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The Impact of Maritime Decarbonization on Ship Design: State-of-the-Art-Report

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ABSTRACT

The maritime industry faces a critical challenge to decarbonize and meet the ambitious goal of net-zero emissions by 2050. This transition requires innovative ship design strategies to address the increasing complexity and multiplicity of technical solutions amidst dynamic regulatory, geopolitical, and market uncertainties. This paper examines the maritime decarbonization challenge's impact on ship design and decision-making under uncertainty, highlighting the necessity for collaboration between researchers and practitioners to tackle this emerging challenge. To navigate the uncertainty, stakeholders can integrate advanced design methods and decision-making processes considering the full lifecycle and fleet-level implications. This paper promotes taking a holistic approach that incorporates regulatory compliance, technological advancements, and commercial considerations, as well as a blend of methods to manage decision-making under uncertainty. Continued research in specific areas is essential to develop and refine frameworks that optimize design and operation for the industry's sustainable future.

KEY WORDS

Ship design; sustainability; maritime decarbonization; energy efficiency; alternative fuels

INTRODUCTION

Sustainability has become a pressing concern in various industries, especially in maritime. The urgency stems from the ongoing climate crisis, highlighted in July 2023 at the International Maritime Organization (IMO) Marine Environmental Protection Committee (MEPC) 80 meeting where its greenhouse gas (GHG) strategy was revised, aiming for net-zero emissions by 2050, setting interim targets, and proposing measures. Further discussions at the MEPC 81 meeting in March 2024 confirmed the direction while discussing existing and mid-term measures needed to achieve the revised targets.

Maritime decarbonization is a complex challenge with no one-size-fits-all solution. Numerous alternative fuels and ship technologies, both existing and under development, complicate the landscape. Industry stakeholders also grapple with uncertainties and dynamics such as shifting regulations and geopolitical events.

The need for immediate action, coupled with numerous options and evolving conditions, requires a substantial shift in the approach of industry players, including ship designers. It is important to stay up to date on the latest maritime decarbonization developments and consider whether the maritime decarbonization challenge presents the need to think differently about how commercial ship design is conducted. This paper offers ship designers a comprehensive overview, combining industry advancements driving decarbonization and recent academic research on sustainable ship design.

Multiple industry reports are regularly updated and readily available on maritime decarbonization topics such as energy efficiency (EE) and alternative fuels as well as industry-level analysis on how the industry can achieve decarbonization by 2050 (MMMCZCS, 2022a; ABS, 2022; DNV, 2023). General decarbonization pathways are provided, and proposed scenarios can be presented to understand broad industry directions. Key stakeholders interested in this type of analysis are mainly regulators from the IMO, regions like the European Union (EU), and countries. This type of information is helpful background for ship designers and ship owners/operators but lacks specific or actionable direction.

At the same time, there is an increasing number of academic research in the areas of sustainability, decarbonization, and, most importantly, design methods, decision-making, and support (Trivyza et al., 2022; Mansouri, Lee, and Aluko, 2015). Most research on ship design is related to "complex ship design" that includes naval vessels, submarines, and specialist commercial vessels like cruise ships. Andrews (2022) describes complex ship design as a "wicked problem," where the

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challenge is not only in the ship's inherent complexity, but in determining what is really wanted (i.e., defining the requirements). Andrews (2022) continues by identifying two types of ships: "those that are part of a wider transportation system and those that go to sea to do something." With the introduction of the maritime decarbonization challenge, ships like container ships, bulk carriers, and tankers are becoming more complex and difficult to define requirements.

With so much uncertainty and changes in how the industry operates, the energy transition presents a case for placing more emphasis on the early stages of design of even simpler ships. The decarbonization challenge also demands a broader perspective than a single vessel design to account for full life cycle impacts and fleet-level considerations affecting future regulatory compliance. This paper is intended to strengthen the collaborative bridge between research and industry by evaluating the need from industry for ship design and operational decision-support, what methods and tools already exist today, and why they are needed now more than ever to help achieve full decarbonization of the maritime industry.

This paper caters to both researchers and practitioners, providing actionable insights for their daily work. For researchers, industry developments are moving quickly, and help is needed to bring relevant use cases and ensure they are addressing the right challenges and applying their research in the most effective way possible to maximize impact. This includes clearly identifying the best applications for given methods available or under development. For practitioners, there is a need to bring ship design methods and decision-making processes into the normal way of working to best handle the inherent uncertainties and dynamics associated with the maritime decarbonization challenge.

THE MARITIME DECARBONIZATION CHALLENGE

This paper focuses on the environmental sustainability challenge of reducing the maritime industry's GHG emissions and how this impacts ship design. In addition to maritime decarbonization, sustainability broadly covers social sustainability and governance for sustainability as well as other environmental sustainability topics such as air pollution and impacts on marine life. Ship designers should not overlook these other topics or how they relate to maritime decarbonization considerations and decisions. Some examples include:

- Reducing nitrogen oxides (NO_X) emissions, which are an air pollutant, from an internal combustion engine usually requires an increase in fuel consumption, leading to increased carbon dioxide (CO_2) emissions, a GHG impacting the climate.
- Black carbon is a type of particulate matter (PM), typically regarded as an air pollutant, that also can have regional short-term global warming potential.
- While ammonia as a fuel has no carbon, which can lead to low GHG emissions, its toxicity can potentially harm marine ecosystems if discharged into water.

Focusing on the maritime decarbonization challenge, projections indicate that emissions will continue to increase if we rely on current decarbonization efforts. Shipping has the least emissions intensity for freight transported, but the maritime industry's enormous scale makes it a noticeable contributor (approximately 3%) to global emissions (IMO, 2020). Moreover, maritime is a hard-to-abate sector. If maritime emissions are not reduced, the sector may be responsible for a greater share of global emissions by 2050, as other sectors decarbonize at a faster pace (e.g., power and road transport). Three segments - bulk, tanker, and container - account for around two-thirds of emissions, making them the key focus areas for future emission reduction pathways (IMO, 2020). Without additional decarbonization efforts, emissions will remain far from the Paris Agreement's 1.5-degree trajectory or science-based targets (MMMCZCS, 2021). It is crucial to act this decade to bend the curve and set the course for the 2030s and beyond.

Historically, the industry has been slow to change and has not dealt with major technological or regulatory disruptions. It remains the most cost- and emission-efficient mode of transportation, which creates limited incentives for competition with other industries. In the early 1900s, the internal combustion engine was introduced with heavy fuel oil (HFO) used for propulsion. HFO is now the dominant fuel with worldwide availability, and the two-stroke diesel engine remains the prime mover of choice for most vessels. There have been some disruptions and innovations, such as the introduction of liquefied natural gas (LNG) as a fuel and regulations including ballast water treatment and the 2020 sulfur cap. However, these have not significantly changed the industry's operations.

As shipping is globally regulated by the IMO, part of the United Nations (UN), decisions are made by consensus, which tends to result in slow decision-making. The initial IMO GHG strategy was only introduced in 2018, but ambition is now increasing. This has led to a regulatory disruption that significantly affects the industry, impacting both fuel and technology use. At the MEPC 80 meeting in July 2023, the IMO’s GHG strategy was revised, aiming for net-zero emissions by 2050 and setting interim targets and proposed measures. Additionally, regional regulations, particularly from the EU, are driving significant regulatory compliance and financial risks for maritime stakeholders. Ships also have a long lifespan of 20-25 years or more in certain segments, meaning decisions made today will determine the industry's makeup in 2050.

There are at least five candidate groups for future wide-use alternative fuels, including hydrogen, ammonia, methane, methanol, and liquid biofuels such as e-diesel and bio-oils. Each group, in turn, contains different types of fuels, distinguished depending on feedstock and fuel production processes. In addition, alternative energies include wind, electricity (energy storage), and nuclear.

Meeting the energy demands and optimizing EE onboard ships can be achieved through a diversity of methods. Every vessel has distinct performance needs dictated by its type, size, and operations. To satisfy these specific needs, there are numerous solution pathways for vessels, encompassing a variety of energy and fuel configurations, onboard technologies, initiatives for enhancing EE, and concepts for power and propulsion systems.

Key stakeholders, such as policymakers, technology developers, fuel suppliers, and ship owners/operators, must make decisions under uncertainty, including interdependencies across stakeholder groups. Uncertainty encompasses fuel/technology availability and cost, willingness to pay/finance, and policy and regulation. Dynamics result from politics, consumer behavior, disruptive innovations, and geopolitical events. The war in Ukraine is an example of an event that has significantly impacted the energy market and led to an acceleration of policy support and investment in renewables within Europe (IEA, 2022).

Vessel owners/operators must evaluate options and decide what they believe is best for their vessel. In addition to the standard newbuild vessel design, vessels can be designed to be adaptable for other fuels or retrofitted with different or new technologies throughout their lifespan. This adds another layer of decision-making complexity, especially with high uncertainty regarding the main future fuels.

In summary, the industry's decarbonization challenge is captured in three main statements:

- First, we need to act now in an industry that is not easy to change.
- Second, there are many options, most of which are not fully mature.
- And third, key stakeholders must handle uncertainty and dynamic conditions.

