and comfort	Implementation cost, novel solution with limited application



(maritimeexecutive.com, 2020)

Bow thruster improvements: The majority of large commercial ships have one or two bow thrusters fitted within transverse tunnels. The geometry around the tunnel opening can be improved by using scallops. Scalping involves shaping the leading or trailing edges of the bow thruster propeller blades in a curved or scalloped pattern. The edge scallops aim to help direct the flow past the tunnel opening with the least possible disturbance.

Application	Benefits	Challenges
New build and retrofits	Enhanced efficiency	Cost and difficulty to retrofit



(Wartsila, 2023)

3.1.1.5 Rudder Geometry

The efficiency of a ship is significantly impacted by the design of its rudder, as it affects both resistance and maneuverability. An optimized rudder is instrumental in directing water flow around the stern, thereby enhancing the ship's wake and reducing resistance. Various types of rudder designs include the following:

Flap rudder: An adjustable flap is added to the trailing edge of the rudder, improving steering responsiveness. The increased action of the flap allows for the use of a smaller overall rudder, and therefore reduces appendage resistance.

Application	Benefits	Challenges
New build, retrofit	Enhanced efficiency and handling and comfort	Cost and maintenance



(nauticexpo.com, 2018)

Efficiency rudder: Efficiency rudders effectively integrate the rudder horn with the propeller hub via a bulb. This bulb improves propulsive efficiency and reduces noise and vibration. Technology Patented by Wartsila.

Application	Benefits	Challenges
New build, retrofit	Enhanced efficiency and handling and comfort	Cost and maintenance



(Wartsila, 2016)

Gate rudder: Instead of a solitary rudder situated behind the propeller, the gate rudder system utilizes two vertically oriented, symmetric blade surfaces that enclose the propeller on both sides. These paired blades are adjustable independently, offering precise control over water flow. This configuration enhances hydrodynamic efficiency by minimizing rudder resistance and generating supplementary thrust, potentially resulting in an energy consumption reduction exceeding 10%. The system is especially advantageous for vessels equipped with heavily loaded propellers, such as container ships or multipurpose vessels.

Application	Benefits	Challenges
New build, large ships	Potential energy consumption reduction exceeding 10%, maneuverability	Implementation cost, maintenance, complexity



(Gaters, 2020)

3.1.1.6 High Performance Antifouling Coatings

Advanced antifouling coatings are engineered to enhance a vessel's hydrodynamic performance by minimizing the friction and drag between the hull and water. This enhancement translates into fuel savings and a decrease in GHG emissions. Typically administered to the submerged sections of ships, including the hull and propellers, these coatings serve to deter the attachment of marine organisms such as barnacles, algae, and mollusks. By preventing the accumulation of these organisms, which can cause surface roughness, these coatings mitigate drag, thereby optimizing the vessel's efficiency and reducing fuel consumption and operational expenses. Various types of low-friction antifouling coatings include:

Self-Polishing Copolymers: These coatings gradually release biocides, which are antifouling agents harmful to marine life, as the outer layer erodes or dissolves. This controlled release prevents fouling organisms from settling on the hull, ensuring a consistently smooth surface.

Application	Benefits	Challenges
New build, retrofit	Fuel savings, decreased emissions, efficiency, supportive of ship maintenance and operating costs	Toxin release

Silicone-Based Coatings: Recognized for their water-repellent properties, silicone-based coatings create smooth surfaces that deter fouling organisms and minimize drag. Despite their efficacy, these coatings tend to be more costly than traditional biocide-based antifoulings. Many require a minimum time underway and operating speed as specified by manufacturers. Industry marketing materials suggest fuel savings and GHG emission reductions ranging from 3% to over 10%. Some variants, such as hydrogel coatings, manipulate the hull's surface to appear as liquid to marine organisms, thereby deterring attachment.

Application	Benefits	Challenges
New build, retrofit	Fuel savings and GHG emission reductions ranging from 3% to over 10%, environmentally friendly	Costly, lower longevity than copolymer coatings, maintenance

Ultrasonic Anti-Fouling: An array of ultrasonic transducers is installed inside of the hull, against the shell plate, and used to emit different frequency sounds. The emitted frequencies produce a high-pressure layer around the hull, which prevents small organisms from attaching to it. The system can be tuned to different frequencies in order to target different organisms such as biofilm, algae, barnacles or mollusks. Ultrasonic anti-fouling systems work better when paired with a properly applied anti-fouling paint coat.

Application	Benefits	Challenges
New build, retrofit	Enhanced efficiency, supportive of ship maintenance	Cost, concerns with URN

3.1.1.7 Hull Air Lubrication

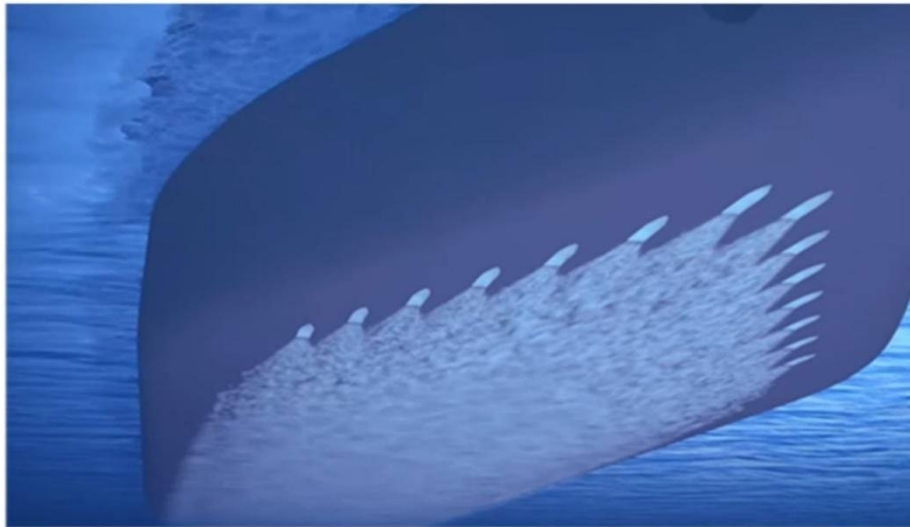
Hull air lubrication involves introducing a layer of air bubbles or a thin layer of air between the ship's hull and the water. The air layer reduces the frictional resistance between a ship's hull and the surrounding water. Frictional resistance, also known as skin friction, is a major contributor to the energy consumption of ships as they move through the water. By reducing this resistance, ships can operate more efficiently. These systems can provide a fuel saving, and therefore emission reduction of 5% to 10%. The systems are particularly effective on ships with a large flat bottom, with relatively high speed and low draft. Examples of hull air lubrication include the following:

Bubble injection involves the introduction of tiny air bubbles either from the ship's surface or along the hull to establish a layer of air between the hull and the water. This continuous layer effectively minimizes the contact and interaction between the hull and the water.

Application	Benefits	Challenges
New build, limited sea states	Enhanced efficiency, reduction in URN	Cost, maintenance, complexity, and space on the vessel

Air cavity systems incorporate a structural design wherein a physical cavity or chamber is integrated along the ship's hull, filled with air. This design aims to eliminate direct contact between the hull and the water, resulting in reduced friction.

