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Advancing a sustainable maritime future: Integrating energy efficiency and underwater radiated noise reduction strategies in commercial shipping☆

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ABSTRACT

Underwater Radiated Noise (URN) from ships has an environmental impact which needs addressing to ensure shipping becomes more sustainable. This paper explores the nexus between energy efficiency (EE) measures and URN mitigation, aligning with the International Maritime Organization's (IMO's) greenhouse gas (GHG) reduction strategy. Investigating the synergy the study addresses the complexities of decarbonizing the maritime sector within a landscape of diverse energy efficiency technologies. Various EE measures, such as speed reduction, wind-assisted propulsion systems, energy saving devices, and air lubrication systems, show promise in achieving GHG emissions reductions. Reductions of 6 dB in URN can be achieved by a 20 % vessel speed reduction, while wind-assisted propulsion and air lubrication systems show even greater efficacy, surpassing 10 dB in URN reduction. Considering the aging vessel fleet and upcoming Carbon Intensity Indicator requirements, the adoption of EE measures is expected to grow, leading to individual vessel URN reduction. Despite a worst-case scenario in seaborne trade growth projecting a 2.38 dB increases in ambient noise levels by 2050, EE measures are anticipated to counteract this impact. Aligning with the Okeanos target of a 3 dB reduction per decade, these measures could effectively mitigate ambient noise. The effectiveness of GHG emission regulations in reducing URN from commercial vessels greatly depends on the approach taken to achieve zero-emission shipping by 2050. While carbon-neutral fuels may not significantly impact URN reduction, the greater role of EE measures in the industry's decarbonization efforts increases the likelihood of reducing URN from commercial vessels.

1. Introduction

Shipping, acknowledged as the most effective means of transporting goods, holds a crucial position in worldwide commerce, accounting for approximately 80 % of cargo volume (UNCTAD, 2023). Nonetheless, it presents notable environmental and socio-economic challenges, contributing to 2.89 % of global greenhouse gas (GHG) emissions (IMO, 2020). Among these challenges, Underwater Radiated Noise (URN) arises as a significant issue associated with commercial ships. URN, although not visually perceptible like other pollutants, imposes harmful effects on marine ecosystems. The continual growth of maritime trade, alongside the expansion of the global fleet in terms of both quantity and displacement as well as the increased distances covered, is likely to contribute to increased URN (Vakili et al., 2020b). This phenomenon has the potential for significant environmental ramifications, in particular adverse impacts on marine life, such as fish, invertebrates, and marine mammals, leading to ecological shifts and changes in population dynamics (Hawkins and Popper, 2017; Rako-Gospić and Picciulin, 2019).

While commercial shipping is acknowledged as a significant contributor to URN, the precise relationship between URN emissions from commercial vessels, maritime traffic, and adverse impacts on marine ecosystems is difficult to quantify. Given the complexity of this issue, a comprehensive, systematic, and transdisciplinary approach involving various stakeholders, including but not limited to ship designers, builders, operators, seafarers, ports, policymakers, technology providers, and classification societies, is necessary (Vakili et al., 2021). Due to the transboundary nature of URN pollution, international, regional, and national cooperation is imperative for its management

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(Vakili et al., 2021; SATURN, 2024). To tackle this challenge, prominent international agencies like the International Maritime Organization (IMO) and the European Union (EU), alongside other regional and national agreements, play a pivotal role in monitoring, regulating, and mitigating URN emissions from commercial vessels.

The IMO has introduced voluntary guidelines and resolutions aimed at mitigating URN emissions from commercial shipping. The 2014 IMO guidelines focused on strategies such as routing adjustments, operational changes, and improvements in ship design and maintenance to address URN (Vakili et al., 2020b). During MEPC 80, revised non-binding IMO guidelines for URN reduction were endorsed, and are applicable to both new and existing vessels. These updated guidelines recognize the interconnectedness of maritime issues, emphasizing the need to address URN alongside concerns like zero emissions, biofouling, and vessel safety. Additionally, the Sub-Committee on Ship Design and Construction has developed an Action Plan to further prevent and diminish URN emissions from ships, aiming to mitigate their detrimental impacts on marine ecosystems, particularly marine wildlife and indigenous communities (IMO, 2024), which has been adopted at IMO MEPC 82.

The European Union has addressed the issue within its Marine Strategy Framework Directive (MSFD). Member states have tasked the EU with evaluating and documenting anthropogenic noise as part of Descriptor 11 of the MSFD, adopted in June 2008. The primary goal of this Directive is to achieve a state of good environmental health by 2020, with each member state devising its own strategy to reach this objective (EU, 2020).

Many technical and operational strategies are available to minimize URN emissions from commercial vessels. However, to engage stakeholders in actively reducing URN emissions from these vessels and hastening the overall reduction process, it's crucial to align these efforts with the reduction of GHG emissions from shipping, which is a primary driver of the maritime sector (Vakili, 2018; Vakili et al., 2020a, 2020b, 2021, 2024). Considering this, the paper asks if complying with the IMO's GHG strategy can lead to a reduction of URN from commercial vessels and consequently reduce ambient noise, and if this can help fulfill the Okeanos URN targets[1] of a global 3 dB reduction from commercial vessels per decade.