The need for immediate action, along with numerous options and evolving conditions, necessitates a substantial shift in the approach of industry players, including ship designers. Keeping abreast of the latest maritime decarbonization developments and their impacts on ship design is crucial.

The solutions to the decarbonization challenge are multifaceted and require development in three main areas: regulation, technical, and commercial. Psaraftis (2019) stated that the main obstacles are not technical or economic in nature but political, manifesting in regulations at global, regional, and local levels. Although the maritime industry has achieved significant EE improvements over the past decade, EE alone will not be sufficient to decarbonize (Cullinane & Yang, 2022). With EE falling short, the industry is turning to alternative fuels to bridge the remaining gap to zero. The number of publications related to alternative fuels in the maritime sector has surged since 2018, with a significant increase starting in 2020 (dos Santos et al., 2022). This heightened attention within academic research is promising and welcomed, but it must now be translated and applied within the industry.

REGULATIONS

There are two main types of maritime decarbonization regulations impacting ship design: EE and emissions. Safety regulations associated with the introduction of new technical solutions to support maritime decarbonization should also be considered in parallel. Environmental sustainability rules and regulations affecting ship design and operation can be at the global, regional, or local levels, depending on where the vessel is intended to operate. This review will focus on global and select regional considerations, mainly related to the EU. An example of an impactful local regulation is provided; however, such local regulations should be considered on a case-by-case basis, depending on expected operations.

At the international level, the 2023 IMO Strategy for the Reduction of GHG Emissions from Ships is driving updates and the introduction of EE and emissions regulations (MMMCZCS, 2023a). The levels of ambition, on a well-to-wake (WTW) GHG emissions basis, include:

- A decline in the carbon intensity of the ship through further improvement of the EE for new ships,
- A 40% carbon intensity reduction by 2030, compared to 2008,
- The uptake of zero or near-zero GHG emission technologies, fuels, and/or energy sources to constitute at least 5%, striving for 10%, of the energy used by 2030, and
- Net-zero GHG emissions by or around 2050 (IMO, 2023).

Indicative checkpoints to reach net-zero absolute GHG emissions include striving for a 20% reduction in 2030 and aiming for a 70% reduction by 2040. Figure 1 provides an overview of the latest IMO efforts related to achieving the ambitions of the 2023 strategy. The IMO has already implemented short-term measures to reduce carbon intensity, including the introduction of the Energy Efficiency Design Index (EEDI) in 2013 and, more recently, the Energy Efficiency Existing Ships Index (EEXI) and Carbon Intensity Indicator (CII). These short-term measures will be revised in 2026. Mid-term measures, such as carbon pricing and a GHG fuel standard, are currently under consideration and are expected to be adopted in 2026, with enforcement planned for 2027.

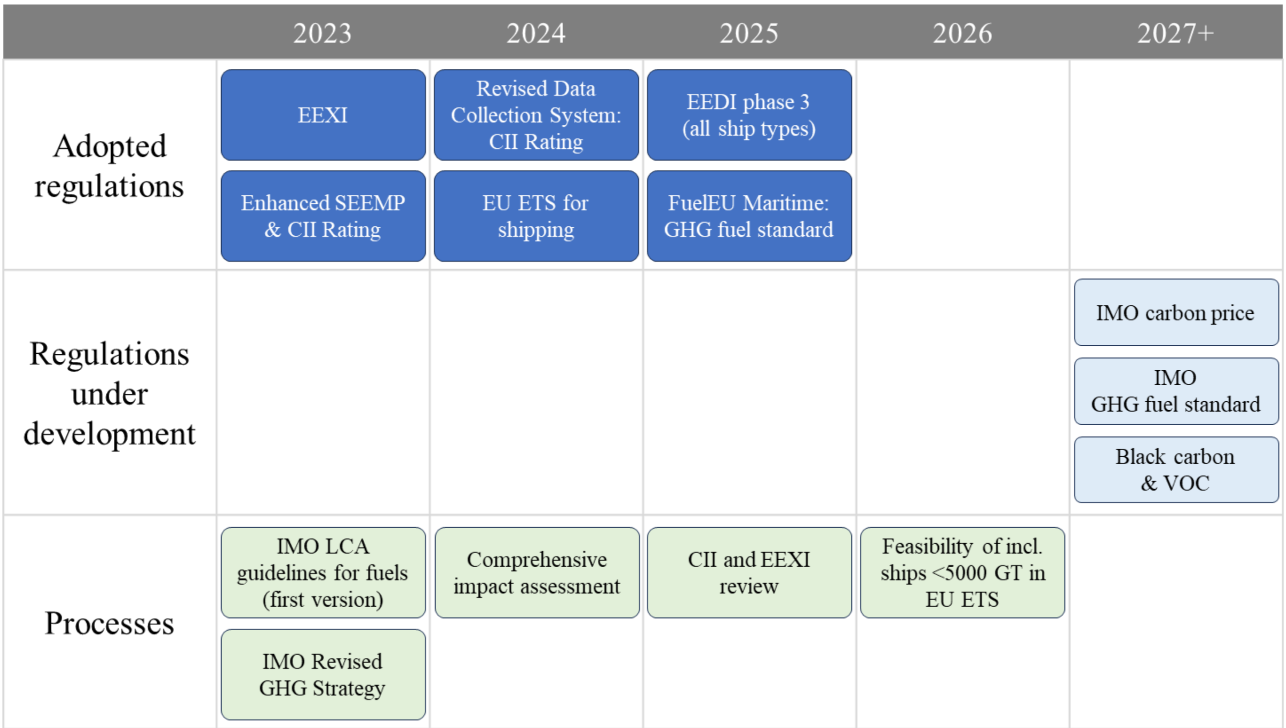

Figure 1: GHG regulatory timeline, adapted from DNV (2023)

This section does not aim to provide detailed descriptions of each regulation and how they function for the various ship types and sizes. It will present the increasing regulatory pressure placed on the maritime industry, necessitating further emphasis within existing areas and the introduction of new solutions, including design for efficient operations, the introduction of alternative energies and solutions, and financial considerations like carbon pricing.

Table 1 provides an overview of the main regulations, their current design impacts, and potential future design impacts. This summary is described in more detail in the following sections.

Energy Efficiency Regulations

This section will highlight the main ship design impacts already identified for each main EE regulation, as well as project what potential impacts could be as these regulations are updated in the future to align with IMO's revised GHG reduction strategy.

EEDI

The EEDI is a design-related hard regulation that is the one-time responsibility of the ship designer or shipyard to prove compliance. The EEDI formula either drives a reduction in CO_2 emissions or an increase in transport work, which mainly relates to the classic ship-engine-propeller matching process (Ren et al., 2019) and involves a balance between ship capacity, power, speed, minimum fuel consumption, and the smallest quantity of CO_2 emitted into the atmosphere (Constantin and Amoraritei, 2019). Optimization of main dimensions can also improve EEDI values (Calisal et al., 2022).

A working group at the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) recently published findings (MMMCZCS, 2023b) related to EEDI compliance, stating, "The combination of derating and propeller diameter changes delivers increased efficiency by aligning the optimal operational point of the propulsive system more closely with the vessel's actual usage. Feedback from working group participants indicates that compliance with the EEDI can be achieved through power reduction alone, without implementing other EE gains (through engine efficiency, retrofits, etc.)".

While evolutionary improvements in hull forms and power generation efficiency have mainly contributed to EEDI compliance, the introduction of energy-saving devices (ESDs) on newbuilds has proven beneficial for business and the environment (Kenney & Palmejar, 2023). Most adopted ESDs are hydrodynamic improvements (e.g., twisted rudders, rudder bulbs/fins, pre-swirl stators, propeller boss cap fins) or engine-related (e.g., waste heat recovery, shaft generators) (EC, 2021). Members of the MMMCZCS working group attribute their introduction mainly to the risk of poor sea trial results.