Application	Benefits	Challenges
New build, limited sea states	Enhanced efficiency, reduction in URN	Cost, maintenance, complexity, and space on the vessel



(Love, 2020)

3.1.1.8 Hull Design

3.1.1.8.1 Hull Geometry

Hull fairing and streamlining are specific design techniques used to improve the ship's hull geometry and hydrodynamic efficiency. Hull fairing involves smoothing out imperfections on the hull surface's curvature. Hull fairing starts in the design process by analysing the hull curvature by means of computer 3D software and therefore is applicable to new builds. Similarly, streamlining involves designing the hull shape in a way that reduces the resistance of the vessel. By optimizing the hull form the ship can experience reduced drag, and therefore reduced fuel consumption. Both streamlining and hull fairing may also be used with a focus to reduce the underwater noise produced by the ship.

Hull design emerged as a prominent theme in interviews among participants and was consistently identified as a crucial factor in minimizing environmental impacts across various contexts, including reductions of emissions (i.e., increasing fuel efficiency by lowering drag and underwater noise). Improved hull design is also thought to have a favourable rate of return relative to other technologies.

In addition, the optimization of the hull geometry for light and efficient construction and the use of high tensile steel during new design are ways to reduce the overall lightweight of the ship and therefore minimize the fuel consumption per unit weight of cargo.

Application	Benefits	Challenges
New build	Enhanced efficiency, reduce URN	Design cost

3.1.2 Aerodynamic Improvements

Aerodynamic improvements are enhancements made to the vessel's design or components to minimize air resistance or drag when moving through the air. These improvements primarily focus on reducing the vessel's aerodynamic profile and optimizing airflow around structures. By streamlining the ship's shape and reducing the resistance caused by wind, aerodynamic improvements can enhance fuel efficiency. Examples of aerodynamic improvements may include sleeker designs, fairings, repositioning or reshaping of structures, and the use of wind tunnel testing to optimize airflow patterns.

3.1.2.1 Superstructure Fairings

Structures designed to deflect wind can be installed on the superstructure or forecastle of a ship to redirect airflow and decrease aerodynamic drag. Wind fairings are frequently installed on container ships and bulk carriers, as these vessel types commonly benefit from such aerodynamic enhancements.

Application	Benefits	Challenges
New build, retrofits. Ships with high superstructures or cargo	Enhanced efficiency	Capital Cost



(FullAvanteNews, 2022)

3.1.3 Outfitting Improvements

Outfitting improvements are energy-efficient technologies and materials that minimize the power consumption of the ship's onboard systems (referred to as hotel power). These technologies and materials are focused on optimizing energy usage across various aspects of the vessel's operations, from lighting and HVAC systems to auxiliary machinery, with the overarching goal of reducing energy demands throughout the ship's life.

3.1.3.16 HVAC Systems

High-efficiency Heating, Ventilation, and Air Conditioning (HVAC) systems are engineered to enhance climate control within a ship while minimizing energy usage. This reduction in HVAC consumption contributes to lower fuel consumption and a decreased carbon footprint for the vessel. Key features of high-efficiency HVAC systems include zoning, where climate settings are autonomously regulated for various areas based on real-time demands; variable speed compressors, which adjust their outputs to match heating and cooling requirements; and the incorporation of high-efficiency filters like HEPA filters, which not only enhance filtration effectiveness but also prolong the lifespan of the HVAC systems.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, comfort	Cost, complexity

3.1.3.2 High Efficiency Insulation

Insulation systems alleviate the strain on HVAC systems. Among the primary energy demands aboard a ship is the energy needed to maintain accommodation spaces within desired temperature and humidity levels. Utilizing modern sandwich insulating materials in floating floors and bulkhead panels enhances both climatic and acoustic insulation, effectively shielding interior spaces from external elements and minimizing sound transmission between areas. Furthermore, modern high-efficiency insulation offers the added benefit of weight reduction compared to conventional insulation methods.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, require little space, reduces onboard noise	Capital Cost

3.1.3.3 LED Lighting

LED lights offer significantly higher efficiency compared to traditional fluorescent or incandescent lighting options. Due to their reduced power consumption and heat generation, ships equipped with LED technology experience lower overall energy usage. Moreover, LEDs boast a longer lifespan, contributing to reduced operational costs for ship owners and operators. The plug-and-play nature of most LED solutions eliminates the need for extensive modifications to the ship, making them an appealing choice for maritime stakeholders.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, reduction in maintenance due to lifespan, reduced operating costs	Cost, sensitivity to harmonic distortion

3.1.3.4 Incinerators

Shipboard incinerators serve as vital waste management tools, effectively handling solid and sludge waste. By burning solid waste, bio residue, and oily sludge onboard, incinerators help diminish waste volume and weight, leading to a more streamlined and compact waste management system. On the downside incinerators produce exhaust greenhouse gases and particulate matter, Recuperative incinerators can recover and use a portion of the waste heat from exhaust gases. Residual ash from the incineration process is collected onboard and disposed of at port facilities.

Application	Benefits	Challenges
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New build, retrofits	Reduce waste volumes and weight	Cost, maintenance, generate emissions (GHG)
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3.1.3.5 Gasifiers

Similar in structure to incinerators, gasifiers differ in their waste treatment approach. Rather than burning waste, gasifiers utilize heat to break down waste into char and gas, with the resulting gas used to fuel the gasification process.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, circular approach, minimize space and weight associated with waste	Cost, complexity, maintenance

3.1.3.6 Trash Compactors

Compactors reduce the volume of solid waste onboard ships. By compacting trash, these systems facilitate easier storage and management of waste, potentially optimizing space allocation within the vessel.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, reduce volume of waste	Cost

3.1.3.7 Advanced Ballast Water Treatment Systems

Water ballast is used in ships to adjust and improve stability and loaded longitudinal strength. Ships load and discharge their ballast tanks with sea water through their ballast pumps, and often there is a potential for microorganisms to get transported between different geographical areas and ecosystems. While water ballast treatment and discharge are regulated through IMO and the ballast water management system (BWMS Code), there are different technologies available to ship owners. All systems work in two stages; the first stage is to prefilter the ballast water with a physical screen filter, and the second stage is to treat or filter the water to eliminate smaller microorganisms. The most commonly available technologies for the second stage filtration are: heat treatment, ultraviolet treatment, ultrasonic treatment, and chemical treatment. From those, heat treatment is an impact reduction technology that uses the waste heat from the ship's main engines or generators to pasteurize any microorganisms in the water.

