European Maritime Safety Agency

HULL AIR LUBRICATION SYSTEMS STUDY

STUDIES ON PROMISING TECHNOLOGIES & ALTERNATIVE FUELS FOR SUSTAINABLE SHIPPING

EMSA

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Document History

Version	Date	Changes
1.0	11/02/2026	Final Study

Executive Summary

This study presents a comprehensive assessment of Hull Air Lubrication Systems (ALS) for maritime shipping, focusing on their technological maturity, economic viability, regulatory context, and safety implications. The study presents ALS as an interesting yet still maturing technology. However, the Shipping Industry still needs to have a clear picture of how systems perform under service conditions. Continued research, full-scale trials, and collaborative efforts among shipbuilders, vendors, regulators, and classification societies are essential to fully exploit the potential of ALS in sustainable maritime operations.

Overview of ALS

ALS technologies aim to reduce a ship's frictional resistance by injecting air into the turbulent water boundary layer beneath the hull, thereby reducing frictional drag and lowering the ship's power demand, fuel consumption, and, consequently, greenhouse gas (GHG) emissions.

ALS systems employ various design philosophies and technologies, and flow topologies such as air-layer, bubble, or cavity drag-reduction are employed. ALS can be active, using compressors, or passive, using venturi effects for injecting the air. Air injection can range from microbubble to air-water mixture injection systems, each one with its own advantages and limitations.

The study includes insights from interviews and workshops with these stakeholders, providing a comprehensive view of the technology's current state and market readiness.

Sustainability

ALS is an emerging technology for reducing hull resistance and improving fuel efficiency. By lowering fuel consumption, ALS directly reduces GHG-emissions and other pollutants, including NO_x, SO_x, and particulate matter.

Case studies were conducted on selected vessels operating in both coastal and deep-sea conditions. The findings indicate potential fuel savings up to 4%, depending on key factors outlined in Section 2.3 Suitability. Beyond emissions reduction, ALS may also decrease underwater radiated noise, supporting marine ecosystem protection and broader sustainability goals.

Performance prediction remains complex for systems with two-phase flow (an air-water mixture next to the hull), as the two-phase flow dynamics cannot be predicted by traditional scaled model tests and are not yet practical with state-of-the-art computational fluid dynamics (CFD) methods, owing to the lack of reliable full-scale data for verification. It remains challenging to determine the realistic savings potential during actual vessel operations, which directly influences the estimated GHG reduction. To address this uncertainty, further investigation based on long-term in-service measurements across various weather conditions and ship types is necessary to establish credible and representative GHG reduction figures for each system.

Suitability

ALS reduce hull resistance through strategic air release, with key factors influencing their performance as follows:

- Lubricated area: drag reduction is most effective when air is released in hydrodynamically favourable areas, particularly the flat bottom forward (FoB).
- Operational drafts: ALS performance is sensitive to the draft. Calibration must be vessel-specific and account for expected operational drafts.
- Utilization: the more frequently a vessel operates, the greater the potential cumulative fuel and emission savings achievable with ALS.
- Compressor power for ALS: active ALS typically requires 3–5% of propulsion power, while passive systems eliminate this need. Integration strategies vary by propulsion type, and existing machinery can often support ALS with minimal modifications.
- Weather Sensitivity: performance may decline in rough seas; adaptive control and real-time monitoring are being explored to maintain effectiveness.

Availability

By July 2025, more than 300 vessels were in service equipped with ALS, either installed during construction or retrofitted, and a similar number of ships on order were equipped with ALS installations. The installation of ALS is currently dominated by LNG carriers and container ships, with cruise ships emerging as the third-largest segment. There are various vendors for ALS for both newbuilds and retrofits, offering these systems to shipyards worldwide.

Although ALS operates on a common principle, variations exist, including Active ALS, Passive ALS, and Air Cavity Systems (ACS). Active ALS is considered at TRL (technology readiness level) 8–9 due to widespread deployment, whereas Passive ALS and ACS remain at TRL 5–7 because of limited market presence.

Techno-Economic Aspects

The technical analysis indicates that ALS are feasible for nearly the entire global fleet, with approximately 99% of vessels technically capable of accommodating ALS and achieving net power gains. ALS is expected to operate effectively at both laden and ballast drafts for about 78% of vessels, and at ballast draft only for around 20%. Just for 1% of vessels are considered technically unsuitable.

Effectiveness varies by ship type. ALS performs well across all drafts for 90% of container ships and 73% of bulk carriers, but only 22% of tankers, underscoring the need for draft-specific assessments. Net power gains are higher when compressor electrical power is supplied by a shaft generator, while auxiliary diesel generators reduce the efficiency gains due to their higher specific fuel consumption. Increasing service speed (+10% or +20%) slightly increases feasibility.

Across the dataset of 9,329 vessels, technically feasible installations could reduce fuel consumption by 1.1 million tons per year, equivalent to 3.5 million tons of CO_2, with savings increasing at higher operating speeds.

Economically, ALS viability is highly sensitive to fuel prices, operating area, and sea conditions, with retrofits being less attractive than newbuilds due to higher CAPEX and OPEX. Depending on the fuel price scenario and operational area, the share of economically feasible newbuilds ranges from 5 to 63%, and for retrofits from 1 to 42%, with feasibility improving significantly as fuel prices rise.

ALS is most cost-effective for newbuilds with shaft generators and for ships with low operating drafts, such as LNG carriers, gas carriers, and RoRo/cruise vessels. Smaller ship classes (Handysize tankers/bulkers, Multi-Purpose carriers (MPP), sub-3000 TEU container ships) also show potential. ALS is generally less suitable for high-draft vessels such as large bulk carriers, tankers, and big container ships.

Economic success strongly depends on vessel operational profiles, sea areas, and wave height conditions. Therefore, installation decisions must be made on a case-by-case basis, considering technical suitability, operational conditions, and fuel price scenarios.

Regulations

The IMO’s Net-Zero Framework (NZF) governing maritime GHG emissions may have a significant transformational impact on shipping. The NZF aims at introducing a global marine fuel standard and a two-tier GHG-intensity pricing mechanism, requiring gradual GHG fuel intensity (GFI) reductions and incentivizing zero-emission technologies. The fuel standard mandates a gradual reduction in the annual GFI of ships, calculated on a well-to-wake basis. Use of ALS is not expected to influence a vessel’s GFI, as it does not alter the type of fuel or energy used by the vessel. ALS can reduce a vessel's fuel consumption, which may eventually result in reduced compliance costs.

The Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) are key IMO measures to promote energy efficiency in new and existing ships. ALS is classified as a Category B-1 technology under MEPC.1/Circ.896, which provides guidance on incorporating innovative technologies into EEDI and EEXI calculations. While the circular outlines preliminary and final verification procedures for a vessel with ALS, reliable standardized methods are not available in the industry for extrapolating sea trial data to EEDI conditions. The International Organization for Standardization (ISO) has developed standards such as ISO 15016 and ISO 19030, which provide methodologies for assessing ship speed-power performance and monitoring hull and propeller efficiency. Similarly, the International Towing Tank Conference (ITTC) guidelines support sea trial analysis. Neither ISO nor ITTC have provisions for extrapolating results from sea trials to the EEDI condition for vessels with ALS.

In the EU, the Fit for 55 package extended the EU ETS to maritime transport from January 2024, requiring ships over 5,000 GT to report CO_2 emissions and surrender allowances. If ALS can reduce vessel fuel consumption, it reduces GHG emissions and the number of required Allowances. The FuelEU Maritime Regulation (effective January 2025) targets onboard energy GHG intensity; ALS does not affect fuel type consumption as it is considered as an energy efficiency measure which are outside the scope of the Fuel EU Regulation (Recital 22) and they are not foreseen to be included. On the contrary, wind assisted propulsion System (WAPS) is considered as a substitute source of energy and not as an energy efficiency measure, that’s why Fuel EU Regulation for WAPS foresees a reward factor for this technology and not for the ALS.

Risk Assessment

ALS technology mainly uses existing marine equipment and introduces no fundamentally new active components, so it does not create new operational safety scenarios. Integration into vessels and hull penetrations are already addressed by current rules and regulatory frameworks concerning hull strength and stability, from a structural and watertightness point of view.

Although there are some variations in ALS design, the fundamental principle remains the same and is applied in a similar manner regardless of the ship type, involving a thin layer of air on the flat bottom (FoB) Section of a vessel’s hull. In other words, this results in fewer design variations compared to other systems aimed at improving ship energy efficiency and decarbonization. The main issues with ALS concern operational performance, as well as noise and vibration from the compressors and pipes used in its operation.

However, a risk assessment was conducted to identify potential safety challenges that may have been overlooked as part of the study. The assessment found no significant risks associated with ALS; of the 15 hazards identified, only 4 were relevant to risk ranking, and none of these were considered high-risk items. One medium-risk hazard was identified: interference with the aft echo-sounder from the air layer, resulting in false depth readings and potentially leading to grounding/contact damage. However, this risk could be easily mitigated by avoiding the use of ALS in shallow waters or by relying on the fore echo-sounder for accurate readings. Essentially, ALS is intended for use in transit, i.e., shallow waters are most likely encountered when approaching a port, where the vessel is moving at lower speeds and is unlikely to be using ALS. This means the probability of this event occurring is very low.

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List of Abbreviations

Abbreviation	Definition
ABS	American Bureau of Shipping
ACS	Air Cavity System
ADR Trial	Actual Reduction Rate from Sea Trial
ALDR	Air Layer Drag Reduction
ALS	Air Lubrication System
ARU	Air Release Unit
BDR	Bubble Drag Reduction
BV	Bureau Veritas
CAPEX	Capital Expenditure
CBPP	Block Coefficient at Scantling Draft
CCS	China Classification Society
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
ClassNK	Nippon Kaiji Kyokai
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EMSA	European Maritime Safety Agency
EMP	Eulerian Multiphase
EPL	Engine Power Limitation
ETAALS	ALS Efficiency
ETAD	Total Propulsion Efficiency
EU ETS	European Union Emissions Trading System
FoB	Flat of Bottom
GFI	GHG Fuel Intensity
GHG	Greenhouse Gas
GPS	Global Positioning System
GWP100	Global Warming Potential over 100 years
HAZID	Hazard Identification
HYKAT	HSVA Cavitation Tunnel
HWO	Han Wha Ocean
IACS	International Association of Classification Societies
IAMCS	Integrated Automation and Monitoring Control System
IMO	International Maritime Organization
ISO	International Organization for Standardization
ITTC	International Towing Tank Conference
KR	Korean Register
LBP	Length Between Perpendiculars
LNG	Liquefied Natural Gas
LNGC	Liquefied Natural Gas Carrier
LOA	Length Overall

LPGC	Liquefied Petroleum Gas Carrier
LR	Lloyd's Register
MARIN	Maritime Research Institute Netherlands
MEPC	Marine Environment Protection Committee
MPV	Multi-Purpose Vessel
MRV	Monitoring, Reporting and Verification
NOx	Nitrogen Oxides
N_2O	Nitrous Oxide
OPEX	Operational Expenditure
PALS	Passive Air Lubrication System
RANS	Reynolds-Averaged Navier-Stokes
RINA	Registro Italiano Navale
RISE	Research Institutes of Sweden (Formerly SSPA)
PM	Particulate Matter
ROI	Return on Investment
RPM	Revolutions Per Minute
RoPax	Roll-on/Roll-off Passenger Vessel
RoRo	Roll-on/Roll-off vessel
RP	Recommended Practice
SALT	Symposium on Air Lubrication Technologies
SFOC	Specific Fuel Oil Consumption
SHI	Samsung Heavy Industries
SOx	Sulphur Oxides
TBL	Turbulent Boundary Layer
TEU	Twenty-foot Equivalent Unit
ULCV	Ultra Large Container Vessel
URN	Underwater Radiated Noise
VLCC	Very Large Crude Carrier
VLSFO	Very Low Sulphur Fuel Oil
VoF	Volume of Fluid
Vref	Reference Speed
WAPS	Wind-Assisted Propulsion System
ZNZ	Zero or Near-Zero Emission Technologies

1. Introduction

1.1 Background

Various air lubrication systems are available on the market. Some systems use air bubbles, others employ air sheets or layers, and some utilise air cavities to reduce the frictional resistance of a vessel. Some are active systems, for example, using air compressors to release air beneath a ship's hull, while others claim to be passive systems, meaning they do not require additional power to generate air lubrication.

For ease of reading, the abbreviation ALS is used for Air Lubrication Systems in the following, regardless of the working principles or system details outlined above.

1.2 Scope and Objectives

The study is the Specific Contract 2 under a framework contract signed with the European Maritime Safety Agency (EMSA) to explore promising technologies and alternative fuels for sustainable shipping. This particular study focuses on Hull Air Lubrication Systems (ALS), a technology designed to reduce hydrodynamic resistance and enhance fuel efficiency in maritime vessels.

The primary objective of the study is to conduct a comprehensive analysis of ALS technologies. This includes gathering and evaluating data through literature reviews, vendor and shipyard consultations, and performance assessments. The study also aims to examine the current regulatory and safety standards, identify any gaps, and propose improvements. A detailed safety assessment is conducted using hazard identification and risk analysis methods. The work is divided into three main tasks: technical and economic analysis, review of safety and environmental standards, and a safety assessment.

1.3 Acronym List

Refer to List of Abbreviations.

2. Use of Air Lubrication Systems in the shipping sector

ALSs are energy-efficiency technologies that aim to reduce friction between a vessel's hull and seawater by introducing air beneath the hull via a piping system. Since air has significantly lower viscosity and density than water, replacing the water in the boundary layer with an air layer or microbubbles reduces frictional drag and enables a vessel to use less propulsion power to achieve the same speed.

2.1 Basics on ship resistance

A vessel's resistance when moving through the water consists of multiple components; the two main components are the frictional resistance and the residual resistance. The residual resistance consists of several components, the most significant of which is wave-making resistance. Other components of residual resistance include eddy resistance, wave-breaking resistance, appendage resistance, and vessel air drag. For higher-speed displacement vessels, frictional resistance can be as low as 40% of total resistance, whereas for low-speed displacement vessels it is the dominant factor, accounting for up to 80% of total resistance.

The diagrams below show the speed-power characteristics and the percentage of frictional resistance for a higher speed displacement vessel, as illustrated in Figure 2-1, where the frictional resistance is around 60% at 19 knots and decreases to about 45% at 23 knots. For a low-speed displacement vessel, as illustrated in Figure 2-2 , the frictional resistance is approximately 80% at 10 knots and about 75% at 16 knots.