Table 1: List of regulations, current, and potential future design impacts

Regulation	Type / Responsible	Current Design Impact	Potential Future Design Impact	References
EEDI	Design, Hard for New Vessels Ship designer, shipyard	Evolutionary improvement of hydrodynamics, propulsion and power generation on newbuilds. Introduction of new ESDs. • Ship-engine-propeller: Derated engines (linked to slow steaming trends) + increase propeller diameter, streamlined hullforms • Energy saving devices: Mostly hydrodynamic improvements (increased speed at fixed power to ensure sea trial results) or engine-related (WHRS, shaft generator) • Introduction of LNG • Increased capacity	Could change metric from CO_2-centric to a power or energy basis or enlarge the scope of emissions. Increased reduction rates. Updating of reference lines to include newer (and usually larger ships). • Incorporation of more innovative ESD technologies including air lubrication and wind-assisted propulsion • Introduction of new main energy converters including hybrid arrangements, all-electric with batteries and fuel cells	Ren et al. (2019), Constantin and Amoraritei (2019), Calisal et al. (2022), MMMCZCS (2023b), Kenney & Palmejar (2023), EC (2021)
EEXI	Design, Hard for Existing Vessels Ship owner	Limited to no design impacts on existing vessels with limited operational (mostly speed) limitations. • Adoption of power limitation that reduces maximum allowable engine power output • Limited to no introduction of new ESDs unless already planned	Older (less efficient) vessels impacted more by power limitation could lead to increased scrapping. Updating of EEDI can lead to updates of EEXI limits if additional phases are introduced or another metric is introduced.	MMMCZCS (2023b)
CII/SEEMP Part III	Operational, Soft (until 2026) Ship owner, technical manager	Higher impact on operations, however, improved designs lead to more operational freedom. • Vessel monitoring system requirement • More efficient designs are able to comply with CII more easily	First operational measures will be exhausted. Then consideration for advanced technologies. Newbuilds to be more energy efficient to give further operational flexibility. Design for efficient operation emphasized. Speeds will generally go down. Wind-assisted propulsion, air lubrication, waste heat recovery systems, shaft generators, and hybridization of the engine room (e.g., using batteries or fuel cells).	MMMCZCS (2023b), Sun et al. (2023)
Fuel Standards (IMO Mid-term Measure, FuelEU)	Operational, Hard Ship owner, technical manager	Major impact for new vessels with expected lifetime of 20+ years as readiness for alternative fuels needs to be considered. Due to small short-term reductions, limited impact for existing vessels with benefits seen from introduction of LNG as a fuel and small modifications required to use liquid biofuels. Use of fossil-based LNG provides compliance window up to at least 2030. Small modifications required for biofuels (to be discussed in next section).	With the anticipated increased reductions upcoming, all new vessels need to address this compliance challenge based on the solutions available (to be discussed in next section). Fleet considerations like FuelEU pooling requires designers to think at vessel and fleet level.	EU (2023), MMMCZCS (2022d)
MBMs (IMO Mid-term Measure, EU ETS)	Operational, Hard Ship owner, technical manager	Unclear as in short term it is a relatively small added cost of operation. Emphasized efficient operation and reducing absolute emissions from vessel.	MBMs more closely linking economic incentives and penalties to the technical description of the vessel. Cost of GHG emissions could become major driver of design decisions (techno-economic analysis).	IMO (2024), Hansson et al. (2023)

The introduction of LNG dual-fuel vessels has also contributed to lower EEDI ratings (around a 20% reduction) due to the tank-to-wake (TTW) carbon factor used to calculate CO_2 emissions. It is important to note that the EEDI formula only considers direct vessel emissions and excludes other GHGs, such as methane. While the primary decision to design a dual-fuel LNG vessel has most likely not been for EEDI compliance alone, it has shown to be an easy way to comply with the latest EEDI Phase 3 requirements. Another method to improve EEDI values is to increase capacity while keeping power low. A good example of this is raising the wheelhouse height on container vessels to accommodate more twenty-foot equivalent units (TEUs) without impairing visibility.

The implementation of EEDI, especially under favorable market conditions, has increased focus on EE and led to more efficient ship designs, including the introduction of ESDs (MMMCZCS, 2023b). However, the EEDI attained values of recent newbuild vessels have plateaued (EC, 2021), and its future is not clear, with discussions on Phase 4 postponed to later in this decade. The IMO is now discussing the development of mid-term measures focused on reducing absolute emissions, which could render aspects of the existing EEDI calculation redundant (MMMCZCS, 2023b). The MMMCZCS working group suggests that the metric could be changed from CO_2-centric to a power or energy basis or expand the scope of emissions. This would coincide with increased reduction rates and the updating of reference lines to include newer (and usually larger) ships. It could lead to wider adoption of more innovative ESD technologies such as air lubrication and wind-assisted propulsion, as well as the introduction of new main energy converters, including hybrid arrangements, all-electric with batteries, and fuel cells.

EEXI

The EEXI is a design-related hard regulation that is the one-time responsibility of the ship owner to prove compliance starting from January 1, 2023. It is based on EEDI reference lines and can be considered as an extension of EEDI to cover existing vessels in addition to newbuilds. Due to the limited time ship owners had to prepare for the introduction of EEXI regulations and the small periods of time vessels operate at higher engine loads, most vessels have adopted a power limitation, which reduces the maximum allowable output of the engine (MMMCZCS, 2023b).

Data suggests that vessels can achieve EEXI compliance with minimal impact on operations. However, EEXI imposes a technical limit if vessels are incentivized to go faster, such as under certain market conditions or when catching up on a schedule (MMMCZCS, 2023b). While having a more significant impact on existing and mostly older vessels, EEXI compliance confirms a trend towards lower installed power and slower speeds as a major EE measure contributing to an overall reduction in GHG emissions. EEXI is an initial example of why operational factors have become more important for ship designers to pay attention to and consider as part of the design process, especially when projecting throughout the lifetime of a vessel.

CII

CII is an operational EE regulation based on annual operational data. It came into effect on January 1, 2023, and will be effective until at least 2030, with a review planned in 2026. CII reduction factors relative to 2019 start at 5% in 2023 and increase to 11% by 2026. If a vessel has low CII ratings for periods of time, corrective actions need to be agreed upon and taken (MMMCZCS, 2023b).

Along with the CII, Part III of the existing Ship Energy Efficiency Management Plan (SEEMP) was introduced in 2023 to ensure proper documentation of each vessel’s implementation plan to obtain the required CII ratings. As part of the SEEMP Part III, the recognized organization, often a classification society, needs to verify its implementation plan, including the use of a vessel monitoring system (MMMCZCS, 2023b).

While intended to improve the operational EE of a vessel, studies have shown that a more efficient ship design can provide additional operational flexibility and higher CII ratings (MMMCZCS, 2023b). Design can be a differentiating factor for operational EE regulatory compliance, placing more emphasis on energy-efficient designs going forward. It is also expected that CII modeling during the design phase will be requested, and an understanding of the impact of EE technologies and operational measures on CII rating will be needed during this phase. This is a new consideration for ship designers and shipyards that previously only had to ensure compliance with EEDI. Subsequently, this raises more awareness of operational considerations and the operational part of the ship’s lifecycle during the design phase, which should further improve the EE of newbuilds.

However, delivering an energy-efficient vessel does not guarantee good CII ratings, as operational conditions mainly drive the final rating, over which the ship owner typically has little control. Very efficient ships can have poor CII ratings. In addition to a focus on vessel efficiency, vessel, port, and canal operations, as well as commercial considerations, can significantly impact a CII rating (MMMCZCS, 2023b). While the ship designer has control over designing an energy-efficient vessel, they should not overlook the other drivers and their relationship to a ship’s design. This includes considerations like expected speed, cargo utilization, and deployment.

How do ship owners intend to achieve CII compliance? Owners expect to first implement as many operational measures as possible, such as performance monitoring. Once operational measures are exhausted, owners must consider introducing advanced technologies like wind-assisted propulsion, air lubrication, waste heat recovery systems, shaft generators, and engine room hybridization, such as using batteries or fuel cells (MMMCZCS, 2023b). Additionally, speed becomes an important parameter for CII compliance, understanding that commercial aspects also need to be considered (Sun et al., 2023).

Emissions Regulations

Emissions regulations are essential for designers to understand, as they can be fulfilled in different ways, including through design and operational solutions. This further integrates the designer into the operational environment where the owner's requirements, including operational profiles and conditions, should now be more deeply explored in an environment of impactful regulatory and economic considerations.

Fuel Standards

GHG fuel standards are expected at the international level through IMO mid-term measures (with enforcement starting in 2027) and regionally in the EU with FuelEU for Maritime, starting enforcement in 2025. The main purpose of fuel standards is to promote the use of sustainable fuels. The measure, which is based on GHG emissions per unit energy on a WTW basis, is independent of the vessel's EE, as a reduction in GHG emissions will also lead to lower energy consumption. As such, this measure requires the introduction of more sustainable fuels.

FuelEU for Maritime required reduction levels start at 2% in 2025 compared to 2020 levels and will increase to 6% in 2030, 31% around 2040, and 80% around 2050 (EU, 2023). FuelEU for Maritime also introduces the concept of pooling, which allows a company to compensate for non-compliant reductions with over-compliant reductions across multiple ships in their fleet for the same time period. This concept changes the focus from single vessel compliance to fleet compliance, granting shipping companies greater flexibility in developing their compliance plans. This also introduces a new consideration for ship designers when defining newbuild design requirements that will join a company's larger fleet. Instead of designing for expected reduction trajectories, designers can introduce near-zero or zero-emission vessels that can help offset emissions from multiple sister vessels within a fleet.

The IMO's GHG fuel standard, considered a mid-term measure, is expected to follow a similar structure as FuelEU for Maritime. However, it is not confirmed, and there will likely be some differences as the IMO targets its revised GHG reduction strategy levels.

While alternative fuels will be discussed further in the next section, it is crucial to highlight that existing vessels either need to introduce biofuel blending or benefit from pooling (as described above). Owners who have introduced alternative-fueled newbuilds, including LNG and methanol dual-fuel vessels, can benefit from the use of compatible fossil and sustainable fuels. Recent studies have shown that LNG-fueled vessels operating on fossil-based LNG can remain compliant with FuelEU for Maritime regulations at least until 2030, based on the regulation's current setup (MMMCZCS, 2022d).