To answer this question, the authors consider the following steps[2]:

- Review the IMO's GHG Strategy Goals: Analyse the IMO's GHG strategy objectives and identify the necessary pathways to achieve these targets.
- Evaluate Synergies: Assess the synergy between the IMO's GHG strategy pathways and EE measures in mitigating air emissions and URN from commercial vessels.
- Examine Seaborne Trade Growth: Investigate the impact of seaborne trade growth on the increase in underwater ambient noise.
- Assess URN Reduction Targets: Determine the required reduction in URN to meet Okeanos targets and propose appropriate measures to achieve these targets while also fulfilling the IMO's GHG strategy goals.

The study's novelty lies in identifying measures that can enhance energy efficiency (EE), thereby reducing GHG emissions and URN simultaneously, while considering their potential in each criterion. It also identifies the role of seaborne trade growth in increasing ambient noise and provides an appropriate pathway to meet both the IMO's GHG strategy and Okeanos URN targets. The study's findings can serve as a guideline for shipowners and policymakers to adopt the most cost-effective measures to meet both the IMO's revised GHG strategy and reduce URN emissions from commercial vessels.

2. Zero emission shipping

The IMO, as the regulatory authority for international shipping, has revised its strategy to achieve zero-emission shipping by approximately 2050 (IMO, 2023). However, achieving this goal necessitates a combination of measures rather than a single solution. To attain zero-emission shipping by the mid-21st century, the maritime sector can leverage a range of operational and technical strategies. These measures, Fig. 1, span across hull design (Molland et al., 2017), economic scale, power and propulsion systems (ABS, 2024), speed optimization, fuel selection (DNV GL, 2019), and weather and voyage planning (DNV, 2022). It is suggested that a synergistic implementation of these measures could potentially achieve a 75 % reduction in GHG emissions (Bouman et al., 2017).

Among these measures, the use of carbon-neutral fuels stands out as a key strategy for mitigating GHG emissions from shipping. Nevertheless, various significant interdisciplinary barriers exist, such as challenges related to the availability and cost of alternative fuels, inadequate bunkering and port infrastructure, logistical constraints, limited scalability of production, technological maturity in onboard vessel systems and supply-side infrastructure, considerations regarding ship and engine design, crew training, safety considerations, and substantial financial investments (Vakili et al., 2024, 2025). As a result, the widespread adoption of carbon-neutral fuels is expected to only gain traction after 2030 and become predominant beyond 2040 (DNV, 2023). In response to these barriers, the maritime industry is compelled to implement a range of measures. These include the adoption of energy-efficient technologies and operational measures, such as speed reduction, and the optimization of logistics to align with the emissions reduction objectives set by the IMO.

Operational and technical EE measures play a crucial role in reducing fuel consumption and emissions in the maritime industry, with the potential to achieve a 4 % to 16 % reduction by 2030 (DNV, 2024). While some of these reductions can be realized through enhanced operational efficiencies—such as optimized vessel handling and improved passage planning—greater reductions necessitate the implementation of advanced technological solutions, including onboard carbon capture and storage, fuel cells, wind-assisted propulsion, and waste-heat recovery systems (Vakili et al., 2024, 2025). These technologies have already demonstrated their potential in delivering emissions reductions. A 16 % reduction alone equates to 120 million metric tons (MT) of CO_2, 40 MT of fuel savings, and increased efficiency across 2,500 large vessels, while 55,000 smaller ships could transition to carbon-neutral fuels. Furthermore, shore power and battery solutions present additional opportunities to cut emissions, with shore power alone capable of reducing 7 % of total energy consumption by replacing onboard fossil fuel-generated electricity while ships are at berth (DNV, 2024). By 2050, EE measures could contribute to a substantial 32 % reduction in GHG emissions from the industry, comprising an estimated 23 % reduction through speed optimization and 9 % through efficiency improvements (DNV, 2023). These findings underscore the urgent need for the widespread adoption of EE measures and supporting technologies to meet decarbonization targets effectively.

3. URN trend and seaborne trade role

Anthropogenic noise levels exhibit variation both spatially and temporally, influenced not only by the intensity of human activity but also by the acoustic properties of the area. Understanding the diverse

[1] To mitigate the impact of shipping on ambient noise levels, the Okeanos Foundation set a target during the international workshop on Shipping Noise and Marine Mammals held in Hamburg. The goal is to reduce the ambient noise energy in the 10–300 Hz frequency band by 3 dB within 10 years and by 10 dB within 30 years from individual ships (Wright, 2008).

[2] This study is a summary of a larger project funded by International Chamber of Shipping (ICS), with the full report presented at the IMO's Sub-Committee on Ship Design and Construction (SDC) 10th meeting.