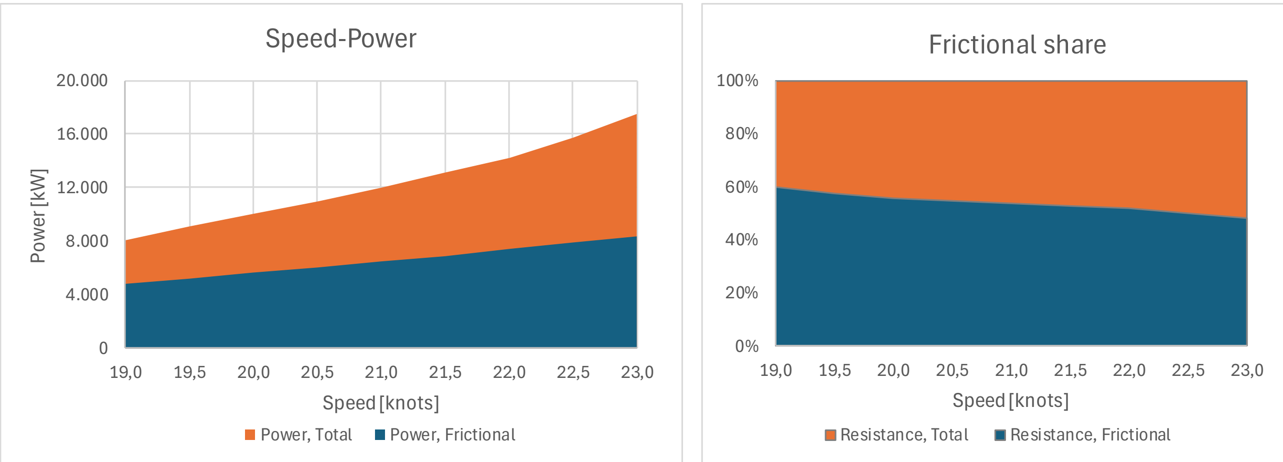


Figure 2-1 Higher speed displacement vessel – Speed-power and Frictional share of total resistance (Source: DNV)

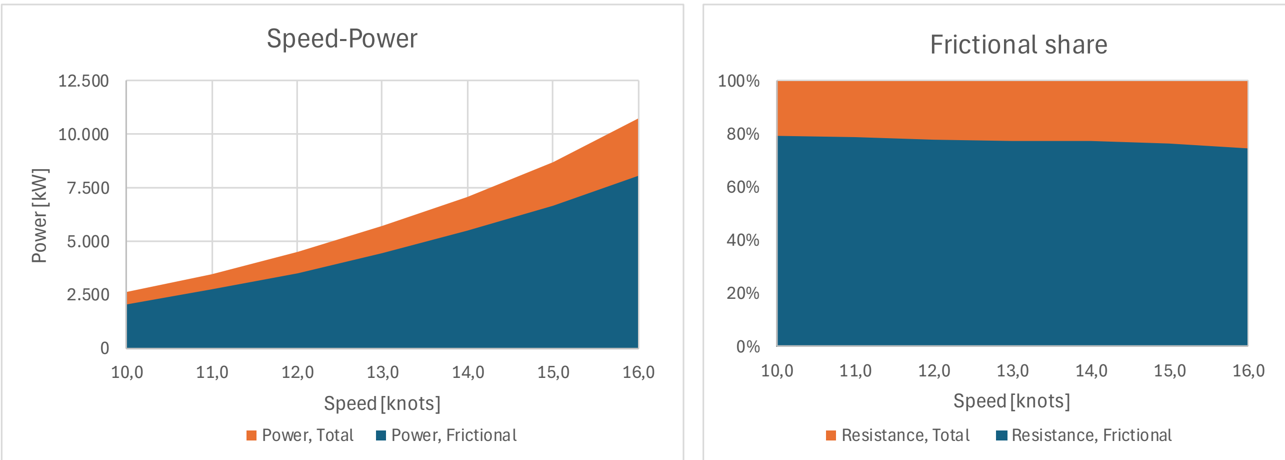


Figure 2-2 Low speed displacement vessel – Speed-power and Frictional share of total resistance (Source: DNV)

2.2 Basics of air lubrication

The frictional resistance of a ship hull moving through the water depends on the wetted surface area of a ship. Air lubrication technology can decrease this resistance for vessels. Since this technology does not significantly alter the hull shape, the remaining resistance stays nearly the same, and only the frictional resistance is reduced.

Bubble-induced skin-friction drag reduction (Elbing et al, 2008)

Elbing et al. report that skin-friction reduction has been studied for many decades, with research showing that injecting gas (air) into the near-wall region of a turbulent boundary layer can significantly decrease drag. Laboratory experiments have shown local drag reductions exceeding 80%, attracting significant research interest. Elbing specifically examined two mechanisms on a flat plate: bubble drag reduction (BDR) and air-layer drag reduction (ALDR). The study identifies three regimes of drag reduction as Figure 2-3: an initial BDR regime where drag reduction increases almost linearly with air injection from zero to about 20%; a transitional regime with a much steeper slope, achieving reductions between 20% and 80%; and finally, an ALDR regime where a stable air layer forms and maximum drag reduction is reached.

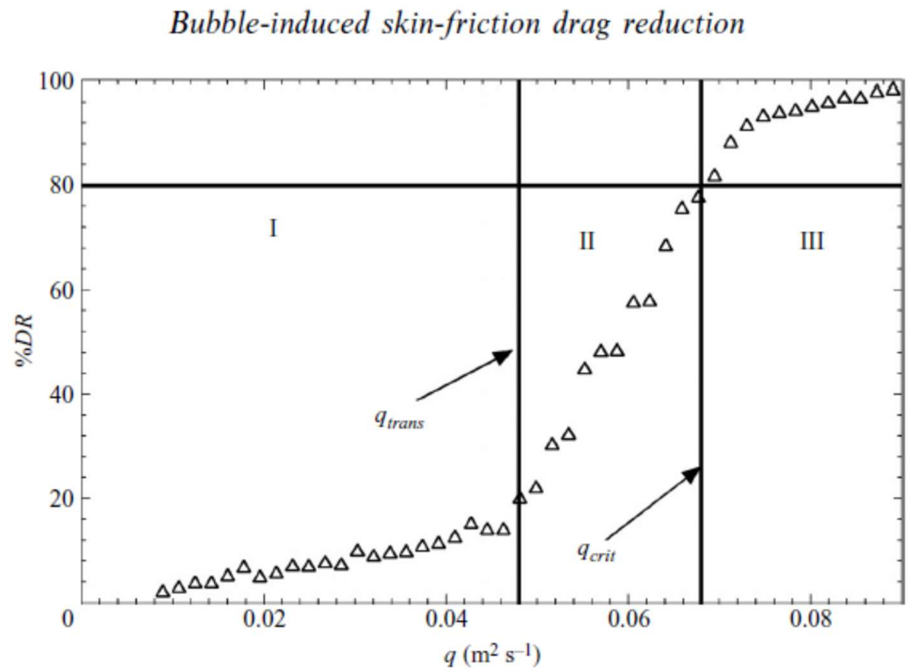
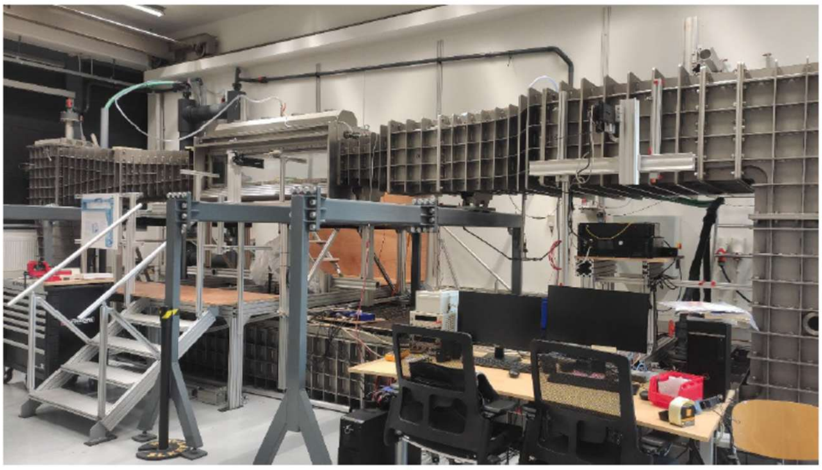


Figure 2-3 The three regimes of bubble drag reduction and air-layer drag reduction (Source: Elbing et al, 2008)

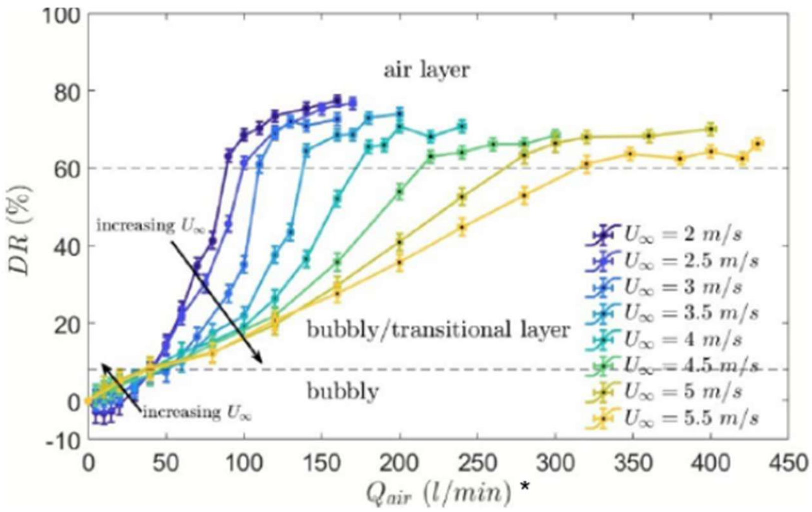
Regime transitions in drag reduction by air lubrication (Nikolaidou, 2025)

Friction drag reduction can be achieved by actively injecting air into the viscous sublayer of the turbulent boundary layer beneath a ship's hull. Depending on factors such as ship speed, airflow rate, and injector geometry, three regimes may form: bubbly, transitional, or air-layer, with the air-layer regime being the most effective for drag reduction. However, maintaining this regime under real-world conditions is challenging, as the system can revert to other regimes.

In an experimental study by Nikolaidou et al. (SALT 2025, Appendix B), drag-reduction measurements across the defined parameter space confirmed the existence of three regimes, each with distinct morphological characteristics. The bubbly regime occurs at low air flow rates and is characterized by dispersed bubbles, which at low freestream velocities may increase drag or provide minimal reduction. The transitional regime features both bubbles and air patches, but increasing the freestream velocity tends to lower drag reduction levels. The air layer regime begins at approximately 60% drag reduction, beyond which further increases in air flow rate have little effect. Combining these measurements with air-phase imaging provided insights into the physical mechanisms of drag reduction. Image processing revealed bubble size, non-wetted area, and air layer thickness, showing that higher drag reduction at increased freestream velocities in the bubbly regime is linked to smaller bubbles organized in multiple layers away from the wall, unlike the single-layer formation of larger bubbles at low inflow water speed ($U\infty$) as shown in Figure 2-4.



(a)



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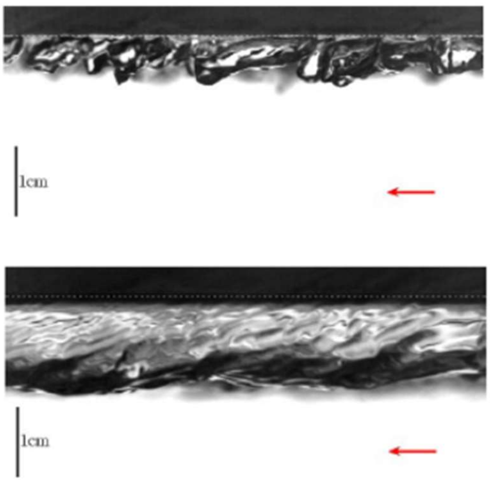


(c)

*) *Qair (l/min): The amount of air injected into the water was not normalised by the width of the injection area during the test*

Figure 2-4 (a) The Multiphase Flow Tunnel. Flow in the test Section is from right to left. (b) Drag reduction measurements for a wide range of velocities and air flow rates. (c) Characteristic instantaneous image of the bubble regime (top) and the air layer regime (bottom), shown in the streamwise–wall-normal (side) view. (Source: Nikolaidou SALT 2025 conference)

2.3 Overview of Air Lubrication Systems

Air lubrication is a technique used to reduce resistance and enhance ship performance. There are various ALS, which can be categorised into two types. The first type involves creating stable air cavities that effectively reduce the hull's wetted surface area (ACS, Air Cavity System). The second type relies on locally reducing density through dispersed air injection, forming either an air layer or numerous bubbles near the hull. These systems operate based on fundamentally different mechanisms.

There are active and passive forms of ALS. Active systems use air compressors to generate the airflow for injecting air bubbles into the boundary layer. Passive systems exploit the venturi effect to draw air from deck level, mixing it with incoming seawater and injecting an air-water mixture into the boundary layer.

The various active systems utilise different units for injecting air into the boundary layer. The larger “air release units” (ARU) are sometimes referred to as “cavities,” but this does not mean they constitute an “air cavity system.” Smaller units are referred to as “air release units,” “air dispense units,” or “air injector nozzles,” depending on the vendor. An array of units is sometimes referred to as an “air distribution band.” In this study, the term “air release units (ARU)” is used to refer to all air injection systems for simplicity.

The air release units are arranged in a V-shaped array following the FoB in the forebody, or in the form of a transverse array in an I-shaped array. Some vendors use a single array; others use two or more arrays distributed along the length of the bottom.

The reduction in the frictional resistance of the hull (mainly at the bottom of the ship) affects the wake field of a ship and, thus, the inflow to the propeller and, finally, the propulsive efficiency.

The net power savings of an ALS result from: a) the reduction in the frictional resistance of a hull and the effect on the propulsion efficiency, visible in the shaft power savings, and b) subtracting the additional electric power demand of the air compressors of the system. Figure 2-5 and Figure 2-6 illustrate the total power, gross power gains, compressor power, and net power gains for two different loading conditions of an LR tanker. These figures highlight that the additional electrical power demand of the system’s air compressors and the gross power gains from the system are key factors influencing the overall net power gains.