Nonetheless, these fuel standards are effectively compelling owners to introduce alternative-fueled vessels, which are now an essential part of a designer's considerations, especially early in the design process when the vessel's requirements are defined.

Market-Based Measures
Market-based measures (MBMs) put a price on GHG emissions to provide an economic incentive to reduce emissions through ship design and operation. The EU has recently included the maritime industry in its Emissions Trading System (ETS), a cap-and-trade system. The IMO is considering a list of potential MBMs as part of their mid-term measures, ranging from contribution schemes for GHG emissions through an ETS to schemes based on actual ship efficiency by design and operation (IMO, 2024). Each of the ten proposed MBMs for the IMO's mid-term measure either requires a direct cost per amount of fuel consumed or emissions, the purchase of related allowances, or sets strict EE standards with associated penalties (IMO, 2024). How any collected revenue from such measures will be used or distributed is yet to be determined.

MBMs are fuel- and technology-agnostic and provide flexibility to designers and operators when selecting solutions to minimize financial impact. Cost-effectiveness and abatement become critical metrics when evaluating solutions. With the expected cost of EU ETS emissions allowances in the short to mid-term, the least-cost measures like increased EE of ship designs and EE operational measures are likely to be implemented first as these abatement costs are typically negative due to fuel savings (Hansson et al., 2023). With higher abatement costs, alternative fuels and technologies would require greater costs associated with a MBM. Lagouvardou et. al. (2023) studied the marginal abatement cost of alternative marine fuels to demonstrate the role of MBMs in helping bridge the price gap between the fossil-based fuels of today and the more expensive alternative fuels of tomorrow. Revenues from MBMs can also be used to fund scaling of alternative fuel production as fuel availability can become a major constraint in the uptake of alternative fuels (Lagouvardou et. al., 2023).

MBMs now link economic incentives and penalties more closely to the technical description of the vessel beyond typical metrics such as the required freight rate (RFR). Techno-economic assessments are now intrinsically linked to the ship design process, and will be in the future, even if MBMs will potentially have an outsized impact on technical decisions compared to typical RFR measures.

Local Emissions Regulations
A pertinent example of an impactful local regulation is the zero-emissions requirement for cruise ships, tourist boats, and ferries in the Norwegian World Heritage fjords by 2026 (NMA, 2023). In response to this upcoming regulation, Norwegian shipowners and designers have developed power solutions to allow large cruise ships to operate emissions-free for up to 12 hours and have conceived zero-emission cruise ship designs (Business Norway, 2024).

Non-Regulatory Drivers/First Movers
Although regulatory compliance is the minimum requirement for an existing or future ship design, some companies prefer to be first movers setting more ambitious targets, including substantial investments in advanced technologies and alternative fuels. First movers seek competitive advantages, such as strong brand recognition, technology leadership, and resource control, while also taking on increased financial, technical, and operational risks (Esau & Bentham, 2023).

These pioneering companies are trying to capitalize on current and expected future demand for "green" transportation. While the demand is currently low, it exists and is growing. While regulations will be the primary driver of the eventual decarbonization of the industry, first movers responding to the market demand for clean transportation have been the start of solution investigation. In addition, various organizations publish guidelines or best practices to be considered. For a ship designer, understanding the motivation and objectives as part of the ship requirements definition is critical.

TECHNICAL SOLUTIONS

Technical solutions are available and under development to help achieve regulatory compliance or to meet individual company decarbonization targets. This section will focus specifically on solutions that impact ship design. Pure operational measures, for example, will not be covered; however, operational measures are in most cases the easiest to implement and should be considered, especially for existing vessels.

While most operational measures are purely operational or behavioral in nature, ship designers still need to understand what operations are expected and if any operational measure impacts ship design, or if the ship design can be optimized to maximize the impact of targeted operational measures. This section will briefly cover some of these operational measures to ensure proper coverage of solutions and ship design-related considerations.

Technical decarbonization solutions can be divided into three main categories:

1. Energy efficiency technologies,
2. Alternative energies and fuels, and
3. Emission reduction technologies.

These solutions will be introduced, but not discussed in detail, as there are plenty of good sources that provide more detail and will be referenced in the associated sections.

This section will provide evidence of a general increase in ship design complexity and more design challenges with the introduction of maritime decarbonization technical solutions. While some solutions can maintain complexity levels (e.g., a newer, more efficient engine), most introduce additional complexities and interdependencies with other systems onboard. This increase in complexity and a high-level identification of the main ship design impacts with examples will be presented and discussed.

Design complexity discussed in this section is focused on the design product, not the design problem or process. Complexity of a design product can be described by the product's structure, such as the physical arrangement, its function like the number and connectivity of systems, and its behavior, such as predictability (Ameri et al., 2008). When discussing the technical solutions in this section, increased complexity is demonstrated by the addition of systems and their connection or relationship to other systems and overall vessel performance. Cost can also be used as a complexity metric and will be indicated where possible in parallel with technical complexity descriptions. Systems with higher complexity generally have higher lifecycle costs (Ameri et al., 2008) and failure rates (Jones, 2021).

Energy Efficiency Technologies

Energy efficiency technologies (EETs) reduce the vessel's energy consumption. MEPC.1/Circ.815 provides guidance on how EETs can be treated for EEDI calculation and verification, including categorization (IMO, 2013):

- "Technologies that shift the power curve, resulting in a change of combination of propulsion power and speed.
- Technologies that reduce the propulsion power but do not generate electricity, leading to increased propulsion efficiency.
- Technologies that generate electricity, leading to saved energy, typically in the form of reduced auxiliary power."

From a ship design impact perspective, three general categories of EETs can be defined:

1. Standard Practice: Low ship design impact baseline technologies that are (or should be) incorporated into any newbuild vessel.
2. Moderate Effects: Medium ship design impact technologies that might cost more and require integration but can be managed without significant design or performance impacts.
3. Systematic Integration: High ship design impact technologies that cost more, have larger systems and interconnections, and implications for the overall ship design and performance.

Table 2 provides an overview of the main EETs, their maturity level, cost and complexity, and ship design impacts. It also includes specific examples of ship designs operating with EETs onboard.

While general technology categories can be grouped by ship design impact level, any novel or new technology within any category might require a more systematic integration study and should be evaluated on a case-by-case basis. A good example of such a case is the novel gate rudder system (Tacar et al., 2020). While within the propulsive loss reduction category that is typically low design impact, being a new and novel system, a more thorough assessment is needed.

Table 2: List of energy efficiency technologies, maturity level, cost, technical complexity, main ship design impacts

Impact Category	Technology Category	EET Type	Maturity Level / Cost ($)	Design Impact & Technical Complexity	Examples / References
Low-Standard Practice	Hullform design	Dimensions, hull, openings optimization, asymmetric stern, skeg shape training edge, twin skeg. Use of model-based simulations.	Mature <500k	Part of normal design process. Enhanced through advanced CFD simulations.	
	Structural design	Superstructure optimization (wind resistance), lightweight reduction. Use of model-based simulations.	Mature <500k	Part of normal design process. Enhanced through advanced CFD simulations.	
	Hull drag reduction	Low friction coating, heating, surface texturing, additives	Low friction coatings well-established (mature), new technologies under development. <1M	Minimal. Can be retrofitted. Part of normal drydocking schedule. Coatings have low impact. Any active system would require additional supporting systems.	
	Propulsive loss reduction	Controllable pitch, contra-rotating, tip raked propellers, propeller nozzle/duct, pre swirl stators, post swirl fins/stators, rudder bulb, thrust fin, twisted rudder, ducktail waterline extension, gate rudder	Mature <1M	Impact on ship performance, both from a propulsion efficiency perspective, but also other important aspects such as reliability, maneuvering, structural fatigue. Can be retrofitted. Usually requires drydocking. Loss of efficiency by designing for an existing hullform. Usually well-known and demonstrated. Part of normal design process. New propulsion devices and rudders such as gate rudders requires integration studies (supporting systems, structural integration) with increased complexity.	Novel Gate Rudder system includes two asymmetric rudders at each side of the propeller (Tacar et. al., 2020).
	Machinery efficiency	Engine design	Mature	Part of normal design process. Improved fuel consumption while maintaining NO_X compliance and other emission targets (e.g., low methane slip)	
Medium-Moderate Effects	Shaft generator	Power take-off (PTO), power take-in (PTI), front-end/aft-end, on-engine, on tank-top, shaft mounted, geared/direct	Mature <1M	Space is a consideration when placed aft of the main engine (could effect hullform), requires switchboard integration. Retrofit can be challenging due to space limitations. Additional system needs to be integrated close to engine, frequency converter and couplings, electrical integration	
	Waste heat recovery	Beyond exhaust gas boilers incl. steam turbine, power turbine, organic rankine cycle	Semi-Mature. Demonstrated onboard vessels. 1-5M (more if combined)	Space/weight requirements, piping, switchboard integration. Retrofit can be challenging due to space limitations. Additional system, piping, electrical integration	
	Solar panels	Solar panels	Not mature. Limited demonstrations <500k	Large amount of deck space needed. Only applicable to certain vessel types (e.g., car carriers). Can be retrofitted. Additional system that requires large area. Electrical integration.	K-Line's Drive Green Highway car carrier installs large solar energy system (Haun, 2016)
	Energy storage/ batteries	Peak load shaving	Semi-mature 1M	Additional system, requires space, electrical integration. Retrofit can be challenging due to space limitations. Space requirements, control and automation integration, fire safety	
	Cold ironing/ shore power	Cold ironing/shore power	Semi-Mature <1M	Additional system that requires space, access, high-voltage cabling, electrical integration. Can be retrofitted. Space requirements and outside access/interface, switchboard integration. Containerized options exist.	
High-Systematic Integration	Air lubrication system (ALS)	Bubble drag reduction, air layer drag reduction, partial air cavity drag reduction	Semi-mature. Demonstrated onboard various vessel types. 1-5M	Interconnected with hullform design, additional support systems such as compressors requiring additional energy demand, piping. Can be retrofitted. Requires drydocking. Loss of efficiency by designing for an existing hullform. Hullform and ALS system designed together - performance dependent on good match (e.g., location of air cavities). Additional power demand and space for supporting systems such as compressors. Risk of air bubble interactions with propeller and sea chests. More suitable for certain types of ships (e.g., draft considerations).	Kim & Steen (2023)
	Wind assisted ship propulsion (WASP)	Wingsails or rigid sails, square rig sail systems, towing kites, flettner rotor	Not mature. Demonstrated onboard a few vessel types. 1-5M	Additional system that has additional weight, requires deck space, supporting systems, structural integration. Can be retrofitted. Current share of retrofits is significant (EMSA, 2023). Air draft restrictions (e.g., bridges), stability, change in operations (wind-based route optimization), visibility.	Pyxis Ocean bulk carrier (operated by Cargill) was retrofitted with two rigid sails (WindWings) (Neuman, 2023), EMSA (2023), Khan et al. (2021)

