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The impact of shipping's energy efficiency measures on reduction of underwater radiated noise, and opportunities for co-benefit

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Acoustics, in the form of sonar, is an important tool for the exploration of the marine environment. It is used by the seismic industry to locate oil and gas reserves, by the military to detect objects, by oceanographers to make measurements and by marine mammals to survive.

Man-made underwater acoustic systems rely upon computers to process the data coming from sensors to interpret the environment. The processing methods within the computer systems are a critical component often defining the overall success of the instrument.

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Executive Summary

This study has been undertaken to assess the interrelationship between measures aimed at enhancing ship energy efficiency and mitigating URN emissions. It commences by conducting a review of the International Maritime Organization's (IMO) initiatives and strategies for decarbonizing the shipping industry. Moreover, it identifies the measures and tools available that can contribute to expediting the transition towards zero-emission shipping by around the year 2050.

In parallel, this study examines ambient underwater noise trends across various regions. This is complemented by projections of seaborne trade growth, enabling an evaluation of the ambient noise trends. These insights are valuable for assessing the feasibility of targets for reducing URN emissions from commercial vessels. Additionally, this report presents cases illustrating the synergies that can be achieved through simultaneously enhancing energy efficiency and reducing URN in commercial vessels. It outlines the potential of various measures and tools in not only improving energy efficiency but also reducing greenhouse gas (GHG) emissions and simultaneously curbing URN emissions.

In pursuit of the IMO's revised GHG strategy, the maritime industry is endeavouring to define the most effective strategies for curtailing GHG emissions and transitioning toward a zero-emission sector. This necessitates the modernization and revitalization of aging vessel fleets and the adoption of carbon-neutral fuels, all within the context of navigating a complex landscape of green technologies. Further complicating this challenge is the extended lifespan of ships, where some vessels prove too antiquated for retrofitting and yet too young for scrapping. Recognizing the absence of a "silver bullet" and "one-size-fits-all" solution for decarbonizing the maritime sector, a diverse array of measures demonstrates considerable potential for achieving substantial emissions reductions. These measures encompass the adoption of carbon-neutral fuels and energy efficiency enhancements, including speed reduction, and logistics optimization.

The study underscores the pivotal role of scaling up the production and availability of carbon-neutral fuels in achieving the goal of zero-emission shipping by 2050. However, this endeavour is met with various challenges, including the cost of alternative fuels, insufficient infrastructure, logistical constraints, the maturity of technology in both onboard vessel systems and supply-side infrastructure, considerations associated with ship and engine design, crew training, safety protocols, and the significant financial investments required. While it is anticipated that carbon-neutral fuel will contribute to approximately 60% of zero emissions by 2050, the study demonstrates that around 32% of emissions reductions will rely on energy efficiency measures, including roughly 23% attributed to speed reduction, to meet the IMO's GHG emission targets by 2050.

The study anticipates that strategies including speed reduction, wind-assisted propulsion systems, Energy Saving Devices (ESDs), and air lubrication systems will assume important roles in realizing the IMO's GHG reduction strategy. Moreover, as the maritime sector undergoes a shift towards vessel electrification, the deployment of fuel cells, batteries, or hybrid technologies, particularly in short sea shipping, holds significant promise for enhancing energy efficiency and expediting progress in alignment with the IMO's GHG reduction strategy.

This study delves into the origins of URN in commercial vessels, and highlights cavitation as the primary source, particularly when the propeller Cavitation Inception Speed (CIS) is exceeded. The research also reveals that an increase in propeller blade area whilst reducing URN, can adversely affect the propeller's energy efficiency. Hence, it is important when designing a propeller to carefully weigh the trade-offs between cavitation, noise reduction, and efficiency. Additionally, the challenges associated with mitigating URN through speed reduction in Controllable Pitch Propellers (CPP) is discussed.

Nevertheless, the study highlights the significant synergy between the implementation of energy efficiency strategies and the reduction of URN. The results suggest that reducing vessel speed by 20% can lead to a significant 6 dB decrease in underwater radiated noise (URN) in fixed-pitch propeller vessels. Wind-assisted propulsion systems have the potential to reduce URN by up to 10 dB, while air lubrication systems can achieve even greater reductions, surpassing 10 dB in URN reduction. Considering the aging fleet of vessels and the forthcoming, more stringent Carbon Intensity Indicator (CII) requirements, the study anticipates a growing trend of vessels implementing energy-efficiency measures to align with the IMO's revised GHG strategy targets. This shift is expected to result in a reduction of URN on individual vessels.

Ross (1976) includes an equation for ambient URN, and this correlates, the most influential factors contributing to deep ocean URN. Applying this equation to worst case scenarios suggests that implementing suitable energy efficiency measures not only reduces the average source level URN from individual ships, but also mitigates ambient noise by an approximately equivalent level. Given that energy efficiency measures, encompassing speed reduction (constituting approximately 23% of these measures), are expected to contribute up to 32% to the reduction of GHG emissions from the shipping industry by 2050, it is conceivable that a 6 dB average reduction in global URN levels can be achieved through a mere 20% speed reduction, with the potential for further reductions through the adoption of other energy-efficient measures.

In consideration of the above, the study underscores that GHG reduction initiatives will exert a substantial influence on diminishing global URN levels. Achieving URN reduction targets, such as the 3 dB per decade Okeanos target, appears to be a feasible outcome. Furthermore, the study reveals that, under a worst-case scenario involving annual growth in transport work of 3.3%, and assuming nothing else changes, ambient noise levels are projected to increase by up to 2.6 dB by the year 2050. In light of these insights, the achievement of the 32% contribution from energy efficiency measures in GHG emission reduction by 2050 could effectively offset the effects of substantial seaborne trade growth and mitigate ambient noise levels, even in the most challenging scenarios.

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Acronyms

BBNJ	Biodiversity Beyond National Jurisdiction
CII	Carbon Intensity Indicator
CIS	Cavitation Inception Speed
CO_2	Carbon Dioxide
CPP	Controllable Pitch Propellers
DCS	Data Collection System
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ESDs	Energy-Saving Devices
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
ICS	International Chamber of Shipping
IMO	International Maritime Organization
JIT	Just In Time
MARPOL	International Convention for the Prevention of Pollution from Ships
MSFD	Marine Strategy Framework Directive
PIDs	propulsion-enhancing devices
SEEMP	Ship Energy Efficiency Management Plan
URN	Underwater Radiation Noise

1. Introduction

Background

Shipping, as the most efficient mode of transportation, holds a crucial position in global trade, accounting for 80% of cargo volume. Nonetheless, it presents significant environmental and socio-economic challenges, contributing to approximately 2.89% of global greenhouse gas (GHG) emissions. One pressing concern arising from commercial vessels is Underwater Radiation Noise (URN), which adversely affects marine life without being visibly detectable like other pollutants.

The continuous expansion of seaborne trade, coupled with the growth of the global fleet in terms of both its numbers and vessel sizes, as well as the increased distances travelled, has likely contributed to an increase in URN from commercial vessels. Many studies have underscored the environmental adverse impacts of this phenomenon, as well as its deleterious effects on marine life, including fish, invertebrates, and marine mammals, leading to ecological and population changes (Hawkins and Popper, 2017; Rako-Gospić and Picciulin, 2019). However, the precise link between URN from commercial vessels, marine traffic, and the extent of its negative impact on the marine ecosystem remains in its infancy and requires further investigation.

Given the transboundary nature of URN pollution and its extension beyond national jurisdictions, international, regional, and national cooperation is essential for its control. To address this issue, high-level international bodies such as the International Maritime Organization (IMO) and the European Union (EU) have taken action. The IMO introduced non-compulsory guidelines and resolutions for reducing URN from commercial shipping, and the EU addressed the matter within the Marine Strategy Framework Directive (MSFD)[1]. Additionally, other regional and national agreements play significant roles in monitoring, controlling, and mitigating URN from commercial vessels.

The 2014 IMO guidelines on reducing URN from commercial vessels emphasized the potential of routing and operational adjustments, as well as ship design and maintenance, in tackling URN. Recently, revised guidelines for the reduction of URN from commercial shipping, aimed at addressing adverse impacts on marine life, have been finalized, offering a progressive step forward. The revised version of the guidelines acknowledges the interconnectedness of oceanic issues, highlighting the importance of contributions between reducing URN from commercial vessels and addressing matters like zero emissions, biofouling, and ship safety.

In the quest to reduce URN from shipping, the International Chamber of Shipping (ICS) has sponsored this study to evaluate the correlation between measures to improve energy efficiency and reduce URN from commercial vessels. The findings of this study have the potential to streamline the worldwide adoption of guidelines and furnish essential information to various stakeholders, such as ship owners, shipyards, ports, classification societies, and regulatory bodies.

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[1] Many nations have developed their own approaches to address ocean noise management. The European Union has been tasked by its member states with the responsibility of assessing and documenting anthropogenic noise under Descriptor 11 of the Marine Strategy Framework Directive, adopted in June 2008. The main objective of this Directive is to achieve a state of good environmental health by the year 2020, with each member state devising its unique strategy to meet this target. Consequently, the Directive has spurred a proliferation of initiatives related to ocean noise in the region. These initiatives include the establishment of noise registers or databases containing comprehensive information on underwater noise.

Scope of work

The primary objective of this report is to address the questions posed by ICS, the study's sponsor. The specific inquiries include:

1. **Comment on global long-term trends for URN**

   Consider what physical measurements have been done on global URN levels, and what trends they reveal. Also, comment on the possible reasons for the trends.

2. **For the global merchant fleet, comment on the % fuel efficiency reductions that will be necessary to achieve IMO's revised GHG strategy.**

3. **Identify the main technologies and operational changes that will be adopted to achieve these efficiency gains.**

   Consider the available technologies, and operational measures that could be adopted to achieve these efficiency gains and on a cost benefit basis, forecast which technologies are likely to be adopted by ship owners.

4. **Forecast the impact of the efficiency measures on global URN levels.**

   Forecast the impact these fuel efficiency measures will have on the URN levels of individual ships, and also the impact on global URN levels.

5. **Consider appropriate target levels of global URN reduction.**

   Identify target URN reduction levels that have been proposed by environmental groups and assess how close the URN reductions forecast at step 4 will come to achieving these targets.

6. **Comment on the effectiveness of the GHG reduction measures in meeting URN reduction targets**.

   By comparing the forecasts made at steps 4 and 5, comment on how closely the target URN reductions will be met as a direct result of the GHG efficiency measures.

7. **Consider alternative URN reduction measures**.

   If there are any energy efficiency measures considered at steps 3 and 4 that may increase URN, forecast the impacts of changing to alternative measures that do reduce URN (e.g., in terms of costs and GHG reduction and URN reduction.

2. Methodology

The present study conducted a literature review, investigating the topic of URN from commercial vessels and its relationship with energy efficiency measures. The review considered technical and operational measures and their capacity to simultaneously mitigate air emissions and URN generated by commercial vessels. The study also investigated the worldwide trends of URN arising from anthropogenic sources and identified relevant international targets for global URN reduction. The authors have commented on the feasibility of achieving such targets as a co-benefit of the IMO's GHG regulations.

3. Meeting the IMO’s Revised GHG Strategy

The International Maritime Organization, as the regulatory authority for international shipping, remains a cornerstone in the global fight against climate change. It is dedicated to aligning with UN Sustainable Development Goal 13, which emphasizes the need for immediate action on climate change and its repercussions. In its pursuit of addressing GHG emissions and achieving its initial GHG strategy[2], IMO has established a comprehensive regulatory framework, encompassing the following components:

1. Energy Efficiency Design Index (EEDI): New ships must be designed and constructed with a focus on enhanced energy efficiency.
2. Ship Energy Efficiency Management Plan (SEEMP): Shipowners use this practical tool to manage environmental performance and enhance operational efficiency.
3. Energy Efficiency Existing Ship Index (EEXI): Came into effect 1st January 2023, EEXI enforces similar design standards as EEDI, with adjustments for situations where design data may be limited.
4. Fuel Oil Consumption Data Collection System (DCS): It requires annual reporting of CO_2 emissions, activity data, and ship particulars for vessels exceeding 5,000 gross tons.
5. Carbon Intensity Indicator (CII): Rates ships above 5,000 gross tons on an A to E scale, measuring their annual performance in terms of CO_2 emissions per deadweight tonnage and distance travelled.

In a bid to address the environmental impact of the global merchant fleet and align it with the objectives of the 2015 Paris Agreement, the IMO has taken substantial strides by revising its GHG strategy. The new strategy sets a target of attaining net-zero GHG emissions by or around 2050. While these new targets might not be entirely congruent with the 1.5°C target, the pursuit of achieving net-zero emissions by around 2050 represents a significant advancement compared to the initial strategy laid out five years ago.

At the 80th session of the Marine Environment Protection Committee (MEPC 80), the IMO also introduced interim checkpoint objectives for 2030 and 2040 (Fig. 1). Including the reduction of carbon intensity of ships through improvement of their energy efficiency by at least 40% by 2030, compared to 2008.

The revised strategy places a robust emphasis on fostering technological innovation and ensuring the availability of zero or nearly zero emissions technologies, fuels, and energy sources within the shipping sector. To this end, the strategy sets an interim target of 5% uptake of alternative fuels (with an

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[2] The initial GHG strategy set forth ambitious objectives, with a primary emphasis on diminishing the carbon intensity of global shipping. This involved a dedicated endeavour to reduce CO_2 emissions per transport work, targeting a minimum reduction of 40% by 2030 and aspiring to achieve an even more substantial 70% reduction by 2050, both in comparison to 2008 levels. Furthermore, the strategy placed a broader emphasis on the overarching goal of curbing the total annual GHG emissions produced by international shipping, aiming for a significant 50% reduction by 2050 when contrasted with the emission levels observed in 2008.

aspirational target of 10%) of the energy employed by international shipping by 2030. Achieving these milestones necessitates the implementation of robust technical, operational, and economic measures on a large scale, with their effective execution taking several years.

To attain net-zero GHG emissions, indicative milestones have been established, each with specific targets. By 2030, the objective is to reduce total annual GHG emissions by a minimum of 20% (with an ambitious target of 30%) in comparison to 2008 levels. This is followed by a more substantial reduction of at least 70% (with a striving goal of 80%) by 2040, also relative to 2008 levels (IMO, 2023). These benchmarks underscore the maritime industry's unwavering commitment to alleviating its environmental footprint and actively contributing to global endeavours aimed at countering climate change.

To ensure the industry meets the revised GHG strategy goals, the IMO has formulated a basket of candidate mid-term GHG reduction measures, which will comprise of:

1. A technical element which will be a goal-based marine fuel standard regulating the phased reduction of marine fuel GHG intensity; and
2. An economic element which is likely to be some form of a levy or fund and reward mechanism.

The mid-term GHG reduction measures are designed to actively drive the transition towards cleaner energy in the shipping industry.

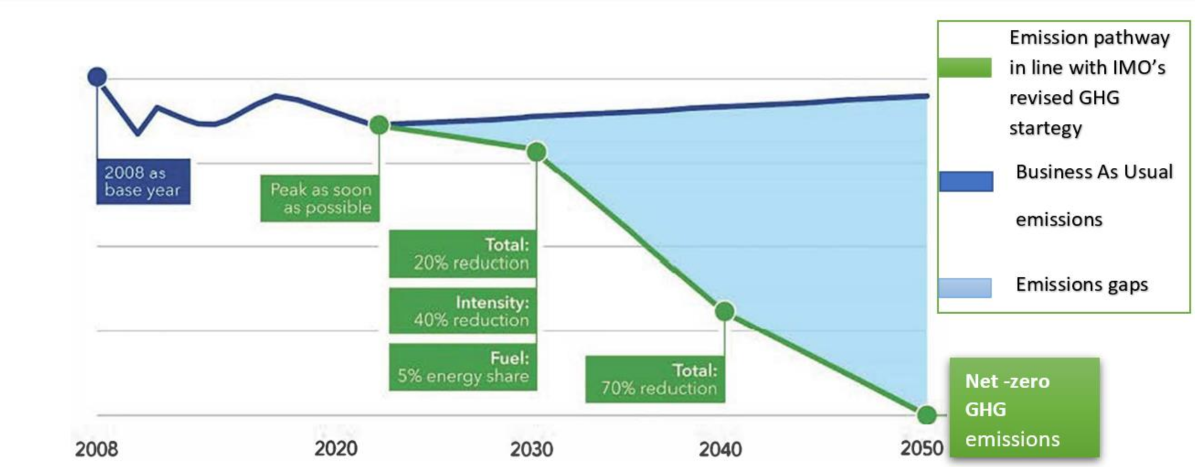

Fig. 1. IMO's revised GHG strategy goals- Adapted from (DNV, 2023).

Fig. 1 underscores the urgent necessity for a substantial shift towards more sustainable and environmentally friendly practices within the shipping sector. As the maritime industry continues to embrace alternative fuel technologies, further advancements are poised to materialize, ushering in progress in mitigating shipping's ecological impact and steering it towards a greener trajectory. The imperative lies in addressing the global merchant fleet's contribution to GHG emissions by scrutinizing the requisite enhancements to efficiency and logistics that align with the IMO's revised strategy. Recognizing the absence of a "silver bullet" or "one size fits all" solution for decarbonizing the maritime sector, a diverse array of measures holds notable potential for significant reduction. Among these approaches, the adoption of alternative fuels, enhancement of energy efficiency including speed reduction, and optimization of logistics prominently stand out[3] (Please see Fig. 2).

The IMO's Fourth GHG Study forecast that 10% speed reduction would contribute approximately 8% to the reduction of GHG emissions from the shipping industry by 2050, while alternative fuels were estimated to contribute around 64% (IMO, 2018). According to DNV's 2022 report, carbon-neutral fuels are expected to have a limited impact on emission reduction before 2030. This is primarily due to various barriers, including challenges related to the availability and cost of alternative fuels, inadequate infrastructure, logistical constraints, limited production scalability, the maturity of technology in onboard vessel systems and supply-side infrastructure, considerations related to ship and engine design, crew training, safety concerns, and the substantial financial investments required (UNCTAD, 2023). However, by 2030, the focus on energy efficiency measures, and logistic improvements becomes important. Carbon-neutral fuels are projected to play a dominant role in decarbonizing the shipping industry after 2040, accounting for approximately 60% of the industry's CO_2 emission reduction by 2050.

Additionally, due to the higher cost of carbon-neutral fuels, the utilization of energy efficiency scales up contributing around 32% to the decreased carbon emissions by 2050, including a 23% reduction attributable to speed reduction. Anticipated developments include the maturation of energy efficiency measures such as batteries and waste heat recovery systems by 2025. By 2030 and beyond, further advancements are expected, encompassing technologies like wind propulsion systems, air lubrication systems, solar panels, next-generation waste heat recovery systems, and improvements in ship design through ballast reduction (DNV, 2022). Additionally, cutting-edge technologies such as digital twins and onboard wind turbines are foreseen to mature beyond 2030.

Furthermore, improvements in logistics are poised to play a substantial role in the industry's decarbonization efforts by 2050, potentially contributing to a 9% reduction in GHG emissions. These supply chain enhancements are projected to increase vessel utilization by approximately 25% for deep-sea trades (with a smaller increase of 5% for deep-sea bulk shipping) and 20% for short-sea shipping. Additionally, economies of scale are expected to enhance fleet efficiency, with anticipated increases in ship sizes of 40% for LNG tankers, 30% for container vessels, and 10% for bulk carriers (DNV, 2022).

As stated by Faber et al. (2023), achieving a reduction of shipping emissions by 28-47% by 2030 relative to 2008 levels is technically viable. However, attaining such emissions cuts would necessitate a speed reduction of 20-30% compared to 2018, widespread integration of wind-assisted propulsion and other technical measures on vessels, and sourcing 5-10% of energy from zero and near-zero-GHG fuels. Roughly half of the emission reductions would stem from operational measures and lower speeds, a quarter from wind-assisted propulsion and technical measures, and another quarter from the utilization of zero and near-zero-GHG fuels.