Application	Benefits	Challenges
New build, retrofits	Support the management of microorganisms	Cost, complexity, maintenance

3.1.4 Propulsion Improvements

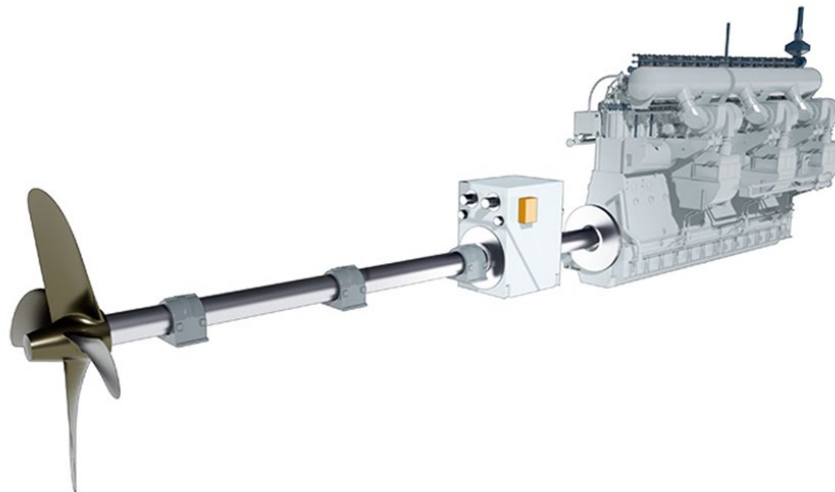
Propulsion improvements are enhancements of the way the ship is propelled, including improvements to the vessel's mechanical systems by upgrading components like generators, engines, and motors. Given that the main engines and generators are significant power consumers, implementing improvements in these areas holds substantial promise for enhancing efficiency and curbing emissions.

Interview respondents consistently underscored mechanical enhancements as impactful technologies for reducing environmental impact, notably emphasizing wind propulsion. They also recognized that the advantages of wind propulsion are heavily contingent on factors such as vessel type, trade routes, and operational patterns, as discussed in subsequent sections of this document. Additionally, interviewees noted the need for additional crew training and a potential increase in workload associated with implementing some of these innovations, which was identified as a significant barrier to adoption.

3.1.4.1 Shaft Generators

Shaft generators are electric generators connected to the main or auxiliary engines of a ship and used for power take off. The main engine is the mover of the shaft generator, and therefore an additional fuel burning engine is not required. The electric power produced by the shaft generators can be used for powering both propulsive and hotel loads. The main disadvantages of shaft generators is that they increase the engine load, and they will require the engines to run while at port.

Application	Benefits	Challenges
New builds, retrofits	Increased efficiency, GHG reduction, noise reduction	Additional power management systems required

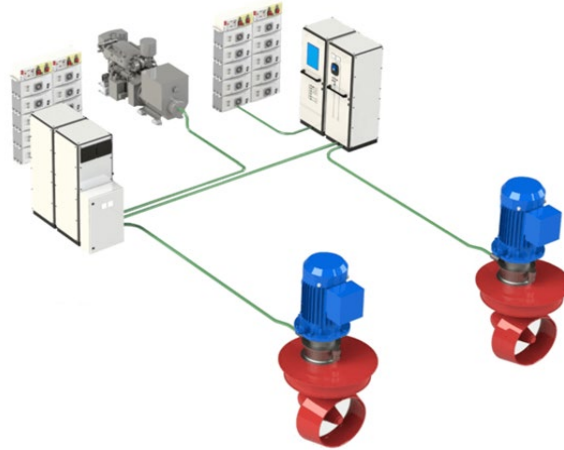


(Wartsila, 2024)

3.1.4.2 Diesel Electric Power Plant

A diesel-electric power system comprises one or more diesel engines responsible for driving generators to generate electricity. This electricity is subsequently managed and dispersed to propulsive electric motors via switchboards. Diesel-electric setups separate the diesel engine from the propeller, offering operational flexibility and modularity compared to conventional direct-drive systems. This enhanced flexibility in power generation boosts the overall propulsive efficiency of the ship, particularly in situations requiring operation at partial loads. Additionally, diesel-electric systems typically produce lower levels of vibration and noise compared to standard direct-drive configurations.

Application	Benefits	Challenges
New build, retrofits. Ships under variable loads	Efficiency, noise reduction, GHG emission reduction	Cost, not feasible for all vessels



(Teknik Ukeblad, 2020)

3.1.4.3 Variable Frequency Drives

A variable frequency drive (VFD) regulates the velocity and power production of electric motors. VFDs facilitate precise control over electric motor operations by adjusting the frequency and voltage delivered to the motor. The capability to operate electric motors at varying speeds in accordance with their workload enables more efficient power utilization compared to conventional constant speed motors. This means that engines can be kept within their most efficient operating speeds, reducing wasted energy.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, weight implications	Cost, complexity

3.1.4.4 Battery Bank Hybrid Systems

Hybrid systems are used together with shaft generators and lithium battery banks to assist the main engines with propulsive loads. The electric energy stored in the battery banks is used for reduced speed loitering, port maneuvers, and hotel loads. The battery banks are connected to the power management system of the ship, and charged by the main engines power take off or by a shore connection.

Application	Benefits	Challenges
New builds	Increased efficiency, GHG reduction, noise reduction	Space and weight, additional safety and power management systems



(Nones, 2017)

3.1.4.5 Fuel Cells

Fuel cells can contribute to a hybrid battery bank system by providing electric charge to the batteries. Fuel cells convert hydrogen into electrical energy. Concerns exist regarding the current limitations of fuel cell technology for larger vessels. The available options are presently constrained to operating within the kilowatt range, which presents challenges in meeting the higher megawatt-scale requirements commonly observed in larger maritime vessels. This disparity highlights a significant obstacle in the adoption of fuel cells for marine propulsion systems, emphasizing the necessity for further advancements to scale up their capabilities and align with the industry's requirements.

3.1.4.6 SO_x Scrubbers

SO_x (sulfur oxides) scrubbers, also referred to as exhaust gas cleaning systems or EGCS (Exhaust Gas Cleaning Systems), remove sulfur oxides from ship exhaust before they enter the atmosphere.

Insights gleaned from interviews shed light on shifting attitudes toward the adoption of scrubbers. Particularly, it was observed that there appears to be declining interest in scrubbers presently, attributed to diminishing cost differentials between low sulfur fuel and conventional fuel. This trend diminishes the economic incentive for scrubber installations compared to the option of purchasing low sulfur fuels. Other factors to consider include the negative impact of scrubber wash water if it is discharged directly into surrounding waters. Closed-loop systems that store wash water on board require storage, treatment, and eventual disposal on land of wash water by products and still release a smaller but highly

contaminated amount of waste. These insights underscore the dynamic and swiftly evolving landscape of technologies within the maritime industry.

Application	Benefits	Challenges
New build, retrofits, fuel oil engines	Reduction of SO ₂ emissions.	Wastewater discharge, maintenance, cost

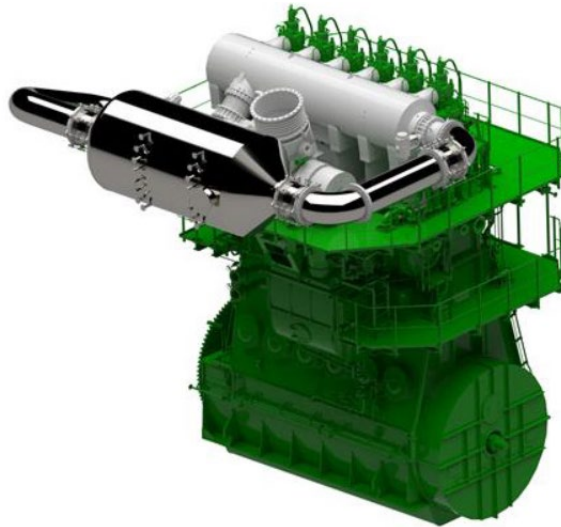


(Andritz.com, 2024)

3.1.4.7 Selective Catalytic Reduction

The use of catalytic converters in the marine industry is most often referred to as selective catalytic reduction (SCR). SCR is a cost and fuel effective way to reduce particulate matter, nitrogen oxide, and nitrogen dioxide emissions from diesel engines. SCR on ships are active systems which require a reducing agent (most frequently urea) to work. Implementing SCR requires additional space for urea tanks and increases the maintenance requirements of the powerplant.