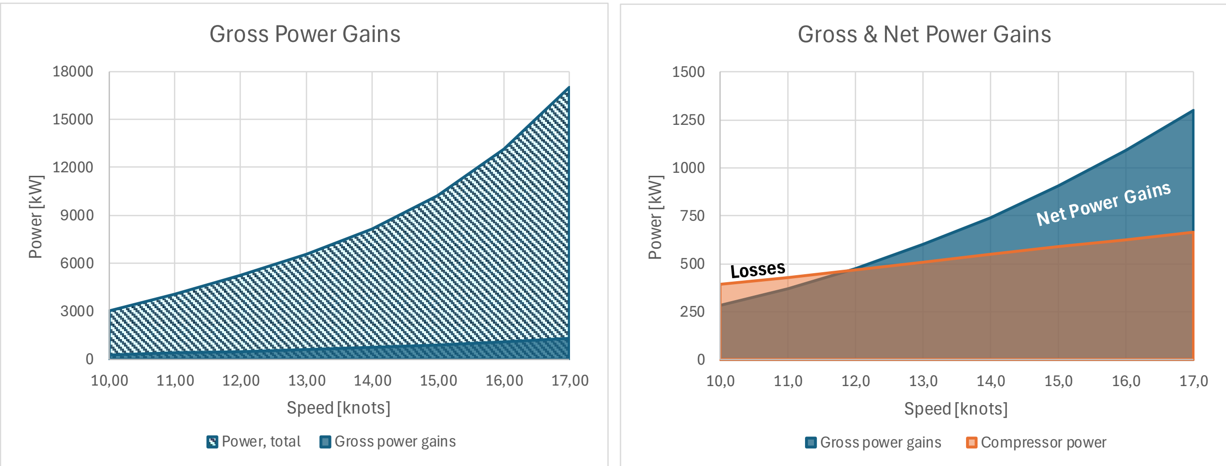


Figure 2-5 Total power, gross power gains, compressor power and net power gains for LR-Tanker, Laden condition (Source: DNV)

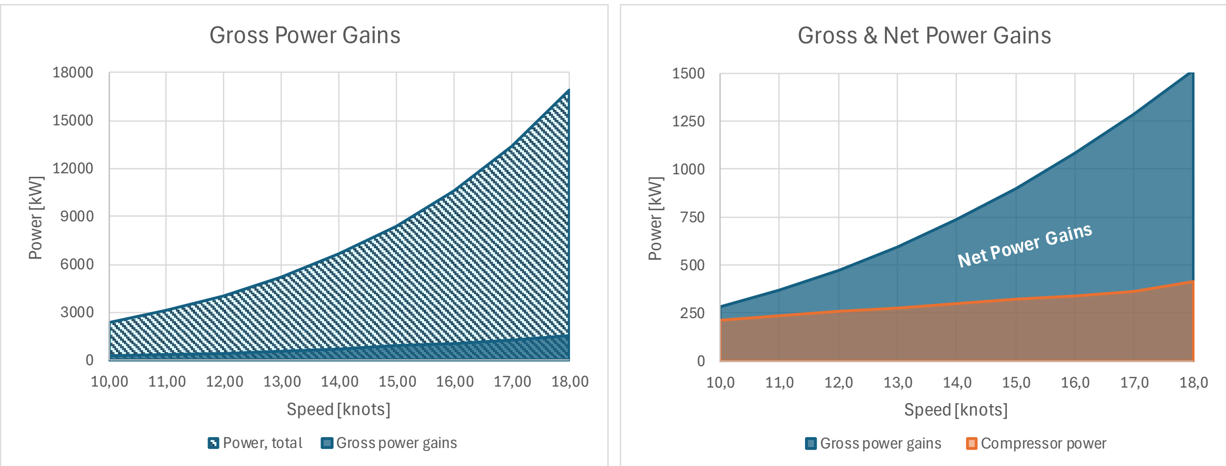


Figure 2-6 Total power, gross power gains, compressor power and net power gains for LR-Tanker, Ballast condition (Source: DNV)

Depending on how the electric power for the air compressors is generated (by auxiliary diesel generators or by a shaft generator driven by the main engine), the savings in fuel consumption may differ from the power savings.

Performance prediction of ships using ALS, based on both experimental fluid dynamics (EFD) and computational fluid dynamics (CFD), suffers from significant scale effects, and in CFD, turbulence models do not capture the physics of bubbly flow. The physical or numerical modelling of complex 2-phase flow and its extrapolation to full-scale ships remains not fully understood, especially regarding the correlation of more advanced Eulerian Multiphase simulations, which lack reliable full-scale measurements and verified results. Details on the performance prediction can be found in 2.4.1 GHG Reduction .

2.3.1 Air Cavity System

The working principle of ACS is to reduce the wetted area on FoB by creating stable air cavities. These cavities form by injecting air beneath the bottom behind a small vertical plate that separates the water flow. Figure 2-7 illustrates ACS. The injected air creates a thin air cavity that must be confined laterally by longitudinal skegs to prevent air from escaping. The system aims to reduce water resistance, particularly for ships with low Froude numbers. The system introduces additional electrical load due to the operation of compressors. The compressors only need to overcome the hydrostatic pressure due to the draught of the vessel. Details of an ALC are provided in Appendix A.

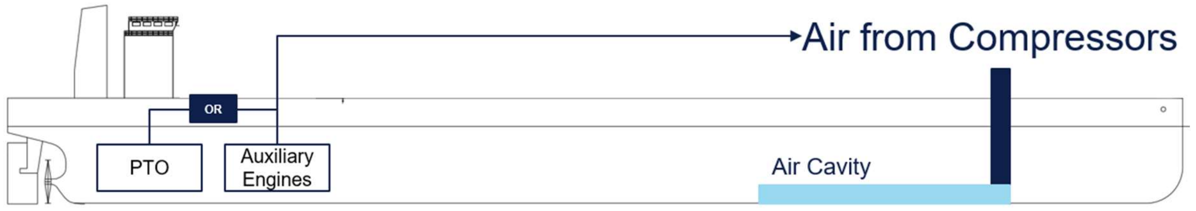


Figure 2-7 Concept of ACS (Source: DNV)

2.3.2 Air Lubrication Systems

Unlike ACS, a method that attempts to avoid contact between hull and water, ALS provide a constant flow of air bubbles to lubricate the FoB of a ship’s hull. Reducing the wetted surface of a vessel by replacing the contact with air or by injecting air into the turbulent boundary layer (the area between the stationary and moving water) thereby alters the viscosity properties of the air-water mixture close to the hull, decreasing the hull's frictional resistance, as illustrated in Figure 2-8.

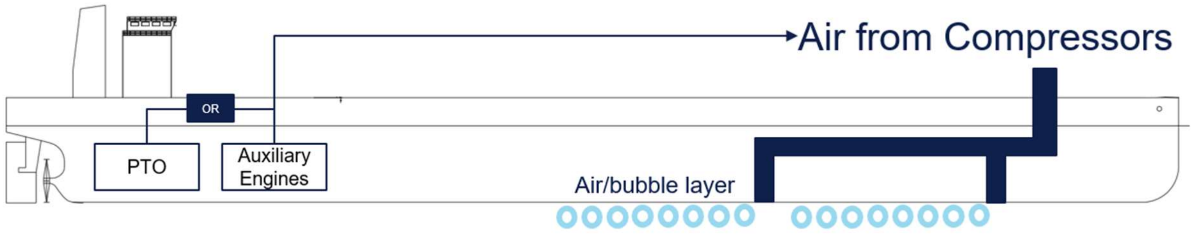


Figure 2-8 Concept of active ALS (Source: DNV)

The system typically consists of Air Release Units (ARUs) installed along the bottom plating, connected to compressors and distribution piping. Different vendors use various ARU arrangements, but the fundamental objective remains the same, which is to achieve uniform air distribution and maintain a stable air or bubble layer beneath the hull. The system introduces additional electrical load due to the operation of compressors. This energy demand is a critical factor in evaluating net power savings. Gross power gains must offset the compressor power consumption and change in propulsive efficiency to achieve a positive net benefit.

The ALS optimization is generally achieved through CFD simulations, model and full-scale testing in cavitation tunnels, and full-scale sea trials. These methods help refine ARU geometry and positioning to minimize energy losses, ensure the stability of the air or bubble layer, and reduce the risk of uneven air coverage. The additional resistance caused by ARUs when the ALS is not in operation is generally reported to be in the range of 0.5% to 1.0%, depending on the case. Details of design considerations for a vessel with ALSs can be referred to Section 2.3.4 and Appendix A.

2.3.3 Passive Air Lubrication Systems

Passive ALS does not require compressors or mechanical air injection. Instead of actively injecting air, passive systems rely on the venturi effect, a phenomenon where the vessel's forward motion creates a pressure differential that draws air from the deck level, as illustrated in Figure 2-9. This air is then mixed with incoming seawater and introduced into the boundary layer along the hull bottom. The resulting air-water mixture forms a lubricating layer that reduces the wetted surface area and frictional drag. The added resistance caused by the water inlets, venturis and system outlets is claimed to be in the order of 0.3-0.7%. Details of a passive ALS are provided in Appendix A (interview with ALS vendors and Basins).

Figure 2-9 Concept of passive ALS (Source: DNV)

2.3.4 Design considerations

Different ALS have unique design considerations that must be carefully managed to prevent operational failure. Additionally, operational strategies are crucial in maximising the performance of the ALS. This Section discusses the design and operational aspects of ALS to optimise its performance.

ARUs are positioned on the FoB of a vessel, and different vendors may have various arrangements of these units, as illustrated in Figure 2-10, Figure 2-11, and Figure 2-12. Although specific configurations differ, the core aim remains the same: to ensure even air distribution and a stable formation of an air layer or bubble stream beneath the hull. Optimization of ARUs is typically achieved through a combination of CFD, cavitation tunnel testing, and full-scale trials. These methods help refine the shape and placement of ARUs to minimize energy loss, enhance air layer stability, and reduce the added resistance when the system is inactive. Vendors also consider operational factors, such as ship speed, draft, and hull geometry, to tailor ARU designs to specific vessel types.

The added resistance caused by ARUs when the ALS is not in operation is generally reported to be minimal. This is attributed to compact and low-profile designs that integrate seamlessly with the hull. CFD simulations are used to estimate drag penalties from the ARUs. Some vendors have performed 1:1 scale model tests with one ARU at full-scale flow velocities. This is believed to be the most accurate method for verifying the additional drag caused by the ARUs. Other vendors have conducted comparative trials between sister ships with and without ALS to confirm negligible differences in resistance, but, based on our experience, these are less accurate than a 1:1 scale model test. The strategic placement of ARUs in low-pressure zones and alignment with flow lines further contribute to minimizing hydrodynamic penalties.

In the case of the ACS, an additional structure at the bottom of a vessel, called the air chamber, is required, which naturally increases the wetted surface and thus the friction resistance when the ACS is not in operation. However, no vendors of air-cavity systems have specified the additional drag their systems impose.

Figure 2-10 Multi-array of OceanGlide ALS (Source: Alfa Laval)

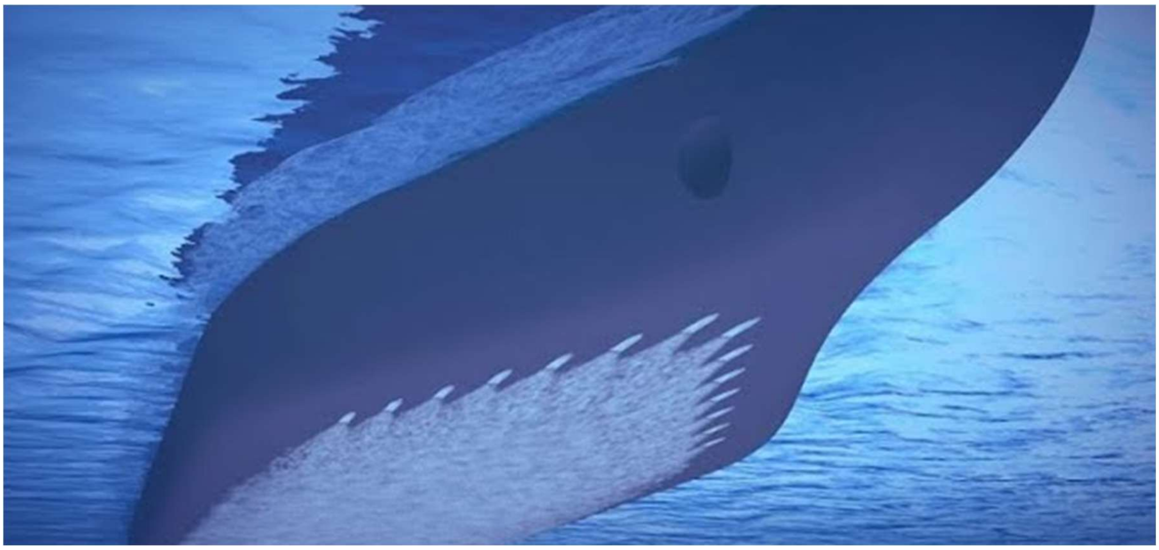


Figure 2-11 Single and V-shaped array of ALS (Source: Silverstream)

Figure 2-12 Single and I-shape array of SAVER Air ALS (Source: Samsung Heavy Industries (SHI))

Preventing air from entering sea chests is a critical design consideration for ALS systems. Vendors employ a range of structural and operational solutions to mitigate this risk. Common approaches include modifying sea chest geometry, such as increasing internal volume, repositioning inlets, extending suction pipes, and adding baffles and air vent holes. CFD simulations are widely used to model bubble trajectories and assess the effectiveness of these modifications. Hanwha Ocean, for instance, validated its sea chest design through full-scale CFD and operational trials, confirming that air bubbles did not interfere with seawater intake systems. In cases where sea chest placement cannot be altered, deflectors or water flow redirection techniques can be employed to shield the intake from bubble intrusion. Some vendors also suggest increasing sea chest vent pipe sizes to facilitate air removal. According to these vendors, such measures have proven effective in maintaining system integrity and preventing operational disruptions, as supported by operational feedback from vessels with ALS.

The interaction between the released air and the propeller remains an area of active research. Current research indicates that the reduction in frictional resistance caused by ALS also affects boundary-layer thickness and, consequently, both hull and rotational efficiency, thereby slightly decreasing propulsion efficiency.

Airflow rate optimisation for various ship speeds and drafts is approached by ALS vendors through a combination of full-scale trials, computational simulations, and empirical calibration. Most vendors conduct in-service trials in which the ALS system is activated and deactivated under different operational conditions to measure net power savings and identify the most effective airflow settings. These trials are often repeated for both ballast and laden drafts due to the absence of standardized scaling methods. CFD simulations are widely employed to model air distribution and flow behaviour, assisting vendors in determining the optimal air supply ratios across forward and aft release units and between individual units. Some vendors utilise correlation factors from prior deployments to enhance their models and calibrate the system for new vessels.