In pursuit of the IMO's 2050 decarbonization ambition, a profound transformation within the shipping industry is imperative. The integration and widespread adoption of near-zero or zero-emission technologies, including alternative low-carbon and zero-carbon fuels are pivotal. Projections from DNV for 2050 anticipate a gradual role for carbon-neutral fuels in emissions reduction before 2030. However,

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[3] The research conducted a literature review to define the potential for GHG emissions reduction inherent in technologies contributing to the decarbonization of shipping (depicted in Fig. 2).

the revamped IMO GHG strategy underscores that by 2030, a minimum of 5% (with aspirations for 10%) of the energy employed in global maritime transportation should derive from sustainable alternative fuels and energy sources. The role of carbon neutral fuel to meet zero emission shipping by 2050 will pick up after 2030 and will be dominant beyond 2040 (DNV, 2022). According to the DNV (2023) report, the shipping industry is anticipated to require approximately 17 million metric tonnes of carbon-neutral fuel by 2030. This demand constitutes a substantial 30% to 40% of the global production capacity. This emphasizes the pressing need to invest in decarbonization, cultivate essential infrastructure for alternative fuels, and establish the production of zero-emission fuels at the necessary scales.

While achieving a 50% reduction in shipping emissions by 2050 may necessitate a substantial investment of $1.4 trillion (Krantz, Søgaard, Smith, 2020), complete decarbonization could potentially result in annual fuel costs increasing by 70 to 100% compared to current levels (UNCTAD, 2023). To provide context, the annual average onboard investment for new fuels and developing engines falls within a range of $8 billion to $28 billion, with ammonia and methanol requiring the most significant investments. Notably, the average annual investment in onshore fuel infrastructure exceeds onboard investment by a factor of 3.5, with figures ranging from $28 billion to $90 billion (DNV, 2022).

The mounting global, regional, and national pressure to combat climate change is ushering in the “Green Transition”, which promises to bring about a significant transformation within the shipping industry. Notably, the IMO has revised its GHG strategy, and is developing a basket of measures including a marine fuel standard and a global economic measure. Additionally, the European Union's EU ETS and FuelEU Maritime initiative, with their well-to-wake requirements, are imposing additional financial burdens on shipowners as they work towards decarbonizing their vessels.

Considering the uncertainties and barriers surrounding the production and availability of carbon-neutral fuel, compounded by the added costs borne by shipowners and the stringent regulatory landscape governing decarbonization efforts in the shipping industry, improving energy efficiency and utilising zero emissions technology assume a pivotal role. Enhancing energy efficiency is essential to help the industry align with the ambitious goal set by the IMO to achieve zero emissions by 2050. Furthermore, the implementation of technical and operational energy-efficiency measures can not only enhance the operational range of the ship but also minimize cargo space loss.

Considering the cube law, which relates power to the cube of speed, it is well-established that a reduction in speed has a pronounced impact on fuel consumption. This effect becomes particularly relevant when addressing waiting times at ports and implementing Just In Time (JIT) strategies. Even a relatively modest 20% reduction in speed can result in a substantial 30-35% decrease in fuel usage. This not only translates to significant cost savings in transportation by optimizing shipping efficiency and reducing operational expenses but also carries positive environmental implications through the reduction of emissions resulting from fuel consumption (Psaraftis and Kontovas, 2014). While Faber et al. (2017) have discussed that achieving a 50% speed reduction might not be feasible while maintaining "business as usual" due to time and economic constraints, a more manageable reduction in speed ranging from 10% to 30% is attainable and viable for most ship types.

With the IMO now aiming to achieve net-zero emissions by approximately 2050 and the corresponding CII requirements in place, there is a growing concern that, if the current system remains unchanged, a substantial number of vessels, potentially exceeding 10,000, could face decommissioning within the next three years. This projection takes into account that approximately 30% of the existing fleet, including tankers, bulk carriers, and container ships, is expected to receive D or E ratings based on the CII assessment (Clarkson, 2023). In light of these developments, the adoption of speed reduction emerges as a strategic consideration to improve the overall efficiency of the fleet. This is especially pertinent given the aging nature of the global fleet, with approximately 30% of vessels having exceeded 15 years of service, and the average age of commercial vessels being 22.2 years at the start of 2023 (UNCTAD, 2023).

However, it's essential to recognize that the economic benefits of speed reduction are not evenly distributed across the various stakeholders in the global supply chain. While ship owners may enjoy reduced fuel costs, they could face reduced revenue potential due to decreased cargo capacity on their vessels. Consequently, there might be a potential need to build additional vessels to compensate for the lost capacity. Moreover, the practice of speed reduction can have implications for cargo owners as well. Extended voyage durations may tie up their capital, leading to increased expenses. This situation could lead to a modal shift toward faster modes of transportation, such as road, rail, or air, potentially resulting in increased air emissions and environmental impacts (APEC, 2019; Vakili et al., 2023). Nevertheless, the convergence of speed reduction practices with JIT principles, coupled with a fair cost and benefit-sharing policy among stakeholders in the shipping sector, can address traffic capacity constraints and ensure equitable distribution of costs and benefits. This integrated approach can concurrently boost fuel efficiency and optimize cargo management, strengthening overall operational efficiency and sustainability. The expected results of JIT implementation encompass a noteworthy reduction in both fuel consumption and GHG emissions, with projected reductions ranging from 14% to 23% (Arjona Aroca et al., 2020).

Furthermore, considering other energy efficiency measures such as utilizing appropriate hull coating, hull and propeller cleaning and weather routing can enhance energy efficiency and reduce emission from the shipping industry. Using the appropriate hull coating and regularly cleaning the hull and propeller of a vessel can enhance its overall efficiency. Biofouling, the accumulation of marine organisms on a ship's hull and propellers, intensifies hydrodynamic resistance, leading to higher fuel consumption and decreased efficiency (Molland et al., 2017). Consistent maintenance in the form of hull and propeller cleaning mitigates this resistance, prevents the spread of invasive marine species, and consequently improves energy efficiency, ultimately translating into fuel savings (IMO, 2015). While the application of suitable hull coatings can contribute to a reduction in GHG emissions of up to 2.55% from the fleet, it is anticipated that hull and propeller cleaning may contribute to a reduction in GHG emissions from shipping by approximately 1-4% on 2050 (IMO, 2020)

Weather routing can improve operational efficiency by optimizing route and speed profiles for sea passage to avoid adverse weather conditions. Weather routing is known to reduce fuel consumption, by at least 3-5%, not accounting for time savings (IAMU, 2014). The practice not only improves energy efficiency but also can also promote safety and reduced wear and tear on vessels.

As the feasibility and scalability of alternative fuel production remain under investigation, it's essential to prioritize energy efficiency and embrace complementary technologies for reduction of GHG emissions. These include ESDs, propulsion-enhancing devices (PIDs), electrification, wind-assisted propulsion systems, air lubrication systems, and waste heat recovery. These innovative solutions can significantly accelerate the maritime sector's decarbonization efforts, leading the industry closer to the ultimate goal of achieving Zero Emissions Shipping.

The landscape of ESDS and PIDs has witnessed the adoption of these technologies on over 6,398 ships, representing approximately 28.1% of the total fleet tonnage (Clarkson, 2023). These innovations, which include propeller ducts, twisted rudders, gate rudders, bulbous bows, and propeller boss cap fins, have the potential to enhance energy efficiency by 1.5-21%. Their collective impact on reducing GHG emissions from the industry is estimated to be in the range of 1-3% on 2050 (IMO, 2020).

Cutting-edge absolute zero-GHG technologies are not just theoretical concepts; they are currently accessible in the commercial sphere and are being progressively integrated into a growing fleet of vessels. While it is anticipated that internal combustion engines will persist as primary energy converters, the influence of electrification and using hybrid systems and fuel cells in the power generation landscape is poised for growth, particularly in the realm of short sea shipping. Certain ship categories are already embracing pure electric systems, whereas hybrid-electric vessels have firmly established their presence. These hybrid propulsion setups exhibit the potential to curtail fuel consumption by an impressive margin of 10-40%, affording ship operators the flexibility to explore diverse alternative fuels. The versatility of these systems allows them to draw power from sources like LNG, diesel, hydrogen, or even leverage the synergy of fuel cells and batteries (DNV GL, 2016).

The global spotlight on hydrogen has witnessed a remarkable surge, and when paired with fuel cells, it stands poised to effectively realize the objectives set forth in the IMO's revised GHG strategy. Illustratively, the deployment of hydrogen-electric propulsion, fortified by fuel cells, is a commercially viable reality on a multi-megawatt scale. The fusion of fuel cells with supplementary energy sources such as hydrogen holds the promise of improving energy efficiency while concurrently mitigating, and in some cases eliminating, atmospheric emissions and noise pollution (Vakili et al., 2020; DNV, 2023). A distinct advantage of hydrogen lies in its combustion, which generates no CO_2, particulate matter, or SOx emissions (Andrews and Shabani, 2012), though NOx can arise at combustion temperatures exceeding 1700K (Mallouppas and Yfantis, 2021). Nevertheless, the prevalent hurdles to hydrogen's competitive dominance within the market persist in the form of production costs, storage capital expenditures, diminished carrying capacity, and safety concerns (Rasul et al., 2022).

Renewable energy sources can produce green fuels or directly integrate into hybrid systems to bolster propulsion or auxiliary power. The maritime sphere has seen experimentation with a range of renewables, including wave, wind, and solar energy. Employing devices like wings or foils at the bow has been shown to save 1-3% of energy (DNV, 2022). While solar energy offers a modest 1% reduction in auxiliary power consumption, its potential contribution to decarbonizing the shipping industry is predicted to be quite marginal, potentially reaching up to 0.3% on 2050 in the best-case scenario (IMO, 2020). In contrast, wind-assisted propulsion systems, which encompass rotor sails, rigid wing sails, soft wing sails, soft sail systems, ventilated foil systems, and kites, have undergone testing on merchant vessels and have demonstrated the capacity for significant improvements in energy efficiency. These improvements can range from 5% to 9% for specific ship types, with claims of reaching up to 25% (DNV, 2023).

When combined with strategies such as speed reduction and weather routing, wind-assisted propulsion systems have the potential to substantially reduce air emissions from ships and improve EEDI and EEXI. The IMO's 2020 report, which attributed only a 1.66% contribution to wind power in the decarbonization of the industry by 2050, offers a limited perspective. However, when we project forward to 2050 and take into account evolving market trends, technological advancements, the maturation of wind-assisted propulsion technology, cost reductions, and the potential for emissions reduction through the integration of various strategies like speed reduction and weather routing, there is a strong anticipation that this technology will play a far more substantial role in the industry's decarbonization efforts, contributing significantly to the transition to zero emissions by 2050.

The air lubrication system represents an innovative approach to reduce the frictional resistance of a ship's hull by generating tiny bubbles (Kumagai et al., 2015; Lloyd et al., 2020). Among the three air supply systems and techniques commercially employed in ships—namely, air cavity, air film, and the small bubble method—the latter has gained favour due to its use of micro-bubbles, which minimizes hull shape alteration (Ceccio, 2010; Murai et al., 2020). Importantly, the small bubble method not only improves energy efficiency by 5-15% but also creates an air bubble curtain that significantly reduces noise propagation from the ship into the marine environment (RINA, 2023). While it was initially predicted that this technology could contribute approximately 2.26% to the reduction of GHG emissions from the industry by 2050 (IMO, 2020), the adoption rate has been relatively modest, with installations on approximately 250 vessels in total (DNV, 2023). However, increased uptake and widespread deployment of this technology have the potential to significantly enhance its contribution towards meeting the IMO's GHG emission reduction targets by 2050.

Waste heat represents untapped energy that dissipates into the surroundings. The utilization of waste heat offers an avenue for enhancing the energy efficiency of ships up to 8% (Barone et al., 2020) and it was predicted to have contributed up to around 3% for decarbonisation of the shipping industry by 2050 (IMO, 2020). In maritime applications, roughly 48-51% of engine-generated energy is released as exhaust gas and jacket water, underscoring the potential of waste heat recovery to generate additional energy output while adhering to emission standards (Pesyridis et al., 2023). The selection of the most suitable heat recovery technologies depends on the specific characteristics of shipboard waste heat and the achievable recovery efficiencies, necessitating a comprehensive assessment of the attributes of each system (Singh and Pedersen, 2016).

3-20%
Machinery
Machinery efficiency improvements
Waste heat recovery
Engine de rating
Battery hybridisation
Engine Vs Fuel cell
Enhance fuel injection system

5-15%
Vessel design and hydrodynamic
Optimum ship size and dimension
Energy Saving Device
Air lubrication system
Hull form optimisation
Hull coating
Hull and propeller cleaning

0-100%
Energy
LNG, LPG
Hydrogen
Ammonia,
Methanol
Electrification
Renewable energy (Wind, Solar)
Biofuels

>20%
Voyage optimization
Speed reduction and Just In Time
Advance port logistic
Optimise vessel utilisation
Power demand optimisation
Weather routing

Fig. 2. Shipping decarbonization technologies' GHG emissions reduction potential.

Conclusions

The IMO, as the regulatory body of international shipping, has set ambitious goals to achieve zero emissions by around 2050. Recognizing that there is no silver bullet or one-size-fits-all solution to meet these objectives, a combination of measures must be considered.

Anticipated developments suggest that carbon-neutral fuels are expected to gain prominence after 2030 and become dominant beyond 2040. These expectations are tempered by significant barriers, including challenges related to the availability and cost of alternative fuels, inadequate infrastructure, logistical constraints, limited production scalability, the maturity of technology in onboard vessel systems and supply-side infrastructure, considerations related to ship and engine design, crew training, safety concerns, and the substantial financial investments involved. Despite these challenges, carbon-neutral fuels are projected to account for approximately 60% of emissions reduction by 2050.

In response to increasingly stringent environmental regulations and policies, coupled with significant challenges such as the scalability of carbon-neutral fuel production, availability issues, and associated costs, the maritime industry finds itself compelled to adopt a range of measures. These include the implementation of energy-efficient technologies, including speed reduction, and the optimization of logistics to align with the International Maritime Organization's emissions reduction objectives.

The implementation of energy efficiency improvement measures including speed reduction plays a pivotal role in mitigating GHG emissions from the shipping industry. By 2050, these measures have the potential to contribute to a substantial 32% [4] reduction in GHG emissions from the sector. This reduction comprises an estimated 23% reduction through speed reduction and around 9% through improvements in energy efficiency. Additionally, improvements in logistics, factoring in economies of scale, could account for an additional 9% reduction, helping to achieve the IMO's GHG emissions strategy.

To meet zero emission shipping close to 2050, the maritime sector can leverage a combination of operational and technical measures, including ESDs, PIDs, electrification, air lubrication systems, waste heat recovery. Furthermore, optimizing logistics processes and harnessing energy sources such as wind have the potential to significantly enhance energy efficiency without sacrificing cargo capacity. Wind propulsion systems can improve energy efficiency by 5-25%,

The CO_2 mitigation capacity attributed to speed reduction surpasses that of alternative technologies. Taking into account factors like the average age of the fleet and the CII regulations, speed reduction, when combined with other optimization strategies can significantly enhance efficiency. However, the cost savings associated with these must be balanced against the supplementary capital expenditures required for the construction of additional vessels. It's worth emphasizing that JIT, coupled with an appropriate cost and benefit-sharing policy among stakeholders, can remove the need for additional capacity by simply ensuring that ships arrive precisely in time to offload, thereby minimising the necessary voyage speed, and eliminating the need for port waiting time, (i.e., time spent at anchor, waiting for an offloading berth to become available).

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[4] The study reviewed research on the decarbonization of the maritime industry and the effectiveness of measures in reducing air emissions from the sector. Each study, based on their respective assumptions, offers valuable insights into the potential of these measures to align with IMO's revised GHG reduction targets. However, for our analysis, we primarily relied on the DNV, (2022) report due to its more recent and comprehensive data, which provided a more accurate assessment of the decarbonization pathway by 2050.

Furthermore, other technology measures such as air lubrication systems, next generation of waste heat recovery, using renewable energies onboard vessels, and cutting-edge packages such as digitalization can play roles in decreasing GHG emission from the shipping industry.

There is an economic driver to consider fully electric and hybrid vessels for short sea shipping, particularly where there is a sufficient renewable electricity and appropriate infrastructures and grid capacity. Although the capex might be high, the fuel can be removed from the bottom line and can reduce operational cost significantly.

Attaining a zero-emission shipping sector by 2050 is a challenging yet feasible goal that requires a collaborative endeavour involving industry, regulators, and governments. Important components for guiding the maritime industry towards a greener and more sustainable future include cooperation among stakeholders, the embrace of innovative technologies, the establishment of sustainable infrastructure, and the formulation of a comprehensive policy framework. While the required technologies to meet the IMO's zero emission targets by 2050 are readily available, it is essential to establish a fitting regulatory framework that promotes balance among stakeholders and addresses the requirements of developing nations. For instance, the IMO's market-based measures have the potential to bridge the price gap between carbon-neutral fuels and conventional options, thereby expediting decarbonization efforts within the sector. Ensuring that the adoption of regulations does not inadvertently lead shipowners towards an unsustainable path is of paramount importance. Shipowners should have the opportunity to adhere to these rules in a cost-effective and affordable manner, facilitating a smooth transition towards a more environmentally friendly and sustainable maritime industry.

4. Trends in Ambient URN

Frisk's research in 2012 firmly established a substantial correlation between economic growth, seaborne trade, and ambient noise levels in the world's oceans. This correlation has notably experienced remarkable growth, more than doubling over the past two to three decades, as reported by Valdenaire in 2022. Studies show that low-frequency noise levels increased by approximately 15 dB between 1950 and 2000, equivalent to a rate of around 3 dB[5] per decade (Frisk, 2009; McDonald et al., 2006). The surge in commercial shipping, indicative of global trade, has been identified as a significant contributing factor to this observed 3 dB per decade increase in noise levels (Andrew et al., 2002). Nevertheless, there are indications of a potential deceleration or stabilization in this upward trend (Andrew et al., 2011). These findings find support in research conducted by Chapman and Price (2011), Miksis-Olds and Nichols (2016), and Harris et al. (2019).

Meanwhile, considering the direct relationship between URN and seaborne trade, with the continuous growth in seaborne trade and the introduction of new shipping lanes, along with the expansion of the global fleet in terms of size, capacity, and power, it is anticipated that the URN levels from three main types of vessels (Container ships, Bulk Carriers, Tankers) will increase by 87% to 102% by the year 2030 compared to 2015, as noted by Kaplan and Solomon (2016).

In the context of energy considerations, Jalkanen et al. (2022) have reported that the URN produced by global shipping is doubling every 11.5 years, while acknowledging significant regional variations. Notably, their study highlights containerships, dry bulk carriers, and liquid tankers as the primary contributors, responsible for emitting 75% of the URN associated with shipping.

North Pacific Ocean

The ambient sound levels in the Northeast Pacific Ocean have shown a gradual increase, especially within the low-frequency range of 10–100 Hz, at a rate of approximately 3 dB per decade (equivalent to 0.55 dB per year) until the 1980s (McDonald et al., 2006; Ross, 1993). However, this upward trend significantly slowed to 0.2 dB per year in subsequent years, as documented by Chapman and Price (2011). Interestingly, despite the expansion in the number and size of ships operating in the region, research conducted by Andrew et al. (2011) indicates that sound levels have been decreasing since the 1990s. This decline has been attributed to improvements in ship hull and propeller design, as well as their interaction, resulting in enhanced efficiency and consequently contributing to the reduction of URN from commercial vessels.

Indian Ocean

In previous research, linear models were employed to discern and depict trends in ambient noise levels, revealing a notable paradox within the context of the Indian Ocean. Specifically, the findings showed an increasing trend from 2002 to 2012, followed by a contrasting decreasing trend observed from 2003 to 2017 (Harris et al., 2019; Miksis-Olds et al., 2013). This dichotomy in trends underscores the intricate

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[5] Acoustic measurements are typically denominated in decibels (dB), a unit that involves logarithmic calculations of different ratios. The logarithmic nature of the dB scale signifies that a 3dB change corresponds to either a doubling or halving of sound energy.

and variable nature of ambient noise dynamics in the Indian Ocean, emphasizing the necessity for a more comprehensive understanding of the underlying factors contributing to these observed patterns.