Application	Benefits	Challenges
New build, retrofits. Fuel oil engines	GHG reduction (emissions)	Space, maintenance, cost, and complexity

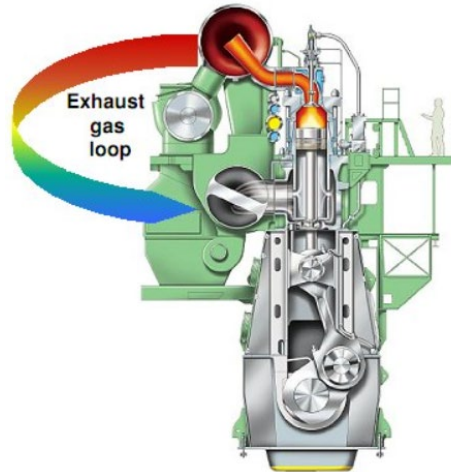


(jsea.or.jp,2022)

3.1.4.8 Exhaust Gas Recirculation

An exhaust gas recirculation system (EGR) employs exhaust gas to mitigate nitrogen oxide emissions from diesel engines. However, a notable drawback of this system is its potential to elevate engine maintenance requirements and possibly reduce available power. EGR systems find greater suitability with slow-speed engines typically found in large bulk carriers.

Application	Benefits	Challenges
New build, retrofits. Slow speed fuel oil engines	GHG reduction (emissions)	Cost, maintenance



(Egcsa, 2014)

3.1.4.9 Waste Heat Recovery

A waste heat recovery system refers to a technology designed to capture and harness surplus heat from various sources, such as the exhaust of main engines or generators. With internal combustion engines aboard ships typically squandering over 50% of valuable fuel energy as exhaust gas and heat losses (Farhat, 2022), there exists significant potential for onboard energy recuperation. Typically, a heat exchanger is installed in the exhaust stack to retrieve waste heat from the combustion engine, which is subsequently converted into steam or electricity via boilers or turbines.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency	Cost, maintenance, complexity

3.1.4.10 Onboard Carbon Capture

Onboard carbon capture (OCC) extracts carbon dioxide from exhaust gases during the vessel's operation. The primary method for carbon capture involves the deployment of chemicals, often ammonia-based, along with heat, to trap and contain carbon dioxide. Once captured onboard, the stored carbon dioxide can be offloaded at a suitable shore facility. While OCC has been recognized by some interviewees as a promising technology for reducing environmental impact and potentially yielding substantial cost savings, challenges related to storage and disposal have been highlighted as impediments to its widespread adoption. Additionally, concerns have been raised regarding the variability in measuring the effectiveness of OCC systems, casting doubts on its viability as a comprehensive solution for the maritime industry.

Application	Benefits	Challenges
New build, retrofits. Requires in-land support	Reduction in GHG emissions: CO ₂	Cost, maintenance, complexity, space, weight

(Hiles, 2020)



3.1.4.11 Wind Propulsion

Wind propulsion in ship design involves harnessing the power of wind to enhance vessel efficiency and reduce environmental impact. It includes various technologies such as sails, rotors, and kites that capture wind energy to supplement or even replace traditional propulsion systems like engines. Overall, savings from wind-assisted propulsion combined with weather routing can reach 30% for existing vessels and even more for new ships. Most projects focused on international shipping wind propulsion are actually wind-assisted propulsion projects. This means that the main propulsion is provided by internal combustion engines. For local transport and special applications, wind propulsion is also considered as a primary propulsion method.

Flettner Rotors are rotating cylinders placed on ship decks, harnessing aerodynamic thrust generated through rotation, powered by the ship's main gensets or battery packs. Generating lift and propulsion power, they offer fuel savings ranging from 5% to 20%, depending on rotor size, ship design, and prevailing wind conditions. Retrofitting existing vessels with these systems entails significant initial costs (EMSA, 2023).

Application	Benefits	Challenges
New build, retrofits. Route dependent, in combination with weather routing	Enhanced efficiency, high propulsive force generation, reduced noise, reduction in all air emissions including pollutants.	Need for crew training, less familiarity relative to other technologies. Does not work with upwind and downwind sailing.



(Downing, 2020)

Rigid / Semi Rigid Sails: These structures resemble aircraft wings in shape but are vertical and rigid or semi-rigid in construction. They can generate greater propulsion force per unit surface area compared to traditional fabric sails. With over 20 installations already in place and more under construction or discussion, the adoption of this technology is on the rise.

Application	Benefits	Challenges
New build, retrofits. Route dependent (less than rotors)	Enhanced efficiency, reduced noise, reduction in emissions including pollutants	Need for crew training, less familiarity relative to other technologies



(Saul, 2023)



(Wallenius Marine, 2020)

(Lewis, 2021)

Soft Sails: Available in multiple high-efficiency configurations, these sails offer the advantage of being stowable in limited space when not in use.

Application	Benefits	Challenges
New build, retrofits. Route dependent	Enhanced efficiency, reduced noise, reduction in emissions including air pollutants.	Need for crew training, less familiarity relative to other technologies



(Cockburn, 2021)

Suction Sails: Suction sails like Ventifoils or Turbosails feature a stationary wing with openings and internal fans or similar mechanisms to generate a suction current, maximizing propulsive force. These systems hold the potential for significant fuel savings and substantial reductions in emissions. Suction wings have been implemented on cargo ships and the first tanker with suction sails is anticipated to launch in 2014

Application	Benefits	Challenges
New build, retrofits, route dependent	Enhanced efficiency, high propulsive force generation, reduced noise, reduction in emissions including air pollutants	Need for crew training, less familiarity relative to other technologies



(Chambers, 2022)

Kites: The deployment of either mobile or stationary kites positioned at significant heights (in some concepts, 100s of meter high) to harness stronger winds, to assist in propulsion or generate both thrust and electrical power.

Application	Benefits	Challenges
New build, retrofits, route dependent	Enhanced efficiency, reduced noise, reduction in emissions including air pollutants	Need for crew training, less familiarity relative to other technologies, wear of the kite, complexity of application



(Berrill, 2023)

3.1.5 Operational Improvements

Operational improvements focus on enhancing efficiency, reducing emissions, and minimizing environmental impact during the vessel's operational phase. Operational improvements include route optimization, just in time arrival, hull cleaning and cold ironing.