Control systems dynamically adjust airflow based on real-time vessel data, including speed, draft, trim, water temperature, and salinity. These systems may feature feedback loops and sensor-based monitoring to continuously optimize performance. In more advanced configurations, artificial intelligence is being explored to enable adaptive control that responds to environmental and operational changes. Passive systems using venturi-driven air-water mixing, where the flow rate is indirectly controlled by vessel motion and water flow, are controlled by adjusting water flow. All vendors acknowledge that scaling from model tests to full-scale remains a challenge, and limitations in sensor accuracy and environmental variability continue to complicate precise optimisation. Nonetheless, iterative testing and data-driven calibration remain the most reliable methods for achieving optimal airflow rates across diverse operating conditions.

There are challenges in CFD and model testing of ALS from limitations in accurately simulating and scaling the complex interactions between air and water at the hull interface. In CFD, conventional tools used in naval architecture struggle to resolve microbubbles and often produce unrealistic air entrainment at the hull-fluid boundary. Volume of Fluid (VoF) methods with practical mesh sizes, while commonly used, are not well-suited for capturing the thin air layers or bubble carpets that characterize ALS performance. Specialized two-phase CFD models are highly sensitive to numerical settings and can yield inconsistent results, making validation difficult without reliable full-scale data. Moreover, CFD simulations often require empirical inputs from model- or full-scale tests to adjust boundary-layer behaviour, thereby limiting their standalone predictive capability.

Model testing, particularly in towing tanks and water tunnels (or cavitation tunnels), faces its own set of challenges. Scaling results from model scale to full scale remain unresolved, particularly due to differences in Reynolds number and bubble behaviour. The ITTC procedures for skin friction drag reduction are scientifically sound but not practically applicable to commercial projects, as they require complex and costly multi-scale testing. Additionally, the physical generation of bubbles in model tests does not accurately replicate full-scale conditions, and the visual observations of air layers cannot be reliably quantified. These limitations make it difficult to extrapolate model-test results to actual performance, and vendors often rely on full-scale trials to validate the effectiveness of ALS. Overall, both CFD and model testing are essential but must be used in combination, with careful calibration against full-scale trials, to mitigate their respective limitations. Details for physical effects governing air-induced drag reduction and numerical methods can be found in Appendix B.

In recent years, ALS development has progressed through various stages of experimental investigation, requiring different approaches and facilities at different design stages to support different tasks in the development process. The overview below provides insights into these steps:

- Water tunnel (or cavitation tunnel) facilities generate a continuous water flow within a circuit. A testing object can be placed in a test Section, which typically has a rectangular or circular cross-Section of a certain length. A flat plate equipped with an air release unit can serve as a test object in such a facility. Depending on its design, it allows for either global or local shear force measurements on the test plate.

- An advantage of water tunnel facilities is their long measurement duration, enabling extended testing such as airflow optimisation and optical flow measurements. However, a problem with this type of facility in experiments with air lubrication can be air recirculation. This occurs when air injected into the test object cannot be properly separated from the water flow and continues to circulate in the loop. This leads to reduced visual accessibility, fluctuations in water flow velocity, variations in the actual air flow rate along the test object and decreased overall measurement accuracy. This negative phenomenon can be reduced by limiting the measurement time until the injected air returns to the measurement Section. Another option could be dedicated air separators built into the circuit. Water tunnel facilities can be used for concept studies, fundamental studies on drag reduction mechanisms, accurate global and/or local shear stress measurement, flow visualization, optical measurements, air flow optimizations, etc. Depending on the facility, tests can be performed at near- or full-scale speed and provide the required airflow rate to create and maintain air cavities.

- Towing tank tests with a ship model are typically used to assess resistance, propulsion, seakeeping, and manoeuvring performance of ships. Using scaling laws, the model test results are extrapolated to full scale. The frictional coefficient is calculated for both the model and full-scale cases. Because the ACS is an ALS based on wetted-area reduction, and air cavities scale with the Froude number, model-scale tests can be used to evaluate the performance of this part of the system in a towing tank. Self-propulsion model-scale tests provide some insight into the interaction between air lubrication and propulsors. It has been observed that the influence of air bubble flow on shear stress is strongly dependent on speed, making the evaluation of air bubble systems on a model scale difficult or even impossible.

- Full-scale tests allow evaluating the power or fuel consumption reductions achieved by air lubrication under real operating conditions. While earlier testing stages help develop the concept, understand fundamental principles, and optimize performance, the final step involves installing ALS on a vessel and verifying its effectiveness at full scale. Because environmental conditions significantly influence performance, special procedures are required to accurately assess improvements. Depending on time and accuracy requirements, testing can include dedicated sea trials, which provide the most reproducible results through double runs to normalize environmental effects but are limited to a single weather condition. A more practical approach is to evaluate performance during normal operations by switching ALS on and off, requiring no extra testing time. Long-term monitoring is another option, comparing performance before and after installation, though its accuracy depends heavily on other changes made to the vessel, data quality and environmental correction models. In addition to fuel savings, full-scale tests can examine side effects, including changes in onboard noise and vibration levels and in underwater radiated noise.

2.3.5 ALS basic principles conclusions

ALS represent a technology for reducing ship resistance and improving energy efficiency, with growing adoption across various vessel types. However, verifying and predicting performance remain difficult due to limitations in current analysis technologies, such as CFD and model tests, and the absence of reliable standardized methodologies. The net savings from ALS depend on balancing the reduction in frictional resistance with propulsion efficiency and the energy demand of compressors, which varies by vessel configuration and operational conditions.

Despite being categorized as near-mature, ALS require further refinement and validation, particularly in full-scale applications. Continued collaboration between vendors, research institutions, and classification societies is essential to address uncertainties and improve system reliability. The industry is developing standards for performance verification to support consistent, credible assessments of ALS effectiveness. ISO is developing sea-trial standards for ALS (ISO 25189). DNV has published their Recommended Practice DNV-RP-0695 “Performance of air lubrication systems”, focusing on long-term in-service measurements.

2.4 Sustainability

ALS are energy-efficiency measures designed to reduce the propulsion power required to move a ship through the water by decreasing hull frictional resistance. This results in lower fuel consumption for the same work, thereby reducing GHG emissions from the propulsion system. When achieving this goal, ALS will therefore have a positive impact on the IMO energy efficiency indexes and the EU Emissions Trading Scheme.

2.4.1 GHG Reduction Potential

Classification societies have received a number of verification reports from designers and shipyards for vessels with ALS for EEDI purposes, indicating significant savings during sea trials.

The verification reports on trial conditions indicate significant savings: large cruise vessels (~8% net power savings), LNGC's (~7% net power savings), and container vessels (2-3% net power savings), with most savings aligning with vendor expectations. Conversely, some owners of the same ship types and sizes have reported no savings from ALS at their ships in service.

In the operational phase, the ALS performance has been assessed for a cruise vessel, various LNGCs, and a combination carrier on behalf of owners, using in-service data supplied by them. The assessment showed lower savings than expected.

Based on feedback from shipowners and the experience gained from the aforementioned real cases, it became clear that the industry lacks a standard for conducting and assessing in-service performance tests with ALS. As a result, DNV developed and published the "RP for the Verification of ALS" in 2025, offering the industry a standardised procedure for evaluating ALS performance.

Based on this RP, some pilot projects have already been carried out, and the following savings have been verified:

- Container Vessel, no net power savings verified at laden conditions (several vessels)
- Bulk carrier, 5-6% net power savings verified at heavy ballast draught (almost level trim)
- RoRo (Roll on and Roll off) vessel, 2% net power savings verified at laden condition

With the container vessels, net savings could not be verified, as the vendor claimed that the operability of the air lubricating system suffered from air leakage in air piping system and valve failures[2].

Summarising the above, it can be stated that the shipping industry does not yet have a clear understanding of how systems perform under service conditions or whether some systems are more advantageous than others. To investigate this further, the study selected representative ship types, and their ALS performance is examined in both trial and service conditions in Section 2.4.2.

2.4.2 GHG and Air pollution reduction for representative ship types

For this EMSA study, the configuration, air release units or band arrangement, and performance indicators for seven representative case vessels (three coastal and four deep-sea vessels) were based on information provided by a single vendor. Details are available in Appendix C.

The analysis of ship types aims to demonstrate the effect of net power savings in [kW] and in [%] under trial or service conditions, and their impact on EEDI and CII. It also correlates the simplified method described in Section 2.6.1 for estimating ALS power gains with the vendor-provided predicted net power savings for these ship types.

A technical analysis of ALS is conducted for representative ship types selected in the study. Using the simplified method for a high-level estimate, the potential range (minimum and maximum) of gains is estimated. This includes the following:

- Operational profile (speed vs. draft combinations) and operational modes (time distribution of different operational modes such as in transit, waiting, and port etc.) from reference vessels.
- Hydrodynamic gross power savings at two draughts and for a range of speeds.
- Net power savings for typical compressor power demand.
- Net fuel savings assuming typical main engine and auxiliary generator arrangement [in t/day] per draft-speed.
- Net fuel and emission savings assuming typical operational profile and utilization in [t/year].

[2] Air leakage results in less optimum air flow rate and reduced gross power savings. The net power savings then turn into losses.

- Net power saving in EEDI/EEXI conditions, at the reference speed (Vref) and at the summer load draft.
- Investigate the improvements in CII.

Two types of trade are considered: coastal - short sea and international - deep sea, with the following specific ship types:

- Coastal: Handysize tanker, Container feeder vessel, and RoPax ferry.
- Deep-sea: Large container vessel, LR1 tanker, Large bulk carrier, LPG/LNG carrier.

2.4.2.1 Coastal trade – Handysize tanker

- Length overall x Breadth moulded: 186 m x 32.20 m
- Deadweight all told: 46,330 dwt
- Main engine maximum continuous rating: 8,900 kW
- Power and fuel savings at most frequent speeds: 14 knots laden (50%), 14 knots ballast (50%)

Table 2-1 Power savings and improvements in EEDI and CII for Handysize tanker (coastal trade)

Power Savings at Trial Condition					
		Laden condition		Ballast Condition	
Gross power savings	kW	405.5	7.9%	381.5	8.3%
Compressor power	kW	-233.2		-150.1	
Net power savings	kW	172.3	3.4%	231.4	5.1%
Power Savings at Service Condition					
		Laden condition		Ballast Condition	
Gross power savings	kW	405.5	6.6%	381.5	6.9%
Compressor power	kW	-233.2		-150.1	
Net power savings	kW	172.3	2.8%	231.4	4.2%
Power Savings at Trial Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	343.8	6.7%	326.6	7.1%
Compressor power	kW	-233.2		-150.1	
Net power savings	kW	110.6	2.2%	176.5	3.9%
Power Savings at Service Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	343.8	5.6%	326.6	5.9%
Compressor power	kW	-233.2		-150.1	
Net power savings	kW	110.6	1.8%	176.5	3.2%
Improvements in EEDI conditions		**V_ref**	**15.2**		
		EEDI Condition			
Gross power savings	kW	447.1	6.7%		
Compressor power	kW	-302.7			
Net power savings	kW	144.3	2.2%		
Improvements in CII		with ALS		w/o ALS	
		Laden	Ballast	Laden	Ballast
FOC Main engine	t/year	3 424	3 037	3 626	3 229
FOC Auxiliaries	t/year	573	518	419	419
FOC Annually	**t/year**	**7 551**		**7 692**	
Nautical miles	n.m.	85 848		85 848	
Deadweight tons	dwt	46 330		46 330	
CII Carbon Intensity Indicator		**6.09**		**6.20**	
CII Reduction		1.8%			

* Trial condition: clean hull, no wind, no sea; Service Condition: including 20% margin for wind, waves and hull fouling.

2.4.2.2 Coastal trade – Container feeder vessel

- Length overall x Breadth moulded: 169 m x 32.20 m
- Deadweight all told: 28,915 dwt
- Main engine maximum continuous rating: 13,200 kW
- Power and fuel savings at most frequent speeds: 14 knots scantling (50%), 14 knots light (50%)

Table 2-2 Power savings and improvements in EEDI and CII for Container feeder (coastal trade)

Power Savings at Trial Condition*					
		Scantling condition		Light Condition	
Gross power savings	kW	328.6	7.9%	323.8	8.3%
Compressor power	kW	-186.5		-147.2	
Net power savings	kW	142.1	3.4%	176.6	4.5%
Power Savings at Service Condition					
		Scantling condition		Light Condition	
Gross power savings	kW	328.6	6.3%	323.8	6.7%
Compressor power	kW	-186.5		-147.2	
Net power savings	kW	142.1	2.7%	176.6	3.6%
Power Savings at Trial Condition (with 95% Confidence)					
		Scantling condition		Light Condition	
Gross power savings	kW	276.8	6.7%	275.2	7.1%
Compressor power	kW	-186.5		-147.2	
Net power savings	kW	90.3	2.2%	128.0	3.3%
Power Savings at Service Condition (with 95% Confidence)					
		Scantling condition		Light Condition	
Gross power savings	kW	276.8	5.3%	275.2	5.7%
Compressor power	kW	-186.5		-147.2	
Net power savings	kW	90.3	1.7%	128.0	2.6%
Improvements in EEDI conditions				**V_ref**	**18.5**
				EEDI Condition	
Gross power savings	kW			625.8	6.3%
Compressor power	kW			-357.9	
Net power savings	kW			267.9	2.7%
Improvements in CII		with ALS		w/o ALS	
		Scantling	Light	Scantling	Light
FOC Main engine	t/year	2 850	2 668	3 011	2 828
FOC Auxiliaries	t/year	660	636	546	546
FOC Annually	**t/year**	**6 815**		**6 931**	
Nautical miles	n.m.	74 022		74 022	
Deadweight tons	dwt	28 915		28 915	
CII Carbon Intensity Indicator		**10.21**		**10.38**	
CII Reduction		1.7%			

* Trial condition: clean hull, no wind, no sea; Service Condition: including 25% margin for wind, waves and hull fouling.