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. 1. Expectation of potential shipping decarbonization technologies' GHG emissions reduction. Source: (ABS, 2024; DNV, 2022, 2023, 2024; DNV GL, 2019).

sources of underwater noise and their cumulative effects on the acoustic environment is important. Industrial and shipping development stands as a significant contributor to the notable rise in underwater noise, alongside activities like seismic surveys, explosions, and wind-related factors (Hildebrand, 2009). While shipping is a contributor to underwater ambient noise in the low-frequency band, considerable uncertainties persist regarding the specific contribution of commercial vessels to the overall acoustic environment of the ocean, their influence on regional noise variability, and the extent of their long-term ecological impacts on marine life. Furthermore, the efficacy of existing and proposed mitigation strategies remains insufficiently understood, necessitating further comprehensive investigation (Vakili et al., 2021).

Fig. 2 illustrates the long-term trends in low-frequency ambient noise levels across various regions globally from 1958 to 1975. The study reveals a gradual rise in ambient noise, with an average increase of approximately 0.55 dB per year, equating to about 5.5 dB per decade in certain areas (Frisk, 2009; Harris et al., 2019). However, this trend is not universally observed; some regions have shown stable or even declining noise levels. Furthermore, the projected underwater noise levels differ significantly across various regions worldwide. As shown in Fig. 3, the URN from ships has increased in most sea areas between 2014 and 2020, but the long-term noise patterns vary across regions, lacking uniform trends and different sea regions may experience varying periods of noise source intensity[3] (Jalkanen et al., 2022). These considerations highlight the importance of moving beyond linear models and adopting nonlinear approaches that account for long-term cyclic dynamics (Park et al., 2023).

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 (Jalkanen et al., 2022). 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.

The IMO's Fourth GHG Study offers a comprehensive forecast of transport activity up to 2050, delineated across four distinct scenarios. When evaluating the density of shipping traffic, understanding not only the volume of trade but also the distances travelled becomes crucial, making transport work (i.e., cargo carried multiplied by distance travelled) a more insightful metric than cargo volume or value. The projections outlined in the Fourth GHG study anticipate that the growth between 2020 and 2050 in transport work will lie in the range 40 % to 100 % (IMO, 2020), translating to an average annual growth rate of approximately 1.13 % to 2.34 %.

In the scenario of a 2.34 % yearly growth rate, by 2033,[4] the authors anticipate a roughly 26 % increase in transport work, accompanied by a corresponding rise in average shipping density. Equation (Eq.) 1 from Ross's (1976) study

$$Ln = Ls - 95 + 10log\delta + 10log\frac{1}{\alpha H}$$

specifies the ambient noise level in dB, where Ln is the ambient noise, Ls is the average sound source level per ship, δ represents the density of ship traffic, α is the attenuation factor, and H denotes the water depth.

Assuming the only variable change is an increase in traffic density, it would lead to an approximate increase of 1 dB in ambient noise. Although a 1 dB increase may appear minor at first glance, the logarithmic nature of the decibel scale means that such an increase represents an approximate 26 % rise in noise intensity relative to its original level. This constitutes a substantial change in noise intensity, with potential implications for noise management and environmental impact. To counteract this rise and achieve the proposed 3 dB reduction advocated by Okeanos, an average reduction of 4[5] dB in the source level per ship would be necessary. Looking ahead to 2050 and employing the same growth rate, a 73.5 % increase in transport work is projected. Utilizing the Ross equation and assuming no other alterations, this would correspond to an approximate 2.38 dB increase in ambient URN.

[3] These variations are influenced by several factors, including global warming's impact on sea surface temperature and ocean acidity, as well as changes in marine species populations, such as whales (Ainslie et al., 2023).

[4] The study's calculations for the reduction of URN from commercial vessels are based on data starting from 2023.

[5] Taking into account Okeanos' target of a 3 dB reduction on noise energy from individual vessels in every decade, the required reduction over 10 years is 3 dB. Additionally, a further 1 dB reduction is necessary to offset the increase in noise energy due to seaborne trade growth. Consequently, a total reduction of 4 dB in noise energy from individual vessels is required from 2023 to 2033.

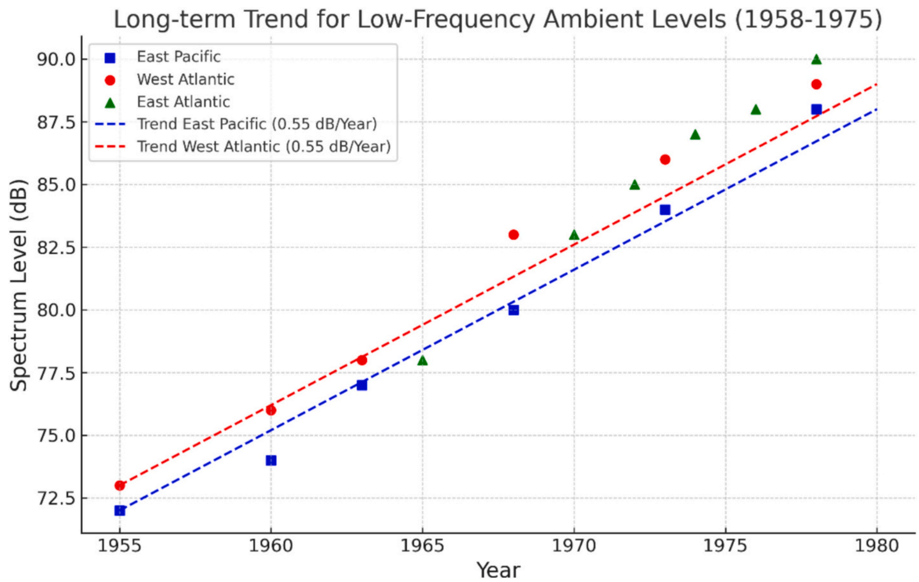

Fig. 2. Long term trend for low-frequency ambient levels (1958–1975). Source: adopted from: (Ross, 1993).