3.1.5.1 Route Optimization

Route optimization tools, including ship sensors and big data analytics, offer real-time predictive insights into weather conditions, enabling shipping companies to enhance decision-making in route planning. By taking into account variables such as wind patterns, sea currents, and storm forecasts, vessels can select routes with favorable conditions, thereby reducing travel times and fuel consumption. Additionally, these tools facilitate strategic planning of bunkering stops to optimize onboard fuel levels. Machine learning tools can be utilized for route optimization, introducing predictive analytics to enhance operational efficiency. This collective insight underscores the potential synergies between advanced technologies, big data analytics, and operational strategies in optimizing ship performance and mitigating environmental impacts.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, reduction in emissions	Familiarity of crew and ship management, charter contracts

3.1.5.2 Just in Time Arrival

The concept of Just-in-Time (JIT) arrival at port involves optimizing the ship's port schedule to minimize idle time. This strategy enhances operational efficiency and reduces emissions during port stays. Studies suggest that globally implementing JIT arrival at ports could potentially reduce emissions by up to 30% (MarineTraffic, 2022).

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, reduction in emissions	Charter contracts/legal, familiarity by ship management

3.1.5.3 Hull Cleaning

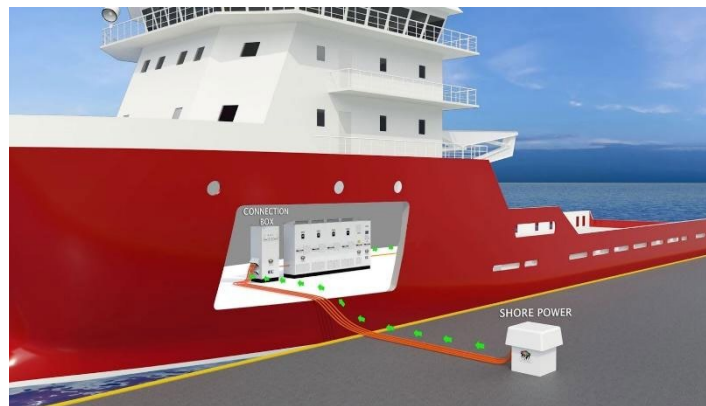
Adhering to a rigorous hull cleaning regimen is essential to prevent the accumulation of fouling organisms on submerged ship surfaces. Keeping the underwater hull clean not only decreases drag, leading to reduced fuel consumption, but also helps mitigate the adverse effects of invasive species. An instance of enhanced hull cleaning practices aimed at minimizing environmental repercussions was highlighted by interviews, which cited the adoption of self-cleaning hulls.

Application	Benefits	Challenges
New build, retrofits	Enhanced efficiency, reduction in emissions, supports maintenance efforts	Biofouling can occur.

3.1.5.4 Cold Ironing

Cold ironing, alternatively termed shore-to-ship power, entails a vessel berthed at port shutting down its onboard generators and instead linking to the local shore grid. This practice significantly reduces fuel consumption and emissions during port stays. To facilitate cold ironing, ports must be equipped with suitable high-voltage electrical connections at berths. This initiative holds promise for achieving a complete emissions reduction of up to 100% while ships are docked at port.

Application	Benefits	Challenges
New build, retrofits. Required port infrastructure	Enhanced efficiency, reduction in emissions	Increased cost for the ports, energy grid improvement and additional renewable energy generation needed



(AKA Energy Systems, 2021)

3.2 Environmental Impacts Affected by Technology

The technologies presented above can affect multiple environmental impact areas. These impacts can be positive or negative. The matrix presented in Table 1 below maps which environmental impacts need to be considered for each technology in the catalogue.

Table 1. The Relationship between Ship Impact Reduction Technologies and the Effects of Marine Shipping

			Environmental Impacts of Marine Shipping			
			GHG Emissions & Air Pollution	Noise & Vibration and Physical Disturbance	Water Pollution from Vessel Discharges (ballast, greywater, blackwater, bilge water, scrubber wash water) & Solid Waste	Introduction of Invasive Species
Existing Impact-Reduction Technologies	Hydrodynamic Improvements	High Efficiency Propellers	X	X		
		Propeller Nozzles/Ducts	X	X		
		Fins and Guides	X			
		Bow Geometry	X			
		Rudder Geometry	X	X		
		High Performance Antifouling Coatings	X		X	X
		Hull Design	X	X		
	Aerodynamic Improvements	Superstructure Fairings	X			
	Outfitting Improvements	HVAC Systems	X			
		High Efficiency Insulation	X			
		LED Lighting	X			
		Incinerators	X		X	
		Gasifiers	X		X	
		Compactors	X		X	
		Advanced Ballast Treatment			X	X
	Propulsion Improvements	SO _x Scrubbers	X		X	
		Selective Catalytic Reduction	X			
		Exhaust Gas Recirculation	X			
		Waste Heat Recovery	X			
		Onboard Carbon Capture	X		X	
		Fuel Cells	X	X	X	
		Variable Frequency Drives	X	X		
		Diesel Electric Power Plant	X	X		
		Wind Propulsion	X	X		
	Operational Improvements	Route Optimization	X	X		X
		Just in Time Arrival	X			
		Hull Cleaning	X	X		X
		Cold Ironing	X	X		

4.0 Priorities and Decision-Making in Ship Design

This section discusses the ship design process, including key priorities, factors, trade-offs, norms and other considerations involved in the decision-making process, with the goal of providing greater understanding of how decisions are made related to adopting impact-reducing technologies.

4.1 An Overview of the Decision-Making Process in Vessel Design

Conventionally, ship design is considered to be an iterative process that follows a spiral approach (**Figure 5**). The different design decisions are often revisited and refined as the design matures. The owner, designer and shipyard are involved in this iterative process, contributing often at different phases of the project to ensure that the final ship will align with its operational requirements, industry standards, regulatory requirements, and budget. **Figure 5** below describes the typical design stages and the key parties involved.