2.4.2.3 Coastal trade – RoPax ferry

- Length overall x Breadth moulded: 226 m x 32.00 m
- Deadweight all told: 11,600 dwt
- Main engine maximum continuous rating: 28,800 kW
- Power and fuel savings at most frequent speeds: 15 knots laden

Table 2-3 Power savings and improvements in EEDI and CII for RoPax ferry (coastal trade)

Power Savings at Trial Condition*				
		Laden condition		
Gross power savings	kW	423.8	7.0%	
Compressor power	kW	-137.6		
Net power savings	kW	286.2	4.7%	
Power Savings at Service Condition				
		Laden condition		
Gross power savings	kW	423.8	5.7%	
Compressor power	kW	-137.6		
Net power savings	kW	286.2	3.9%	
Power Savings at Trial Condition (with 95% Confidence)				
		Laden condition		
Gross power savings	kW	349.9	5.8%	
Compressor power	kW	-137.6		
Net power savings	kW	212.3	3.5%	
Power Savings at Service Condition (with 95% Confidence)				
		Laden condition		
Gross power savings	kW	349.9	4.7%	
Compressor power	kW	-137.6		
Net power savings	kW	212.3	2.9%	
Improvements in EEDI conditions		**V_ref**	**22.2**	
		EEDI Condition		
Gross power savings	kW	1092.3	5.1%	
Compressor power	kW	-476.2		
Net power savings	kW	616.1	2.9%	
Improvements in CII		with ALS		w/o ALS
		Laden		Laden
FOC Main engine	t/year	8 185		8 591
FOC Auxiliaries	t/year	1 671		1 529
FOC Annually	**t/year**	**9 855**		**10 121**
Nautical miles	n.m.	86 549		86 549
Deadweight tons	dwt	11 600		11 600
CII Carbon Intensity Indicator		**31.47**		**32.32**
CII Reduction		2.6%		

* Trial condition: clean hull, no wind, no sea; Service Condition: including 21.5% margin for wind, waves and hull fouling.

2.4.2.4 Deep-sea – 23k TEU Container vessel

- Length overall x Breadth moulded: 400 m x 61.50 m
- Deadweight all told: 281,500 dwt
- Main engine maximum continuous rating: 60,400 kW
- Power and fuel savings at most frequent speeds: 18 knots scantling (50%), 18 knots design (50%)

Table 2-4 Power savings and improvements in EEDI and CII for 23k TEU Container vessel (deep-sea case)

Power Savings at Trial Condition**					
		Design condition		Scantling Condition	
Gross power savings	kW	1580.2	6.1%	1645.3	5.9%
Compressor power	kW	-1010.5		-1115.0	
Net power savings	kW	569.7	2.2%	530.3	1.9%
Power Savings at Service Condition					
		Design condition		Scantling Condition	
Gross power savings	kW	1580.2	5.2%	1645.3	5.0%
Compressor power	kW	-1010.5		-1115.0	
Net power savings	kW	569.7	1.9%	530.3	1.6%
Power Savings at Trial Condition (with 95% Confidence)					
		Design condition		Scantling Condition	
Gross power savings	kW	1277.5	4.9%	1319.3	4.7%
Compressor power	kW	-1010.5		-1115.0	
Net power savings	kW	267.0	1.0%	204.2	0.7%
Power Savings at Service Condition (with 95% Confidence)					
		Design condition		Scantling Condition	
Gross power savings	kW	1277.5	4.2%	1319.3	4.0%
Compressor power	kW	-1010.5		-1115.0	
Net power savings	kW	267.0	0.9%	204.2	0.6%
Improvements in EEDI conditions		**V_ref**	**21.5**		
		EEDI Condition			
Gross power savings	kW	2202.3	4.9%		
Compressor power	kW	-1788.2			
Net power savings	kW	414.1	0.9%		
Improvements in CII		with ALS		w/o ALS	
		Design	Scantling	Design	Scantling
FOC Main engine	t/year	18 582	20 044	19 400	20 889
FOC Auxiliaries	t/year	2 371	2 445	1 657	1 657
FOC Annually	**t/year**	**43 442**		**43 604**	
Nautical miles	n.m.	118 260		118 260	
Deadweight tons	dwt	281 500		281 500	
CII Carbon Intensity Indicator		**4.18**		**4.20**	
CII Reduction		0.4%			

* Trial condition: clean hull, no wind, no sea; Service Condition: including 17% margin for wind, waves and hull fouling.

2.4.2.5 Deep-sea – LR Tanker

- Length overall x Breadth moulded: 250 m x 42.00 m
- Deadweight all told: 109,700 dwt
- Main engine maximum continuous rating: 14,000 kW
- Power and fuel savings at most frequent speeds: 13 knots laden (50%), 14.5 knots ballast (50%)

Table 2-5 Power savings and improvements in EEDI and CII for LR tanker (deep-sea case)

Power Savings at Trial Condition*					
		Laden condition		Ballast Condition	
Gross power savings	kW	600.3	9.2%	814.3	10.9%
Compressor power	kW	-509.6		-309.1	
Net power savings	kW	90.7	1.4%	505.3	6.8%
Power Savings at Service Condition					
		Laden condition		Ballast Condition	
Gross power savings	kW	600.3	7.7%	814.3	9.2%
Compressor power	kW	-509.6		-309.1	
Net power savings	kW	90.7	1.2%	505.3	5.7%
Power Savings at Trial Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	522.3	8.0%	725.4	9.7%
Compressor power	kW	-509.6		-309.1	
Net power savings	kW	12.7	0.2%	416.3	5.6%
Power Savings at Service Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	522.3	6.7%	725.4	8.2%
Compressor power	kW	-509.6		-309.1	
Net power savings	kW	12.7	0.2%	416.3	4.7%
Improvements in EEDI conditions		**V_ref**	**15.1**		
		EEDI Condition			
Gross power savings	kW	819.5	7.8%		
Compressor power	kW	-592.0			
Net power savings	kW	227.5	2.2%		
Improvements in CII		with ALS		w/o ALS	
		Laden	Ballast	Laden	Ballast
FOC Main engine	t/year	4 314	4 842	4 624	5 271
FOC Auxiliaries	t/year	900	767	564	564
FOC Annually	**t/year**	**10 823**		**11 022**	
Nautical miles	n.m.	84 315		84 315	
Deadweight tons	dwt	109 719		109 719	
CII Carbon Intensity Indicator		**3.75**		**3.82**	
CII Reduction		1.8%			

* Trial condition: clean hull, no wind, no sea; Service Condition: including 19% margin for wind, waves and hull fouling.

2.4.2.6 Deep-sea – Large bulk carrier (ALS for ballast condition only)

- Length overall x Breadth moulded: 292 m x 45.00 m
- Deadweight all told: 182,000 dwt
- Main engine maximum continuous rating: 15,500 kW
- Power and fuel savings at most frequent speeds: 11.5 knots laden (50%), 11.5 knots ballast (50%)

Table 2-6 Power savings and improvements in EEDI and CII for a Large bulk carrier (deep-sea case)

Power Savings at Trial Condition*					
		Laden condition		Ballast Condition**	
Gross power savings	kW	0.0	0.0%	569.2	12.7%
Compressor power	kW	0.0		-393.7	
Net power savings	kW	0.0	0.0%	175.5	3.9%
Power Savings at Service Condition					
		Laden condition		Ballast Condition	
Gross power savings	kW	0.0	0.0%	569.2	10.7%
Compressor power	kW	0.0		-393.7	
Net power savings	kW	0.0	0.0%	175.5	3.3%
Power Savings at Trial Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	0.0	0.0%	515.9	11.5%
Compressor power	kW	0.0		-393.7	
Net power savings	kW	0.0	0.0%	122.2	2.7%
Power Savings at Service Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	0.0	0.0%	515.9	9.7%
Compressor power	kW	0.0		-393.7	
Net power savings	kW	0.0	0.0%	122.2	2.3%
Improvements in EEDI conditions		**V_ref**	**14.2**		
		EEDI Condition			
Gross power savings	kW	0.0	0.0%		
Compressor power	kW	0.0			
Net power savings	kW	0.0	0.0%		
Improvements in CII		with ALS		w/o ALS	
		Laden	Ballast	Laden	Ballast
FOC Main engine	t/year	5 013	2 948	5 013	3 264
FOC Auxiliaries	t/year	599	877	599	599
FOC Annually	**t/year**	**9 438**		**9 476**	
Nautical miles	n.m.	75 555		75 555	
Deadweight tons	dwt	181 259		181 259	
CII Carbon Intensity Indicator		**2.21**		**2.22**	
CII Reduction		0.4%			

* Trial condition: clean hull, no wind, no sea; Service Condition: including 19% margin for wind, waves and hull fouling.
**It is assumed that ALS is designed for "ballast condition only" as the expected net power saving at the laden condition otherwise would become negative due to a higher compressor power demand.

2.4.2.7 Deep-sea – LNG Carrier

- Length over all x Breadth moulded: 289 m x 45.60 m
- LNG Cargo tank capacity: 162,000 cbm
- Main engine maximum continuous rating: MCR 38,000 kW
- Power and fuel savings at most frequent speeds: 18 knots laden (50%), 18 knots ballast (50%)

Table 2-7 Power savings and improvements in EEDI and CII for LNG carrier (deep-sea case)

Power Savings at Trial Condition					
		Laden condition		Ballast Condition	
Gross power savings	kW	1745.6	10.8%	1668.7	10.2%
Compressor power	kW	-795.0		-631.9	
Net power savings	kW	950.6	5.9%	1036.8	6.3%
Power Savings at Service Condition					
		Laden condition		Ballast Condition	
Gross power savings	kW	1745.6	9.3%	1668.7	8.8%
Compressor power	kW	-795.0		-631.9	
Net power savings	kW	950.6	5.1%	1036.8	5.5%
Power Savings at Trial Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	1558.6	9.7%	1479.2	9.1%
Compressor power	kW	-795.0		-631.9	
Net power savings	kW	763.6	4.7%	847.2	5.2%
Power Savings at Service Condition (with 95% Confidence)					
		Laden condition		Ballast Condition	
Gross power savings	kW	1558.6	8.3%	1479.2	7.8%
Compressor power	kW	-795.0		-631.9	
Net power savings	kW	763.6	4.1%	847.2	4.5%
Improvements in EEDI		**V_ref**	**21.0**		
		EEDI Condition			
Gross power savings	kW	2429.3	8.5%		
Compressor power	kW	-1292.3			
Net power savings	kW	1136.9	4.0%		
Improvements in CII		with ALS		w/o ALS	
		Laden	Ballast	Laden	Ballast
FOC Main engine	t/year	11 493	11 720	12 538	12 712
FOC Auxiliaries	t/year	1 522	1 419	1 017	1 017
FOC Annually	**t/year**	**26 154**		**27 284**	
Nautical miles	n.m.	118 260		118 260	
Deadweight tons	dwt	90 494		90 494	
CII Carbon Intensity Indicator		**7.84**		**8.17**	
CII Reduction		4.1%			

* Trial condition: clean hull, no wind, no sea; Service Condition: including 16% margin for wind, waves and hull fouling.

2.4.2.8 Summary of Air Pollution analysis for representative ship types

The use of ALS is expected to reduce power consumption during transit by lowering frictional resistance. As a result, fuel consumption naturally decreases. Consequently, GHG and air pollutants such as NO_x, SO_x and particulate matter (PM) are also reduced proportionally to the fuel savings.

Net power savings from ALS were estimated for the ships analysed in this Section and converted into corresponding fuel consumption reductions, showing a potential GHG and air pollutant reduction of up to 5.6% under trial conditions (assumed clean hull, no wind, and calm seas), and up to 4.5% reduction under service conditions where an additional margin was applied for each ship to account for fouling and weather effects. The results are summarized in Table 2-8.

Table 2-8 Case study for net power savings and annual fuel consumption estimation for the ship types analysed

Cases		**Net power savings [%]**			**Annual fuel consumption saving* [%]**	**Remarks**
		Trial conditions (Laden - Ballast) or (Full laden - Light)	**Service conditions** (Laden - Ballast) or (Full laden - Light)	**EEDI Conditions** (Summer load draft)		
Coastal operation	Handymax Tanker	2.2 - 3.9	1.8 - 3.2	2.2	1.8	-
	Container feeder vessel	2.2 – 3.3**	1.7 - 2.6**	2.7	1.7	Generally operating in Light and full laden
	RoPax ferry	3.5 - NA	2.9 - N/A	2.9	2.5	Generally operating in laden
Deep sea operation	23k TEU Container vessel	0.7 - 1.0**	0.6 - 0.9**	0.9	0.4	Generally operating in Light and full laden
	LR tanker	0.2 - 5.6	0.2 - 4.7	2.2	1.8	-
	Capesize Bulk carrier	N/A - 2.7	N/A - 2.3	0	0.4	It is assumed that ALS is designed for “ballast condition only” as the expected net power saving at the laden condition
	162k LNG Carrier	4.7 - 5.2	4.1 - 4.5	4.0	4.1	-
*) Annual Fuel savings with 95% confidence (lower limit) estimated based on a typical operational profile (including time ratios for speed and draft combinations) and utilization (time spent in transit per year). **) Full laden – Light conditions						

2.4.3 Other Environmental Aspects

ALS may contribute to the reduction of underwater radiated noise (URN) by introducing a layer of air bubbles between the ship's hull and the surrounding water. This bubble layer acts as an acoustic barrier, effectively masking structural noise emitted from the hull. The presence of air in the boundary layer alters the transmission of sound waves, reducing their intensity and propagation into the marine environment. Full-scale trials, such as those conducted by a Korean yard and vendor, have confirmed that ALS operation in most cases has led to a measurable reduction in URN across a wide frequency range.

From a regulatory perspective, the International Maritime Organization (IMO) adopted revised guidelines in 2023 for the reduction of underwater radiated noise from commercial shipping. These guidelines are non-mandatory but provide technical recommendations for ship design, operation, and maintenance to mitigate URN. Classification societies have also responded with their own frameworks. For example, DNV offers the SILENT class notation, which defines acceptable underwater noise levels for specific vessel types, whereas ABS and ClassNK provide optional notations and guidelines aligned with IMO recommendations.

2.4.4 Sustainability Conclusions

ALS is a promising technology for reducing hull resistance and improving fuel efficiency, thus reducing fuel consumption, particularly for vessels with substantial FoB areas such as LNG carriers. Reductions in fuel use from ALS directly contribute to decreased GHG-emissions and other air pollutants such as NO_x, SO_x, and particulate matter.

According to the case study, the estimated annual fuel savings are up to 4%. The net savings depend not only on the reduction of drag but also on the energy required to operate the system, particularly the compressors, which consume between 3% and 5% of propulsion power. Passive systems have an advantage by completely eliminating compressor energy consumption.

Beyond fuel and emissions reductions, ALS systems may also reduce underwater radiated noise, contributing to marine ecosystem protection. This aligns with broader sustainability goals, suggesting that ALS can support both climate and environmental objectives when properly designed, operated, and verified.

It remains challenging to determine the realistic savings potential during actual vessel operations, which directly influences the estimated GHG-reduction. To address this uncertainty, further investigation based on long-term in-service measurements across different ship types and under various weather conditions is necessary to establish credible and representative GHG reduction figures for each system.