The EETs with the highest complexity are also the ones with the highest potential. Two good examples are the air lubrication system (ALS) and wind-assisted ship propulsion (WASP). Potential net power savings of ALS technologies can range from 2-22% (Kim & Steen, 2023), while WASP can provide up to 30% savings (EMSA, 2023).

ALS technologies are considered semi-mature and have been demonstrated onboard various vessel types. With high initial capital expenditure (CAPEX) of around $1-5 million (M), ensuring sufficient savings to justify the investment is critical. Additionally, the ALS is interconnected with the hull form design, and performance will depend on a good match (e.g., location of air cavities). Additional power demand and space for supporting systems such as compressors are also required. The risk of air bubble interactions with the propeller and inlets like sea chests also needs to be managed.

WASP technologies are not considered mature yet, but demonstrators are currently onboard a few vessel types. Like ALS, WASP has high CAPEX ($1-5M), and ensuring maximum savings is critical. With multiple WASP systems added to a ship design, the additional weight and deck space can be limiting factors. Structural reinforcement is also required (Khan et al., 2021). Air draft restrictions (e.g., bridges), stability with large weights on deck, and visibility need evaluation. WASP performance will also depend on operations, creating an important link between design and operations. For example, the vessel can deviate from the shortest route if additional WASP savings can be achieved.

ALS and WASP provide two examples of high-impact ship design considerations that require systematic integration. While "low-hanging fruit" with low to moderate impact do exist, significant savings will usually require acceptance of increased cost and complexity.

Alternative Energies and Fuels

While significant EE improvements can and should be made due to their favorable emission abatement economics, EE alone is not enough. This has been highlighted by recent fuel standards being implemented or developed, as well as continued trade growth projections that will only lead to increased emissions without the introduction of other solutions (Cullinane & Yang, 2022).

To reduce the emissions per unit of energy required by ships, alternative energies and fuels have been proposed and introduced in the maritime industry to replace fossil fuels like HFO, diesel, and LNG. Along with the introduction and development of alternative energies and fuels, new and modified energy converters such as dual-fuel internal combustion engines and fuel cells are being developed.

The main energies and fuels currently under consideration within the maritime industry are listed in Table 3 and include wind, electricity, liquid biofuels (including biodiesel and bio-oils), methane, methanol, ammonia, and hydrogen. These energies and fuels can be produced or provided in different ways. Renewable energy is used to produce e-fuels, fossil feedstocks are used as a basis to produce blue fuels, while bio-diesel and bio-oils include a range of techniques that convert biological material into an oil-like substance. Depending on the feedstock and production process, each pathway has a certain level of WTW emissions relative to fuel oil. A WTW methodology that includes the emissions from fuel production and onboard the vessel is needed to unlock carbon-based fuel pathways like methane and methanol.

While the molecular makeup of fuels can be identical, their emission intensities can vary. From a ship design perspective, the integration of "green ammonia" versus "blue ammonia" is identical; however, it's important to properly account for the source and production method when calculating lifecycle emissions (on a WTW basis).

The main energies and fuels have different maturity levels and commercial readiness levels, as seen in the number of alternative-fueled vessels delivered or on order. Based on DNV's Alternative Fuels Insight (as of April 9, 2024), with over 1,000 vessels in operation and on order, methane-based vessel designs are the most prevalent, with only 16 ammonia-fueled vessels on order.

While technical complexity generally increases with the introduction of alternative energies and fuels, this is not always the case. Most of the design complexity for fuels such as methane, ammonia, and hydrogen come from their storage requirements and proper management of liquefied gases onboard the vessel. They also require dual-fuel engines with two fuel supply systems and additional support systems and spaces, such as ventilation, double-walled piping, and fuel preparation rooms. Methanol is more easily stored but still requires additional systems like inerting and dual-fuel engines. In addition to the typical NO_X reduction after-treatment technologies that are required, ammonia-fueled vessels may require additional systems to mitigate ammonia slip and nitrous oxide (N_2O) emissions, as well as ammonia release mitigation systems due to its toxicity.

Table 3: List of alternative energies/fuels, maturity levels, technical design complexity, main ship design impacts

Energy/ Fuel	Maturity Level	Design Impacts	Technical Complexity		
			Port Interface	Energy Storage	Energy Conversion & After-Treatment
VLSFO	Mature	-	Standard bunkering	Integrated tank	Mono-fuel engine. NO_X reduction (EGR/SCR).
Wind	For more than EE, majority of energy demand to be met. Not yet mature for this application.	Class guidelines and incorporation into EEDI/EEXI calculations available. Potential change in operations such as speed (wind-based route optimization). Deck space, air draft restrictions (e.g., bridges), stability, visibility.	-	-	-
Electricity	Semi-Mature	Class guidelines available, risk-based approval process. Relationship between endurance, energy density and space requirements.	Power connection	Battery	-
Bio-Diesel/ Bio-oils	Mature	Minor modifications potentially needed.	Standard bunkering.	Integrated tank. Small modifications potentially needed.	Mono-fuel engine. Small modifications potentially needed. NO_X reduction (EGR/SCR).
Methane	Mature	Prescriptive rules in IGF Code. Well-established design considerations. Additional storage volume requires an evaluation of endurance and cargo loss. Locating key spaces like the tank connection space, fuel preparation room and vent mast important for arrangement.	Liquified bunkering requires additional systems including vapor return line, safety measures, operational procedures.	Liquified at -163 deg C, requires independent prismatic (Type A/B), cylindrical (Type C) or membrane tanks, stainless steel, aluminum or nickel steel, tank aeration, tank connection space, inerting, vent mast and piping, boil-off gas management (e.g., reliquification).	Dual-fuel engine. Two fuel supply systems. Fuel preparation room. Fuel heating. Ventilation. Double-walled piping. Pilot fuel consumption. NO_X reduction (EGR/SCR).
Methanol	Semi-Mature	IMO Interim Guidelines with risk-based approval. Integrated tanks require cofferdams that impacts required space in addition to energy density difference. Alternative designs can be proposed to reduce the impact of the cofferdam requirement.	Usually requires additional bunker lines (due to higher quantities for same amount of energy), vapor return, safety measures, operational procedures.	Integrated tank with proper coating. Liquid under ambient conditions. Inerting. Vent mast and piping.	Dual-fuel engine. Two fuel supply systems. Fuel preparation room. Ventilation. Pilot fuel consumption. NO_X reduction (EGR/ SCR/ water injection).
Ammonia	Not Mature	Class guidelines available, risk-based alternative design required. Gas dispersion and quantitative risk assessment analyses recommended. Additional storage volume requires an evaluation of endurance and cargo loss. Locating key spaces like the tank connection space, fuel preparation room and vent mast important for arrangement. Additional integration of emissions and safety systems to achieve equivalent safety levels to methane and meet emissions regulations.	Requires additional bunker lines (due to higher quantities for same amount of energy), vapor return(s), safety measures, operational procedures.	Liquified at -34 deg C or 18 bar pressure, requires independent prismatic (Type A/B) or cylindrical (Type C) tank. Low temperature or high tensile steel. Tank aeration, Tank connection space, inerting, vent mast and piping, boil-off gas management (e.g., reliquification).	Dual-fuel engine. Two fuel supply systems. Fuel preparation room. Fuel heating. Ventilation. Double-walled piping. Pilot fuel consumption. NO_X reduction (EGR/SCR), potential need to reduce ammonia slip and nitrous oxide (N_2O) via additional catalyst. Ammonia release mitigation system.
Hydrogen	Not Mature	Class guidelines available, risk-based alternative design required. Additional storage volume can pose a significant design challenge that requires an evaluation of endurance and cargo loss. Locating key spaces like the tank connection space, fuel preparation room and vent mast important for arrangement.	Requires additional bunker lines (due to higher quantities for same amount of energy), vapor return(s), safety measures, operational procedures.	Liquified at -253 deg C or compressed at above 200-300 bar, requires usually a well-insulated cylindrical (Type C) tank. Special low-temperature material that avoids embrittlement. Tank connection space, inerting, vent mast and piping, boil-off gas management (e.g., reliquification).	Large two-stroke engines not currently being developed. Most likely converter for direct hydrogen use is fuel cells. NO_X reduction (EGR/SCR) if burned in an engine.