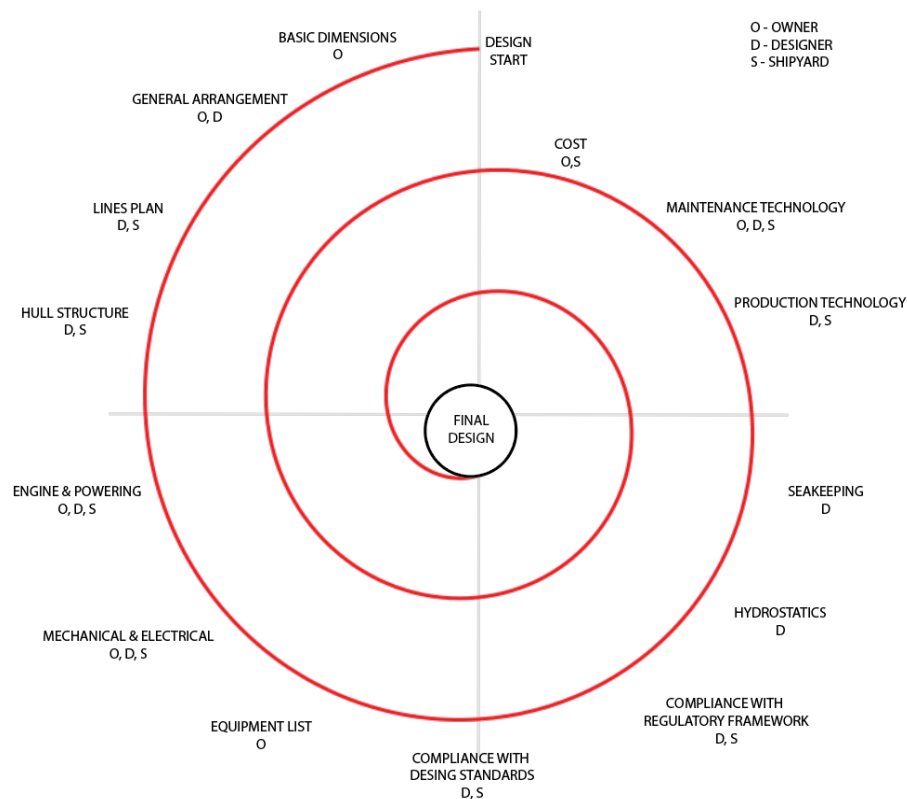


Figure 1. Vessel Design Stages

The decision-making process regarding the adoption of specific technologies or features considers a range of factors, including:

- Vessel type, mission, and operational profile. For example, speed, range, draft, air draft limitations, and requirements for navigating restricted water passages (e.g., channels).
- Regulatory requirements, encompassing both current regulations and anticipated future regulations, including environmental mandates.

- Operational considerations, including operational costs, crew training requirements, and maintenance needs.
- Vessel structure, function, and arrangements, taking into account factors such as weight, available space, layout, and their implications for critical functions such as cargo operations. Additionally, this will assess whether the vessel's support systems, such as freshwater production or power generation, have the capacity to accommodate the selected technologies.
- Familiarity with impact technologies, acknowledging that designers often opt for technologies they are familiar with or have utilized previously due to their understanding of associated risks, performance, interfaces, geometry, and weights.

4.2 Roles and Responsibilities in the Decision Making Process

The principal stakeholders involved in ship design include (Figure 6):

- **Ship Owners:** Responsible for setting requirements and budget constraints. Ship owners oversee ship management and operations. They typically prioritize technologies with proven reliability and familiarity.
- **Ship Designers:** Naval architects and engineers tasked with developing technical specifications and layouts that meet owners' requirements and budget constraints. They assess various technological options for hull design, propulsion systems, stability, and general arrangement.
- **Shipyards:** Responsible for constructing ships according to the designs provided by ship designers. Shipyards collaborate closely with owners and designers to ensure integration of design choices into the construction process, requiring facilities and expertise capable of working efficiently with chosen technologies.
- **Ship Management Companies:** Ship management companies play a pivotal role in facilitating coordination among stakeholders and providing expertise to ensure that technological features incorporated into ships align with operational, regulatory, and financial objectives. While management companies' main role is to provide owners and charterers various fleet management services such as technical, commercial, and financial management, they may also assist owners in the technology selection process during the design phases. In addition, management companies work closely with classification societies and regulatory bodies to ensure the ship's compliance with operational requirements.
- **Equipment Manufacturers/Vendors:** External companies responsible for manufacturing most ship equipment, listed within the shipbuilding specification/contract's 'Makers List'. Ship designers rely on equipment manufacturers information, especially concerning emerging technologies.
- **Classification Societies:** Establish technical standards for ship design, construction, operation, and maintenance. They review and approve technical plans, supervise construction, and ensure vessels comply with regulations through surveys and visits.
- **Flag Administrations:** Enforce national and international safety, environmental, and labor regulations throughout a ship's lifecycle. They may delegate functions to Classification Societies.
- **Regulatory Bodies:** Organizations such as the IMO and Transport Canada (TC) develop and enforce regulations governing ship design, construction, and operation to ensure safety and environmental compliance.

- **Charterers:** Lease ships for defined periods and may have preferences for onboard technologies, influencing ship performance and equipment selection.
- **Marine Insurance Underwriters:** Assess operational risk and provide insurance coverage. They may incentivize safety measures and consider environmental practices and technology claim history when setting premiums.
- **Marine Financial Institutions:** Provide capital for acquiring, operating, and maintaining marine vessels and infrastructure. They offer financial products tailored to the maritime industry, including ship mortgages, lease financing, and project financing. Some financial institutions would provide cheaper and easier finance to green assets. In some cases, some financial institutions would not provide finance for non-green assets. There are common criteria to define green assets in the EU, named the EU taxonomy. The Poseidon Principles are a voluntary standard that aim to decarbonise shipping. The Poseidon Principles are supported by 34 major financial institutions around the world, with each committing to align their ship finance portfolios with environmental sustainability objectives.

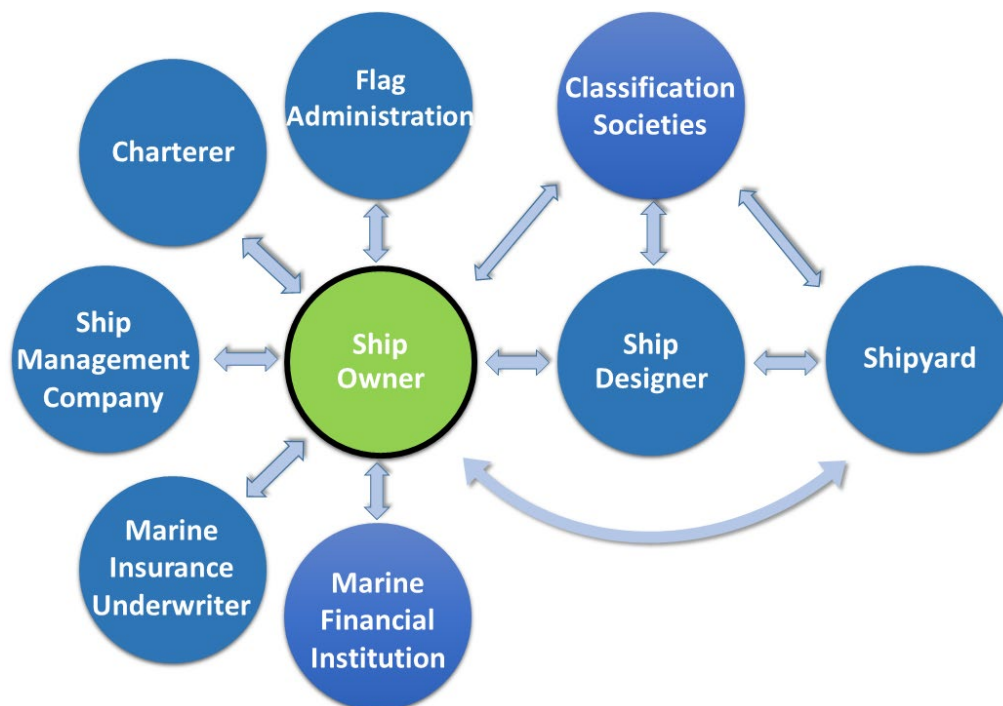


Figure 2. Stakeholders in the Decision Making Process

4.3 Priorities in the Concept Design Phase

The conceptual design of a ship is a complex endeavor, primarily aimed at translating the owners' requirements and expectations into a viable design with minimal or quantifiable levels of design risk for the shipbuilder (or the entity undertaking Basic Design). Prior to evaluating impact reduction technologies, the following elements are considered:

Propulsion Load: The propulsion load refers to the amount of power or force required to propel the vessel through water. The propulsion load can be assessed through various methods, such as empirical calculations, regression analysis, model tank testing, and Computational Fluid Dynamics (CFD). To

ascertain it, the designer must first establish the ship's principal characteristics, including dimensions, hull form, displacement, and speed. It is during this process that designers may contemplate implementing Hydrodynamic Improvements.