2.5 Suitability

ALS is technically suitable and effective by examining how hull shape, draft, operating profile, power-supply configuration, and weather conditions influence its performance. The analysis aims to determine which vessels can maintain a stable air layer, achieve meaningful drag reduction, and integrate the system efficiently, while also assessing installation practicality for both newbuilds and retrofits.

2.5.1 Risks and uncertainties

As described in Section 2.3, ALS use similar equipment, with pipes and valves installed regardless of the vendor, although there are some differences. These systems are integrated into both the hull structure and the vessel's operational systems, such as piping and compressors. Classification societies review and approve the system, ensuring that structural modifications like hull penetrations and air release unit installations comply with safety and strength standards. Additionally, classification societies typically assess ALS installations against statutory requirements on behalf of the flag administration, including those outlined in SOLAS, MARPOL, the Load Line Convention, and tonnage measurement regulations. Details of the classification societies' rules can be found in Section 3.3.

The following Table 2-9 outlines the expected risks and uncertainties associated with ALS, based on interviews conducted with system vendors. Due to limited operational experience with ALS-equipped vessels, these risks are actively monitored by operators and vendors to support ongoing performance optimization and risk mitigation.

Table 2-9 List of risks, uncertainties, and mitigation strategies from ALS based on interview with vendors

Risk and uncertainties	Description	Mitigation Strategies
Air accumulation in sea chests	■ Air bubbles entering sea chests may disrupt seawater intake and pump operation.	■ Modified sea chest design. ■ Strategic ARU placement. ■ Deaeration systems.
Cavitation and erosion on propeller	■ Air bubbles may alter flow near propellers, affecting cavitation behaviour.	■ CFD analysis for streamline. ■ Full-scale trials.
Added resistance when ALS is off	■ Air release units may increase drag when the system is inactive.	■ Compact nozzle design. ■ CFD validation. ■ Sea trial verification.
Performance degradation in high sea states	■ Ship motions may destabilize air layer, reducing drag reduction.	■ Long-term full-scale measurement in ALS On and OFF conditions. ■ Dynamic control of ALS.
Control system complexity	■ ALS requires adaptive control based on vessel and environmental conditions.	■ Real-time control systems. ■ Statistics/AI integration. ■ Speed/draft automation.
Compressor power consumption	■ Compressor energy demand may offset the savings.	■ Real-time monitoring. ■ Air flow calibration.
Uncertainty in performance prediction, prior to sea trial	■ CFD and model tests struggle to simulate bubbly flow accurately.	■ Long-term full-scale measurement in ALS On and OFF conditions.
Radiated noise (URN)	■ Any impact of additional noise from the units associated with ALS and interaction with the propeller.	■ ALS can alter the flow dynamics around the propeller, reducing the severity of cavitation. ■ Noise suppression.
Noise and Vibration	■ Noise from the outlets or pipes due to the compressed air flow, especially in retrofit cases. ■ Operating compressors close to the crew and client cabins.	■ Use vibration-damping mounts and flexible supports to isolate the piping from the hull structure. ■ Design piping layouts to minimize sharp bends, sudden expansions, and contractions. ■ Mount compressors on vibration-isolating bases.
Change of propulsive efficiency	■ ALS influences the flow along the hull and affects the wake field of a ship, thus changing the propulsive efficiency.	■ Long-term full-scale measurement in ALS On and OFF conditions.

2.5.2 Design and operational criteria

The suitability of ALS for a particular ship design depends on various factors, such as hull shape, draft, operational profile, and weather conditions. This Section briefly discusses factors to be considered when evaluating the effectiveness of air lubrication as a fuel-saving measure.

2.5.2.1 Lubricated Bottom Area

The effective lubricated bottom area depends on vessel shape, the location of ARUs, and airflow rates. Full coverage is not always necessary; rather, strategic placement and control of air release are key to maximizing ALS effectiveness. The ratio of FoB area to total wetted surface area varies by ship type, with tankers, bulk carriers, and gas carriers typically having a ratio of around 30 - 40% and ultra-large container vessels (ULCVs) around 25 -35% in laden condition. These ratios help determine how much of the wetted surface can be effectively lubricated.

A representative model basin in Europe emphasizes that the most effective drag reduction occurs in the forward portion of the hull. Their split-plate tests revealed that the first 1 meter of a 7-meter plate accounted for nearly all of the 20–25% reduction in resistance, while the remaining 6 meters contributed only 5–6%.

A major ALS vendor in Europe focuses on the extent of the FoB area that can be lubricated. Their concept studies use CFD to determine the optimal layout of air release units and the reach of the bubble carpet. They apply correlation factors from full-scale trials to estimate how much of the FoB can be effectively covered, which directly influences the predicted savings.

A major ALS vendor in Korea uses full-scale CFD simulations to assess the distribution of the air layer over the hull surface. They evaluate the density and volume ratio of air coverage and optimize the arrangement of air release units to maximize the net power saving. Their findings suggest that ALS effectiveness depends on both the location and the extent of air coverage, particularly in relation to hull pressure distribution and flow streamlines.

A major ALS vendor in Europe, with its passive system, aims to saturate the viscous sublayer of the boundary layer with a thin air-water mixture. Their design focuses on delivering air precisely into areas of laminar flow, using CFD to identify optimal pod placement. They emphasize that even partial coverage, if well-targeted, can yield substantial drag reduction.

2.5.2.2 Operational Draft-Speed Profile

Major ALS vendors emphasize that the air flow rate required for optimal performance must be tailored to the vessel's typical operational drafts and speeds. These parameters directly affect the pressure distribution along the hull and the stability of the air layer or bubble carpet. For example, higher speeds generally improve the shearing mechanism that sustains the bubble layer while deeper drafts increase hydrostatic pressure, requiring more energy to maintain effective lubrication.

A representative of a model basin in Europe agrees with major ALS vendors that ALS calibration must be performed separately for ballast and laden conditions, as the hydrodynamic behaviour and air layer and bubble carpet differ between these drafts. They also point out that there is no universally agreed method to scale ALS performance across different operational profiles, making vessel-specific calibration essential.

A major European vendor, citing its passive system, adds that it is particularly suited to slow-steaming and deep-draft operations, where conventional active ALS may have difficulty maintaining air-layer and bubble-carpet stability. Their design allows dynamic control of air-water mixture delivery based on real-time draft and speed data.

Overall, ALS performance is highly sensitive to operational conditions. Effective implementation requires adaptive control systems and calibration procedures that account for variations in draft and speed to ensure consistent drag reduction and energy savings.

2.5.2.3 Time in Transit

The fuel savings and emission reductions achieved through ALS scale with time in transit. In other words, the more a vessel is operated, the greater the cumulative fuel savings from reduced propulsion power demand. This translates directly into reduced GHG emissions and OPEX. Moreover, high-utilization, indicating long time spent in transit, vessels often have predictable routes between loading and unloading ports and operating conditions, which makes it easier to calibrate and optimize ALS performance.

Based on Automatic Identification System (AIS) data collected between 2017 and 2024, the operational profiles of seven selected ship segments have been analysed. These segments correspond to the same ship types and sizes used for the air pollution analysis of representative ship types in Section 2.4.2.

The AIS analysis shows that vessels with a larger DWT generally have more time in transit, especially large container vessels and LNG carriers. ALS is currently installed on these two vessel types due to several factors: a larger bottom area, higher operational speeds, higher utilization rates, and minimal difference in operational drafts. These characteristics collectively explained the selection.

According to AIS data from about 2100 vessels, Handymax Tankers with a deadweight (DWT) between 40k and 60k DWT exhibit an average utilization rate of approximately 55% as illustrated in Figure 2-13. These vessels typically operate at speeds ranging from 11 to 13 knots and in ballast, intermediate, and laden conditions.

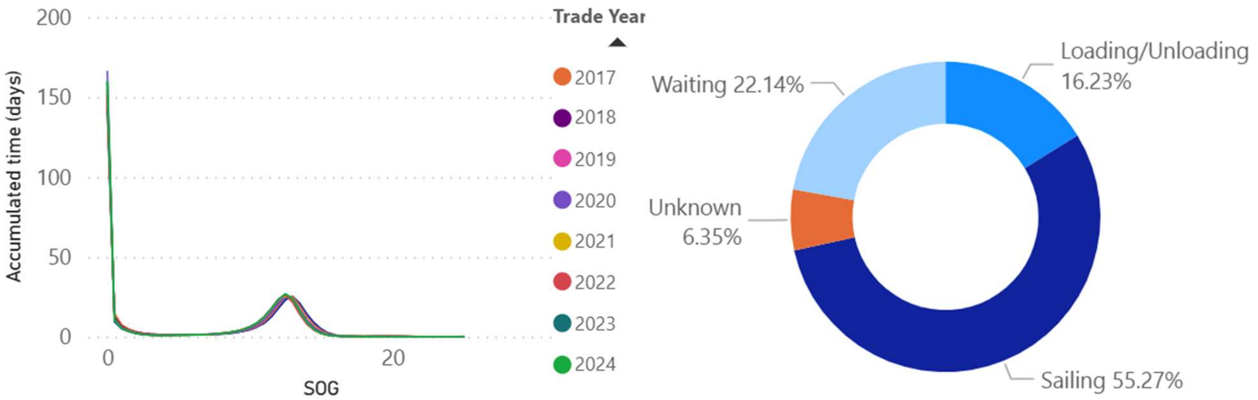


Figure 2-13 Handymax Tankers' historical speed profile (left) and Time distribution in different operations (right). "Unknown" time distribution sector relates to missing AIS information. (Source: DNV)

According to AIS data from about 2600 vessels, Container feeder vessels between 500 TEU and 2000 TEU exhibit an average utilization rate of approximately 58%, as illustrated in Figure 2-14. These vessels usually operate at a wide range of speeds from 11 to 17 knots and under laden conditions.

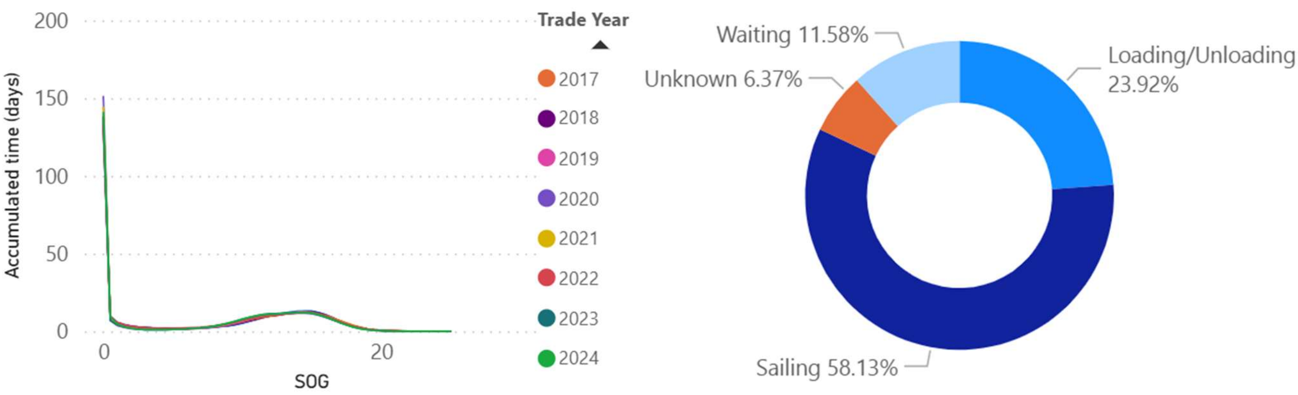


Figure 2-14 Container feeder vessels' historical speed profile (left) and Time distribution in different operations (right). "Unknown" time distribution sector relates to missing AIS information. (Source: DNV)

According to AIS data from about 320 vessels, passenger vessels and ferries between 5,000 and 15000 DWT exhibit an average utilization rate of approximately 63%, as illustrated in Figure 2-15. These vessels typically operate at a wide range of speeds, from 13 to 21 knots, mostly when laden.

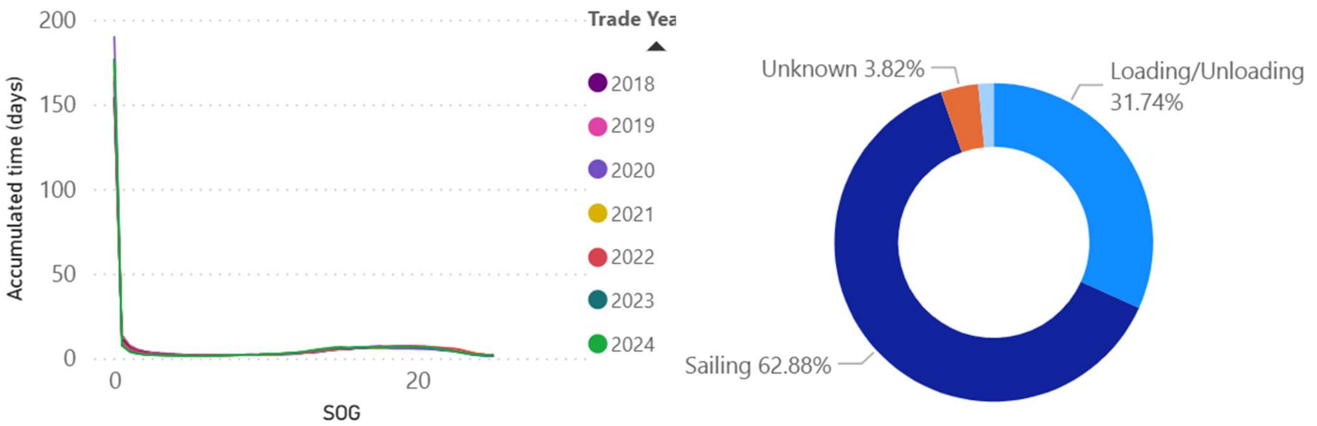


Figure 2-15 Passenger vessels and Ferries' historical speed profile (left) and Time distribution in different operations (right). "Unknown" time distribution sector relates to missing AIS information. (Source: DNV)

According to AIS data from about 110 vessels, Ultra Large Container Vessels (>20k TEU) exhibit an average utilization rate of approximately 64%, as illustrated in Figure 2-16. These vessels typically operate at speeds ranging from 17 to 19 knots and predominantly in laden condition.