The escalation in ambient noise levels in the Indian Ocean can be partly attributed to the activities of shipping and seismic airgun operations, which are widely acknowledged as major contributors to acoustic trends in the region (Frisk, 2012). This association between shipping activities and noise levels in the Indian Ocean is striking, particularly evident in the case of low-frequency noise, which has seen a notable increase of 2-3 dB over the course of the past decade, as elucidated by Miksis-Olds et al. (2013; 2014). Nevertheless, it is important to recognize that changing ice dynamics resulting from climate change also exert a significant influence, contributing to the upsurge in low-frequency noise within the Indian Ocean (Matsumoto et al., 2014).

Moreover, an analysis conducted at the Indian Ocean station (Cape Leeuwin), located off the southwest coast of Australia, revealed statistical reductions in sound pressure levels across all statistical percentiles for different frequency bands (Robinson et al., 2019). This apparent contradiction in the ambient noise trend in the Indian Ocean leads to hypotheses suggesting that deep-water ambient noise dynamics in the Indian Ocean are influenced by Antarctic Sea ice extent and melt dynamics, and that linear models may not fully capture the long-term ambient noise trends (Park et al., 2023).

Furthermore, with the robust Middle East economy and the projected growth in trade across East African states (African Development Bank Group, 2023; The World Bank, 2021), the region's acoustic landscape is expected to experience an increase in anthropogenic noise. Various activities, including seismic exploration, fossil fuel exploitation, the establishment of shipping routes, and the expansion of ports, all contribute to the amplified presence of anthropogenic noise within the region.

Equatorial Pacific and the South Atlantic Ocean

Miksis-Olds and Nichols (2016) undertook a comprehensive study to assess the rate and magnitude of change in low-frequency sound over the past decade in regions. Interestingly, the findings revealed a decrease in sound levels in both the Equatorial Pacific and the South Atlantic Ocean. The study, highlighted that in the South Atlantic, seismic airgun signals emerged as the dominant source of noise, significantly contributing to the acoustic environment. On the other hand, in the Equatorial Pacific location, shipping and biological sources played a more substantial role in shaping the ambient sound levels.

Arctic

Over the past two decades, the Arctic region has experienced a notable upswing in shipping activity, particularly during the summer months. The number of ships entering the Arctic surged by 25% between 2013 and 2019, covering a significantly increased sailing distance of 75%, from 6.5 million nautical miles to 9.5 million nautical miles during the same period. Consequently, this surge in shipping has resulted in a substantial increase in underwater noise levels, which have risen by 5-15 dB over the past decade (PAME, 2021). This increase is comparatively rapid when compared to the Northeast Pacific Ocean, where soundscapes have evolved more gradually, with noise levels increasing at a rate of 2-3 dB per decade over a longer period of 30-40 years (McDonald et al., 2006).

In the Arctic, achieving similar increases in a significantly shorter timeframe can have a more profound ecological impact on marine species inhabiting the region. These species may not be accustomed to such rapid changes and might not have had sufficient time to adapt to the increased noise levels. These findings underscore the importance of identifying specific sources contributing to ambient noise levels in different regions. Understanding the implications of heightened shipping noise is essential for preserving the delicate ecosystems and marine life in the Arctic.

Australia

The maritime regions of Australia provide valuable insights into understanding the primary sources of underwater noise. In their comprehensive analysis of the marine soundscape, Erbe et al. (2021) conducted validation studies at 25 different stations, ultimately identifying wind and shipping as the dominant contributors to underwater noise in Australia. Notably, within Australia's Exclusive Economic Zone, wind-generated noise surpasses ship-related noise, particularly along the southern coast. However, specific areas along the eastern seaboard and northwest waters, situated near busy shipping lanes, exhibit a prevalence of shipping noise. This regional variability in noise sources underscores the importance of considering local factors when evaluating ambient noise levels.

North Sea

The impact of human activities on underwater noise levels extends beyond shipping alone. Sertlek et al. (2019) emphasized that shipping contributes the most to acoustic energy in the Dutch North Sea, followed by seismic surveys, explosions, and wind. In the context of the region, maritime transportation exerts significant influence in the southern area and extends along the northern coastal areas. Conversely, seismic surveys exhibit a degree of locality, with their spatial and temporal occurrence closely tied to exploration activities. These findings underscore the importance of considering multiple sources of underwater noise and their cumulative effects on the acoustic environment.

Covid impact

Several studies offer valuable insights into the potential impact of reduced human activities on ocean ambient noise levels during the COVID-19 pandemic. The pandemic had widespread effects on global trade, leading to significant reductions in vessel traffic across various oceans and national waters, resulting in a decrease in ocean ambient noise during the pandemic (March et al., 2021). Container ships experienced a 13% reduction in traffic, while passenger ships saw reductions of up to 42% (Millefiori et al., 2021). This disruption in trade and shipping services almost brought URN from ships back to levels last observed in 2017, indicating a 6% reduction in global shipping noise source energy in the 63 Hz 1/3 octave band (Jalkanen et al., 2022). However, as the world economy recovers, it is expected that growth in world trade will increase shipping activity. Whether this will result in increased URN will depend on the relative impact on URN of the progressive energy efficiency measures that are increasingly being adopted to ensure compliance with the GHG regulations. Studies focused on the North American coast have provided valuable insights into these observed changes. Sound pressure levels near the Port of Vancouver decreased by 1.5 dB in early 2020, indicating a reduction in noise levels (Thomson and Barclay, 2020). Measurements along the Oregon coast of the USA during the spring of 2020 showed a reduction of approximately 1.6 dB in sound pressure levels within specific frequency bands compared to previous years (Dahl et al., 2021). Similar reductions in underwater noise and vessel traffic were observed in the approaches to Halifax Harbour, Canada (Breeze et al., 2021). Furthermore, the pandemic led to a decrease in low-frequency vessel noise within the Monterey Bay National Marine Sanctuary, with 2020 exhibiting the lowest levels of shipping activity and noise compared to previous years (Ryan et al., 2021).

In the European Union, there was an 8% reduction in URN from ships starting in March 2020 (Jalkanen et al., 2022). The North Sea demonstrated a decline in sound pressure levels across a range of frequencies, with a 5% reduction noted for the 63 Hz 1/3 octave band. Similar reductions of 14% and 9% were observed in the Baltic Sea and Mediterranean Sea, respectively, corresponding to the decreased level of shipping activity (Basan et al., 2021).

While most studies have focused on shallow seas, less attention has been given to the deep sea. Robinson et al. (2023) conducted a comprehensive analysis of deep-ocean acoustic noise levels during 2020 and preceding years. The results revealed reductions ranging from 1 to 3 dB in the frequency range of 10 to 100 Hz for most stations within the ocean basins (Pacific, Atlantic, and Indian), with significant local reductions observed in areas where transport links, such as ferries, ceased operations during the pandemic. Additionally, Jalkanen et al. (2022) highlighted a noticeable decrease in URN from ships (at a frequency of 63 Hz in the 1/3 octave band) along the main shipping routes between China and the EU. Specifically, there was an observed reduction of noise levels in the Arabian Sea by 8%, the Red Sea by 5%, and the Mediterranean Sea by 9%. However, the reduction of URN was not uniform, with only a 3% reduction of URN in the Eastern China Sea, and even an increase in URN from ships in some areas such as the Gulf of Thailand (13%).

Although sound maps, particularly in Europe under the EU MSFD, have gained recognition for acoustic impact assessments, there is a lack of historical quantitative studies on the global trend of underwater ambient noise changes, especially in deep-sea regions. Merchant et al. (2016) suggests that a minimum of three decades of uninterrupted monitoring is necessary to identify trends of comparable magnitude to the historical increases in noise levels observed in the Northeast Pacific. Nonetheless, recent research and noise budgeting efforts have shed light on the underwater noise spectrum and its variations in different areas.

Taking the above discussions into consideration, previous studies have predominantly relied on linear models to detect and visualize patterns in ambient noise levels. However, these approaches have yielded contradictory findings in some cases. For instance, in the Indian Ocean, an apparent inconsistency was observed, with an upward trend from 2002 to 2012 followed by a downward trend from 2003 to 2017 (Harris et al., 2019; Miksis-Olds et al., 2013). Recognizing the limitations of linear models, Park et al. (2023) conducted an extensive investigation into continuous low-frequency deep ocean ambient noise off the coast of Cape Leeuwin, Australia, spanning 18 years. The results reveal a pronounced annual variation with a range of 4–6 dB and evidence of a nonlinear trend over the period 2003–2020. The study provides convincing evidence of a decreasing nonlinear trend, suggesting the presence of long-term cyclic dynamics. This non-linear trend aligns with variations in oceanographic sea surface temperature, which are believed to drive changes in Antarctic Sea ice extent. These findings underscore the influence of Antarctic Sea ice extent and melt dynamics on ambient noise dynamics, indicating that linear models may not fully capture the long-term trends and dynamics of ambient noise.

Coastal enhancement effect

When considering levels of ambient noise, it is important to be aware of the coastal enhancement effect. This was described by Ross as “a mechanism whereby sounds from near-surface sources can be propagated to a distant receiver by low-loss, deep channel, near-horizontal refractive paths.” It occurs when sound rays striking an outwardly sloping bottom are transformed by twice the slope angle of the bottom. Thus, one or two reflections from a moderate slope will change the vertical angles of rays leaving a surface source between 6 degrees and 18 degrees to rays propagating with effective angles of less than 6 degrees and can therefore propagate greater distances. Originally the effect was called the "megaphone effect."

Ross reports that a dramatic example of this effect was discovered when sounds from small explosives dropped in continental coastal waters could be picked up by deep channel receivers at distances as great as 10,000 km, even though signals from shots in deep waters at closer distances were undetectable. Hence the impact of sources located adjacent to such coastal shallow water locations can disproportionately impact URN levels within the deep ocean.

Conclusions

Anthropogenic noise levels exhibit variability across both space and time, primarily driven by the intensity of human activity and the acoustic propagation characteristics specific to a given region. Recognizing the multifaceted sources of underwater noise and their cumulative impacts on the acoustic environment is essential. One of the significant contributors to the substantial increase in underwater noise is industrial and shipping development. In addition to seismic surveys, explosions, and wind-related factors, shipping plays a significant role in elevating underwater noise levels. However, while shipping is a significant contributor to underwater ambient noise, the specific contribution of commercial shipping remains unclear and warrants investigation.

Studies have indicated that ambient noise has increased by approximately 3 dB per decade in certain parts of the world. It's important to note that this trend is not uniform across all regions; some areas have shown a plateau or even a decrease in noise levels. Furthermore, there are discrepancies in the predictions of underwater noise levels in various global regions. These disparities underscore the importance of moving away from linear models and instead considering nonlinear trends that account for long-term cyclic dynamics. Achieving this goal necessitates a minimum of three decades of uninterrupted monitoring to identify trends comparable in magnitude to the historical increases in noise levels observed in the Northeast Pacific.

The COVID-19 pandemic provided valuable insights into the potential impact of reduced human activities on ocean ambient noise levels. The decrease in shipping activity led to a 6% reduction in global shipping noise source energy within the 63 Hz 1/3 octave band, returning noise levels to those last observed in 2017. Notably, these reductions were unevenly distributed, with significant local decreases occurring in areas where transportation links, such as ferries, ceased operations during the pandemic, as well as along major shipping routes between China and the EU.

It is important to emphasize that for more accurate predictions of URN on a global scale, greater attention must be devoted to the deep sea. The increase in low-frequency ocean sound is not consistent worldwide, cautioning against drawing universal conclusions about uniformly rising low-frequency sound levels at a global level.

When considering the factors that influence ambient noise, it is important to be aware of the coastal enhancement effect, which allows the URN from sources close to the coast to be heard far away in the deep ocean.

5. Synergy Between Improvement of Energy Efficiency and Reduction of URN from Commercial Vessels

The IMO implements measures to mitigate GHG emissions from shipping through the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI. These measures encompass the EEDI/EEXI, the SEEMP, and DCS, which necessitates the annual reporting of CO_2 emissions. Furthermore, IMO has adopted a dual-tier approach to implement short-term decarbonization measures, as discussed during the 75th Marine Environment Protection Committee (MEPC) meeting in 2020. This approach combines a technical measure, i.e., the design indexes EEDI/EEXI, with an operational measure, the CII (Vakili and Ölçer, 2023). In addition, at MEPC 80, to ensure that the industry aligns with the revised GHG strategy goals, the IMO has developed a comprehensive basket of candidate mid-term GHG reduction measures. This multifaceted approach combines a technical element, which involves the establishment of a goal-based marine fuel standard regulating the phased reduction of marine fuel GHG intensity, with an economic measure (IMO, 2023).

The introduction of EEXI and CII signifies an important step toward maritime decarbonization. The EEXI serves as a comprehensive framework for assessing the energy efficiency and CO_2 emissions of existing vessels exceeding 400 gross tonnages. This index draws inspiration from the methodology established for the EEDI, a metric tailored for newly constructed ships. EEXI serves as a measure to gauge a ship's carbon emissions, standardizing the measurement of CO_2 emissions while accounting for factors such as installed engine capacity, transportation capabilities, and ship speed. Emission calculations hinge on important variables including the primary engine's installed power, fuel oil consumption, and a conversion factor that equates fuel usage to corresponding CO_2 mass.

Concurrently, the CII requires that vessels surpassing 5,000 gross tons quantify and disclose carbon emissions arising from their ongoing operations. This initiative equips ship operators with a baseline against which they must annually reduce carbon emissions to align with regulatory stipulations and facilitate continuous enhancement. Vessel performance will undergo evaluation on a five-tier scale (ranging from A to E) to assess their energy efficiency achievements. Shipowners and operators can refer to the measures outlined in Fig. 3 to ensure compliance with IMO’s GHG regulations.

EEDI (New ships only) & EEXI (All ships)

Hull and propeller Optimization- Energy Saving Devices (ESD)- Machinery efficiency improvements- Power limitation- Engine de rating- Enhance fuel injection system- Alternative fuels - Waste heat recovery- Battery hybridization- Engine Vs fuel cell- Optimization of ship size and dimension - Renewable energy- Air bubble system- Carbon capture etc.

CII: All ships

Speed optimization and just In Time (JIT) – Biofouling management- Hull and propeller cleaning and maintenance- Plan Maintenance Programme (PMP)- Power demand optimization- Advance port logistics- Weather routeing- Optimize vessel utilization- Alternative fuel etc.

Fig. 3. Measures and tools to meet IMO's GHG strategy objectives.

Note: Majority of the above EEDI and EEXI measures can also improve a vessel’s CII rating.

URN generated by ships primarily originates from three main sources: propellers, machinery, and the hull (Hildebrand, 2009). For newly designed vessels, incorporating well-suited and optimized ship designs during the early developmental stages offers a twofold advantage: significant reduction in expenses related to addressing URN and avoidance of costly retrofits in the future. Implementing efficient design optimization in the initial development phases not only enhances the EEDI of the ships, thus reducing URN, but also proves to be a financially prudent approach that eliminates the need for additional modification costs later (Vakili et al., 2020). To support decision-makers, the application of computational modelling techniques such as Computational Fluid Dynamics, Direct Numerical Simulation, Statistical Energy Analysis, Boundary Element Method, and Finite Element Analysis can enhance the efficiency and cost-effectiveness of both design and retrofitting efforts aimed at mitigating air emissions and reducing URN in commercial vessels (Grigoropoulos et al., 2017; Li et al., 2018).

Examining the current fleet, as emphasized in Veirs' 2018 research, highlights an important point: approximately 50% of underwater noise can be attributed to a mere 15% of commercial ships. Achieving a reduction in underwater noise by addressing only the loudest vessels would have limited fleet-wide effects. However, when we consider the necessity for 30% of the global fleet to adopt proactive measures such as speed reduction and the integration of energy-efficient technologies like wind propulsion systems, air lubrication systems, and ESDs in order to meet carbon intensity mandates, the prospect of a substantial reduction in underwater noise from maritime sources becomes an attainable goal. Key elements in this approach include speed reduction, wind-assisted propulsion systems, and air lubrication systems, all of which are important in achieving the IMO's GHG strategy and reducing URN emissions from commercial vessels.

Given the nature of URN emanating from commercial vessels and its intricate relationship with energy efficiency, this section of the report is primarily dedicated to the identification of the principal URN sources originating from commercial vessels. Additionally, it outlines a comprehensive approach to mitigating URN emissions while concurrently addressing GHG emissions from these vessels. These URN sources encompass the propeller system, hull design and wake flow dynamics, onboard machinery, and operational measures, with a specific focus on maintenance procedures. To optimize the effectiveness of our actions, this study considers measures and tools that exhibit a synergistic effect on both energy efficiency enhancement and URN reduction, as elucidated in Table 1, Table 2 also provides a comprehensive categorization of technical and operational measures .

Technical measures have been further segmented into three categories: propeller optimization and its interaction with the ship's hull, machinery and engine room design, and computational modelling. Meanwhile, machinery and engine room design fall into the following subcategories: the appropriate design and layout of machinery, low noise machinery, and the utilization of resilient mountings.

The potential of operational measures in enhancing energy efficiency and URN reduction must not be underestimated. These are subdivided into five primary categories: ship’s hull and propeller cleaning and maintenance, JIT practices and speed reduction, ship handling optimization, passage planning, power demand management, and weather routing, along with convoy strategies.

Upon reviewing the comprehensive set of proposed measures outlined in Table 2, it becomes evident that the majority of these measures are conducive to simultaneously decreasing both URN and GHG emissions from ships. It is essential to recognize that the effectiveness of each measure, as well as potential synergies among them, may vary depending on the specific context of implementation. These combinations can be integrated either during the vessel's design phase or incorporated into operational protocols, either as standalone initiatives or in combination, to maximize their impact.

Table 1. Actions to reduce URN from commercial vessels.

Disciplines	Categorization	Sub - Categorization
Technical	Optimization of propeller and its interaction with ship’s hull.	*Propeller and hull design.* *PIDs & ESDs.* *Air lubrication system.* *Alternative propulsion types.*
	Machinery and engine room design.	*Proper design and layout of machinery.* *Low noise machinery.* *Resilient mountings.*
Operational	Ship’s hull and propeller cleaning and maintenance.	
	Just in time and speed reduction.	
	Optimization of ship handling.	
	Passage planning, power demand and weather routing.	
	Convoy.	

Technical measures

In this section, the report considers the technical measures that are intended to mitigate URN emissions from commercial vessels.

Optimization of propeller and its interaction with the ship’s hull.

Propeller and hull design

The optimization of propeller design and its interaction with a ship's hull plays a pivotal role in enhancing energy efficiency and reducing URN emitted by commercial vessels. Although a ship's hull's contribution to URN is relatively minor when compared to the propeller and machinery, it assumes an important role in the genesis of propeller cavitation, which stems from irregular flow patterns and wake phenomena (Prins et al., 2016).

The propulsion system of ships represents a significant URN source, especially at frequencies below 200 Hz (Wittekind and Schuster, 2016). Noise propagation from the propeller is influenced by several factors. These encompass the displacement of water by the propeller blade profile, the frictional disparities between the suction and pressure surfaces of the propeller, the dynamics of flow over the propeller blade surfaces, the fluctuations in cavity volumes around the blades due to varying wake interactions with the propeller, and the abrupt bursting of cavitation bubbles (Lidtke et al., 2016). Propeller noise can be categorized into two principal types: non-cavitation noise and cavitation noise. The first three factors contribute to noise irrespective of cavitation conditions, while the latter two are contingent on the occurrence of cavitation phenomena (Yusvika et al., 2020). Cavitation, accounting for 80-85% of ship radiated noise once the CIS is reached, not only generates noise but can also lead to accelerated metal erosion and damage to propeller blades (Ross, 1976).