To offset this rise and fulfill the 10 dB reduction within 30 years target proposed by Okeanos,[6] a reduction of 11.38[7] dB in the average source level per ship would be required (See Fig. 4).

4. Synergy between improvement of energy efficiency and reduction of urn from commercial ships

URN has emerged as a growing environmental concern, with significant repercussions for marine species. Many technical and operational strategies are available to minimize URN emissions from commercial vessels. However, to engage stakeholders in actively reducing URN emissions from these vessels and accelerating the overall reduction process, it is important to align these efforts with improvements in vessel EE (Vakili et al., 2020a).

Improving EE while reducing URN presents a few challenges, including: i) increasing blade area at the propeller to mitigate cavitation noise, reduces propeller efficiency (Carlton, 2018; Yusvika et al., 2020); ii) ship speed reduction may not necessarily lead to a reduction in URN for Controllable Pitch Propellers (CPP); and iii) implementing technologies like exhaust scrubbers and onboard carbon capture may increase machinery noise. However, the majority of other EE measures exist that can simultaneously enhance EE and mitigate URN emissions (Vard Marine Report, 2023; Vakili et al., 2024) (See Fig. 5).

Fig. 6 shows the likely reduction in ship noise levels for the important EE measures.[8] It is significant to note that cavitation is the primary source of noise once the vessel reaches its Cavitation Inception Speed (CIS) (Yusvika et al., 2020). Consequently, optimizing the propeller in conjunction with the ship's hull configuration plays a significant role in reducing cavitation and in mitigating URN emissions. The implementation of Energy Saving Devices (ESDs) and Propulsion Improvement Devices (PIDs) has the potential to enhance both EE (by up to 10 %) and URN reduction (by up to 5 dB), often resulting in short payback periods as an added benefit (Vard Marine Report, 2023).

Innovative EE measures, such as air lubrication systems and wind-assisted propulsion systems, present promising solutions with positive impacts on URN reduction (exceeding 10 dB and up to 10 dB, respectively) and the enhancement of EE (15 % and up to 25 %, respectively) (RINA, 2023; Vakili et al., 2024; Vard Marine Report, 2023). A study found that the URN generated by a conventionally fueled vessel is equivalent to that of 25 vessels utilizing 40 % wind propulsion. The latter, a ship using 40 % wind-assisted propulsion, has the potential to reduce URN by 14 dB at 100 Hz and decrease the disturbance distance by 28 km (MEPC 80, 2023).

However, there still exists a gap in research examining the actual performance of these methods under real operating conditions, including variations in vessel speed, loading conditions, sea states, and long-term durability in mitigating URN emissions from commercial vessels. This highlights the necessity for full-scale evaluations to assess their effectiveness, reliability, and practical implementation challenges.

Furthermore, as the maritime industry explores vessel electrification, the adoption of fuel cell, battery, or hybrid technologies shows potential for improving energy efficiency, particularly in short sea shipping and other operational profiles where these technologies align with specific requirements. However, the feasibility and effectiveness of such systems remain highly case-dependent, with energy efficiency improvements reaching up to 10 % under optimal conditions. Within these electrified systems, incorporating azimuth propulsion and podded propulsors, along with their associated machinery, can reduce URN emissions from vessels by over 10 dB[9] (Vard Marine Report, 2023).

Machinery noise is the dominant contributor to URN emissions in commercial vessels during operations below the CIS (Smith and Rigby, 2022). Achieving reductions in URN from machinery in commercial vessels can be based on various strategies, including enhancing machinery design, utilizing quieter machinery, optimizing the layout of engine rooms and machinery placement, and implementing resilient

[6] Okeanos aims to reduce URN from vessels by approximately 3 dB per decade and 10 dB over 30 years.

[7] Taking into account Okeanos' target of a 10 dB reduction on noise energy from individual vessels over 30 years, the required reduction over 27 years is approximately 9 dB. Additionally, a further 2.38 dB reduction is necessary to offset the increase in noise energy due to seaborne trade growth. Consequently, a total reduction of 11.38 dB in noise energy from individual vessels is required from 2023 to 2050.

[8] The selection of these measures is based on their effectiveness in improving energy efficiency and their potential impact on reducing URN from commercial ships.

[9] While reductions exceeding 10 dB have been reported in certain studies, these findings are largely based on model-scale testing and numerical simulations. The real-world effectiveness of such systems in commercial operations remains uncertain and warrants further full-scale investigations to validate their noise reduction potential under diverse operational conditions.