Operational Profile(s): The operational profile (or profiles) provides a quantitative description of how the ship is intended to operate, detailing factors such as the percentage of time spent in port, at economic and maximum speeds, maneuvering, and on dynamic positioning (DP)¹, among others. Multi-role ships may have multiple profiles to consider. These operational profiles are crucial in determining the optimal choices for impact reduction technologies. For example, if a ship primarily operates on dynamic positioning (DP) with limited transit time, greater emphasis should be placed on reducing DP load (e.g., by considering the size and center of windage area and the type and efficiency of thrusters). Conversely, an internationally trading cargo ship that spends extended periods transiting at near-constant speeds is more likely to benefit from the hydrodynamic improvements outlined previously. To achieve impact reduction, discussions between the designer and the owner should revolve around understanding fixed requirements versus negotiable ones within the operational profile. For instance, improvements in port handling (loading/discharge) could potentially lead to shorter port stays and slower transit speeds while still maintaining the overall schedule.

Environmental Conditions: Linked to the operational profile is the typical and restrictive environmental conditions. In the context of ship transit operations, this often materializes as a Sea Margin, commonly stipulated by the owner in their specifications or requirements document. Extreme temperature requirements can significantly augment the Heating Ventilation and Air Conditioning (HVAC) load, particularly prominent on larger passenger vessels and Special Purpose Ships (SPS).

Load Balance: Propulsion/maneuvering and hotel loads contribute to the Load Balance, which dictates the power requirements for each operation and the overall installed power. By analyzing the peaks and troughs in the Load Balance, potential methods of load balancing (e.g., utilizing batteries) can be investigated.

Interviews revealed that during the design phase, owners/operators most often collaborate with shipyards, third-party designers, and consultants to establish estimates and enhance confidence in performance before deployment.

4.4 Priorities in the Ship Construction Phase

In the ship building phase, decision-making is primarily driven by ship owners and heavily influenced by regulations. In instances where regulations are absent, the integration of technologies targeting environmental impact reduction often lags.

4.4.1 New Build Projects

During the initial design phases, when assessing impact-reduction technologies, owners collaborate with designers to draft a ship specification document detailing all aspects to be incorporated into the vessel. Designers provide insights into the feasibility of implementing specific technologies within the ship's

¹ Dynamic positioning (DP) in shipping refers to a system utilized to automatically maintain the position and heading of a vessel by using a combination of thrusters, propulsion systems, and sensors.

primary parameters and suggest alternatives as needed. Additionally, the choice of technology is influenced by the location and conditions of the shipyard where construction will take place. Not all shipyards possess the expertise or resources to construct or install complex or unique technologies, potentially leading to additional building costs if specialized tools, training, or subcontracting are required. Decisions on technologies should be made before the contract is signed, during a feasibility study phase or soon after as part of the concept design. This is because the cost of implementing any change, including these technologies after these phases could be very high or even prohibitive. In many shipbuilding and refit contracts, owners typically have the flexibility to make new requests after the contract has been signed. This process is governed by the Variation to Contract (VTC) clause included in these agreements. However, implementing VTCs can incur significant costs. Generally, the more complex the construction or refitting process, the higher the potential expenses associated with VTCs.

Ultimately, owners have the final say in selecting which technologies are implemented in the ship, considering various factors to inform their decision-making process:

4.4.1.1 Capital Cost

The initial investment required for implementing the new technology. The technology's return on investment hinges on its capital cost and operational expenses compared to alternatives.

4.4.1.2 Operational Cost

The cost implications, whether increased or reduced, associated with implementing the technology. Operational costs encompass fuel expenses, crew training expenses, and maintenance costs.

4.4.1.3 Regulatory Compliance

Technologies integrated must comply with all relevant national and international regulations. Owners prioritize adopting technologies that ensure compliance with existing and future/anticipated regulations.

4.4.1.4 Competitiveness

While regulatory compliance and costs may drive competitiveness, other factors such as the perception of innovation and environmental responsibility can enhance the ship's marketability in the future.

4.4.1.5 Reliability and Risk

Despite the allure of novel technologies on paper or in controlled studies, ship owners prioritize the track record of reliability for the technology. They aim to mitigate operational disruptions stemming from unfamiliarity with the technology, lack of port support, or unforeseen technical issues.

4.4.1.6 Industry Trends

Adoption patterns within similar fleets can significantly influence ship owners' decisions to adopt a technology. Owners may feel compelled to embrace technologies to maintain competitiveness in line with industry trends.

4.4.1.7 Familiarity

The owner's existing knowledge of the technology plays a crucial role when deciding its implementation. A high level of familiarity of the crew will ensure smooth operations and less added operational risk. The level of supporting expertise within ship suppliers will also play an important role in the technology

implementation because it will have a direct impact not only in the operational and maintenance costs, but the feasibility altogether.

4.4.1.8 Finance

Financing options play a pivotal role for ship owners when considering the adoption of new technologies. Securing capital and operational costs may necessitate exploring various financial models such as traditional loans, leasing arrangements, or partnerships. However, depending on the total cost and associated risk levels, certain financing avenues may not be accessible to owners, or the borrowing conditions may not be favorable. Additionally, government assistance in subsidizing technology investments can significantly influence the implementation process.

Insights derived from the interview process highlight that cost emerges as a crucial factor influencing decision-making processes. It can be argued that cost acts as a significant constraint in the adoption or exploration of technologies that require additional capital for their implementation. This underscores the importance of carefully assessing the financial implications and potential return on investment associated with integrating such technologies into existing systems or operations.

4.4.2 Retrofit Projects

The decision-making process regarding the implementation of technologies in existing ships, or retrofits, adheres to many of the same principles outlined above for new builds. However, for retrofits, ship owners must also take into account an additional set of constraints, including:

- **Compatibility with current vessel systems:** Although new technologies may be available, they may not be compatible with the existing installed technologies on the ship. Owners are hesitant to install technologies that would necessitate extensive modifications to their vessel.
- **Lifespan of the vessel:** Another consideration is the remaining operational lifespan of the vessel in relation to the potential rate of return on investment. This centres on understanding how much longer the vessel can be effectively utilized for profitable operations compared to the anticipated financial gains it can generate over that period. It may include factors such as the vessel's current condition, maintenance history, depreciation, market demand for its services, projected revenue streams, and replacement cost. By aligning the remaining life expectancy of the vessel with the expected return on investment, stakeholders can make informed decisions regarding asset management, fleet renewal, and capital allocation in the maritime industry.
- **Downtime and potential loss of business:** Despite owners' interest in certain technologies, the prospect of significant downtime and potential loss of business from taking the ship offline for an extended period can deter implementation. Owners often need to balance charter time, ship operations, scheduled inspections and drydocking, and regular maintenance. In some cases, retrofitting can only occur partially while the ship is underway to minimize disruption to sailing schedules.
- **Space limitations and structural adjustments:** In retrofit scenarios, the system being installed may require different spatial accommodations compared to the existing system. Substantial structural changes may prompt class authorities to request additional drawings and analysis to verify the adequacy of the existing ship structure. These constraints may dampen owners' enthusiasm for implementing technologies that may seem appealing initially but pose logistical challenges in

practice.