Effectively mitigating noise propagation from commercial vessels entails the implementation of several important measures. These encompass advancements in propeller design, raising the CIS threshold, and potentially reducing the ship's operating speed to levels below the CIS. The extent of cavitation is significantly influenced by propeller design, its interaction with the vessel's hull, and the dynamics of wake flow into the propeller (Supponen et al., 2018). A well-optimized hull design ensures a uniform and streamlined inflow to the propeller, resulting in reduced cavitation, heightened overall efficiency, and decreased levels of vibration and noise. Customizing the propeller design to align with the specific ship type and its unique wake inflow patterns is essential for enhancing overall efficiency while minimizing cavitation and associated noise. For instance, the incorporation of Contracted and Loaded Tip propellers on vessels with higher block coefficients, such as tankers and bulk carriers, can boost propulsion efficiency and contribute to noise mitigation (Bertetta et al., 2012).

The optimization of propellers, encompassing factors like diameter, blade number, blade area, pitch, skew, rake, and blade sectional shape, can yield substantial reductions in URN emitted by ships. While noise-reducing propeller designs are available in many instances, practical constraints, whether technological or geometrical, may limit their applicability. For example, expanding the blade area can effectively reduce cavitation and consequently decrease URN from commercial vessels. However, it is essential to recognize that this increase in blade area may adversely impact the energy efficiency of the propeller (Carlton, 2018). Consequently, it is important to prioritize an optimal propeller design while carefully considering the trade-offs among cavitation, noise reduction, and efficiency to achieve the desired noise reduction objectives.

Taking into consideration factors such as ship size and type, the effective management and mitigation of cavitation can be realized through early-stage design optimization and, when deemed necessary, retrofitting of the propeller to enhance its performance. This optimization not only serves to enhance efficiency in alignment with the requisite EEDI, EEXI, and CII requirements but also contributes to the reduction of URN (Vakili et al., 2021). For instance, MAERSK LINE achieved a substantial enhancement in fleet efficiency and a corresponding URN reduction of 6 dB in the low-frequency band (8–100 Hz) and 8 dB in the high-frequency band (100–1000 Hz) through the retrofitting of its G-class container ships, compared to their pre-retrofit conditions (TM, 2017).

Many technologies have demonstrated their effectiveness in diminishing propeller cavitation and mitigating URN emanating from ships. For instance, the introduction of air into cavitation zones can yield a URN reduction of 10-15 dB within the frequency range of 40-400 Hz (Baudin and Mumm, 2015). Additionally, techniques such as high skew propellers, Kappel propellers, and Contracted Loaded Tip propellers have proven successful in concurrently improving efficiency and URN mitigation in ships. Furthermore, innovations in material selection for propeller manufacturing, such as composite propellers, have the potential to enhance efficiency and reduce URN. For example, composite propellers, despite their higher cost compared to traditional propellers, offer advantages such as reduced URN across all frequencies, with potential reductions of up to 5%, as well as improved energy efficiency by up to 4% (Vard Marine Report, 2019; Young et al., 2016).

Propulsion Improving Devices & Energy Saving Devices

In the realm of ESDs and PIDs, an impressive total of 6,398 vessels, constituting approximately 28.1% of the overall fleet tonnage, have effectively integrated these cutting-edge technologies, as reported by Clarkson in 2023. These innovative solutions encompass a range of advancements, including propeller ducts, twisted rudders, gate rudder, bulbous bows, propeller cap turbines, pre-swirl stators, Mewis ducts, and propeller boss cap fins. These technologies have showcased their substantial potential to enhance energy efficiency, with improvements ranging from 1.5% to an impressive 21%. Furthermore, by optimizing the flow dynamics in the vicinity of the propeller, these technologies offer the added advantage of potentially reducing URN by a notable 5 to 10 dB (Vard Marine Report, 2023).

When assessing the cost-effectiveness of these technologies, several pivotal factors come into play. These encompass the initial capital investment, the specific type of technology employed, the vessel's size, the extent of fuel savings achieved, and the prevailing fuel costs. Notably, these technologies typically feature a brief payback period, rendering them an economically viable choice for vessel operators aiming to enhance efficiency and mitigate URN emissions.

Air lubrication system

Air lubrication systems enhance energy efficiency by reducing the hydrodynamic resistance between a ship's hull and seawater. This is achieved through the injection of air along the flat bottom area of the vessel. As of 2023, this innovative system has been implemented in approximately 250 vessels (DNV, 2023) and is anticipated to see wider adoption in the future. Remarkably, this technology holds the potential to deliver substantial energy efficiency improvements, ranging from 5% to 15%, while concurrently achieving a remarkable reduction in URN of over 10 dB (Vard Marine, 2019; RINA, 2023).

It is important to note that although model tests utilizing scaled models have been employed in assessing the efficacy of these systems, the extrapolation of these findings to full-scale applications presents a considerable challenge. This underscores the significance of addressing issues related to the reliability and effectiveness of these measures, which are among the primary barriers to accurate prediction of URN reductions in emissions from commercial vessels.

Alternative propulsion types

The alternative propulsion system is categorized into wind-assisted propulsion systems and Fuel Cell, Battery, and Hybrid systems.

Wind-assisted Propulsion systems have already been deployed on 28 large vessels as of 2023 (DNV, 2023), and their adoption is projected to increase substantially in the coming decade. This technology harnesses aerodynamic forces to reduce a vessel's propulsion requirements, resulting in potential energy efficiency enhancements ranging from 5% to 9% for specific ship types, with claims of achieving up to 25% (DNV, 2023). Furthermore, they can significantly reduce URN by more than 10 dB. However, it is important to carefully consider the interaction between the ship's hull and the propeller when implementing such technologies, as adjustments to the propeller design may be necessary to accommodate the new power requirements. A thorough examination and assessment of these factors are necessary to ensure the successful integration of these technologies for URN reduction in ships.

These technologies also have the potential to substantially improve EEDI and EEXI compliance and improve CII requirements although vessel redesign efforts may be required. The payback period varies depending on factors such as the technology type, vessel size, the number of technologies integrated, and the specific vessel in question. Considering the cost differential between conventional and carbon-neutral fuels, these technologies can be deemed cost-effective measures for enhancing energy efficiency and reducing emissions in the industry.

There are currently 575 ships equipped with hybrid/battery propulsion systems. Out of the total 1,046 alternative fuel ships on order, 417 are equipped with hybrid/battery propulsion systems (Clarkson, 2023), indicating a growing trend in their adoption. The implementation of technologies like fuel cells, diesel-electric systems, and battery systems represents effective strategies for mitigating air emissions and URN emissions from ships. These technologies can notably enhance energy efficiency and reduce emissions, particularly in domestic shipping and short sea shipping operations. Furthermore, depending on the type of propulsion system employed, these technologies not only increase the CIS but also significantly reduce URN up to 10 dB across all frequency ranges in commercial vessels.

Machinery and engine room design

Machinery-generated noise stands as a dominant source of URN when a ship's speed falls below the CIS, predominantly within the frequency range below 100 Hz (Nolet, 2017). The levels of engine vibrations are contingent upon a multitude of factors, including the cylinder count, the design of exhaust gas conduits, the number of bends therein, and interactions with other onboard equipment such as scrubbers, waste heat recovery, and boilers (Van Hauwermeiren et al., 2021).

To achieve the highest possible URN reduction requires meticulous machinery design, judicious selection of suitable machinery, the optimization of machinery placement and foundations, and enhancements in the anti-vibration properties of main engines and generators. Additionally, exploring the potential advantages of employing hybrid engines and machinery holds promise for concurrently mitigating emissions and underwater noise (van Biert et al., 2016). Nonetheless, further research and thorough investigations can comprehensively discern the benefits of these approaches.

Many technological solutions are available to concurrently reduce GHG emissions and URN emanating from vessels. Rigorous machinery design and selection, tailored to the specific characteristics of each vessel, have proven effective in minimizing vibrations, enhancing efficiency, reducing maintenance expenditures, and mitigating URN (IMO, 2014). Furthermore, the optimization of machinery placement, with a particular emphasis on centralized alignment, plays an important role in diminishing vibration and the radiation of URN (IMO, 2017). Scientifically validated measures, such as the integration of resilient mounts, acoustic enclosures, and structural damping tiles, have demonstrated their efficacy in mitigating URN and enhancing the comfort of both crew and passengers (Salinas and Moreno, 2015).

Ocean-going vessels predominantly employ two types of engines: 2-stroke engines directly connected to the single screw propeller shaft and 4-stroke engines with medium speed linked to the propeller shaft via a reduction gear. Resilient mounting is typically deemed unsuitable for 2-stroke engines due to their substantial size and weight, which results in the transmission of vibrations from the ship's hull into the water (Audoly et al., 2017). Conversely, for 4-stroke engines, often used in short sea shipping, and diesel generators, the adoption of flexible couplings and resilient mounting has proven effective in dampening vibrations and URN, resulting in a noteworthy URN reduction of more than 10 dB (Kendrick and Terweij, 2019). However, it is important to acknowledge that employing resilient mounts may entail additional capital and maintenance costs over the vessel's lifespan.

Manufacturers who provide comprehensive data on the airborne sound levels and vibrations generated by their machinery can facilitate enhanced design, technology, and mitigation strategies aimed at minimizing noise and vibration (IMO, 2017). The hull itself plays a role in transmitting machinery-induced vibrations to the surrounding water. Careful consideration of optimizing the structural design, including features like ballast and fuel tanks, cofferdams, and double hulls tailored to the type of machinery, can serve as effective buffers, further reducing URN propagation. These comprehensive approaches collectively contribute to the effective reduction of the environmental impact of commercial vessels.

Operational measure

Operational measures hold the potential to reduce both GHG emissions and URN from ships. Strategies such as vessels’ hull and propeller cleaning and maintenance, JIT and speed reduction, optimized ship handling, passage planning, power demand, and weather routing, and use of convoy are operational measures that can significantly enhance energy efficiency and contribute to the reduction of URN.

Cleaning and maintenance of vessels' hulls and propellers

Marine fouling poses a significant challenge as it can substantially increase resistance, disrupting the smooth flow to the propeller. This disruption leads to higher fuel consumption and increases URN from vessels. However, the adoption of appropriate hull coatings, regular hull cleaning, and diligent maintenance practices can effectively enhance energy efficiency and reduce URN emissions from vessels up to 5 dB (Baudin and Mumm, 2015). In addition, this maintenance approach plays an important role in minimizing the introduction of invasive marine species into the environment (Oliveira et al., 2022).

Just In Time and speed reduction

JIT involves optimizing vessel speed to ensure timely arrivals at ports, reducing anchor time, and alleviating congestion (Yang et al., 2021). The JIT approach not only prioritizes timely arrivals but also has the potential to significantly reduce air emissions from ships, aligning with IMO's revised goals for GHG reduction. Additionally, JIT can effectively address concerns related to URN in cases where reducing vessel speed is necessary.

Projections indicate substantial benefits from implementing JIT strategies, including a noteworthy 14-23% reduction in fuel consumption and GHG emissions (Arjona Aroca et al., 2020; IMO, 2022), as well as a remarkable 45% reduction in sound energy (Blue Visby Solution, 2023). Achieving these outcomes requires a high level of cooperation among all stakeholders, including charterers, ship operators, owners, and ports. Furthermore, revising charter party agreements and exploring cost and benefit sharing mechanisms among stakeholders are essential steps to overcome potential conflicts of interest and effectively reduce URN emissions from commercial vessels.

Speed reduction is a measure that can be implemented without any capital cost and can significantly impact fuel consumption, operational costs, and URN from fixed pitch propeller vessels. Taking into account the IMO short-term measures, EEXI and CII, along with the revised GHG emissions strategy, it becomes evident that speed reduction can play an important role in attaining these objectives.

The adoption of EEXI would result in a decrease in CO_2 emissions, estimated at approximately 6.6%, and a reduction in carbon intensity by about 4.6%, specifically for bulk carriers (Napa, 2021). Referring to the revised version of IMO's GHG strategy and the CII requirements, it is predicted that over the next three years, a considerable number exceeding 10,000 vessels could potentially be earmarked for decommissioning. Considering that approximately 30% of the existing fleets for tankers, bulk carriers, and containers—accounting for 75% of URN emissions from commercial vessels—are projected to receive D or E CII ratings (Clarkson, 2023), speed reduction emerges as a viable strategy to improve the overall efficiency of the fleet. This is especially pertinent because as of the start of 2023, the global fleet's average age exceeded 22 years (UNCTAD, 2023). Additionally, in the forthcoming years, approximately 30% of vessels will have surpassed 15 years in service (Clarkson, 2023).

Research studies have shown that a 20% reduction in speed can result in a notable 30-35% decrease in fuel consumption, and such speed reduction also has the potential to reduce the URN source level of vessels. However, the measure prolongs the duration of noise propagation. The extent of URN reduction depends on ambient sound conditions and vessel types (Pine et al., 2018). However, if the reduction in speed falls below the CIS, the reduction in URN becomes even more significant. This effect is more pronounced for fixed-pitch propellers than for CPP.

For instance, in a deep ocean environment, a 20% reduction in vessel speed results in a 6 dB reduction in source level for individual commercial vessels (Findlay et al., 2023). As an example, considering a container ship with a source level of 185.6 dB re 1 mPa @ 1 m, a 20% reduction in speed would lower the vessel's source level to 179.6 dB re 1 mPa @ 1 m. Meanwhile, a 10% reduction in speed could lead to a substantial 40% reduction in global sound energy from shipping (Leaper, 2019).

It's important to note that there is no linear relationship between speed reduction and URN reduction because URN depends on various factors, such as the type and size of the vessel, machinery types, and loading conditions, all of which can vary from one ship to another. However, the results from the ECHO program demonstrated that ships with a higher block coefficient and lower designated speed, such as general cargo ships (2.8 dB/knot) and tankers (2.6 dB/knot), exhibit a higher rate of URN reduction per knot compared to ships with higher designated speeds, such as container vessels (1.5 dB/knot), car carriers (1.6 dB/knot), and passenger ships (1.5 dB/knot) (Port Vancouver, 2017).

Optimized ship handling

The initial design of vessels involves consideration of specific speed and trim parameters to ensure optimal operational efficiency. However, maintaining precise load conditions, trim settings, and speed levels throughout a vessel's service life presents a practical challenge. This challenge arises from the influence of variations in hydrostatic pressure on the propeller, which directly affects the occurrence of cavitation phenomena. Notably, the propeller's proximity to the sea's surface significantly impacts the extent of cavitation, thereby determining the CIS, which is the threshold at which cavitation begins.

Furthermore, alterations in load and ballast conditions can induce deviations in the propeller's depth from its original design specifications. This deviation can result in reduced hydrostatic head pressure, consequently intensifying the prevalence of cavitation and the propagation of associated noise (Ligtelijn et al., 2014). Thus, optimizing trim and ballast conditions is important, as it not only enhances energy efficiency but also serves as a strategy for reducing URN from vessels.

Passage planning, power demand, and weather routing

Efficient passage planning assumes a significant role in ensuring the safety of both the vessel and its crew, preserving the marine environment, and optimizing the energy efficiency of the ship. The passage planning process encompasses four distinct phases: appraisal, planning, execution, and monitoring. A comprehensive appraisal necessitates a thorough evaluation to determine whether the intended voyage will traverse nationally and internationally designated protected areas, regions characterized by heightened seasonal concentrations of noise-sensitive marine life, or areas recognized as Important Marine Mammal Areas.

The sharing of important information ensures that ship captains and officers are equipped with essential data to facilitate informed decision-making throughout the passage planning process. Given the goals set forth by the Biodiversity Beyond National Jurisdiction (BBNJ) Treaty, which aims to establish marine protected areas in the open seas and effectively conserve and manage 30% of terrestrial and aquatic areas by 2030 (Gurney et al., 2023), ship captains must take appropriate actions during vessel operations. The treaty is expected to enter into force in a few years' time, and limitations within protected areas may involve reducing speed, exploring alternative routes, and implementing specific precautions, such as disabling ultrasonic anti-fouling systems that could harm fragile marine species. Particular emphasis should be placed on the protection of seasonal marine species that are vulnerable to URN from vessels.

Commercial vessels primarily contribute to URN through cavitation and machinery noise, with their impact contingent on vessel speed (Yusvika et al., 2020). Effective passage planning, accounting for factors such as tides, currents, and seasonal conditions, empowers captains to reduce power demand during sailing, alleviating engine strain and consequently reducing both GHG emissions and URN.

Weather routing emerges as a highly effective technique for enhancing onboard energy efficiency, offering potential efficiency gains of up to 5%, depending on vessel type, size, and typical routes. Notably, weather routing significantly benefits vessels equipped with various wind propulsion systems, allowing the harnessing of additional energy, albeit the extent varies by system. Research by Dupuy et al. (2023) demonstrates that weather routing yields the highest benefits for rotor sails, followed by suction wings, and least for wing sails.

The integration of weather routing effectively manages onboard power demand during sailing, reducing resistance and minimizing engine load. This results in substantial energy efficiency improvements and a simultaneous reduction in URN emissions from commercial vessels. Beyond its energy-related advantages, weather routing enhances vessel and crew safety by mitigating fatigue and potential weather-related damages, promoting an overall safer voyage.

Use of convoy

A convoy refers to a group of vessels that sail together for a specific purpose, This approach proves particularly valuable in areas such as ports and designated national and international protected areas, especially those with seasonally high concentrations of noise-sensitive marine life. Successful implementation of this measure relies on collaboration among stakeholders in the region, with a particular focus on engaged port authorities responsible for managing port logistics (Vakili et al., 2020a). This management can lead vessels to reduce their speed, with a more pronounced impact on faster vessels such as container ships and car carriers. Consequently, it can yield positive outcomes in terms of reducing both air emissions and URN emissions from vessels, while also extending periods of silence in the area (Williams et al., 2019). Nonetheless, it is important to acknowledge that the passage of a convoy may lead to a temporary increase in the levels of noise experienced by marine species. Therefore, thoughtful consideration of this potential impact is essential to safeguard marine life during convoy transits.

Conclusions

URN stands as an emerging environmental concern, and its adverse effects on marine species are significant. Many technical and operational strategies are available for the purpose of minimizing URN emissions from commercial vessels. Nevertheless, to energize stakeholders towards actively reducing URN emissions from these vessels and expediting the overall reduction process, it is important to align these efforts with enhancements in energy efficiency aboard the vessels.

While it is true that certain contradictions may arise in the pursuit of simultaneously improving energy efficiency and reducing URN emissions from commercial vessels—such as the potential trade-off between increasing blade area at the propeller to mitigate cavitation and the resultant reduction in propeller efficiency, the fact that reducing vessel speed may not necessarily lead to a reduction in URN for CPP, and the possibility of increased machinery noise when implementing technologies like waste heat recovery—there exists many energy efficiency measures that can concurrently elevate energy efficiency and curtail URN emissions.

It is noteworthy that cavitation stands as the most significant source of noise after the vessel reaches its CIS. Hence, the optimization of the propeller in conjunction with the ship's hull configuration assumes a significant role in the reduction of cavitation and consequently, the mitigation of URN emissions from commercial vessels. Moreover, the adoption of ESDs and PIDs holds the potential to enhance both energy efficiency and URN reduction, typically yielding short payback periods as an added benefit.

Innovative energy efficiency measures, such as air lubrication systems and wind-assisted propulsion systems, represent promising solutions with positive impacts on URN reduction and the enhancement of energy efficiency. Notably, a gap exists in research that investigates the real-world effectiveness of these methods in mitigating URN emissions from commercial vessels. This underscores the importance of full-scale evaluation of the effectiveness and reliability of such measures.

Furthermore, as the maritime industry undergoes a transition towards vessel electrification, employing fuel cell, battery, or hybrid technologies, particularly in the realm of short sea shipping, offers substantial potential for energy efficiency improvement. Within these electrified systems, the incorporation of azimuth propulsion and podded propulsors, along with their related machinery, can significantly reduce URN emissions from vessels.