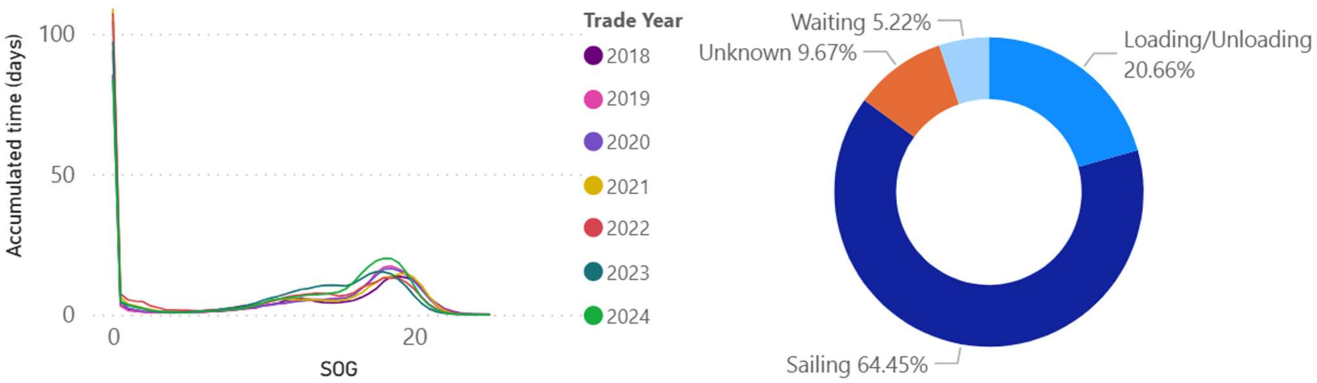


Figure 2-16 Ultra Large Container Vessels' historical speed profile (left) and time distribution in different operations (right). "Unknown" time distribution sector relates to missing AIS information. (Source: DNV)

According to AIS data from about 800 vessels, Long Range (LR) Tankers between 90k and 110k DWT exhibit an average utilization rate of approximately 56%, as illustrated in Figure 2-17. These vessels typically operate at speeds ranging from 11 to 13 knots in laden condition, and higher speeds in ballast conditions.

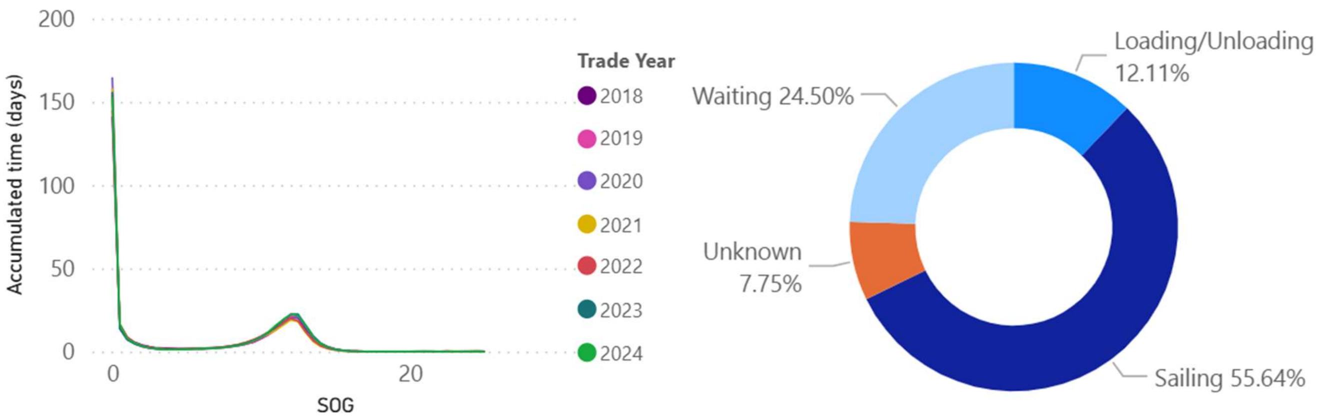


Figure 2-17 LR Tankers' historical speed profile (left) and Time distribution in different operations (right). "Unknown" time distribution sector relates to missing AIS information. (Source: DNV)

According to AIS data from about 1700 vessels, Bulk carriers between 170k and 220k DWT exhibit an average utilization rate of approximately 67%, as illustrated in Figure 2-18. These vessels typically operate at speeds ranging from 10 to 12 knots in laden condition, and higher speeds in ballast condition.

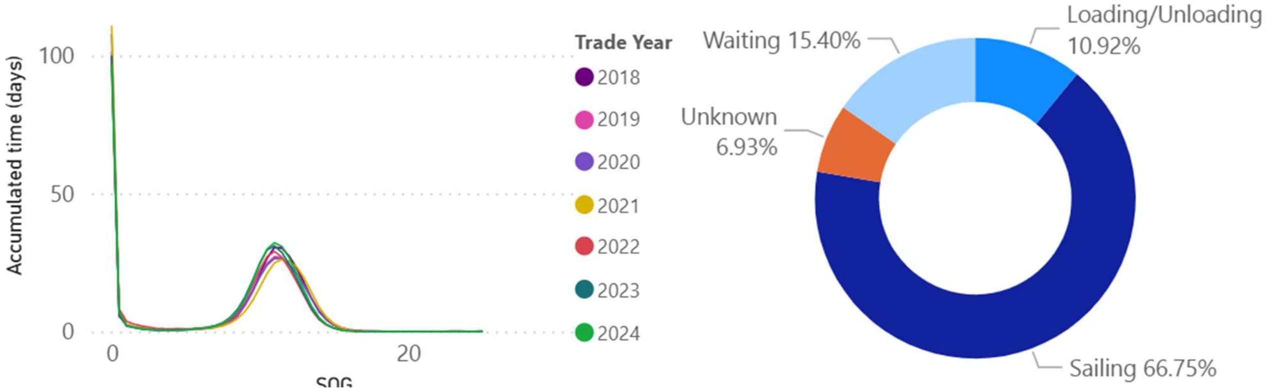


Figure 2-18 Bulk Carriers' historical speed profile (left) and Time distribution in different operations (right). "Unknown" time distribution sector relates to missing AIS information. (Source: DNV)

According to AIS data from about 540 vessels, LNG carriers between 140k and 180k CBM exhibit an average utilization rate of approximately 78%, as illustrated in
Figure 2-19. These vessels typically operate at speeds ranging from 16 to 19 knots in laden and ballast conditions.

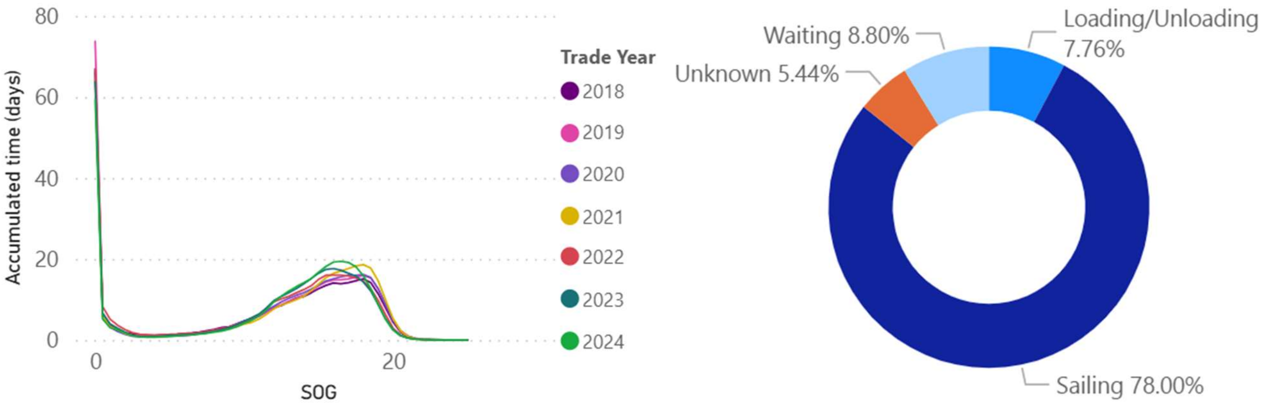


Figure 2-19 LNG Carriers' historical speed profile (left) and Time distribution in different operations (right). "Unknown" time distribution sector relates to missing AIS information. (Source: DNV)

2.5.2.4 Compressor power supply for ALS

The energy required to operate the ALS, particularly the compressors, corresponds to approximately 3% to 5% of propulsion power. Passive ALS eliminates the need for compressor energy. There are typically three propulsion system configurations used in coastal and deep-sea vessels, and ALS operating power can be supplied in different ways.

The most common machinery system for deep-sea vessels is a low-speed, two-stroke engine directly coupled to the propeller as illustrated in Figure 2-20. Most of these vessels do not have a shaft power generator (Power Take Off, PTO) and therefore must operate auxiliary engines during sailing to supply power for ALS operation and hotel loads. Retrofitting PTO is generally challenging due to a lack of machinery room space, thus retrofitted ALS will typically rely on power from auxiliary generators. For newbuilds with ALS installed, PTO systems are widely adopted, utilising the higher main engine efficiency compared to auxiliary engine-driven generators.

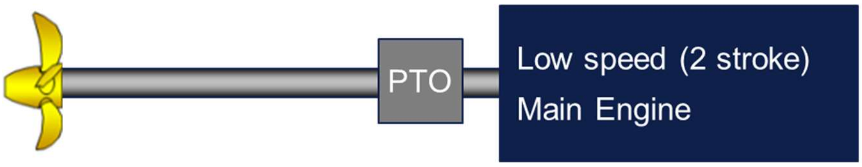


Figure 2-20 Low-speed, two-stroke engine directly coupled to the propeller with or without PTO (Source: DNV)

Another configuration uses four-stroke engines with a reduction gearbox coupled to the shaft and propeller, as illustrated in Figure 2-21. These engines are generally medium-speed units suitable for coastal and deep-sea vessels, as high-speed engines with sufficient power are limited. Additionally, single-stage gearboxes have restricted reduction ratios, and propeller efficiency decreases significantly at high RPM. Gearboxes can easily accommodate a shaft generator connected to the main engine, allowing ALS and hotel loads from the generator for both newbuild and retrofit cases. This setup is common for ferries and RoPax vessels.

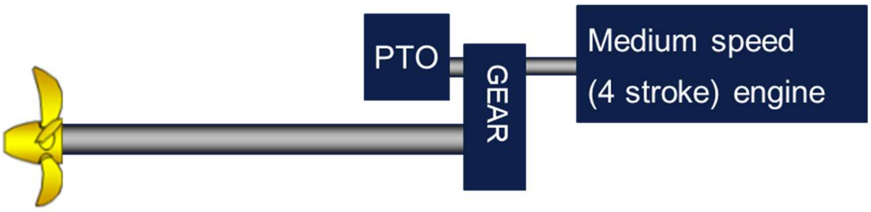


Figure 2-21 Four-stroke engines with a reduction gearbox coupled to the shaft and propeller (Source: DNV)

Electric propulsion systems employ electric motors to drive the propeller(s) as illustrated in

Figure 2-22. Power for these motors is typically supplied by generators driven by reciprocating engines (main engines) or other energy sources such as gas turbines, steam turbines, fuel cells, batteries, or solar panels. Electrical power also supports ALS operation and hotel loads, enabling optimized genset operation with balanced loading. This propulsion system is commonly used in cruise ships, car ferries, and LNG carriers prior to the introduction of dual-fuel two-stroke main engines.

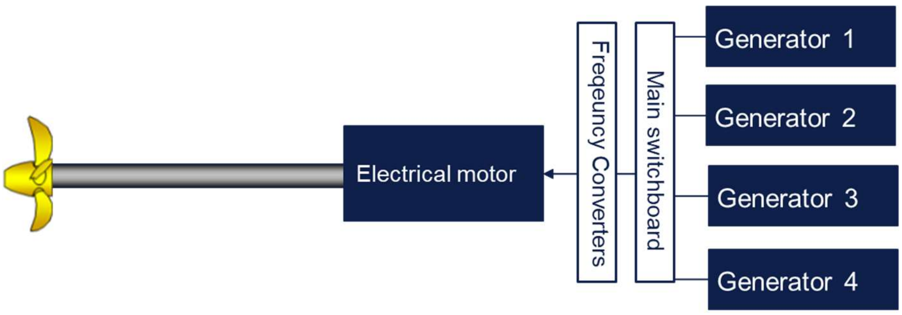


Figure 2-22 Electric propulsion systems (Source: DNV)

2.5.2.5 Arrangement of ALS equipment

ALS adds only negligible weight and minimal complexity to the arrangement of additional components, potentially making it suitable for both existing vessels and newbuilds. ARU, pipes, and valves are typically arranged in existing void spaces and/or ballast tanks. In a few cases, ballast tanks have had to be repurposed into void spaces. The compressors are typically arranged in the ship's forecastle stores. The arrangement of a retrofit ALS generally does not affect cargo hold space and has only a negligible impact on cargo carrying capacity. However, the placement of compressors and piping should be carefully planned to minimize noise and vibration in accommodation, especially on passenger ships.

2.5.2.6 Operation in different weather conditions

ALS performance varies with environmental conditions. In rough seas, ship motions such as roll, pitch, and heave can destabilize the air layer or cavity, splitting it into bubbles or patches and decreasing drag reduction efficiency. While some systems claim to stay effective up to Beaufort 5, others may need to be switched off in harsh conditions to prevent inefficiency, as the energy cost of running compressors will likely exceed the benefits. Table 2-10 is the relation between the Beaufort scale for wind speed and the resulting significant wave height.

The distribution of wind speeds for different sea areas can be characterized by an average wind speed (Uavr). Table 2-11 shows wind climate statistics from a publication by Schenzle presenting the average wind speed for different sea areas.