Main ship design impacts with the introduction of alternative energies and fuels include increased fuel storage volumes, additional space for fuel management and safety systems, as well as key integration challenges such as placement of vent masts and routing of fuel piping. Ship performance is usually impacted, and compromises need to be made in terms of endurance, speed, and/or cargo capacity. Typically, alternative-fueled vessels will not have the same endurance as their conventional-fueled counterparts, where fuel capacity is not as constrained. Methanol-fueled vessels have their own integration challenges, including the need for additional space around the fuel tanks for cofferdams. However, alternative designs can be proposed to reduce the impact of the cofferdam requirement.

Hydrogen-fueled vessels have significant ship design challenges, including the lack of internal combustion engine development and the need for large storage volumes (Ustolin et al., 2022). There has yet to be a large hydrogen-fueled deep-sea oceangoing vessel developed. Hydrogen as a fuel has been successfully implemented on smaller vessels, though (Comyn et al., 2022). All-electric solutions have been implemented for smaller vessels, while batteries are mostly considered an EET on larger vessels. Industry and academic studies have indicated the advantage of using batteries for smaller short-sea vessels such as ferries, like hydrogen (Wang et al., 2022).

Nuclear propulsion has also gained renewed interest with the development of advanced nuclear reactor technologies, including small modular reactors and microreactors. Benefits of nuclear-based technology and applications include a zero-emission, base-load power source with more predictable financials compared to other alternative fuels that struggle with both availability and high price concerns. While commercial nuclear for maritime applications shows promise, there are several concerns and barriers to implementation that would need to be addressed. In addition to the well-known concerns of non-proliferation, nuclear accidents, and public perception, there are barriers associated with maturing the technologies for maritime application, merging nuclear and maritime regulations to form a viable regulatory framework and pathways, as well as the need to rethink how risks are calculated. The broader societal and industry impacts of such applications can also not be forgotten.

While the technical design complexity discussion has mostly revolved around the use of internal combustion engines as the main energy converter of today and will likely remain well into the future, alternative energy converters such as fuel cells are under development and show promise for use with alternative fuels. The use of hydrogen directly in fuel cells or the use of a cracker or reformer with fuels like ammonia, methanol, and methane can provide increased conversion efficiencies compared to internal combustion engines (Herdzik, 2021). While fuel cell technologies and their applications onboard vessels are not fully mature, their ship design implications should be considered and can, in most cases, lead to a less complex design compared to an alternative-fueled internal combustion engine design.

The introduction of new alternative energies and fuels has also raised safety concerns and the need to rethink how risk assessments and risk-based approvals are done. Comparing alternative fuels with different characteristics, such as flammability, explosiveness, and toxicity, that can impact safety can be challenging and requires new types of analyses and updated risk-based frameworks.

Emission Reduction Technologies

Emission reduction technologies or after-treatment technologies have been used within the maritime industry to address mainly air pollutant emissions but are now also being considered to reduce GHGs and other alternative fuel-related emissions. Figure 2 provides a high-level overview of the emission risks for the main fuels and potential solutions to mitigate these risks, originally introduced by MMMCZCS (2022b).

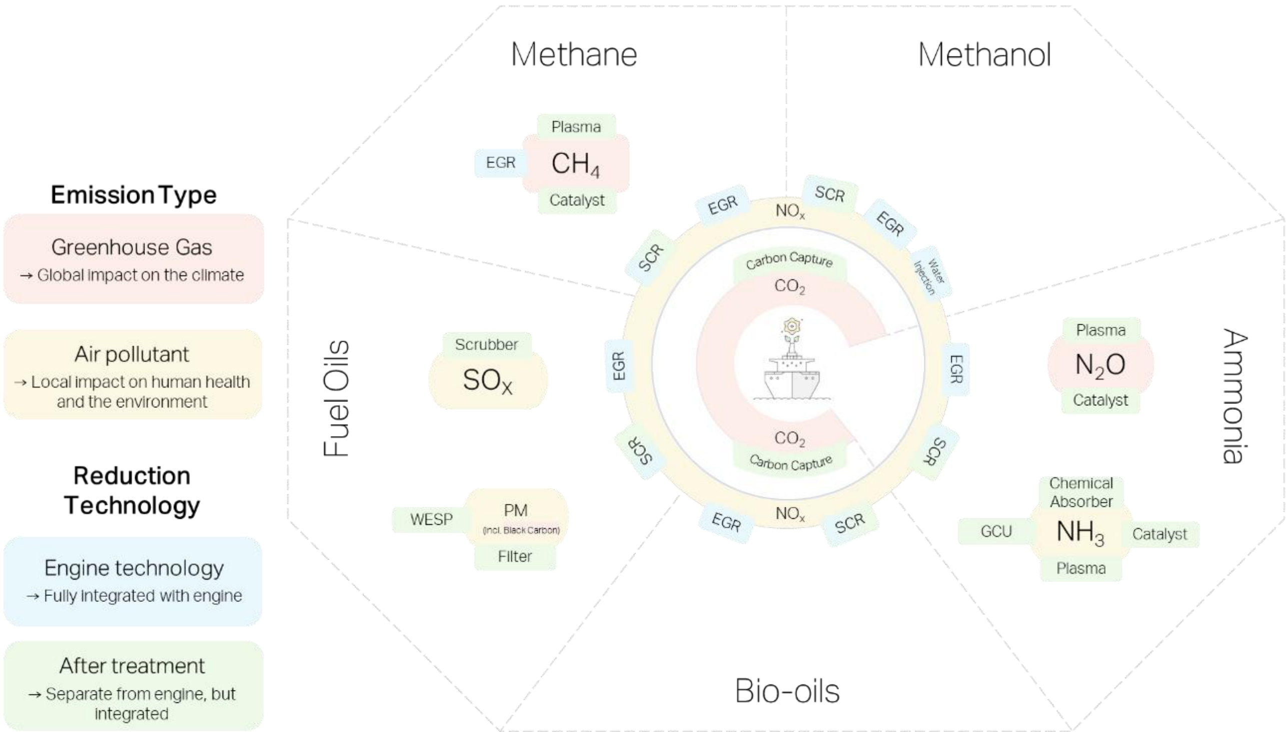

Figure 2: Highlighting emission risks for main fuels, reprinted with permission from MMMCZCS (2022b)

The most notable technologies used today include exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) systems to reduce NO_X and exhaust gas cleaning systems (commonly known as scrubbers) to reduce sulfur oxides (SO_X) and PM from engine exhausts.

EGRs and SCRs are not going anywhere, as NO_X compliance will still be required with the use of alternative fuels, and most of the fuels under consideration require after-treatment. SO_X scrubbers will become a technology of the past as HFO use will decrease as the first fossil fuel impacted by upcoming regulations. HFO is also not expected to be used as a pilot fuel for alternative fueled vessels in the long term.

One of the main emission reduction technologies currently under development for maritime applications are shipboard carbon capture (SCC) systems that can, most commonly, capture CO_2 from engine exhaust onboard a vessel. There are different types of SCC systems, and each has its own integration challenges and considerations. More extensive studies have been completed on amine-based absorption systems, as they are the most mature and are already used onshore. While studies have shown SCC to be technically feasible, there are high energy requirements, significant CAPEX investment, and integration challenges on certain vessel types due to the space requirements for the capture system, liquefaction, and CO_2 storage (MMMCZCS, 2022c).

Finally, with the introduction of alternative fuels including methane, methanol, and ammonia, emission reduction technologies either need to be applied and developed to ensure compliance with air pollutant emissions while limiting other GHG emissions in addition to CO_2, such as methane and N_2O. Special regional considerations for emissions like black carbon (BC) should also be considered (MMMCZCS, 2022b).

UNCERTAINTY AND DYNAMICS

With the understanding that future regulations will be stricter and that there are many technical solutions that can help fulfill these regulatory requirements, commercial decisions will ultimately be driven by economics. In addition to economics, the added complexity due to adoption of new technical solutions presents an integration challenge, especially as regulations develop and evolve. While techno-economic assessments can be completed, the ability to capture the broad and varying types of uncertainties and dynamics can be challenging.