Machinery represents another significant source of URN emissions in commercial vessels, particularly when the vessel operates at speeds below the CIS. Enhancing URN reduction in commercial vessels can be achieved through various means, including the improvement of machinery design, the utilization of quieter machinery, the strategic design of engine rooms and machinery placement, and the implementation of resilient mounting systems. It is essential to emphasize that, in addition to evaluating the noise generated by individual machinery components, a comprehensive assessment must account for the interaction and collective contribution of these machineries as an integrated system.

Similar to the efforts aimed at reducing GHG emissions within the shipping industry, operational measures assume a pivotal role in the mitigation of URN emissions from commercial vessels. A notable avenue for enhancing energy efficiency lies in the relationship between power and the cube of speed, where a significant potential exists for efficiency improvements through speed reduction. Moreover, the direct correlation between cavitation with vessel speed underscores the importance of speed reduction, particularly for vessels equipped with fixed pitch propellers, which can lead to a substantial reduction in URN emissions.

It is worth noting that speed reduction can increase URN emissions from CPP. However, optimizing CPP combinator settings can prove important in mitigating early cavitation onset, both on the pressure and suction sides, during constant-speed operations and acceleration. These optimization measures can simultaneously bolster propeller efficiency under such operating conditions. Additionally, other operational and technical measures are available to curtail URN emissions from CPP equipped vessels. Nevertheless, it is important to emphasize that, owing to the sensitivity and the importance of high manoeuvrability in most CPP vessels, the safety of these vessels and their associated operations must consistently take precedence.

It should also be noted that only about a third of ships are equipped with CPP, the other two thirds being equipped with fixed pitch propellers.

Additional operational measures encompass vessel hull and propeller cleaning and maintenance, passage planning, and the utilization of weather routing strategies. These measures hold the potential to enhance both energy efficiency and URN reduction in commercial vessels without imposing significant additional costs on shipowners, thus paving the way for a mutually beneficial arrangement for all stakeholders involved.

The enhancement of energy efficiency plays a pivotal role in aligning with the revised GHG strategy set forth by the IMO. Given its strong synergy in reducing URN from commercial vessels, the implementation of energy efficiency measures is expected to result in quieter vessels compared to their counterparts.

In conclusion, it is imperative to recognize that compliance with GHG regulations could indeed lead to a reduction in URN from commercial vessels, contingent upon the chosen pathway and strategy for meeting the IMO's revised GHG strategy. The more significant the role played by energy efficiency measures in the industry's decarbonization efforts, the greater the likelihood of reducing URN from commercial vessels. Furthermore, it is anticipated that speed reduction, wind-assisted propulsion systems, and air lubrication systems will make the most substantial contributions among energy efficiency measures to expedite progress towards the IMO's revised GHG strategy and the reduction of URN from commercial vessels.

Table 2. Technological and operational impacts on improving energy efficiency and reducing URN from commercial vessels. Source: adapted from: (Kendrick and Terweij, 2019; Leaper and Renilson, 2012; Vakilki et al., 2020; Vard Marine report, 2019; 2023).

Measures	Note	Energy efficiency	URN
High Skew Propeller: Through the incorporation of a swept-back blade design, there is an enhancement in the cavitation patterns. This advancement facilitates a seamless traversal through diverse wake fields while concurrently diminishing the strain on the propeller tip. As a result, there are notable decreases in propeller cavitation, and this contributes to a heightened CIS (Yu et al., 2023).	This propeller type does not significantly enhance efficiency or reduce GHG emissions. However, it has the potential to reduce URN from commercial vessels by 5-10 dB. Depending on the angle of skew, the capital cost can be 10-15% higher compared to conventional propellers.	-	5-10 dB
Contracted loaded tip propellers: Employing an end plate as part of the innovative approach maximizes the loading at the propeller tip, resulting in diminished cavitation occurrences and an elevation in the CIS. The propeller's capacity to deliver enhanced thrust per unit area contributes to decreased URN, reduced vibration, and a boost in the CIS (Gaggero et al., 2012).	This propeller type enhances efficiency and reduce GHG emissions up to 5%, while generating reduced vibration and underwater noise (5-10 dB). It enhances the comfort of both crew and passengers. However, due to its more intricate design compared to conventional propellers, it comes at a higher cost of approximately 20%.	Up to 5%	5-10 dB
Kappel propellers: Refining propeller blade configuration by introducing a curvature towards the suction side of the tips, aimed at mitigating the intensity of the tip vortex. This alteration enhances operational efficiency, diminishes the occurrence of tip vortex cavitation, and augments the Cavitation Inception Speed (Sánchez-Caja et al., 2012).	While the propeller requires additional design efforts and results in a 20% cost increase compared to conventional propellers (Renilson, 2009), it enhances efficiency around 4%. It holds the potential to reduce URN by up to 5% across the 40-300 Hz frequency range.	Around 4%	Up to 5%
Podded propulsors: This propulsion method attains enhanced wake efficiency for the propeller, resulting in decreased cavitation and a higher CIS. Nevertheless, the drivetrain arrangement has the potential to elevate medium to high-frequency noise levels (Tian et al., 2022).	The impact on energy efficiency varies depending on the type of vessel and its operational context, ranging from a potential decrease of 5% to an increase of 1%. While the system can enhance wake flow to the propeller, its effect on reducing URN remains uncertain and warrants further investigation.	Depends on ships' type and system is varied between -5% to 1%	Needs further investigation
Azimuth propulsors: Azimuth propulsors can incorporate motors within the vessel's hull with transmission gears (electro-mechanical), or they can be positioned outside the hull within a propeller fairing (fully electric). Electro-mechanical variants might necessitate efforts to minimize gear-related noise, whereas fully electric versions could entail managing electric motor noise (Zhang et al., 2023).	While it enhances the vessel's manoeuvrability, it demonstrates slightly lower efficiency (up to 6% less) compared to conventional diesel propulsion systems. Furthermore, it possesses the capability to reduce vibrations and machinery noise, unlike traditional propulsion systems. Nevertheless, its impact on URN requires more in-depth investigation.	Depends on ships' type and system is varied between -6% to 0%	Needs further investigation

Composite propellers: Employing advanced composite materials to enable controlled blade (tip) deformation under operational loads, thereby delaying the onset of cavitation and mitigating blade vibrations (Choi et al., 2023).	A composite propeller is lighter compared to conventional propeller types and has the potential to enhance the comfort of crew and passengers. Nevertheless, it is anticipated to come with a higher cost and greater complexity compared to conventional options. It has the capability to improve energy efficiency and reduce GHG emissions up to 4% and reduce URN across all frequencies by up to 5dB.	Up to 4%	Up to 5 dB
Propeller Boss Cap Fin: By affixing fins to the propeller's hub, the hub vortex cavitation is minimized, leading to a reduction in both noise and vibration while augmenting the CIS. Additionally, this design facilitates the recovery of rotational energy that would otherwise be lost, contributing to enhanced efficiency (Fikry et al., 2023).	The technology offers the potential to decrease emissions and improve efficiency up to 7%. However, it requires additional design refinement. The typical payback period is estimated to be around 4-6 months, and it can effectively reduce URN by up to 10 dB for frequencies less than or equal to 1.0 kHz.	Up to 7%	Up to 10 dB
Propeller Cap Turbines: By integrating hydrofoil-shaped blades into the hub cap, resembling the PBCF concept, the reduction of hub vortex cavitation is achieved, concurrently enhancing the CIS. This inventive configuration also facilitates the recovery of rotational energy that would otherwise be lost, consequently leading to an increase in overall operational efficiency (Smith and Rigby, 2022).	The technology has the capability to improve energy efficiency and reduce GHG emissions up to 5%. However, it necessitates additional design refinement. The usual payback period falls within 4-6 months, and it can effectively reduce URN by up to 10 dB for frequencies less than or equal to 1.0 kHz.	up to 5%	Up to 10 dB
CPP Combinator Optimization: Fine-tuning the pitch and rpm configurations of controllable pitch propellers effectively counteracts the premature initiation of cavitation on both the pressure and suction sides. Such adjustments prove beneficial not only when maintaining consistent speeds but also during acceleration, ultimately enhancing propeller efficiency under these circumstances (Mohammad Danil et al., 2020).	The technology has the potential to enhance efficiency and reduce GHG emissions up to 10% but requires additional design efforts. It necessitates the use of suitable software and sensors, and it has the capability to reduce noise levels by up to 10 dB across all frequencies.	Up to 10%	Up to 10 dB
Resilient Mounts: Attaining the mitigation of vibration energy transfer from machinery and the reduction of energy transmission from the hull to the water demands a meticulous process of mount selection and installation. This strategy is notably more suitable for 4-stroke engines compared to their 2-stroke counterparts, primarily due to the inherent weight and size considerations (Fragasso et al., 2019).	The implementation of resilient mounts has the capacity to reduce URN by over 10 dB across all frequencies, thereby improving the comfort of both crew and passengers. The anticipated cost for implementation is up to $2000.	-	Over 10 dB
Foundation Isolation Techniques: Isolating machinery by constructed platform from steel offers a means to alleviate the transmission of	It has the potential to enhance the comfort of both crew and passengers, while also having the capability to	-	Over 10 dB

vibration-induced noise. This configuration is frequently employed for engines, gearboxes, and generators in 4-stroke engine setups, with limited applicability to 2-stroke engines due to their weight (Qiu et al., 2019)	reduce URN by more than 10 dB across all frequencies. However, it does contribute to increased weight on the vessel and necessitates additional weight accommodations. It's worth noting that its implementation comes at a significant cost, possibly reaching around 10% of the total installed machinery costs.		
Control of velocity of Flow Exhaust gases: An element incorporated within the exhaust flow system of a 2-stroke diesel engine, it addresses noise issues by regulating the sudden expansion of gases' velocity during the combustion and exhaust stages (Vigneshraj et al., 2016).	While it does not have any impact on improvement of energy efficiency, this technology requires supplementary design endeavors. It has the capacity to decrease URN by up to 5 dB.	-	Up to 5 dB
Fuel Cell: Produces electricity through chemical reaction and is quieter than internal combustion engines. (Takahashi et al., 2019).	Fuel cell can improve efficiency up to 10% but its potential for reduction of GHG emissions depends on the fuel source. The technology provides more efforts on design due to its complexity compared to conventional sources of energy and burden cost compared to traditional system of propulsion. In addition, it has high potential in reduction of URN over 10 dB across all frequency and leads to improve comfort of crew and staff.	Up to 10%	Over 10 dB
Battery and hybridization: Employing batteries results in a noiseless operation. Nonetheless, their limited energy density confines their application to short sea shipping routes. Batteries also prove advantageous for navigation within national and international designated protected areas and areas with seasonally high densities of noise sensitive marine life (Tronstad et al., 2017).	This technology has the capability to enhance energy efficiency and reduce GHG emissions up to 10%. However, its implementation requires additional space and introduces additional weight to the vessel, along with a substantial capital cost. It is particularly applicable to vessels engaged in short sea shipping. Its capacity to reduce URN by more than 10 dB across all frequencies contributes to improved passenger and crew comfort.	Up to 10%	Over 10 dB
Air Injection: Introducing air into the propeller blade tips through small openings or utilizing a nozzle-like device positioned ahead of the propellers minimizes the area under low pressure, thus mitigating cavitation and increase CIS (MARIN, 2023).	While it does not impact the vessel's efficiency, the introduction of air injection into cavitation has been demonstrated to reduce URN by up to 5 dB.	-	Up to 5 dB
Hull Air Lubrication: Air lubrication systems enhance energy efficiency by diminishing resistance (Lube et al., 2019). Assertions have been made regarding the system's potential to lower URN.	While it has the capacity to enhance efficiency and reduce GHG emission up to 15% (RINA, 2023), this technology requires additional effort in terms of ship design and can lead to increased maintenance onboard the vessel. Implementing this technology introduces extra costs to the vessel's	Up to 15%	Over 10 dB

	design. However, it offers the potential to reduce URN by more than 10 dB.		
Wind (Flettner Rotors, Kite Sails and Conventional Sails): Producing a propulsive force and thrust with the ability to alleviate the load on conventional machinery power and potentially enhance energy efficiency (Viola et al., 2015), while also reducing URN.	While it holds the potential to enhance efficiency 5-25%, this technology requires a more complex design and additional effort in terms of both vessel design and construction. The payback period for its implementation varies based on the type, size, and number of technologies involved. Nevertheless, when compared to the cost difference between conventional fuels and green fuels, it can be considered a cost-effective measure to reduce emissions and lower URN up to 10 dB through decreasing the required thrust and load from engines.	5-25%	Up to 10 dB
Waste heat recovery: Waste heat represents untapped energy that dissipates into the surroundings. In the maritime applications, roughly 48-51% of engine-generated energy is released as exhaust gas and jacket water, underscoring the potential of waste heat recovery to generate additional energy output while adhering to emission standards (Pesyridis et al., 2023). The selection of the most suitable heat recovery technologies depends on the specific characteristics of shipboard waste heat and the achievable recovery efficiencies, necessitating a comprehensive assessment of the attributes of each system.	The utilization of waste heat offers an avenue for enhancing the energy efficiency and reducing GHG emissions up to 8% (Barone et al., 2020). The technology does not reduce the URN emissions from commercial vessels, and it may have some contribution to the noise spectra of the machinery.	Up to 8%	-
Onshore power system: Supplying the necessary energy for hybrid and battery-powered vessels, both for deep-sea vessels like cruise ships and container ships, as well as for short-sea shipping vessels. This enables vessels to deactivate all auxiliary engines while in port, contributing to reduced.	The technology offers the potential to improve energy efficiency and reduction of GHG emissions depends on the source of the electricity generation to provide the system (Vakili and Ölçer, 2023a). However, its implementation requires additional space both onboard vessels and in ports, leading to added costs for infrastructure. The exact expenses vary depending on the system's size, ranging from around $1.5 million per berth to $400,000 per vessel. This system holds the capability to reduce frequencies less than 1kHz by up to 10 dB.	Up to 100% depends on the source of produced electricity	Up to 10 dB
Hull Forms optimization: Hull designs that are optimized for hydrodynamic efficiency require additional design effort. However, they play a significant role in reducing power requirements, thus helping to mitigate noise	Hull form optimization can reduce the required power and increase energy efficiency and reduce GHG emissions up to 10%. The appropriate hull design	Up to 10%	Up to 5 dB

emissions from both machinery and propulsion systems while enhancing overall efficiency. Furthermore, these specific hull configurations often possess favourablee wake characteristics, which subsequently raise the threshold speeds for cavitation. Through the reduction of power demands and the enhancement of flow dynamics, these streamlined hull designs contribute significantly to noise reduction and overall improvement in vessel performance (Bertetta et al., 2012; Prins et al., 2016).	can reduce URN up to 5dB within all frequencies.		
Pre-swirl Stator: Incorporating stator blades positioned on the stern boss ahead of the propeller, this design redirects the flow prior to entering the propeller. This redirection optimizes overall flow performance, resulting in diminished cavitation, and a subsequent increase in the CIS is observed (Zondervan et al., 2011).	The implementation of a pre-swirl stator has the potential to enhance efficiency and reduce GHG emissions up to 4% (Saettone, Regener, and Andersen, 2016). However, it requires additional design efforts for the vessel. This technology can reduce URN by up to 5 dB across all frequencies. The usual payback period hinges on the extent of energy efficiency improvements and prevailing fuel prices, averaging around 24 months.	Up to 4%	Up to 5 dB
Anti-Fouling Coating: Utilizing a distinct coating to provide protection against fouling for both the hull and propeller surfaces is recognized for its role in maintaining sustained operational efficiency and reduction of URN (Oliveira et al., 2022)	By minimizing resistance, anti-fouling coatings have the capacity to boost efficiency and decrease GHG emissions up to 5%. This technology also leads to reduced maintenance requirements. It shows promise in reducing URN by up to 5 dB within all frequencies. The added benefit is a reduction in required maintenance, further contributing to operational efficiency.	Up to 5%	Up to 5 dB
Mewis Duct: It is a hydrodynamic device installed around a ship's propeller hub, aimed at optimizing propulsion efficiency. By reducing swirl and improving thrust, Mewis Ducts enhance a vessel's overall performance, leading to reduced fuel consumption and lower emissions. This technology has proven effective in enhancing both manoeuvrability and fuel efficiency for a wide range of maritime applications.	While it requires more extensive development compared to conventional designs, this inventive device holds the capability to enhance energy efficiency by up to 10%. Additionally, it can contribute to reducing URN by improving wake flow to the propeller, with a potential reduction of up to 5 dB (Zalachoris in 2020). Depending on the achieved fuel savings, the payback period for this innovation could be approximately one year.	Up to 10%	Up to 5%
Twisted Rudder: The pressure distribution on the rudder blades is balanced by the design, aiming to prevent cavitation and enhance the manoeuvrability of a full spade rudder. The systems can effectively mitigate cavitation and leading to reduced maintenance expenses. Additionally, the Twist Rudder contributes to	This technology offers the potential to enhance efficiency and reduction of GHG up to 3% and also improve maneuverability, all the while decreasing the maintenance demands on the rudder. However, its design necessitates more extensive efforts compared to traditional rudders. By	Up to 3%	Up to 5 dB

a reduction in cavitation-induced noise (Kim et al., 2014).	diminishing cavitation, it can contribute to a reduction in URN by up to 5 dB.		
Gate Rudder: The technology represents a specialized maritime propulsion component engineered with the primary objective of augmenting vessel manoeuvrability and control. This distinctive rudder configuration comprises two autonomously manoeuvrable sections, affording the capability for differential steering and meticulous adjustments, a feature of considerable utility in the context of larger vessels. The technology improves navigating in confined waterways, thereby rendering it a coveted asset for vessels operating in densely trafficked ports and confined spaces.	The is predominantly utilized in single-propeller vessels and boost energy efficiency and reduces GHG emissions by up to 8%. It has been claimed that the technology can reduce URN up to 15 dB (IMO, 2023a).	Up to 8%	Up to 15 dB
Asymmetric Body: Tailored for Single Screw Vessels, the purpose of engineering an asymmetric aft section is to rectify the uneven flow patterns stemming from a single screw propeller's rotation around the vessel's centreline. This strategic design alteration subsequently leads to an increase in the CIS (DNV, 2017).	Accompanied by enhancement in energy efficiency, ranging from 3% to 9% according to DNV (2017), this technology has the potential to reduce URN by up to 5 dB in vessels. However, in comparison to traditional designs, it demands more intensive efforts in terms of design and implementation.	Up to 9%	Up to 5 dB
Acoustic Enclosures: Enhancing the hull arrangement and encompassing the machinery section with a freshwater tank, ballast tank, cofferdam, and dual hull structure (Audoly et al., 2015). This strategy is generally employed in conjunction with smaller diesel engines and gas turbines.	This measure is widely adopted to mitigate noise in naval and research vessels. By effectively reducing noise levels by more than 10 dB within the frequency range of 125 to 500 Hz, it significantly enhances the comfort of both crew and passengers. However, its implementation requires additional design efforts and dedicated space within the engine room. Moreover, it comes with an added cost of around 10% of the initial installed equipment cost.	-	Over 10 dB
Damping Tiles: Incorporating specialized vibration-damping tiles directly into the vessel's framework effectively mitigates the transfer of vibrational energy, which is a common source of URN (Salinas and Moreno, 2015).	Depends on extend of use can reduce URN up to 5 dB. It enhances crew and passenger comfort. However, add more weight to the vessel. The cost is between 50$ to 150 $ per M^2.	-	Up to 5 dB
Optimized ship handling (Cargo loading, trim and draft): The hydrostatic pressure acting on the propeller plays an important role in determining the occurrence of cavitation and CIS. A propeller situated at a greater distance from the sea's free surface experiences reduced cavitation and increased CIS. Effective ship handling, along with considerations for design speed and trim, can lead to improvements in efficiency and a	Considering as a low hanging fruit operational measures can increase energy efficiency and reduce GHG emissions to 2-10% and reduce URN less than 5 dB.	Up to 2-10%	Up to 5 dB