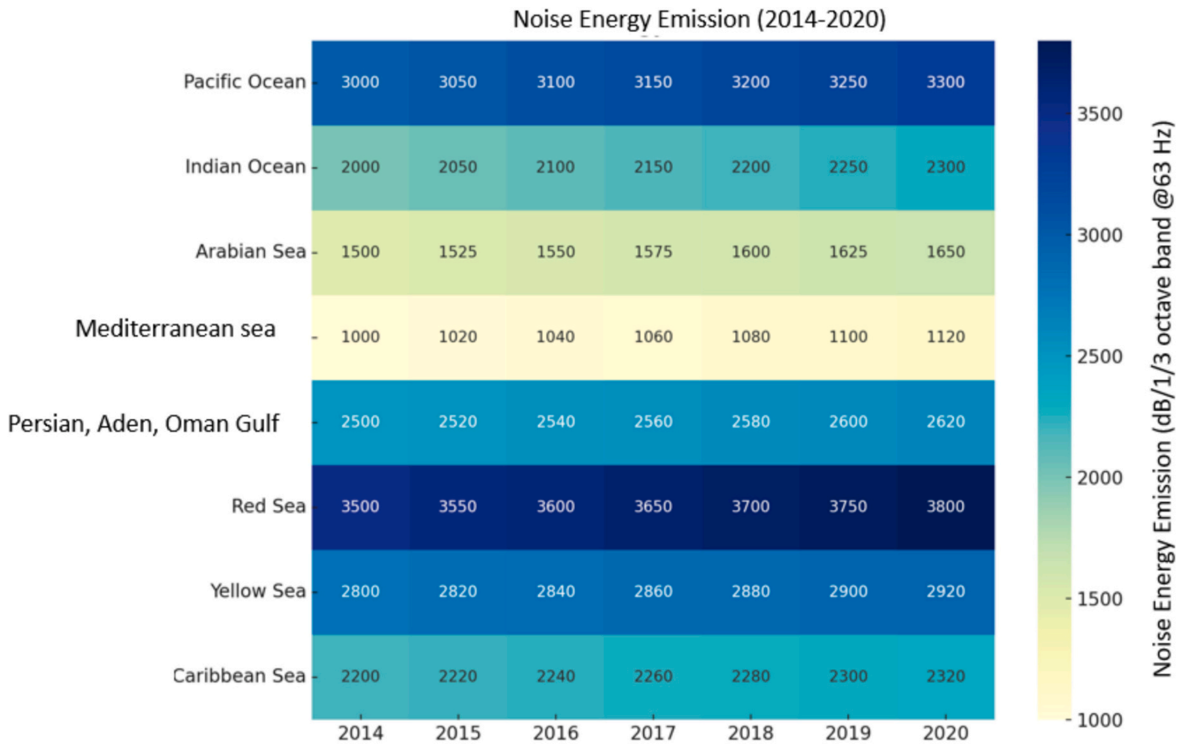

Fig. 3. Regional trends in underwater noise source energy from ships at a 63 Hz frequency within a 1/3 octave band from 2014 to 2020. Source: adopted from: (Jalkanen et al., 2022).

mounting systems (Harris et al., 2019; Vard Marine Report, 2023). It is crucial to stress that, in addition to assessing the noise generated by individual machinery components, a comprehensive evaluation must consider the interaction and combined contribution of all the machinery as an integrated system (Vakili et al., 2021).

Operational strategies are pivotal in mitigating URN emissions from commercial vessels. Reduction in service speed, with the approximate cubic relationship to propulsive power reduces cavitation in fixed pitch propellers and offers an opportunity for improving EE (Vakili et al., 2023). Such reductions can lead to a substantial decrease in URN emissions, with a 10 % reduction in speed resulting in around 2 dB reduction in mean source level and a 20 % reduction in speed leading to a predicted mean source level decrease of 6 dB across all frequencies for fixed pitch propellers (Findlay et al., 2023).

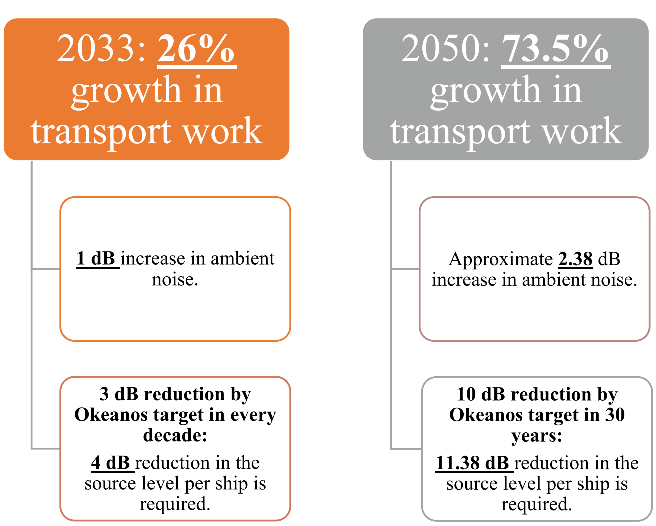

Fig. 4. Prediction of seaborne trade effect on ambient noise level and the required actions to meet Okeanos target.