4.5 Incentives, Penalties, and Technology Selection

The most important monetary penalty impacting technology selection is carbon pricing. The goal is to increase the cost of traditional fossil fuel usage thereby favoring the adoption of technologies and fuels that reduce GHGs.

The leading example of this is the EU emission trading scheme (ETS) which comes into effect in 2024 for all vessels involved in shipping with a gross tonnage equal to or greater than 5,000 gross tons. Vessels will be required to report emissions in 2025 and pay for 40% of their GHG emissions (on 50% of their GHG emissions for voyages to or from a non-EU port). By 2027, they will be liable for 100% of their GHG emissions, with payment calculated per tonne of CO₂ equivalent. The current price for an allowance is set at EUR 100 per ton of CO₂eq (as of February 2023). Similarly, the UK ETS is slated to commence in 2026.

The IMO has outlined a timeline for implementing economic-based measures with enforcement starting in 2027. Discussions within the IMO are ongoing regarding the specific economic measures to be implemented. Possible options include an Emissions Trading System (ETS), a carbon levy, a carbon tax, or a combination of these mechanisms.

4.6 Risk and Incentives in Decision Making

Insights gleaned from interviews underscored the critical role of risk distribution in driving innovation within ship design decision-making processes. Interviewees highlighted how the risks associated with innovation can act as barriers to the adoption of new technologies, emphasizing the need for incentives or financial assistance to mitigate these risks for vessel owners and operators.

Furthermore, interview findings revealed that incentives significantly influence technology choices in the maritime industry, although their impact varies depending on regional regulations. Participants stressed the importance of incentives, such as tax breaks and support for alternative fuels, in managing the costs associated with environmentally friendly technologies. However, concerns were raised regarding the effectiveness of incentives as the sole driver of technology adoption. Additionally, the emphasis on corporate social responsibility and the pride associated with environmental initiatives were noted as contributing factors in the decision-making process.

4.7 Importance of Scale in the Decision-Making Process

Consideration of scale holds significance in the decision-making process. For example, interviewees pointed out that small vessel owners face challenges in investing in innovative technologies due to financial limitations and capacity constraints. These constraints can hinder their ability to adopt advanced solutions to improve environmental performance or operational efficiency. In contrast, larger operations may have the resources and capabilities to overcome these barriers. Their scale allows them to allocate more substantial budgets for research, development, and implementation of innovative technologies. Additionally, larger operations may benefit from economies of scale, enabling them to negotiate better deals with technology providers and absorb the initial costs more effectively. Therefore, the scale of the

operation plays a crucial role in determining the feasibility and success of adopting innovative technologies in the maritime industry.

4.8 Accounting for Uncertainty in the Decision-Making Process

This section delineates how uncertainty factors into the decision-making process, alongside the evaluation of risks and opportunities during the selection and implementation of impact-reduction technologies.

Interview participants highlighted various strategies employed to navigate uncertainties, risks, and opportunities within the decision-making process. These strategies encompassed risk mitigation through the monitoring of technological adoptions by prominent industry players, which offers insights into the preparedness of different ports to support specific technologies, such as storing alternative fuel types. Some organizations relied on the extensive operational hours of other operators to validate technologies before integrating them into their own operations. Flexibility was also utilized as a risk reduction measure, such as designing for fuel flexibility when selecting engine types. However, these measures entail trade-offs, including considerations of space and cost.

Furthermore, reliability models and failure mode and effect analyses were in some cases conducted to evaluate the likelihood and frequency of equipment failure, thereby informing decision-making processes. A prominent theme emerging from the interviews pertained to the distribution and transfer of risk among contractors, shipyards, and designers. The significance of cost and reliability as primary sources of uncertainty was underscored, with scenario creation utilized to weigh different factors. In-house analyses, in one case Monte Carlo simulations, were identified as a valuable tool for estimating weights and electric load, aiding in addressing uncertainties. Additionally, uncertainties surrounding impending regulations were identified as issues more reliant on human judgment.

4.9 Decision Support Tools

Research conducted for this study has exposed an absence of formalized decision support tools in the selection of impact-reduction technologies in the maritime sector. Although models and simulations are used extensively to support decision making at different stages of the design and decision-making process, the research did not uncover any good examples of the use of an overarching decision support tools that encompasses all environmental impacts.

Decision support tools could support marine shipping stakeholders in identifying fit-for purpose technological alternatives for reducing environmental impacts of vessels. For example, these tools may:

- Address the uncertainty and complexity inherent in decision-making processes related to the implementation of impact-reduction technologies;
- Make implicit judgments explicit so as to avoid decision errors and facilitate communication among teams;
- Present a comprehensive view of available options and the decision-making environment/process and provide formal techniques and support for judging trade-offs across multiple criteria;
- Provide a replicative process that can be utilized by others and adjusted with different inputs over time to accommodate changes, uncertainties, and external factors, particularly relevant for

accountability, ESG reporting, and financing purposes;

- Be used to anticipate and accommodate shifts in regulations; and
- Account for interactions between technologies using sub models.

Computerized decision support systems could help to store, organize, and analyze a wealth of information far beyond the cognitive capabilities of individual decision-makers. Computerized decision support can assist in situations characterized by uncertainty, with factors such as incomplete data or unpredictability. By leveraging advanced algorithms and data-processing capabilities, these systems can effectively handle vast amounts of information, identify patterns, and generate insights that might elude human cognition alone. Thus, they serve as powerful tools for decision-makers navigating complex and uncertain environments, enabling them to make more informed and confident decisions.

5.0 Conclusion

This report provides an examination of impact-reduction technologies in shipping, offering insights gleaned from a thorough technological review and in-depth interviews. The technological review included hydrodynamic improvements, aerodynamic enhancements, outfitting innovations, propulsion improvements and operational strategies. Most technologies on offer are focused on efficiency improvements to reduce fuel consumption. This is likely due to the strong focus on regulatory compliance for air pollution and on operating cost reduction through fuel efficiency.

The analysis of the design and decision-making process for new and retrofit ship projects revealed the pivotal roles of cost and regulatory compliance in decision-making processes. Additionally, the review underscores the importance of considering the trade-offs inherent in various impact reduction technologies. Environmental impact reduction was found to be a secondary consideration unless it was contained in current regulations.

Formalized decision support tools are currently not commonly used in the selection of impact-reduction technologies in the maritime sector, but their use could provide valuable support for marine shipping stakeholders in identifying fit-for purpose technological alternatives for reducing environmental impacts of vessels.

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