reduction in cavitation occurrences (Ligtelijn et al. in 2014). Consequently, these measures contribute to enhanced maneuverability, increased efficiency, and a decrease in emissions.			
Hull and propeller maintenance: Neglecting proper upkeep of hull and propeller surfaces can result in heightened resistance and subsequent fuel consumption. This escalation in fuel consumption can elevate machinery load and propel RPM requirements to maintain consistent speeds, thereby augmenting URN levels.	Hull and propeller cleaning can enhance efficiency and reduce GHG emissions up to 5%. Prioritizing maintenance practices can effectively curtail URN up to 5 dB (Baudin and Mumm, 2015) in all frequencies.	Up to 5%	Up to 5 dB
Speed reduction and just in time: Taking into account the cube law, which relates power to the cube of speed, it is well-established that reducing speed significantly impacts fuel consumption. Nevertheless, the convergence of speed reduction practices with JIT principles, coupled with a fair benefit-sharing policy among stakeholders in the shipping sector, can address traffic capacity constraints and ensure equitable distribution of benefits. This integrated approach can concurrently boost fuel efficiency and optimize cargo management, strengthening overall operational efficiency and sustainability.	The adoption of the JIT concept offers significant benefits, including anticipated reductions in fuel consumption and greenhouse gas emissions, as reported by the IMO in 2022, with estimates ranging from 14% to 23%. Impressively, the JIT approach demonstrates even greater potential, with a notable 45% reduction in sound energy achieved by the Blue Visby solution in 2023. Furthermore, a projected 10% reduction in vessel speed, as suggested by Leaper in 2019, is expected to result in a substantial 40% decrease in sound energy emanating from global shipping operations. Additionally, according to Findlay et al. in 2023, a 20% reduction in speed yields a predicted mean source level decrease of 6 dB across all frequencies for fixed pitch propellers. The successful implementation of these measures necessitates the formulation of appropriate policies to ensure smooth logistics and mitigate the need for additional vessels to maintain normal maritime trade operations.	Speed reduction: proportional to square of speed reduction. JIT: 14-23%.	Speed reduction: 10% reduction in speed leads to 40% drop in sound energy 20% reduction in speed decreases the predicted mean source level by 6 dB across all frequencies for fixed pitch propellers. JIT: potential for 45% decrease in sound energy
Passage planning, power demand and weather routing: URN originating from ships is primarily attributed to cavitation noise, which vary based on vessel speed, as highlighted by Yusvika et al. in 2020. Effective passage planning that considers factors such as wind, tides and currents can lead to reduced power demand during sailing, thereby lessening engine strain and emissions. Weather routing aims to minimize resistance, decrease engine load, and enhance energy efficiency, resulting in decreased URN emissions	Weather routing strategies can elevate vessel energy efficiency and reduce GHG emission up to 5%, especially for vessels equipped with wind propulsion systems like rotor sails, which demonstrate the highest benefits, as outlined by Dupuy et al. in 2023. This approach not only conserves energy but also boosts safety by mitigating fatigue and weather-associated risks for a safer voyage. The successful implementation of this measure can also reduce URN up to 5 dB.	Up to 5%.	Up to 5 dB

6. Global Target Levels for URN from Commercial Vessels

The only international targets the authors have found are those proposed by the Okeanos Foundation. These appear in the 2008 report of an Okeanos URN workshop:

> *"We call for initial global action that will reduce the contributions of shipping to ambient noise energy in the 10-300 Hz band by 3 dB in 10 years and by 10 dB in 30 years".*

The targets were previously endorsed by the International Whaling Commission, and also appear in the conclusions of a report of a 2019 URN workshop held at IMO.

To assess how feasible, it would be to achieve these targets, the authors have carried out a high-level assessment. This utilises the equation (1) from Ross (1976), which correlates the main factors within an overall assessment of ambient noise. This includes terms relating to the average sound source level of individual ships, shipping traffic density, water depth, and attenuation factors. The real-life situation is more complex, but for purposes of predicting the magnitude of impacts and assessing sensitivities, the equation (1) is a useful starting point.

Equation (1)

$$\underbrace{L_n}_{\text{Ambient noise in dB}} = \underbrace{L_s}_{\text{Average sound source level per ship}} - 95 + 10 \log \underbrace{\delta}_{\text{Density of ship traffic}} + 10 \log \frac{1}{\underbrace{\alpha_T}_{\text{Attenuation factor}} \underbrace{H}_{\text{Water depth}}}$$

Considering Ross's term for the density of shipping traffic, projecting forward to 2050 is inherently difficult as this is dependent on economic activity, for which there will be many political, technical, and economic influences that are difficult to foresee. Nevertheless, IMO's 4th GHG Study provides a detailed projection of transport work through to 2050, based on 4 different scenarios. When considering the density of shipping traffic, it is not only important to understand the volume of trade, but also how far it is being transported and therefore, transport work (i.e., cargo carried x distance travelled), can be a more informative metric than volume or value of cargo. The IMO's Fourth GHG study projections for transport work range from a 40% to 100% increase from 2020 to 2050 (see Fig. 4 for details). This translates to an average annual growth rate of approximately 1.3% to 3.3%.

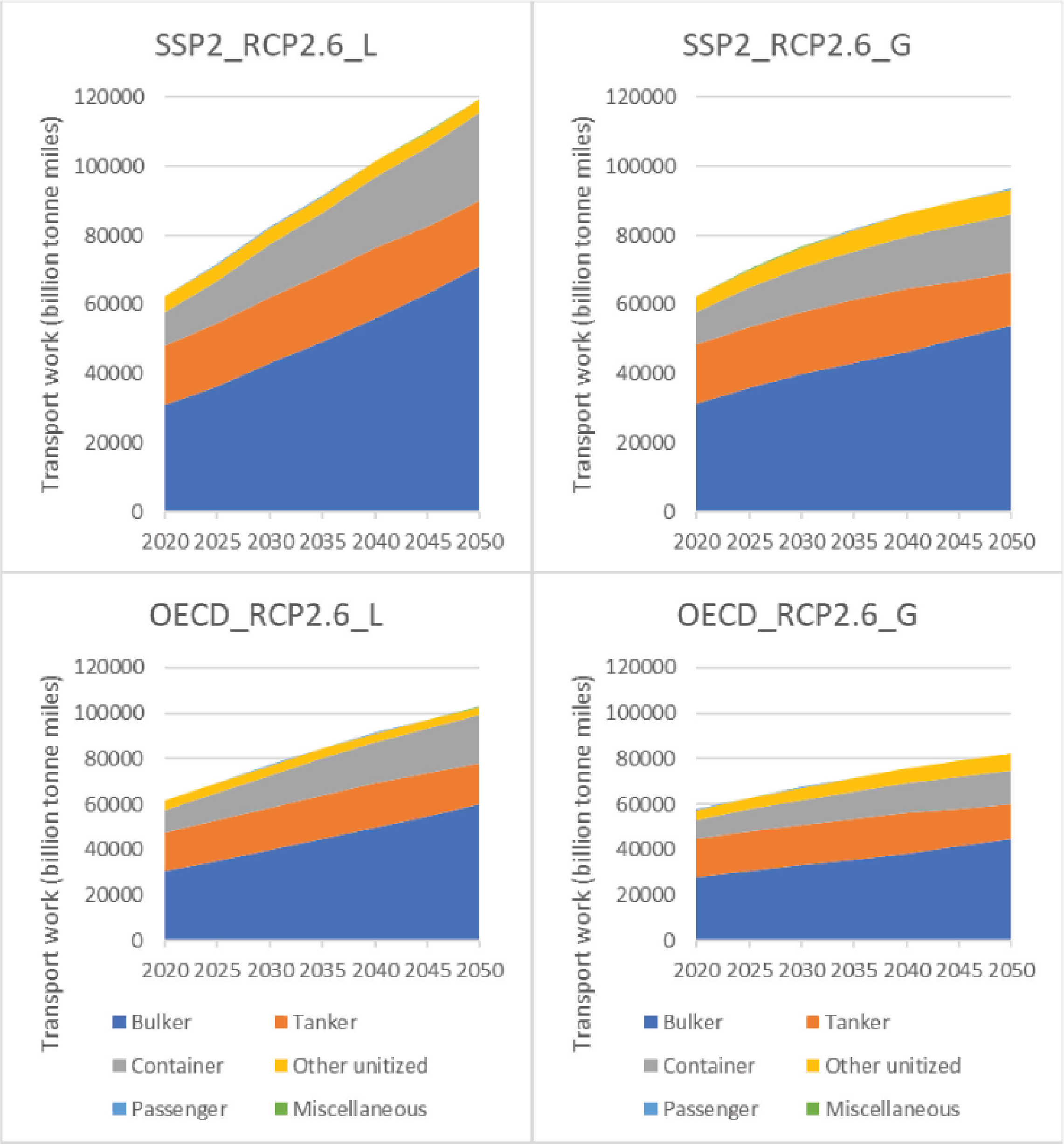

Fig. 4. Transport work projections (billion tonne miles) – IMO 4th GHG study.

Taking the worst-case scenario of 3.3% growth per year and considering the decade ahead, by 2033 we would see about a 33% increase in transport work, and an equivalent increase in average shipping density. From Ross's equation and if nothing else changed, such an increase in traffic density would result in about a 1.4 decibel increase in ambient URN. To counteract this and provide the 3-decibel reduction proposed by Okeanos would require a reduction in the average source level per ship of 4.3 decibels.

Looking ahead to 2050, and assuming the same growth rate would see transport work increase by 86%. According to the Ross equation and if nothing else changed there would be a corresponding increase in ambient URN of about 2.6 decibels. To counteract this and provide the 3 decibel per decade reduction proposed by Okeanos would require a reduction in the average source level per ship of 10.4 decibels.

As previously stated, the real-life situation is more complex with significant variations in regional traffic density, varying contributions in source level from different vessel types and potential growth in vessel size. Also, variations in attenuation and transmission of URN. Hence, the analysis reflects approximate averages for the deep oceans. However, it is understood that the 3 decibel per decade historical growth in URN quoted by Ross and the 3 decibel per decade Okeanos target, are also intended to reflect approximate averages for the deep ocean. In this context, the figures from our analysis can provide a useful comparison.

Conclusions

The Okeanos Foundation has proposed targets for ambient underwater noise generated by commercial vessels of a 3 dB reduction within a decade, and a 10 dB reduction within 30 years. The targets have previously garnered support from the International Whaling Commission

When this study considers the synergies between energy efficiency and URN reduction it becomes evident that accomplishing a 3 dB reduction in shipping's contribution to ambient noise within a decade is a feasible goal, e.g., through speed reduction. The addition of other efficiency measures (e.g., either air lubrication or wind assisted propulsion) could provide the necessary further reductions to also put the 10 dB within 30 years goal within reach.

7. Final Comments

Notably, there is a dearth of research examining the interplay between energy efficiency and the reduction of URN in the commercial shipping industry. Acknowledging the substantial connection between improved energy efficiency and the reduction of GHG emissions through URN reduction in commercial vessels, this study was instigated in response to a request from the International Chamber of Shipping. Its objective is to address this knowledge gap and elucidate the synergies between advancements in energy efficiency, particularly in energy efficiency measures, and the mitigation of URN in commercial vessels. The analysis takes into consideration the evolving trends in seaborne trade and assesses the actions taken by the IMO in pursuit of zero emissions within the maritime industry and its synergy with reduction of URN from commercial vessels.

Shipping is the most fuel-efficient mode of transportation. Nevertheless, the shipping industry carries a substantial responsibility for mitigating its environmental footprint. As a pivotal component of the global economy, it holds a leadership position in addressing its 2.89% share of global GHG emissions. The International Maritime Organization, as the regulatory authority governing international shipping, has embraced this responsibility by implementing rigorous GHG regulations and striving for the achievement of zero-emission shipping by around 2050.

Attaining the IMO revised GHG emissions targets for ships presents a formidable challenge. Undoubtedly, the central challenge facing the maritime industry is the pursuit of decarbonisation. It is imperative to confirm a sustainable transition during the industry's decarbonization journey to ensure a prosperous, equitable, and resilient future for maritime transport. The maritime sector grapples with a significant level of uncertainty as it strives to pinpoint effective strategies for reducing carbon emissions and transitioning to lower or zero-carbon fuels. This multifaceted endeavour includes the modernization of aging vessel fleets, and the intricate navigation of a landscape teeming with alternative fuels and green technologies, while contending with uncertainties regarding their effectiveness.

Nevertheless, the driving forces behind decarbonisation are the increasingly stringent environmental regulations. Recognizing the absence of a universal solution, key measures facilitating the transition toward a zero-emission industry encompass the adoption of carbon-neutral fuels, enhancements in energy efficiency including speed reduction, and the optimization of logistics, all with a specific emphasis on achieving economies of scale.

It is essential to recognize the barriers linked to the broad adoption of carbon-neutral fuels. These challenges encompass the availability and cost of alternative fuels, insufficient infrastructure, logistical limitations, scalability of production, the maturity of technology in both onboard vessel systems and supply-side infrastructure, considerations related to ship and engine design, crew training, safety considerations, and the substantial financial investments required. Consequently, carbon-neutral fuels are not expected to play a pivotal role in reducing air emissions by 2030, but their significance is projected to grow significantly beyond 2040, contributing to approximately 60% of emissions reduction by 2050. On the contrary, speed reduction and energy efficiency measures are positioned to assume pivotal roles in attaining the IMO's GHG emissions reduction goals by 2030, and they remain significant factors even as we approach 2050. Energy efficiency improvement is expected to account for a 32% reduction in emissions, with 23% attributable to speed reduction. Additionally, with the increasing adoption of wind assisted propulsion systems and zero emissions technologies such as air lubrication system, the importance of energy efficiency measures is expected to continue to grow, ultimately making a substantial impact by 2050.

Speed reduction plays a significant role in expediting GHG emissions reduction, especially considering the aging global fleet and the necessity for vessels to adhere to the CII requirements. Notably, this measure stands out due to the cubic relationship between power and speed. Integrating speed reduction with JIT operations can offset potential fleet capacity losses, and equitable distribution of benefits can be ensured through the implementation of appropriate policies, promoting fair benefit-sharing among charterparty stakeholders.

Many other energy efficiency measures offer short payback periods, including the use of ESDs, PIDs, hull and propeller cleaning, voyage optimization, and advanced weather routing techniques, all of which have the potential to enhance energy efficiency. Cutting-edge technologies such as air lubrication (offering efficiency gains ranging from 5% to 15%) and wind-assisted propulsion systems (yielding efficiency gains from 5% to 25%) hold great promise in this regard. In the context of short sea shipping, electrification, hybrid systems, battery technologies, and fuel cell solutions offer substantial promise for meeting the IMO's GHG emissions targets within the sector. In addition, other measures, such as waste heat recovery technologies, can contribute to improving energy efficiency and reducing GHG emissions.

Recognizing the significant contribution of commercial vessels to ambient noise, it is important to determine the precise proportion of this environmental burden attributed to commercial maritime activities. Empirical investigations have shown a consistent upward trajectory in underwater noise levels, with an increase of about 3 decibels per decade. However, it is noteworthy that this increase in underwater noise is not uniformly evident across all geographic regions. Recent research indicates stable underwater noise levels globally, and in some regions, even a noticeable reduction. This intriguing development has led to the hypothesis that contemporary vessels may emit lower acoustic noise compared to older counterparts, possibly due to advances in energy efficiency inherent to modern vessel designs.

Given these considerations, establishing appropriate target levels for reducing global underwater noise becomes a multifaceted endeavour. Recent research has highlighted the limitations of linear methodologies in determining universal underwater noise trends, with paradoxical fluctuations in specific geographic areas. An alternative, non-linear perspective proposes fluctuations in underwater noise levels that span from 4 to 6 decibels during prolonged observation periods. Consequently, to comprehensively understand global underwater noise trends and set effective targets, the acquisition and analysis of at least three decades' worth of data are essential.

It is essential to recognize that complying with GHG regulations has the potential to lead to a decrease in URN generated by commercial vessels. This outcome is contingent upon the specific approach and strategy chosen to meet the IMO revised GHG strategy. Considering the hypothesis that newer vessels are quieter than older ones due to advancements in energy efficiency, it is important to acknowledge that while contradictions exist in certain energy efficiency measures, particularly in relation to variables such as propeller blade area and speed reduction for CPP, the majority of energy efficiency measures have the potential to mitigate underwater noise emanating from commercial vessels. This suggests that ship owners, by integrating energy efficiency measures to meet the IMO's GHG strategy and carefully selecting appropriate measures, can enhance vessel efficiency to align with the ambitious goals of achieving zero-emission shipping and concurrently reduce URN without incurring additional costs. It is anticipated that speed reduction, wind-assisted propulsion systems, and air lubrication systems will make the most significant contributions among energy efficiency measures to expedite progress towards the IMO's revised GHG strategy and the reduction of URN from commercial vessels.

When assessing long-term global trends in underwater noise, it becomes evident that many factors require careful examination. Of importance are projections concerning seaborne trade, advancements in energy efficiency, and their intricate interplay with underwater noise stemming from individual vessels. Given these determinants and the observed symbiotic relationship between speed reduction measures and energy-efficient technologies in mitigating both underwater noise and air emissions, there is a plausible expectation that forthcoming vessels will exhibit diminished acoustic signatures compared to their older counterparts. This expectation is incentivised by stringent international and regional regulations aimed at achieving zero GHG emissions in the maritime sector by around 2050.

The Okeanos Foundation has proposed targets for ambient underwater noise generated by commercial vessels of a 3 dB reduction within a decade, and a 10 dB reduction within 30 years. The targets have previously garnered support from the International Whaling Commission

When this study considers the synergies between energy efficiency and URN reduction, and even after taking account of worst-case projections for growth in transport work, it becomes evident that accomplishing a 3 dB reduction in shipping’s contribution to ambient noise within a decade is a feasible goal, e.g., through speed reduction. The addition of other efficiency measures (e.g., either air lubrication or wind assisted propulsion) could provide the necessary further reductions to also put the 10 dB within 30 years goal within reach.

Appendix 1

Responses to the questions

In this section, our primary objective is to provide direct and concise answers to the questions posed by ICS, addressing the core inquiries raised. It is important to emphasize that the main body of the report encompasses a wealth of supplementary information, featuring comprehensive discussions and a robust array of references, which collectively furnish a deeper contextual understanding and further insights into the subjects under consideration.

Q1. Comment on global long-term trends for URN.

For more information regarding the question, please consult "Section 4: URN Trends from Commercial Vessels".

Comment on global long-term trends for URN

Studies have indicated that ambient noise has increased by approximately 3 dB per decade in certain parts of the world. It's important to note that this trend is not uniform across all regions; some areas have shown a plateau or even a decrease in noise levels. Furthermore, there are inconsistencies in the predictions of underwater noise levels in various global regions. These underscore the importance of moving away from linear models and instead considering nonlinear trends that account for long-term cyclic dynamics. An alternative non-linear approach suggests that during extended observation periods, annual fluctuations in URN ranging from 4 to 6 decibels may occur. To accurately identify long-term trends in URN within the oceans that are comparable in magnitude to historical increases in noise levels observed in the Northeast Pacific, a minimum of three decades of uninterrupted monitoring is required.

It is important to emphasize that for more accurate predictions of URN on a global scale, greater attention must be devoted to the deep sea. The increase in low-frequency ocean sound is not consistent worldwide, and we urge caution against drawing universal conclusions about uniformly rising low-frequency sound levels at a global level.

Consider what physical measurements have been done.

The following studies have been referenced by the report, and all reference physical measurements of URN.

McDonald, M. A., Hildebrand, J. A., & Wiggins, S. M. (2006). Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. The Journal of the Acoustical Society of America, 120(2), 711-718.

Andrew, R. K., Howe, B. M., Mercer, J. A., and Dzieciuch, M. A. (2002). “Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast,” Acoust. Res. Lett. Online 3, 6570.

Andrew, R. K., Howe, B. M., & Mercer, J. A. (2011). Long-time trends in ship traffic noise for four sites off the North American West Coast. *The Journal of the Acoustical Society of America*, *129*(2), 642-651.