Speed reduction may increase URN emissions in some CPP (Smith and Rigby, 2022). However, optimizing CPP combinator settings is crucial for mitigating early cavitation onset on both the pressure and suction sides during constant-speed operations and acceleration (Vakili et al., 2020b). These optimizations can also enhance propeller efficiency under such conditions. Additionally, measures such as optimized pitch control algorithms, improved maintenance of CPP mechanisms to minimize cavitation, and regular hull and propeller cleaning to reduce flow disturbances can further contribute to reducing URN emissions from CPP-equipped vessels (Vakili et al., 2021).

Additionally, operational measures such as hull and propeller cleaning, regular maintenance, optimized passage planning, and the use of weather routing strategies can enhance both EE by up to 5 % and reduce URN by up to 5 dB in commercial vessels (Baudin and Mumm, 2015; Vard Marine Report, 2023). These improvements can be achieved without imposing significant additional costs on shipowners, creating a mutually beneficial arrangement for all stakeholders involved (Vakili et al., 2024).

5. Discussion and conclusions

To overcome the barriers to decarbonization and the reduction of URN from commercial vessels, a holistic, systematic, and trans-disciplinary approach involving the engagement of all stakeholders must be considered. It is seen that it is worth considering the relationship between initiatives aimed at improving ship EE and mitigating URN emissions. As the maritime industry strives to adhere to the IMO revised GHG strategy, efforts are underway to identify effective strategies for reducing GHG emissions and transitioning towards a zero-emission sector. This involves modernizing and rejuvenating aging vessel fleets, as well as adopting carbon-neutral fuels, all amidst a landscape of evolving green technologies and improving energy efficiency (Vakili et al., 2024).

Adding to the complexity of this endeavour is the prolonged lifespan

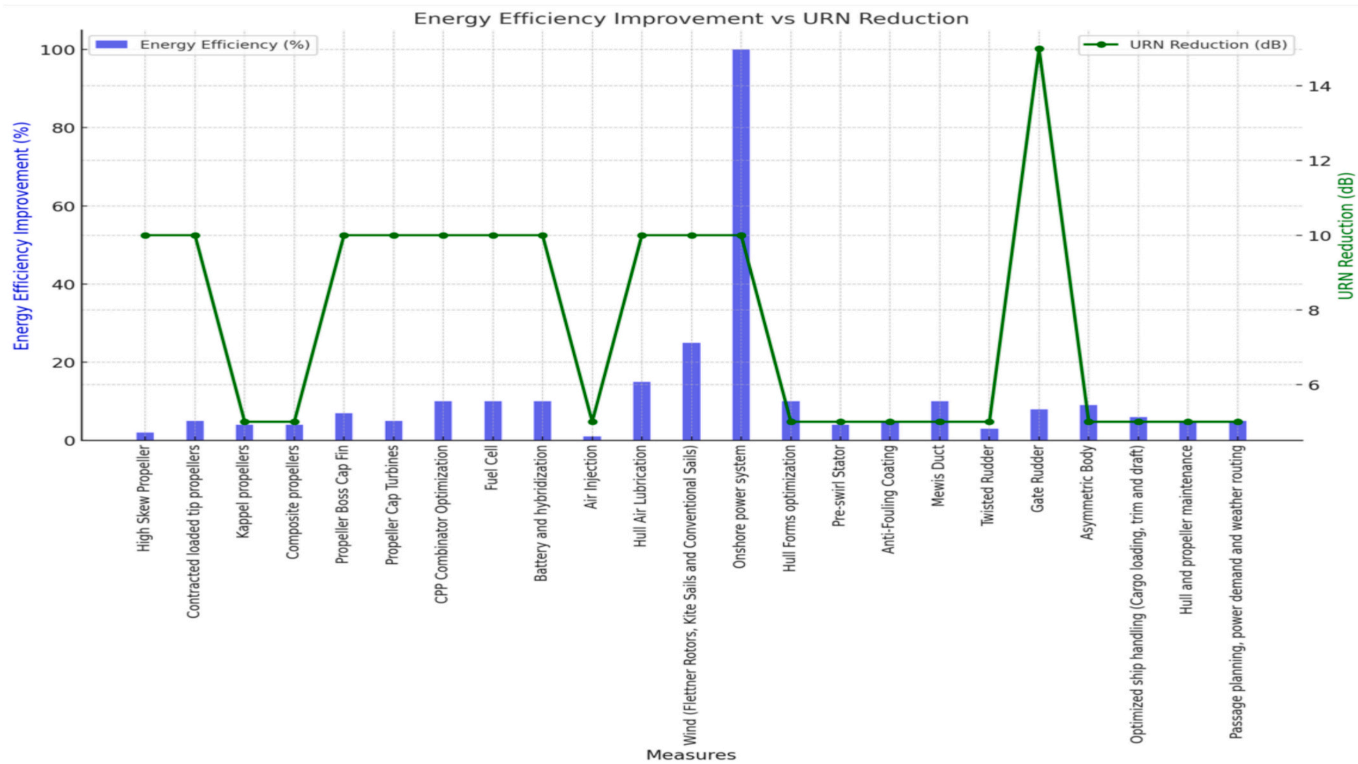

Fig. 5. Energy efficiency improvement versus URN reduction.