Uncertainty exists due to upcoming policy and regulation, technology and alternative fuel advancements (Trivyza et al., 2022), fuel specifications and standards, customer demand, and finance sector mobilization (MMMCZCS, 2022a). Conditions are constantly changing as more knowledge is gained about potential solutions being developed and policy decisions are made, in addition to the occurrence of disruptive innovations like advanced nuclear reactor technologies or geopolitical events such as the war in Ukraine or Houthi attacks on ships in the Red Sea. Uncertainty levels are also higher because maritime decarbonization is a long-term challenge that is at least 25 years from its achievement and the regulatory, technical, and commercial solutions are not yet in place today (Erikstad & Lagemann, 2022).

Key decision-makers include policymakers, technology developers, fuel suppliers, ports, ship owners, operators, charterers, and cargo owners. Each decision-maker has its own objectives but must consider decisions being made by all others along the value chain and across the industry. A good example is the relationship between alternative fuel producers and ship owners/operators. Fuel producers might not be able to proceed with the financial investment of building a new fuel production plant without long-term off-take agreements from shipowners/operators, who are in turn reluctant to lock in high prices not knowing future market dynamics. This example highlights the uncertainty associated with customer willingness to pay the additional costs to decarbonize and the uncertainty regarding how the additional investments will be supported by the financial sector.

Questions that now need to be addressed include:

- What decarbonization targets can be realistically achieved, and by when?
- Which alternative fuels will be available, by when, and at what price?
- What can I do with my current fleet to accelerate decarbonization?
- Should I ensure my newbuilds are generically "future fuel-ready," or should I focus on specific fuels?
- What roadmap should I follow to implement the transition of my vessel or fleet?

The link between company strategy and understanding the various uncertainties and dynamics becomes more important than ever. One of the main alternative-fueled design considerations is the evaluation of optionality and conversion potential related to preparing a vessel to be converted to an alternative fuel later in the vessel's lifetime. This is mainly driven by the uncertainty around when and at what price alternative fuels will be available in the future, combined with the uncertainty around future regulations. For ammonia, it is also due to the onboard technologies not being commercially available yet, such as the engine.

Future alternative fuel availability, and associated pricing, for the maritime industry continues to be one of the main uncertainties that stakeholders need to understand and manage. To a large extent, the development of alternative fuel availability and pricing within the maritime industry will be externally driven as multiple sectors compete for a limited supply of renewables. With renewables being a scarce resource over the next decades, Lindstad et al. (2023) suggests renewable energy should first be prioritized for replacing coal fired electricity production then to electrify road transport. Hard-to-abate sectors including shipping and aviation would be expected to continue fossil fuel use until more renewable energy becomes available.

The decisions do not stop once the vessel is delivered and is in operation, which is both a positive in the sense that there are options to mitigate any uncertainty or dynamics, but also options mean you need to constantly evaluate them and select the best for your current situation. Based on a selected baseline fuel pathway, you have options to use fuels directly onboard or decide to convert your vessel to change from one pathway to another. Especially with such long lifetimes and the aggressive industry-level targets being set, replacing newbuilds with alternative-fueled vessels will not be enough. This means that fuel conversions will need to play a role in maritime decarbonization.

One example is starting with the LNG/methane fuel pathway, you can use fossil liquid fuels like HFO, low-sulfur fuel oil, marine gas oil, use liquid biofuels like biodiesel or bio-oils, fossil-based LNG, or bio- or e-methane. Additionally, you can decide to convert to the ammonia pathway, for example. This optionality, even in operation, demonstrates the requirement to take a holistic lifecycle approach to ship design that can consider changes in operations and operational decisions (Erikstad & Lagemann, 2022).

With the tightening of EE regulations and the introduction of fuel standards like FuelEU Maritime that provides the flexibility to consider fleet-level operations and compliance, ship design will take on another dimension: fleet design. A larger system perspective that considers a fleet of vessels versus a single ship will become even more important (Erikstad & Lagemann, 2022).

When attempting to capture the main maritime decarbonization regulatory, technical and economic drivers related to ship design, the following uncertainties and dynamics should be considered:

- Timing and levels of global, regional, and local regulatory requirements related to EE, fuel standards, and market-based measures.
- Technical maturity, commercial availability, and pricing of alternative energies, fuels, and technologies.
- Customer demand and finance sector mobilization.

In addition, two key macro trends have been identified that need to be captured when attempting to better understand and model these uncertainties and dynamics:

- A holistic lifecycle approach including design and operation,
- Concepts of optionality and flexibility/changeability, and
- Fleet-level design, operations, and perspectives.

DECISION-MAKING UNDER UNCERTAINTY

Decision-making under uncertainty and dynamics is a broad and thoroughly studied research area, as well as an activity most organizations engage in regularly. With the urgency to act in an industry not easy to change, combined with many technical solutions and the introduction of various uncertainties and dynamics, the obvious next question is, how should key stakeholders make decisions?

Zwaginga & Pruyn (2022) highlight the deep uncertainties of the maritime energy transition and that, while uncertainty is not uncommon in ship design, the maritime decarbonization challenge introduces such high levels of uncertainty that new methods to deal with them are needed.

In their 2022 *Design Methodology State-of-the-Art Report*, Erikstad and Lagemann (2022) present four main design strategies that have emerged from the design spiral model: optimization, set-based, system-based, and configuration-based. While this paper is not intended to be a complete review of all ship design approaches and their applicability to the maritime decarbonization challenge, a central theme is that ships like container ships, bulk carriers, and tankers are becoming more complex and difficult to define requirements for. Transitioning from the classic design spiral to more advanced design strategies as presented by Erikstad and Lagemann (2022) can be beneficial and this section will describe some of these along with other strategic approaches that can be taken to manage uncertainty with specific examples relevant to ship design and the maritime decarbonization challenge.

Garcia Agis (2020) provides a good structure that defines four types of strategic approaches, each with several methods that can be applied: ignore (not the preferred option if the uncertainties are known), delay, reduce/control, and accept/protect. The "ignore" approach will not be covered in detail in this section as the main argument of this paper is that the use of deterministic models and approaches is not sufficient. This section will cover each of the remaining three strategic approaches (delay, reduce/control, accept/protect). The final part of this section will briefly discuss further development areas related to maritime decarbonization and environmentally sustainable ship design decision-making under uncertainty.

Delay

Delaying decisions while gaining knowledge can be a helpful approach, especially during ship design. Applicable methods include concurrent engineering, set-based design, or real options (Garcia Agis, 2020). Most uncertainties and dynamics will not go away during the design process and will continue into a vessel's operation. This is why delay methods can capture decision-making throughout the vessel's lifetime.

Pomaska & Acciaro (2022) propose a real option analysis approach to hydrogen as an alternative fuel. The analysis demonstrated the value of deferring investment decisions to get a better understanding of regulation, fuel price, and technology developments while benefiting from potentially decreased hydrogen prices in the mid-term future. Metzger (2022) presents the use of the fuzzy pay-off method for real options analysis to better understand the impact of market-based measures on the valuation of greening technologies. The potential level and timing of a price on carbon are one of the main uncertainties key stakeholders must consider. While set-based design has been proven within the ship design context, its principles could be extended to apply to a full lifecycle perspective where set convergence could continue after the delivery of a vessel on certain design and operational aspects.

Reduce/Control

Reducing or controlling uncertainty by gaining more information and increasing communication involves using scenario planning integrated into a strategic decision-making framework, data analytics, simulation, and optimization (Garcia Agis, 2020). When attempting to understand and model decision-making under uncertainty, the main goal is to increase knowledge so that uncertainties can be reduced or controlled as best as possible. Two main approaches that have been applied to the maritime decarbonization challenge are the use of scenario thinking and simulation and optimization with sensitivity analysis.

Scenario Thinking

Scenario thinking evaluates changes in specific values or metrics under different scenarios. For this type of analysis, specific scenarios need to be defined that include different values for defined variables. This could be a baseline scenario, a best-case scenario, and a worst-case scenario, for example. Scenario analysis promotes a holistic big-picture perspective that can focus efforts on important and relevant areas.

Scenario thinking is a tool that helps manage uncertainty by looking into the future and building a structure used to assign priorities (Bentham, 2023a). A good starting point for an individual stakeholder or company is to adapt broad scenario definitions such as those by Lehmacher & Lind (2022) to their specific decision-making situation and circumstances:

- "Storms: A world of nationalism, geopolitical conflicts, and a worsening climate crisis. Both the Paris climate goals and the IMO 2018 decarbonization ambitions are missed.
- Swells: Initially, businesses and governments concentrate on growth and decarbonization advances slowly. Then, as the climate crisis intensifies and disrupts shipping services and ports, quick, abrupt changes are needed and finally initiated. These are costly and cause significant disruptions. Accelerated decarbonization is late but eventually meets the Paris goals…
- Clear Sky: Politicians, business leaders, citizens, and investors worldwide align to meet the Paris climate goals..."