Chapman, N. R., & Price, A. (2011). Low frequency deep ocean ambient noise trend in the Northeast Pacific Ocean. The Journal of the Acoustical Society of America, 129(5), EL161-EL165.

Miksis-Olds, J. L., & Nichols, S. M. (2016). Is low frequency ocean sound increasing globally? The Journal of the Acoustical Society of America, 139(1), 501-511.

Harris, P., Sotirakopoulos, K., Robinson, S., Wang, L., and Livina, V. (2019). “A statistical method for the evaluation of long-term trends in underwater noise measurements,” J. Acoust. Soc. Am. 145, 228242.

Ross, D. (2005). “Ship sources of ambient noise,” IEEE J. Ocean. Eng. 30, 257–261.

Miksis-Olds, J. L., Bradley, D. L., & Maggie Niu, X. (2013). Decadal trends in Indian Ocean ambient sound. *The Journal of the Acoustical Society of America*, *134*(5), 3464-3475.

Miksis-Olds, J. L., Bradley, D. L., & Maggie Niu, X. (2014). Erratum: Decadal trends in Indian Ocean ambient sound. The Journal of the Acoustical Society of America, 135(3), 1642-1642.

Matsumoto, H., Bohnenstiehl, D. R., Tournadre, J., Dziak, R. P., Haxel, J. H., Lau, T. K., ... & Salo, S. A. (2014). Antarctic icebergs: A significant natural ocean sound source in the Southern Hemisphere. Geochemistry, Geophysics, Geosystems, 15(8), 3448-3458.

Robinson, S. P., Harris, P. M., Wang, L., Cheong, S. H., & Livina, V. (2019, June). Evaluation of long-term trends in deep-ocean noise in the Southern Ocean. In OCEANS 2019-Marseille (pp. 1-6). IEEE.

Park, J., Haralabus, G., Zampolli, M., & Metz, D. (2023). Low frequency ambient noise dynamics and trends in the Indian Ocean, Cape Leeuwin, Australia. The Journal of the Acoustical Society of America, 153(4), 2312-2312.

Erbe, C., Schoeman, R. P., Peel, D., & Smith, J. N. (2021). It often howls more than it chugs: wind versus ship noise under water in Australia's maritime regions. Journal of Marine Science and Engineering, 9(5), 472.

Thomson, D. J., & Barclay, D. R. (2020). Real-time observations of the impact of COVID-19 on underwater noise. The Journal of the Acoustical Society of America, 147(5), 3390-3396.

Dahl, P. H., Dall'Osto, D. R., & Harrington, M. J. (2021). Trends in low-frequency underwater noise off the Oregon coast and impacts of COVID-19 pandemic. The Journal of the Acoustical Society of America, 149(6), 4073-4077.

Ryan, J. P., Joseph, J. E., Margolina, T., Hatch, L. T., Azzara, A., Reyes, A., ... & Stimpert, A. K. (2021). Reduction of low-frequency vessel noise in Monterey Bay National Marine Sanctuary during the COVID-19 pandemic. Frontiers in Marine Science, 587.

Comment on the possible reasons for the trends.

Plausible factors contributing to upward trends in regional URN are the myriad of anthropogenic activities. Specifically, the expansion of economic and trade activities, including seismic exploration, fossil fuel extraction, the establishment of shipping routes, and port expansions. These activities can collectively contribute to an increase in regional anthropogenic URN.

In the domain of shipping and maritime trade, several factors could contribute to the increasing URN levels seen in certain regions These comprise the growing number of vessels, the expansion of vessel travel distances, the increase in vessel sizes, and the adoption of more powerful propulsion This is supported by empirical evidence obtained from ambient noise measurements during the COVID-19 pandemic. During this period, the contraction of global trade and shipping operations resulted in a noticeable reduction in URN originating from ships, reverting to levels last observed in 2017. This reduction represented a 6% decline in the energy output of global shipping noise sources within the 63 Hz 1/3 octave band.

Conversely, there have been instances where ambient noise in specific regions of the world has either remained relatively constant or decreased. While it is important to emphasize the necessity of employing a non-linear approach and conducting long-term data analysis to discern prevailing trends in oceanic ambient URN, the possibility arises that, despite the escalation of seaborne trade and the introduction of larger vessels equipped with more powerful machinery, vessel design improvements and the adoption of energy-efficient technologies may produce lower acoustic emissions compared to their older counterparts, and therefore contribute to downward trends in regional URN levels.

Q2. For the global merchant fleet, comment on the % fuel efficiency reductions that will be necessary to achieve IMO’s revised GHG strategy.

Taking account of IMO’s revised GHG strategy (which is to be confirmed in early July 2023), review competent forecasts of the necessary level of fuel efficiency savings through to 2050. For example, DNV’s 2050 Maritime Forecast predicts about 10% further reductions in emissions relative to 2022, plus about a further 20% reduction in emissions attributable to speed reduction.

N.B. The forecasts should take account of the projected growth in world trade, and consequential growth in the world fleet.

For more information regarding the question, please consult "Section 3: Meeting the IMO’s Revised GHG Strategy".

The achievement of carbon neutrality in the shipping industry by 2050 hinges primarily on the increased production and accessibility of carbon-neutral fuels. The effectiveness of energy efficiency improvements can vary depending on different scenarios. However, the research suggests that achieving the IMO’s GHG emissions targets for 2050 necessitates approximately a 32% improvement in energy efficiency, with roughly 23% of that improvement attributed to speed reduction when compared to the year 2022. Additionally, with the increasing adoption of wind assisted propulsion systems and zero emissions technologies such as air lubrication system, the importance of energy efficiency measures is expected to continue to grow, ultimately making a substantial impact by 2050.

Q3. Identify the main technologies and operational changes that will be adopted to achieve these efficiency gains.

Consider the available technologies, and operational measures that could be adopted to achieve these efficiency gains and on a cost benefit basis, forecast which technologies are likely to be adopted by ship owners.

For more information regarding the question, please consult "Section 3: Meeting the IMO’s Revised GHG Strategy". This section offers comprehensive insights into the topic.

It is anticipated that critical measures that will contribute the majority of the energy efficiency gains are speed reduction, wind-assisted propulsion systems, and air lubrication systems. These elements play a central role in meeting the IMO’s revised GHG strategy. Additionally, as the maritime industry transitions toward vessel electrification, the use of fuel cells, batteries, or hybrid technologies, especially in short sea shipping, offers substantial potential for improving energy efficiency and accelerating compliance with the IMO’s GHG strategy.

Q.4. Forecast the impact of the efficiency measures on global URN levels.

Forecast the impact these fuel efficiency measures will have on the URN levels of individual ships.

Most energy efficiency measures hold the potential to significantly decrease URN generated by commercial vessels, and the potential impact of each measure has been outlined in Table 2. As previously discussed in response to question 3, it is anticipated that speed reduction, wind-assisted propulsion systems, and air lubrication systems will play a central role in realizing the IMO’s GHG strategy. These measures also possess substantial potential to reduce URN emissions from commercial vessels.

For instance, a 20% reduction in vessel speed can yield a notable 6 dB reduction in URN. Wind-assisted propulsion systems exhibit the capability to reduce URN by up to 10 dB, and for air lubrication systems, reductions in URN in excess of 10 dB are possible. Considering the age of the vessels and with reference to the anticipated tightening of the future CII requirements, it is expected that vessels will increasingly adopt energy efficiency measures, consequently leading to a progressive reduction in URN emissions on an individual vessel basis. It's important to note that the combined potential for URN reduction from these measures is not simply a summation of the potentials of individual measures. Therefore, when adopting multiple measures, a ship owner should carry out a tailored assessment of the overall impact, both on energy efficiency and URN.

Forecast the impact these fuel efficiency measures will have on global URN levels.

Within the report, reference is made to Ross's work, which offers an equation that correlates the key factors that impact underwater radiated noise, i.e., the average source level per ship, ship density per unit area, water depth, and the attenuation of underwater noise during acoustic propagation. The authors of this report recognise the inherent complexity in forecasting ambient URN, but for predicting the magnitude of impacts and assessing sensitivities, the Ross equation is a useful starting point.

By inspection of Ross's equation, it is apparent that a change in the average source level of each ship results in an equivalent change in ambient level of URN. Therefore, if we consider the situation in deep ocean and assume the terms relating to water depth, attenuation and shipping density remain constant, average changes in source level for the world fleet will yield approximately equivalent reductions in ambient URN.

As discussed, a 20% reduction in vessel speed alone can result in a significant 6 dB reduction in URN from commercial vessels. Under the hypothesis that reducing URN emissions from commercial vessels leads to a proportional reduction in ambient noise levels, it can be expected that a collective 20% reduction in vessel speeds across the globe would lead to an average reduction of the order of 6 dB in global URN levels. Furthermore, considering the potential adoption of additional energy efficiency measures such as wind-assisted propulsion systems, air lubrication systems, and other ESDs on vessels, even greater reductions in global ambient noise levels are anticipated.

Q 5. Consider appropriate target levels of global URN reduction.

Identify target URN reduction levels that have been proposed by environmental groups.

For example, the International Whaling Commission has proposed a 3 dB reduction in 10 years and a 10dB reduction in 30 years.

The only international targets identified by this study are the targets proposed by the Okeanos Foundation. These are the same targets referred to by the question and have previously been endorsed by the International Whaling Commission. It is confirmed that these include a 3 dB reduction in ambient noise within a decade, complemented by the objective of achieving a 10 dB reduction over a 30-year timeframe. The underlying rationale for these targets is to counteract the discernible trend of a 3 dB escalation per decade, as substantiated by a multitude of research studies.

Assess how close the URN reductions forecast at step 4 will come to achieving these targets.

Building upon the insights from question 4, a 20% reduction in vessel speed alone could lead to an average reduction of about 6 dB in global ambient noise. However, when taking into account the adoption of additional energy efficiency measures like wind-assisted propulsion, air lubrication, and other ESDs, it is anticipated that even more significant reductions in global URN will be attainable. Given these considerations, achieving a 3 dB reduction in ambient noise levels within a decade appears to be a feasible goal.

Q.6. Comment on the effectiveness of the GHG reduction measures in meeting URN reduction targets.

By comparing the forecasts made at steps 4 and 5, comment on how closely the target URN reductions will be met as a direct result of the GHG efficiency measures.

When this study considers the synergies between energy efficiency and URN reduction, and even after taking account of worst-case projections for growth in transport work, it becomes evident that accomplishing a 3 dB reduction in shipping's contribution to ambient noise within a decade is a feasible goal, e.g., through speed reduction. The addition of other efficiency measures (e.g., either air lubrication or wind assisted propulsion) could provide the necessary further reductions to also put the 10 dB within 30 years goal within reach.

Q.7. Consider alternative URN reduction measures.

If there are any ENERGY EFFICIENCY measures considered at steps 3 and 4 that may increase URN, forecast the impacts of changing to alternative measures that do reduce URN (e.g. in terms of costs and GHG reduction and URN reduction.

The two most notable measures that could contribute energy efficiency gains whilst increasing noise, are the optimisation of the propeller blade area ratio, and speed reduction for ships equipped with Controllable Pitch Propellers (CPPs).

With respect to the blade area ratio, reducing the blade surface area can improve efficiency by reducing surface friction with the water. However, this also increases the pressure differential across the blades, thereby increasing cavitation noise. Therefore, this measure must be exercised with care, and the best compromise achieved between efficiency and noise.

For controllable pitch propellers, changes in speed and power are normally achieved by varying the propeller blade pitch. This is different to fixed pitch propellers where changes in ship speed are achieved by changing shaft RPM. Reducing speed for a ship fitted with a CPP necessitates reducing the propeller blade pitch. Whilst this improves energy efficiency it also has the effect of increasing cavitation noise. Again, care must be exercised with this measure and the best compromise between efficiency and noise achieved. In this respect, the propeller manufacturer’s combinator curves, can be utilised to establish the best pitch settings.

For both these measures it is important to raise awareness among ship designers and ship owners of this conflict, and to ensure it is well managed. Nevertheless, for propellers there are several other measures that do provide co-benefits of efficiency improvement and noise reduction. These include adoption of the contracted loaded tip propeller, the Kappel propeller, and utilizing a boss cap fin.

References

African Development Bank group. (2023). East Africa Economic Outlook 2022. Retrieved from: https://www.afdb.org/en/documents/east-africa-economic-outlook-2022.

Andrews, J., & Shabani, B. (2012). Where does hydrogen fit in a sustainable energy economy? Procedia engineering, 49, 15-25.

Andrew, R. K., Howe, B. M., & Mercer, J. A. (2011). Long-time trends in ship traffic noise for four sites off the North American West Coast. *The Journal of the Acoustical Society of America*, *129*(2), 642-651.

Andrew, R. K., Howe, B. M., Mercer, J. A., and Dzieciuch, M. A. (2002). “Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast,” Acoust. Res. Lett. Online 3, 6570.

APEC (2019). Analysis of the impacts of slow steaming for distant economies, APEC Transportation Group, APEC Project: TPT 03 2018A, produced by Starcrest Consulting Group for the Asia-Pacifc Economic Cooperation Secretariat, December.

Arjona Aroca, J., Giménez Maldonado, J. A., Ferrús Clari, G., Alonso i García, N., Calabria, L., & Lara, J. (2020). Enabling a green just-in-time navigation through stakeholder collaboration. European Transport Research Review, 12(1).

Audoly, C., Gaggero, T., Baudin, E., Folegot, T., Rizzuto, E., Mullor, R. S., ... & Kellett, P. (2017). Mitigation of underwater radiated noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO project. *IEEE Journal of Oceanic Engineering*, *42*(2), 373-387.

Audoly, C., Rousset, C., Rizzuto, E., Mullor, R. S., Hallander, J., & Baudin, E. (2015, May). Mitigation measures for controlling the ship underwater radiated noise, in the scope of AQUO Project. In OCEANS 2015-Genova (pp. 1-6). IEEE.

Barone, G., Buonomano, A., Forzano, C., Palombo, A., & Vicidomini, M. (2020). Sustainable energy design of cruise ships through dynamic simulations: Multi-objective optimization for waste heat recovery. Energy Conversion and Management, 221, 113166.

Basan, F., Fischer, J. G., & Kühnel, D. (2021). Soundscapes in the German Baltic Sea before and during the Covid-19 pandemic. Frontiers in Marine Science, 8, 689860.

Baudin, E., & Mumm, H. (2015). Guidelines for regulation on UW noise from commercial shipping (projects AQUOSONIC). In SONIC deliverable 5.4.

Bertetta, D., Brizzolara, S., Canepa, E., Gaggero, S., Viviani, M., (2012). EFD and CFD characterization of a CLT propeller. Int. J. Rotating.

Blue Visby Solutions. (2023). A multilateral platform for reducing shipping GHG emission by about 15% through eradicating the practice of “Sail Fast, Then wait”. Retrieved from: https://bluevisby.com/.

Breeze, H., Li, S., Marotte, E. C., Theriault, J. A., Wingfield, J., & Xu, J. (2021). Changes in underwater noise and vessel traffic in the approaches to Halifax Harbor, Nova Scotia, Canada. Frontiers in Marine Science, 8, 674788.

Carlton, J. (2018). *Marine propellers and propulsion*. Butterworth-Heinemann.

Ceccio, S. L. (2010). Friction drag reduction of external flows with bubble and gas injection. Annual Review of Fluid Mechanics, 42, 183-203.

Chapman, N. R., & Price, A. (2011). Low frequency deep ocean ambient noise trend in the Northeast Pacific Ocean. The Journal of the Acoustical Society of America, 129(5), EL161-EL165.

Choi, Y. S., Hong, S. Y., & Song, J. H. (2023). Investigation of the effect of adaptive characteristics on non-cavitating noise for flexible propeller in non-uniform flow via the fluid-structure interaction model. *International Journal of Naval Architecture and Ocean Engineering*, 100541.

Clarkson. (2023). Green Technology Tracker: July 2023.

Dahl, P. H., Dall'Osto, D. R., & Harrington, M. J. (2021). Trends in low-frequency underwater noise off the Oregon coast and impacts of COVID-19 pandemic. The Journal of the Acoustical Society of America, 149(6), 4073-4077.

DNV. (2017). How to sculpture an asymmetric stern. Advanced computer technology and modelling techniques are helping revive an old idea: twisting the stern section of the hull to optimize flow and save fuel. Retrieved from: https://www.dnv.com/expert-story/maritime-impact/How-to-sculpture-an-asymmetric-stern.html.

DNV. (2022). Maritime forecast to 2050. Retrieved from: https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html.

DNV. (2023). Energy Transition Outlook 2023. MARITIME FORECAST TO 2050. A deep dive into shipping's decarbonization journey. Retrieved from: Launch of the Energy Transition Outlook 2023 (dnv.com).

DNV GL. (2016). DNV GL Handbook for Maritime and Offshore Battery Systems. DNV GL: Oslo, Norway.

DOSITS. Discovery Of Sound In The Sea. (2023). How does sound travel in shallow water? Retrieved from: How does sound travel in shallow water? – Discovery of Sound in the Sea (dosits.org).

Dupuy, Maxime & Letournel, Lucas & Paakkari, Ville & Rongère, François & Sarsila, Severi & Vuillermoz, Louis. (2023). Weather Routing Benefit for Different Wind Propulsion Systems. Conference: International conference on innovation in high performance sailing yachts and wind-assisted ships at Lorient.

Erbe, C., Schoeman, R. P., Peel, D., & Smith, J. N. (2021). It often howls more than it chugs: wind versus ship noise under water in Australia's maritime regions. Journal of Marine Science and Engineering, 9(5), 472.

Faber, J., Huigen, T., & Nelissen, D. (2017). *Regulating speed: a short-term measure to reduce maritime GHG emissions*. CE Delft.

Faber J., Seters D.V., Scholten P. (2023). Shipping GHG emissions 2030 Analysis of the maximum technical abatement potential. Delft, CE Delft, June 2023. Publication code: 23.230208.097.

Fikry, I., Ariana, I. M., & Kusuma, C. (2023, May). Propeller Performance Analysis on The Modification of Trailing Edge Shape as Anti-Singing. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1166, No. 1, p. 012005). IOP Publishing.

Findlay, C. R., Rojano-Doñate, L., Tougaard, J., Johnson, M. P., & Madsen, P. T. (2023). Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals. *Science Advances*, *9*(25), eadf2987.

Fragasso, J., Moro, L., Lye, L. M., & Quinton, B. W. (2019). Characterization of resilient mounts for marine diesel engines: Prediction of static response via nonlinear analysis and response surface methodology. Ocean engineering, 171, 14-24.

Frisk. G. V. (2009). Long-term trends in ambient noise levels. *J Acoust Soc Am* 126, 2195..

Frisk, G. V. (2012). Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. Scientific reports, 2(1), 437.

Gaggero, S., Viviani, M., Villa, D., Bertetta, D., Vaccaro, C., and Brizzolara, S. (2012). "Numerical and Experiment Analysis of a CLT Propeller Cavitation Behavior," Proceedings of the 8th International Symposium on Cavitation, CAV2012, Abstract. 84, Singapore.

Grigoropoulos, G. J., Campana, E. F., Diez, M., Serani, A., Goren, O., Sariöz, K., ... & Stern, F. (2017, May). Mission-based hull-form and propeller optimization of a transom stern destroyer for best performance in the sea environment. In *VII International conference on computational methods in marine engineering MARINE2017*.

Gurney, G. G., Adams, V. M., Álvarez-Romero, J. G., & Claudet, J. (2023). Area-based conservation: Taking stock and looking ahead. *One Earth*, *6*(2), 98-104.

Harris, P., Sotirakopoulos, K., Robinson, S., Wang, L., and Livina, V. (2019). “A statistical method for the evaluation of long-term trends in underwater noise measurements,” J. Acoust. Soc. Am. 145, 228242.

Hawkins, A. D., & Popper, A. N. (2017). A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. *ICES Journal of Marine Science*, *74*(3), 635-651.

Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series*, *395*, 5-20.

IAMU. (2014). Istanbul Technical University, Improving Energy Efficiency of Ships Through Optimisation of Ship Operations. Retrieved from: Business-Case-Weather-Routing.pdf (stormgeo.com).

IMO. (2014). Marine Environment Protection Committee (MEPC), 2014. Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life (CIRC/MEPC/01/833.doc).

IMO. (2015). SHIP-BOARD ENERGY MANAGEMENT. Energy efficient ship operation. Retrieved from: Slide 1 (imo.org).

IMO. (2017). Marine Environment Protection Committee. (MEPC), 2017. Collaboration to Reduce Underwater Noise from Marine Shipping (Agenda/MEPC 71/16/5).

IMO. (2018). Initial IMO strategy on reduction of GHG emissions from ships. MEPC, 72, 17.

IMO. (2020). Fourth IMO GHG Study 2020. Full Report. London, UK.

IMO. (2022). Just In Time Arrival Emissions reduction potential in global container shipping. Retrieved from: JIT-Container-Study.pdf (imo.org).

IMO. (2023). MEPC 80/WP.12. Reduction of GHG emissions from ships. Revised GHG reduction strategy for global shipping adopted. Retrieved from: http://www.imo.org/en/About/Pages/Default.aspx.

IMO. (2023a). Workshop on the Relationship between Energy Efficiency and Underwater Radiated Noise from Ships. H2020 Project GATERS.

Jalkanen, J. P., Johansson, L., Andersson, M. H., Majamäki, E., & Sigray, P. (2022). Underwater noise emissions from ships during 2014–2020. Environmental Pollution, 311, 119766.

Kaplan, M. B., & Solomon, S. (2016). A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. *Marine Policy*, *73*, 119-121.

Kendrick, A., Terweij, R., (2019). Ship Underwater Radiated Noise. Vard Marine Inc. Report 368-000-01, Rev. 4, TP 15411 E, Prepared for Transport Canada.

Kim, J. H., Choi, J. E., Choi, B. J., & Chung, S. H. (2014). Twisted rudder for reducing fuel-oil consumption. International Journal of Naval Architecture and Ocean Engineering, 6(3), 715-722.

Krantz R, Søgaard K, Smith T (2020). The scale of investment needed to decarbonize international shipping. January. Available at: https://www.globalmaritimeforum.org/content/2020/01/Getting-toZero-Coalition_Insight-brief_Scale-of-investment.pdf.

Kumagai, I., Takahashi, Y., & Murai, Y. (2015). Power-saving device for air bubble generation using a hydrofoil to reduce ship drag: Theory, experiments, and application to ships. Ocean Engineering, 95, 183-194.

Leaper, R. (2019). The role of slower vessel speeds in reducing greenhouse gas emissions, underwater noise and collision risk to whales. *Frontiers in Marine Science*, *6*, 505.

Leaper, R. and Renilson, M. (2012). A review of practical methods for reducing underwater noise pollution from large commercial vessels. International Journal of Maritime Engineering 154: A79-A88. doi:10.3940/rina.ijme.2012.a2.227?

Li, D. Q., Hallander, J., & Johansson, T. (2018). Predicting underwater radiated noise of a full scale ship with model testing and numerical methods. *Ocean Engineering*, *161*, 121-135.

Lidtke, A. K., Turnock, S., & Humphrey, V. (2016). Multi-scale modelling of cavitation-induced pressure around the Delft twist 11 hydrofoil.

Ligtelijn, D., Nojiri, T., Walsh, R., & Wittekind, D. (2014). A review of practical methods for reducing underwater noise pollution from large commercial vessels. *INTERNATIONAL JOURNAL OF MARITIME ENGINEERING*, *156*, 203-206.

Lloyd, T., Foeth, E., Lafeber, F. H., & Bosschers, J. (2020). Progress in the prediction and mitigation of propeller cavitation noise and vibrations. Proceedings of 26th HISWA.

Long, N. V. D., Lee, D. Y., Kwag, C., Lee, Y. M., Lee, S. W., Hessel, V., & Lee, M. (2021). Improvement of marine carbon capture onboard diesel fueled ships. *Chemical Engineering and Processing-Process Intensification*, *168*, 108535.

Lube, G., Breard, E. C., Jones, J., Fullard, L., Dufek, J., Cronin, S. J., & Wang, T. (2019). Generation of air lubrication within pyroclastic density currents. Nature Geoscience, 12(5), 381-386.

Mallouppas, G., & Yfantis, E. A. (2021). Decarbonization in shipping industry: A review of research, technology development, and innovation proposals. Journal of Marine Science and Engineering, 9(4), 415.

March, D., Metcalfe, K., Tintoré, J. & Godley, J. (2021). Tracking the global reduction of marine traffic during the COVID-19 pandemic. Nat. Commun. 12, 2415. https://doi.org/10.1038/s41467-021-22423-6.

MARIN. (2023). Mitigating ship noise using bubble injection," SATURN Proj. Res. Newsletter, no. 2, pp. 16-17. Retrieved from: https://www.saturnh2020.eu/post/newsletter-issue-no-2.

Matsumoto, H., Bohnenstiehl, D. R., Tournadre, J., Dziak, R. P., Haxel, J. H., Lau, T. K., ... & Salo, S. A. (2014). Antarctic icebergs: A significant natural ocean sound source in the Southern Hemisphere. Geochemistry, Geophysics, Geosystems, 15(8), 3448-3458.

McCreery, C. S., Duennebier, F. K., & Sutton, G. H. (1993). Correlation of deep ocean noise (0.4–30 Hz) with wind, and the Holu Spectrum—A worldwide constant. *The Journal of the Acoustical Society of America*, *93*(5), 2639-2648.

McDonald, M. A., Hildebrand, J. A., & Wiggins, S. M. (2006). Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. The Journal of the Acoustical Society of America, 120(2), 711-718.

Merchant, N. D., Brookes, K. L., Faulkner, R. C., Bicknell, A. W., Godley, B. J., & Witt, M. J. (2016). Underwater noise levels in UK waters. Scientific reports, 6(1), 36942.

Miksis-Olds, J. L., Bradley, D. L., & Maggie Niu, X. (2013). Decadal trends in Indian Ocean ambient sound. *The Journal of the Acoustical Society of America*, *134*(5), 3464-3475.

Miksis-Olds, J. L., Bradley, D. L., & Maggie Niu, X. (2014). Erratum: Decadal trends in Indian Ocean ambient sound [J. Acoustic Soc. Am. 134 (5), 3464–3475 (2013)]. *The Journal of the Acoustical Society of America*, *135*(3), 1642-1642.

Miksis-Olds, J. L., & Nichols, S. M. (2016). Is low frequency ocean sound increasing globally? The Journal of the Acoustical Society of America, 139(1), 501-511.

Millefiori, L. M., Braca, P., Zissis, D., Spiliopoulos, G., Marano, S., Willett, P. K., & Carniel, S. (2021). COVID-19 impact on global maritime mobility. *Scientific reports*, *11*(1), 18039.

Mohammad Danil, A., Danny, F., Fanny, O., & Karina, A. (2020). Analysis of the Effect of Changes in Pitch Ratio and Number of Blades on Cavitation on CPP. International Journal of Marine Engineering Innovation and Research, 5(4), 255-264.

Molland, A. F., Turnock, S. R., & Hudson, D. A. (2017). *Ship resistance and propulsion*. Cambridge university press.

Murai, Y., Sakamaki, H., Kumagai, I., Park, H. J., & Tasaka, Y. (2020). Mechanism and performance of a hydrofoil bubble generator utilized for bubbly drag reduction ships. Ocean Engineering, 216, 108085.

NAPA. (2021). NAPA analysis shows EEXI would lead to a 6.6% cut in emissions, demonstrating the scale of the challenge to reach IMO goals. Retrieved from: NAPA analysis shows EEXI would lead to a 6.6% cut in emissions, demonstrating the scale of the challenge to reach IMO goals – NAPA.

Nolet, V. (2017). Understanding anthropogenic underwater noise. *Prepared for Transport Canada. xviii*.

Oliveira, D. R., Lagerström, M., Granhag, L., Werner, S., Larsson, A. I., & Ytreberg, E. (2022). A novel tool for cost and emission reduction related to ship underwater hull maintenance. Journal of Cleaner Production, 356, 131882.

PAME. (Protection of the Arctic Marine Environment). (2021). Underwater noise pollution from shipping in the arctic. Retrieved from: https://www.arcticwwf.org/threats/underwater-noise.

Park, J., Haralabus, G., Zampolli, M., & Metz, D. (2023). Low frequency ambient noise dynamics and trends in the Indian Ocean, Cape Leeuwin, Australia. The Journal of the Acoustical Society of America, 153(4), 2312-2312.

Pesyridis, A., Asif, M. S., Mehranfar, S., Mahmoudzadeh Andwari, A., Gharehghani, A., & Megaritis, T. (2023). Design of the Organic Rankine Cycle for High-Efficiency Diesel Engines in Marine Applications. Energies, 16(11), 4374.

Pine, M. K., Hannay, D. E., Insley, S. J., Halliday, W. D., & Juanes, F. (2018). Assessing vessel slowdown for reducing auditory masking for marine mammals and fish of the western Canadian Arctic. *Marine Pollution Bulletin*, *135*, 290-302.

Port Vancouver, (2017). Echo Action program.

Prins, H.J., Flikkema, M.B., Bosschers, J., Koldenhof, Y., de Jong, C.A.F., Pestelli, C., Hyensjo, M. (2016). Suppression of underwater noise induced by cavitation: SONIC, Trans. Res. Procedia 14 2668–2677.

Psaraftis, H. N., & Kontovas, C. A. (2014). Ship speed optimization: Concepts, models and combined speed-routing scenarios. *Transportation Research Part C: Emerging Technologies*, *44*, 52-69.

Qiu, Y., Xu, W., & Li, Z. (2019). Performance evaluation of a novel intelligent distributed mounting system for marine mechanical equipment. *International Journal of Advanced Robotic Systems*, *16*(6), 1729881419883562.

Rako-Gospić, N., & Picciulin, M. (2019). Underwater noise: Sources and effects on marine life. In World Seas: an environmental evaluation (pp. 367-389). Academic Press.

Rasul, M. G., Hazrat, M. A., Sattar, M. A., Jahirul, M. I., & Shearer, M. J. (2022). The future of hydrogen: Challenges on production, storage and applications. Energy Conversion and Management, 272, 116326.

Renilson Marine Consulting Pty Ltd. (2009). “Reducing underwater noise pollution from large commercial ships,” The Int. und for Animal Welfare (I AW), Rep.

RINA. (2023). Damen to supply Air Cavity System to Amisco for reduced emissions. Retrieved from:Damen to supply Air Cavity System to Amisco for reduced emissions - RINA.org.

Robinson, S., Harris, P., Cheong, S. H., Wang, L., Livina, V., Haralabus, G., ... & Nielsen, P. (2023). Impact of the COVID-19 pandemic on levels of deep-ocean acoustic noise. Scientific Reports, 13(1), 4631.

Robinson, S. P., Harris, P. M., Wang, L., Cheong, S. H., & Livina, V. (2019, June). Evaluation of long-term trends in deep-ocean noise in the Southern Ocean. In *OCEANS 2019-Marseille* (pp. 1-6). IEEE.

Ross, D. (1976). Cavitation. In: Mechanics of Underwater Noise, pp. 202–242.

Ross, D. (1993). “On ocean underwater ambient noise,” Acoust. Bull. 18, 5–8.

Ryan, J. P., Joseph, J. E., Margolina, T., Hatch, L. T., Azzara, A., Reyes, A., ... & Stimpert, A. K. (2021). Reduction of low-frequency vessel noise in Monterey Bay National Marine Sanctuary during the COVID-19 pandemic. Frontiers in Marine Science, 587.

Saettone, S., Regener, P. B., & Andersen, P. (2016). Pre-swirl stator and propeller design for varying operating conditions. *Proceedings of PRADS2016*, *4*, 8th.

Salinas. R and Moreno. A. (2015). "Assessment of the solutions to reduce underwater radiated noise," Achieve Quieter oceans by shipping noise footprint reduction, WP: Practical Guidelines Task T5.3, Revision 1.

Sertlek, H. Ö., Slabbekoorn, H., Ten Cate, C., & Ainslie, M. A. (2019). Source specific sound mapping: Spatial, temporal and spectral distribution of sound in the Dutch North Sea. *Environmental pollution*, *247*, 1143-1157.

Singh, D. V., & Pedersen, E. (2016). A review of waste heat recovery technologies for maritime applications. Energy conversion and management, 111, 315-328.

Smith, T. A., & Rigby, J. (2022). Underwater radiated noise from marine vessels: A review of noise reduction methods and technology. Ocean Engineering, 266, 112863.

Spence, J. H., & Fischer, R. W. (2016). Requirements for reducing underwater noise from ships. IEEE Journal of Oceanic Engineering, 42(2), 388-398.

Supponen, O., Obreschkow, D., & Farhat, M. (2018). Rebounds of deformed cavitation bubbles. *Physical Review Fluids*, *3*(10), 103604.

Sánchez-Caja, A., González-Adalid, J., Pérez-Sobrino, M., & Saisto, I. (2012, August). Study of end-plate shape variations for tip loaded propellers using a RANSE solver. In 29th Symposium on Naval Hydrodynamics, Gothenburg, Sweden (pp. 26-31).

TAKAHASHI, R., MIYOSHI, J., Mizoguchi, H., & TERADA, D. (2019). Comparison of underwater cruising noise in fuel-cell fishing vessel, same-hull-form diesel vessel, and aquaculture working vessel. Transactions of Navigation, 4(1), 29-38.

The World Bank. (2021). Middle East and North Africa. Retrieved from: https://www.worldbank.org/en/region/mena/overview.

Thomson, D. J., & Barclay, D. R. (2020). Real-time observations of the impact of COVID-19 on underwater noise. The Journal of the Acoustical Society of America, 147(5), 3390-3396.

Tian, Y., Zhang, C., Yang, L., Ouyang, W., & Zhou, X. (2022). Analysis of Vibration Characteristics of Podded Propulsor Shafting Based on Analytical Method. *Journal of Marine Science and Engineering*, *10*(2), 169.

TM, M. (2017). Underwater noise comparison of pre-and post-retrofitted MAERSK G-class container vessels.

Tronstad, T., Åstrand, H. H., Haugom, G. P., & Langfeldt, L. (2017). Study on the use of fuel cells in shipping.

United Nations Conference on Trade and Development (UNCTAD) (2023). Review of Maritime Transport 2023.Towards a green and just transition. UNCTAD/RMT/2023.

Vakili, S., Ballini, F., Schönborn, A., Christodoulou, A., Dalaklis, D., & Ölçer, A. I. (2023). Assessing the macroeconomic and social impacts of slow steaming in shipping: a literature review on small island developing states and least developed countries. Journal of Shipping and Trade, 8(1), 2.

Vakili, S & Ölçer, A. I. (2023). Are battery-powered vessels the best solution for the domestic ferry segment? Case study for the domestic ferry segment in the Philippines. Energy, 128323.

Vakili, S., & Ölçer, A. I. (2023a). Techno-economic-environmental feasibility of photovoltaic, wind and hybrid electrification systems for stand-alone and grid-connected port electrification in the Philippines. *Sustainable Cities and Society*, *96*, 104618.

Vakili, S. V., Ölcer, A. I., & Ballini, F. (2020). The development of a policy framework to mitigate underwater noise pollution from commercial vessels. *Marine Policy*, *118*, 104004.

Vakili, S. V., Ölçer, A. I., & Ballini, F. (2020a). The development of a policy framework to mitigate underwater noise pollution from commercial vessels: The role of ports. *Marine Policy*, *120*, 104132.

Vakili, S., Ölçer, A. I., & Ballini, F. (2021). The development of a transdisciplinary policy framework for shipping companies to mitigate underwater noise pollution from commercial vessels. *Marine Pollution Bulletin*, *171*, 112687.

Valdenaire.D. (2022). Technical, operational and energy pathways for maritime transport to reduce emissions towards 2050. Retrieved from: Technological-operational-and-energy-pathways-for-maritime-transport.pdf (concawe.eu).

van Biert, L., Godjevac, M., Visser, K., & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. *Journal of Power Sources*, *327*, 345-364.

Van Hauwermeiren, W., Filipan, K., Botteldooren, D., & De Coensel, B. (2021). Opportunistic monitoring of pavements for noise labeling and mitigation with machine learning. *Transportation Research Part D: Transport and Environment*, *90*, 102636.

Vard Marine Report. (2019). Ship Underwater Radiated Noise, Report 368-000-01, rev 3.

Vard Marine Report. (2023). SHIP ENERGY EFFICIENCY AND UNDERWATER RADIATED NOISE. Report 545-000-01, rev 1.

Veirs, S., Veirs, V., Williams, R., Jasny, M., & Wood, J. (2018). A key to quieter seas: half of ship noise comes from 15% of the fleet. PeerJ Preprints. https://doi.org/10.7287/peerj.preprints.26525.

Vigneshraj, C. T., Kannan, R. K., & Vivek, C. (2016). NOISE REDUCTION IN TWO STROKE ENGINE BY CONTROLLING THE VELOCITY OF EXHAUST GAS. International Journal of Advances in Engineering & Technology, 9(4), 507.

Viola, I. M., Sacher, M., Xu, J., & Wang, F. (2015). A numerical method for the design of ships with wind-assisted propulsion. Ocean Engineering, 105, 33-42.

Williams, R., Veirs, S., Veirs, V., Ashe, E., & Mastick, N. (2019). Approaches to reduce noise from ships operating in important killer whale habitats. *Marine pollution bulletin*, *139*, 459-469.

Wittekind, D., & Schuster, M. (2016). Propeller cavitation noise and background noise in the sea. *Ocean Engineering*, *120*, 116-121.

Wright, A.J. (ed) 2008. International Workshop on Shipping Noise and Marine Mammals, Hamburg, Germany, 21st-24th April 2008. Okeanos - Foundation for the Sea, Auf der Marienhohe 15, D-64297. Darmstadt. 33+v p. Available from http://www.sound-in-the-sea.org/download/ship2008_en.pdf

Wärtsilä. (2021). Wärtsilä and Solvang to collaborate on retrofitting carbon capture and storage system on Clipper Eos. Retrieved from: https://www.wartsila.com/media/news/20-10-2021-wartsila-and-solvang-to-collaborate-on-retrofitting-carbon-capture-and-storage-system-on-clipper-eos-2992717.

Yang, J., Xie, H., Yu, G., & Liu, M. (2021). Achieving a just–in–time supply chain: The role of supply chain intelligence. *International journal of production economics*, *231*, 107878.

Young, Y. L., Motley, M. R., Barber, R., Chae, E. J., & Garg, N. (2016). Adaptive composite marine propulsors and turbines: progress and challenges. *Applied Mechanics Reviews*, *68*(6), 060803.

Yu, K., Park, D., Choi, J., Seol, H., Park, I., & Lee, S. (2023). Effect of skew on the tonal noise characteristics of a full-scale submarine propeller. *Ocean Engineering*, *276*, 114218.

Yusvika, M., Prabowo, A. R., Tjahjana, D. D. D. P., & Sohn, J. M. (2020). Cavitation prediction of ship propeller based on temperature and fluid properties of water. *Journal of Marine Science and Engineering*, *8*(6), 465.

Zalachoris, A. (2020). Evaluation of the efficiency of a Mewis duct by performance monitoring.

Zhang, R., Zhou, M., Yan, P., & Zhou, J. (2023, June). Research on the Momentum Distribution Mechanism Within the Diffuser Chamber Nozzles of the Azimuth Waterjet Propulsion System. In *The 33rd International Ocean and Polar Engineering Conference*. OnePetro.

Zondervan, G., Holtrop, J., Windt, J., & Van Terwisga, T. (2011, June). On the design and analysis of pre-swirl stators for single and twin-screw ships. In Second International Symposium on Marine Propulsors, Hamburg, Germany.