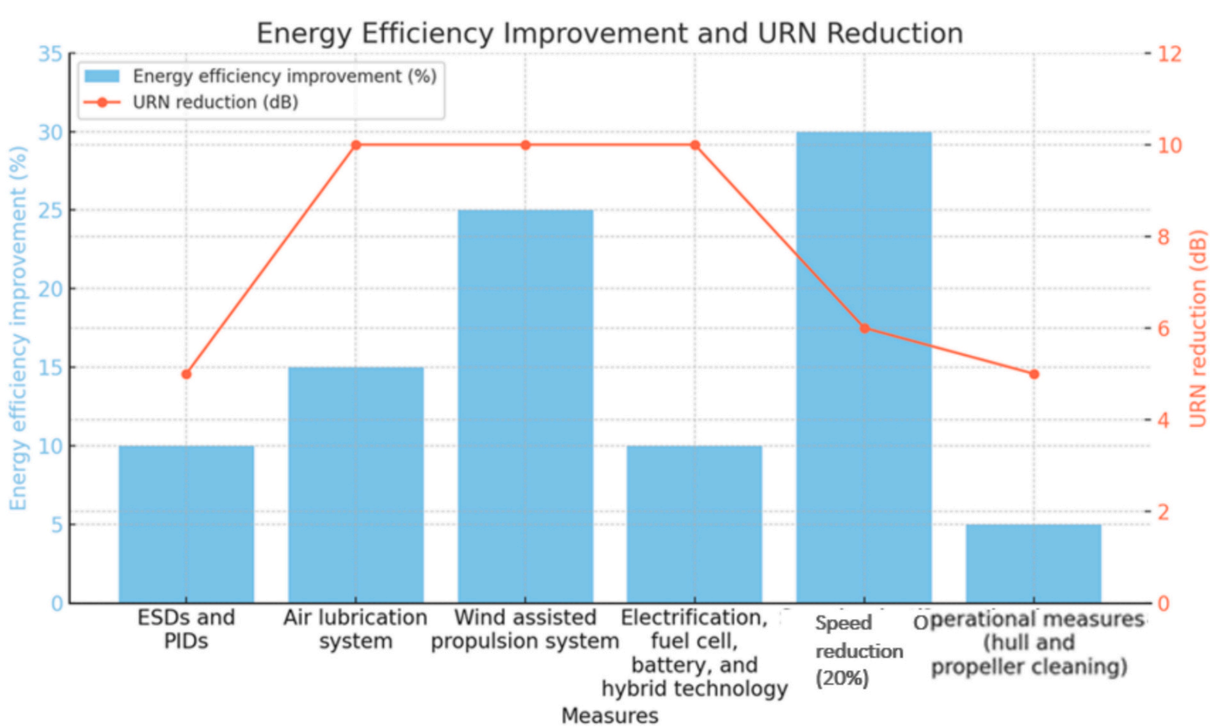

Fig. 6. Enhancing Energy Efficiency Measures to Reduce URN from Commercial Ships.

of ships, where some vessels are too old for retrofitting yet too young for scrapping (UNCTAD, 2023). Recognizing the absence of a "silver bullet" and "one size fit all" solution for decarbonizing the maritime sector, a diverse range of measures shows significant potential for achieving substantial emissions reductions. These measures include adopting carbon-neutral fuels and improving EE through measures like speed reduction and logistics optimization (DNV, 2022, 2024).

While carbon-neutral fuels are pivotal in decarbonizing the shipping industry, interdisciplinary barriers associated with their utilization have led the industry to pursue alternative measures. Considering the aging vessel fleet, forthcoming stringent requirements like the Carbon Intensity Indicator, and the anticipated high costs of alternative fuels, the study anticipates a rising trend of vessels implementing EE measures to align with the IMO's revised GHG strategy targets (Vakili et al., 2024, 2025).

With the reduction of GHG emissions becoming a primary concern for the shipping industry and URN emerging as another negative environmental impact of shipping, there is worth in preferring those solutions that both reduce URN and improve EE. Studies indicate that the majority of EE measures have the potential to decrease URN emissions from ships (Vard Marine Report, 2023), thereby presenting a win-win situation for shipowners as long as ships remain safe (Vakili et al., 2023).

Strategies such as speed reduction, wind-assisted propulsion, PIDs, ESDs, and air lubrication systems will all play crucial roles in achieving the IMO GHG reduction strategy (DNV, 2023; Vakili et al., 2024). Furthermore, as the maritime sector transitions towards vessel electrification, the adoption of fuel cells, batteries, or hybrid technologies, especially in short sea shipping, holds significant promise for improving EE and accelerating progress in alignment with the IMO's GHG reduction strategy (Vakili and Ölçer, 2023).