Mestemaker et al. (2020) presented a scenario-based life cycle assessment (LCA) method that incorporated variable fuel prices and emission costs. Scenario thinking has also been associated with improving a business's competitive advantage by acting earlier (Bentham, 2023b).

Simulation and Optimization

Multi-objective optimization and multi-criteria approaches, decision-support systems, and simulation models have been studied but have not fully addressed the need to move from deterministic to stochastic modeling while managing the increased complexity of the decarbonization problem (Mansouri et al., 2015; Frangopoulos, 2020; Frangopoulos, 2018; Trivyza et al., 2022). Methods like LCA can be used to quantify the environmental impact of a fuel or ship over its lifetime (Trivyza et al., 2022); however, LCA is a deterministic method that does not capture inherent uncertainties, for example, fuel specifications and standards. Typically, LCA is used to calculate the climate impact (in terms of GHG emissions) of an alternative fuel over its lifetime (i.e., WTW emissions).

Various decision-support tools have been developed to help evaluate and compare technologies and their impact on ship design (Robertson et al., 2022). Wei & Liu (2022) proposed a multi-objective optimization method based on a parametric ship model to reduce the negative impact of regulatory uncertainty that identified, in some cases, a ship design can be too eco-friendly based on a given regulatory scheme.

When using optimization methods and simulation models, it is important to incorporate uncertainty either by conducting sensitivity analysis or considering uncertainties during the optimization (Trivyza et al., 2022). Lagemann, Lindstad, et al. (2022) developed a deterministic model to optimize a ship's lifetime fuel and power system but identified that there is significant uncertainty related to the fuel prices and retrofit costs assumed. This highlights the need for sensitivity analysis when utilizing optimization within a decision-making framework. Lagemann et al. (2023) followed up this work with a two-stage stochastic optimization model that considers uncertain fuel and carbon emission prices while also capturing the ability to convert to other fuels during a vessel's lifetime.

Accept/Protect

Another approach is to accept the uncertainty and develop strategies that can handle uncertainties, including adaptive control, use of margins, resilience, robust design, optimization under uncertainty, Markov Decision Process (MDP), and fuzzy decision support (Garcia Agis, 2020).

Ship design concepts of flexibility/changeability, modularity, and robustness have been studied extensively and demonstrated to be effective under uncertain lifetime conditions (Rehn et al., 2018; Choi et al., 2018; Schank et al., 2016). Lagemann, Erikstad, et al. (2022) describe the introduction of agility as a parameter for fuel-flexible ships, including preparing vessels to be converted later in life. Agility, a characteristic of flexibility and changeability, can help mitigate future unpredictability and uncertainty, for example, related to emission regulation compliance. Niese (2012) introduced a ship-centric MDP (SC-MDP) that can improve early-stage design decisions related to uncertain environmental policy and non-technical disturbances. SC-MDPs are now used in long-term strategic decision-making and can help better understand key decisions (Garcia Agis, 2020). Kana & Harrison (2017) presented a Monte Carlo approach to SC-MDP to analyze whether a containership should convert to LNG to comply with Emission Control Area regulations. The results demonstrated how variations in uncertainties can significantly impact optimal decision strategies.

While most previous case studies have been applied to ballast water treatment and air pollutant emissions like SO_X and NO_X, the same methodologies are applicable to the maritime decarbonization challenges today. A good example of this approach is the introduction of dual-fuel internal combustion engines that can utilize a mix of conventional liquid fossil-based fuels as well as alternative fuels like LNG, methanol, and ammonia. While the push for dual-fuel capability is rooted in the need for a pilot fuel for alternative fuels, it provides fuel flexibility that allows the owner to maintain the use of conventional fuels until they want or are required to use alternative fuels.

Further Development Areas

As part of a state-of-the-art review of decision support methods for sustainable ship energy systems, Trivyza et al. (2022) identified eight areas for future research, including uncertainty & stochasticity and the expansion of borders: holistic ship design and supply chain analysis. Trivyza et al. (2022) conclude their paper by noting that the maritime industry faces huge challenges due to the explosion in technological developments, the complexity of marine systems, and its conservatism, all while operating within an environment that is becoming increasingly sensitive and demanding.

While basic frameworks exist to consider maritime decarbonization decision-making under uncertainty, the latest research has also shown a need for further research in certain areas, particularly what decision-making strategies for managing uncertainty should be used for the maritime decarbonization challenge or, more likely, what strategies should be used for certain aspects of the overall challenge and how do they all connect to form an overall strategy. A comprehensive evaluation of ship design strategies and methodologies as they relate to the maritime decarbonization challenge is needed.

The methods identified above are usually best used to manage decision-making under certain types of uncertainty. This leads to the belief that there will not be one solution that fits all the challenges of the maritime decarbonization problem, but a collection of multiple strategies under an overarching framework. With increased pressure to change the way we have done things for a long time, combined with the increased complexity of the available solutions and the increased uncertainty they bring, there is a need to expand existing design strategies, approaches, methods and decision-support tools to a wider segment of the maritime industry where in the past design has not been a distinguishing or competitive advantage (most focus on producibility). This is a call to action for ship designers, and especially shipyards, to adapt their way of designing commercial vessels.

CONCLUSIONS

Responding effectively to the maritime industry's decarbonization challenge is necessitated by the urgent need to reduce GHG emissions and meet global climate targets, such as the Paris Agreement and the IMO's revised GHG strategy aiming for net-zero emissions by 2050. The maritime industry, traditionally slow to change, must undergo a substantial shift in approach due to the proliferation of alternative fuels and technological options, as well as evolving regulatory, geopolitical, and market conditions.

Figure 3 provides a summary of the maritime decarbonization cause-and-effect chain that can be used to describe the overall challenge and the knock-on effects of maritime decarbonization on ship design. Industry stakeholders, including ship designers and owners, can enhance their methods and decision-making support for ship design and operation, incorporating considerations for a change in emphasis and new focus areas, including design for efficient operation, reduced emissions per unit of energy, and carbon pricing. EETs, alternative energies and fuels, and emission reduction technologies are available or are being developed to help achieve maritime decarbonization; however, they come with emerging economic and technical considerations.

These considerations include increased ship costs and complexity, the need to rethink safety, risk assessments, and reliability, increased uncertainty, the need for a lifecycle approach, and a fleet-level perspective. The significance of emerging economic and technical considerations for shipping segments such as container ships, bulk carriers, and tankers is creating a gap that needs to be filled; a gap that academic research already has the tools to support from experience with more complex ship design activities and decision-making under uncertainty.

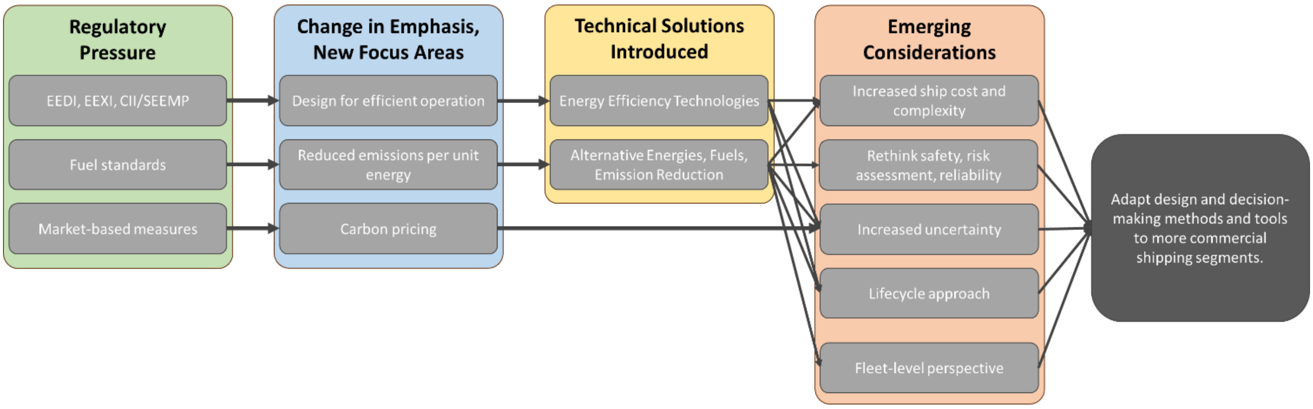

Figure 3: Maritime decarbonization ship design cause-and-effect chain

To tackle the complexities and uncertainties involved, researchers and industry practitioners must strengthen their collaboration, with each having the ability to provide valuable contributions. Researchers are called upon to ensure applications are addressing the right challenges and utilizing relevant use cases to maximize impact. Practitioners are advised to integrate advanced ship design methods and decision-making processes into their standard operations to manage uncertainties effectively.

Ultimately, there is an imperative for immediate action, suggesting that a combination of regulatory compliance, technical progress, and innovative commercial strategies is essential to decarbonize the maritime industry. Decision-making under uncertainty is an important aspect that requires new strategies, tools, and a holistic approach that includes design, operation, and fleet-level perspectives.

Considering the complexity and dynamic nature of the decarbonization challenge, the maritime industry should employ a blend of strategic approaches to manage uncertainties. It is necessary to continue research in specific areas related to decision-making under uncertainty to better support the industry in reaching its ambitious decarbonization goals.

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