There is a correlation between the adoption of EE strategies and the reduction of URN. Speed reduction can reduce GHG emissions and URN from commercial vessels. However, ship economic viability can be maintained with such a drop in vessel speed is a key challenge.[10] Systems that reduce the power needed to propel the ship such as wind-assisted propulsion system and air lubrication system both show potential for reduction of GHG emissions, as well as URN reduction of up to 14 dB and 10 dB, respectively (Vard Marine Report, 2023; MEPC, 80). In addition, operational measures such as vessel hull and propeller cleaning and maintenance, optimizing vessel handling, improved passage planning, and utilizing weather routing strategies, provide opportunities to improve both EE and URN reduction in commercial vessels (Vakili et al., 2020b). Importantly, these measures do not entail significant additional costs for shipowners, establishing a mutually beneficial arrangement for all stakeholders involved.

While there is a projected increase in ambient noise of approximately 3 dB per decade globally,[11] projections indicate that transport activity could see a surge to an annual growth rate of approximately 1.13 % to 2.34 %. By 2033, to achieve the targeted 3 dB reduction proposed by Okeanos, an average reduction of 4 dB per ship in source level would be necessary and this would be 11.38 dB per ship in source level for 2050. Despite a worst-case scenario in ambient noise levels by 2050, the study posits that the 32 % contribution from EE measures could counteract the impact of seaborne trade growth, effectively mitigating ambient noise even in challenging scenarios.

It is important to underscore the importance of focusing on the deep sea for more precise predictions of URN on a global scale. The variation in low-frequency ocean sound increase across different regions cautions against generalizing about uniformly escalating low-frequency sound levels worldwide. Additionally, the coastal enhancement effect[12] (Ross, 1993) needs consideration when examining factors influencing ambient noise, as it amplifies URN from coastal sources, making them audible in the deep ocean. Considering that the majority of coastal vessels are not regulated by the IMO, it is crucial for governments to implement regulations for coastal shipping to address both GHG emissions and URN reduction. Additionally, incentive measures provided by ports[13] can play a vital role in accelerating the transition towards cleaner and quieter oceans (Vakili et al., 2020a, 2020b).

In summary, enhancing EE is pivotal in aligning with the revised GHG strategy outlined by the IMO. The implementation of EE measures is expected to result in quieter vessels compared to conventional ones, as most of these measures have the potential to reduce URN from commercial vessels, thereby contributing to overall URN reduction. Vessel owners have the opportunity to improve efficiency in accordance with the IMO's GHG strategy, enabling the pursuit of zero-emission shipping goals while concurrently mitigating URN, without incurring further additional costs. This scenario presents a mutually beneficial arrangement. However, it prompts the question of whether distinct regulatory frameworks and specific noise reduction targets remain necessary given the potential noise reduction achieved through GHG strategy adherence. Although the existence of such regulatory frameworks would more clearly highlight the benefits of GHG reduction strategies that also control URN.

The effectiveness of GHG emission regulations in reducing URN from commercial vessels hinges on the approach taken to achieve zero-emission shipping by 2050. While the use of carbon-neutral fuels may not significantly impact URN reduction, the greater role played by EE measures in the industry's decarbonization endeavours increases the likelihood of URN reduction from commercial vessels. Addressing this inquiry requires a comprehensive investigation to elucidate the intricate relationship between EE measures and compliance with the IMO's GHG strategy, particularly regarding their actual influence on underwater noise reduction within the domain of commercial vessels.

CRediT authorship contribution statement

Seyedvahid Vakili: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul White:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Stephen Turnock:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This study provides a summary of a comprehensive project funded by the International Chamber of Shipping (ICS), with the full report presented at the 10th meeting of the IMO's Sub-Committee on Ship Design and Construction (SDC).

[10] Speed reduction can be considered a "win-win" solution in both environmental and economic terms (Zhen et al., 2020). However, when opting for speed reduction, the economic viability of the ship remains a key challenge that must be carefully assessed, requiring further investigation for each scenario. Moreover, a relationship exists between ship speed, fuel prices, and freight rates (Vakili et al., 2023), highlighting a trade-off between speed and fuel costs. As fuel costs rise, the optimal operating speed decreases, reinforcing the "win-win" scenario. However, this advantage holds only if all ship operators face increased fuel costs. Those who do not incur higher fuel expenses will have a competitive edge, as they can transport goods faster at the same cost, capturing more trade (Molland, 2011).

[11] The trend in increasing the ambient noise of approximately 3 dB per decade is not consistent across all areas, with some regions experiencing a plateau or even a decrease in noise levels. Furthermore, discrepancies in the forecasts of underwater noise levels in different regions necessitate nonlinear models that can accommodate long-term cyclic dynamics (Vakili et al., 2024).

[12] The coastal enhancement effect is a mechanism whereby sounds from near-surface sources can be propagated to a distant receiver by low-loss, deep channel, near-horizontal refractive paths.

[13] Ports play a crucial role in controlling, monitoring, and mitigating URN from commercial vessels, through the use of appropriate technologies such as onshore power system and the adoption of policy measures, such as speed reduction and incentive schedules (Vakili et al., 2020a, 2020b).

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Data availability

The data that has been used is confidential.

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