Table 2-10 Relation between wind speed (Beaufort scale) and significant wave height [m]:

			BF 2	BF 3	BF 4	BF 5	BF 6	BF 7	BF 8	BF 9
Sign. Waves	up to	0,00 m	0,20 m	0,60 m	1,25 m	2,40 m	3,80 m	5,50 m	7,40 m	9,75 m

Table 2-11 Wind climate statistics from a publication by Schenzle

	Uavr[m/s]	0,0 m/s	3,4 m/s	5,4 m/s	7,6 m/s	10,1 m/s	12,7 m/s	15,5 m/s	18,6 m/s	21,7 m/s	24,8 m/s
Tropical seas	6	12%	22%	26%	21%	12%	5%	2%	0%	0%	
North Sea	8	7%	14%	19%	21%	18%	12%	6%	2%	1%	
Nordic Oceans	10	4%	9%	14%	17%	18%	15%	11%	7%	4%	
40-50° South	12	3%	7%	11%	14%	16%	16%	12%	10%	8%	5%

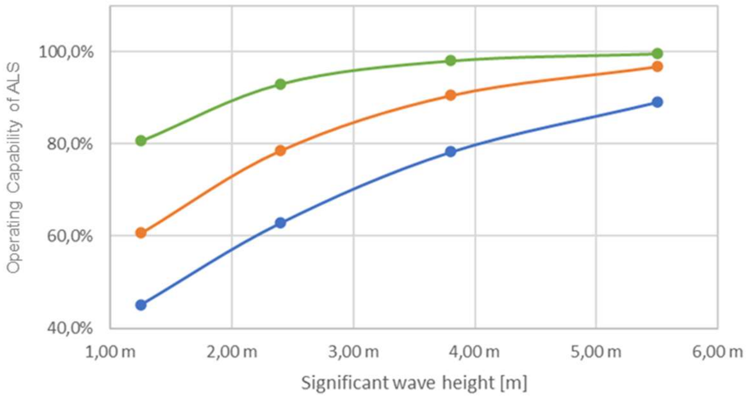


Figure 2-23 Percentage of full operating capability of ALS estimated as a function of the significant wave height [m] for “Tropica seas” (green), “North Sea” (orange) and “Nordic Oceans” (blue) (Source: DNV)

To illustrate the methodological approach for estimating ALS's operational capability under various weather conditions, as applied in the economic analysis in Section 2.7.3, an LNG Carrier is used as an example. The vessel is 180 m in length, for which the ALS is effective up to a wind speed of around BF5.

The limiting significant wave height is approximately 1% of the ship's length, which equates to 1.8 m, slightly below the BF5 value. Applying a maximum sea state of 1,8 m to the data set in Figure 2-23, we find that an LNGC could expect to deploy an installed ALS between 54% and 88% of the time spent in transit, depending on the area of operation.

2.5.3 Suitability Conclusions

The effectiveness of ALS is dependent on a number of factors, which will determine the technology’s suitability for a given ship type:

- The ratio of FoB area to total wetted surface area.
- Operational draft.
- Speed through water.

- Time in transit vs. idle.
- Power plant configuration.
- Area of operation (weather conditions).

One of the factors to consider is the lubricated bottom area and the release of air to establish a stable air layer in hydrodynamically favourable hull regions. Ship types with a large ratio of FoB area to total wetted surface can benefit more from ALS than ships with lower ratios.

ALS performance is sensitive to the draft. Calibration must be vessel-specific and account for both ballast and laden conditions. ALS is more suitable for vessels with predictable and stable operating profiles, than ships having a large draft difference between laden and ballast conditions.

Utilization, indicating time spent in transit, is another critical factor. The more frequently a vessel operates, the greater the potential cumulative fuel and emission savings achievable with ALS. High-utilization vessels, e.g., LNG carriers, benefit more due to their consistent routes and operating conditions, which allow for better ALS calibration and optimization. AIS data supports this, showing that larger vessels tend to have higher utilization rates. The utilization in Table 2-12 gives a general overview of the typical operating speeds and utilization for each ship type, and each vessel should analyse the same to evaluate the suitability of ALS installation.

Table 2-12 Typical operating speeds and Utilization of the different ship cases analysed

Ship types		Typical operating speeds [knots]	Utilization [%]
Coastal operation	Handymax Tanker	11-13	55
	Container feeder vessel	11-17	58
	RoRax ferry	13-21	63
Deep sea operation	Ultra Large Container vessel	17-19	65
	LR tanker	11-13	56
	Bulk carrier	10-12	67
	162k LNG Carrier	16-19	78

Power supply strategies for ALS vary by propulsion system, two-stroke engines in deep-sea vessels often rely on auxiliary engines for retrofits, while newbuilds use PTO systems for better efficiency. Four-stroke engines with gearboxes can integrate shaft generators, and electric propulsion systems, common in cruise ships and LNG carriers, provide flexible power for ALS and hotel loads. Since the power demand for ALS is limited, the existing machinery system can be utilized. However, it is essential to assess potential operational challenges and efficiency losses arising from the additional power requirement before installing ALS.

ALS can be equipped in both existing vessels and newbuilds without major barriers. The placement of compressors and piping should be carefully planned to minimize noise and vibration in crew cabins, particularly on passenger ships.

ALS performance under different weather conditions remains uncertain. Rough seas may destabilize the air layer, reducing drag reduction benefits. Based on a vendors claim that the ALS will be effective up to Beaufort 5, an LNGC could expect to be able to deploy an installed ALS between 54% and 88% of the time spent in transit, depending on the area of operation.

ALS can be installed on both existing vessels and newbuilds without significant obstacles. The placement of compressors and piping should be carefully designed to reduce noise and vibration in areas sensitive to such disturbances as described in Table 2-9.

2.6 Availability

This Section examines the current and future use of ALS and assesses its technological readiness using the TRL scale.

2.6.1 Current/Planned Applications

Air lubrication technologies have attracted significant attention in the shipping industry as a means of reducing fuel consumption and emissions. According to Clarkson Research Services Limited, more than 300 vessels either equipped with or retrofitted with an ALS are reported to be in service, while approximately 300 vessels are on order with an ALS installation, as illustrated in Figure 2-24 Vessels equipped with ALS by ship type (left: ALS delivered, right: ALS on order, Source: Clarkson)Approximately 98% of vessels in service with ALS installed are equipped with active ALS, and a few vessels have a Passive ALS or ACS installed, as illustrated in Figure 2-25. LNG carriers and container ships are the primary segments in which ALS has been installed, and this trend is expected to continue based on the order book.

Major shipyards in Korea have their own ALS for newbuilds, while independent ALS vendors in Europe, China, and North America provide ALS solutions for both newbuilds and retrofits, offering these systems to shipyards worldwide.

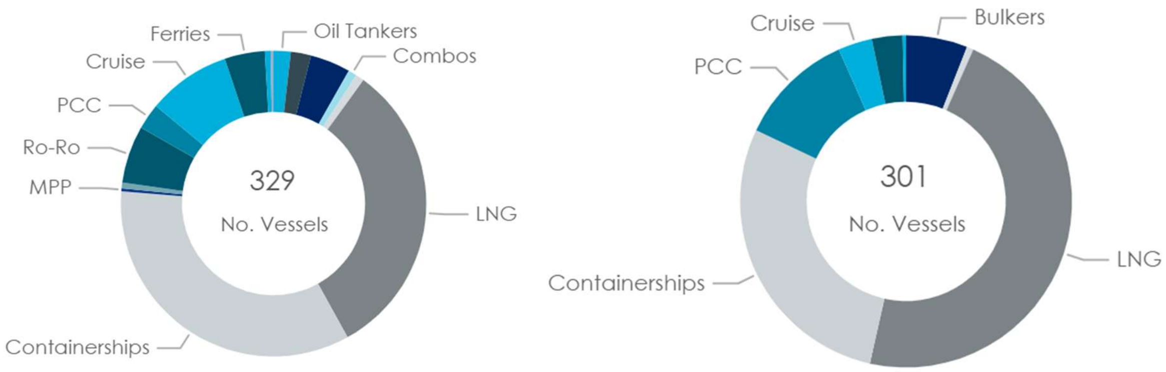


Figure 2-24 Vessels equipped with ALS by ship type (left: ALS delivered, right: ALS on order, Source: Clarkson)

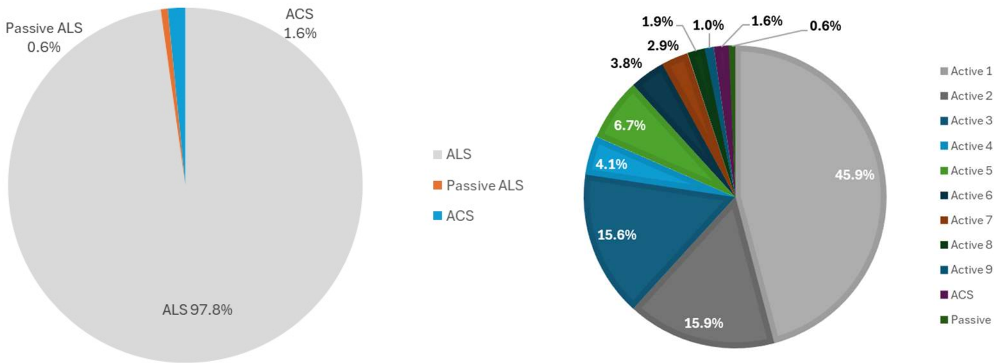


Figure 2-25 Application of different ALS for the vessels in service (left: different systems, right: different vendors, Source: DNV)

2.6.2 Level of Maturity of Technologies

The TRL scale, originally defined by NASA, is "a type of measurement system used to assess the maturity level of a particular technology." This scale evaluates the maturity of a technology through a series of indicators, ranging from TRL 1 (basic principles observed and reported) to TRL 9 (technology proven and ready for full-scale deployment).

The TRL scale was introduced into EU-funded projects in 2012 and has since become the standard reference for determining the development stage or maturity of research, as well as its readiness for market uptake and potential investments. TRL is a valuable tool for assessing the maturity of research project results and defining the necessary steps to bring them to market. The methodology used for this assessment is based on the EURAXESS guidelines[3]. Table 2-13 provides an overview of the scale.

Table 2-13 TRL assessment levels.

TRL1	Define basic properties
TRL2	Analytical study
TRL3	Proof of concept
TRL4	Pre-prototype
TRL5	Pre-prototype tested in lab
TRL6	Prototype tested in relevant environment
TRL7	Approved prototype
TRL8	Pre-serial manufacturing
TRL9	Product on market

To safely implement this methodology, it is necessary to make certain assumptions to accurately link existing developments with their respective TRLs. This approach helps mitigate potential pitfalls and errors in the evaluation process.

- TRL1–4: Assessment or demonstration of basic technological components and systems in a low-fidelity environment, development activities and prototyping. Technology performance for various ship types, proof of concept and pre-prototype of compartments of ALS.
- TRL5–7: Development activities and prototyping of the technologies in realistic environments that resemble the marine environment.
- TRL8–9: Market products of the technology have been demonstrated onboard in configurations with desired fully or partially functional characteristics, receiving the necessary approvals for ship installation and tested in the marine environment. This category also includes market products repeatedly installed on board ships.

While the core mechanism of ALS is consistent, various conceptual approaches exist, such as ALS, passive ALS, and ACS, as outlined in Section 2.3. Based on the number of installations, as illustrated in Figure 2-25, ALS can be classified as TRL 8–9, with installations on more than 300 vessels across various ship types, while passive ALS and ACS must be classified as TRL 5-7 due to the limited market share. Multiple vendors are active in the market, working alongside research institutions, classification societies, and universities to enhance system performance by improving the understanding of air–water mixture dynamics along the hull bottom. Operational data suggests that risks associated with ALS are minimal; however, opinions remain divided regarding its actual fuel-saving potential.

[3] TRL | EURAXESS

2.6.3 Availability conclusions

Active ALS have a high level of technological maturity, classified as TRL 8–9, meaning they are proven and ready for full-scale application. More than 300 vessels are currently equipped or retrofitted with Active ALS, and approximately 300 additional installations are on order. Passive ALS and ACS, owing to the limited market share, are classified as TRL 5-7.

There are various vendors for ALS for both newbuilds and retrofits, offering these systems to shipyards worldwide.

2.7 Technical and economic analysis of ship segments

Technical and economic analysis is to assess under which conditions the installation of ALS becomes feasible across different ship types and operational environments. The analysis aims to determine how sensitive ALS feasibility is to both current and future fuel price levels, as well as to variations in operational areas and sea states. It seeks to identify the relative advantages of ALS installation on newbuilds where lower CAPEX and access to shaft-generator power improve viability, compared to retrofits, which tend to be less favourable due to higher installation costs and reliance on diesel-generator power.

In addition, the study evaluates which vessel classes are most suited for ALS based on their operating drafts and profiles and quantifies the proportion of the global fleet for which ALS offers a payback period of less than fifteen years under a range of fuel cost and weather scenarios. Finally, the analysis estimates the potential fleet-wide fuel and CO2 savings achievable if ALS is adopted where economically justified, demonstrating that the technology could yield substantial reductions in fuel consumption and emissions by 2030 and even greater savings under high fuel-cost scenarios toward 2050.

2.7.1 Introduction to the technical and economic analysis of ALS

The technical and economic feasibility is assessed at a high-level for each individual ship of the 9,329 vessels in the dataset and aims at generalization of results of the technical analysis of the selected representative ship types (chapter 2.2.2), assessing the impact on technical and economics, assessing the technology applicability for more ship segments, and assessing trade sensitivity impact based on the verified in-service database.

The dataset was gathered from the DNV Project “1.5°C Initiative, Decarbonization Trajectories for the Shipping Industry”, efficiency and GHG reduction measures have been assessed based on the verified in-service database for 9,329 vessels from 2020, 2021 and 2022.

Data collection began on 1 January 2019. The database aggregates data such as fuel consumption, distance travelled and hours underway for individual ships of 5,000 GT and above.

The dataset has been merged with more specific data for each individual ship from publicly available Marine Fleet Registers, including owner and registration, safety and certification, construction, dimensions and tonnage, cargo and capacities, and machinery. The dataset not only aggregates total fuel consumption but also consumption by fuel type, such as heavy fuel oil (HFO), very low sulphur fuel oil (VLSFO), marine diesel oil (MDO), liquid natural gas (LNG), and liquid petroleum gas (LPG).

Relevant fuel prices are retrieved from World Bunker Prices database, and are weighted per world regions assuming the following share: 15% China (CHN), 20% Europe (EUR), 3% India (IND), 5% Latin America (LAM), 20% Middle East & Africa (MEA), 5% North America (NAM), 5% North-East Europe (NEE), 5% Ocean-Pacific Area (OPA), 20% South-East Asia (SEA), 2% Sub-Sahara Africa (SSA).

A detailed description of the technical and economic assessment methods can be found in chapters 2.6.2.2 and 2.6.3.2.

2.7.2 Technical analysis of ALS

This Section provides an overview of the technical feasibility and potential benefits of installing ALS across different vessel types.

2.7.2.1 Overview of the technical analysis workflow

The technical analysis comprises the following steps:

- Estimating the effective air length, the effective air width, and the effective air lubricated area.
- Estimating the hydrodynamic (gross) power savings [kW].
- Estimating the necessary compressor power [kW] for laden draft and ballast condition.
- Calculating the net power gains [kW] from the gross power savings, deducted by the compressor power, for laden draft and ballast conditions.
- Calculating the net fuel savings [t/day] from the gross power savings at the main engine, deducted by the additional load from the compressors, either on the shaft generator or auxiliary engines.
- The net fuel savings [t/day] are converted into annual fuel savings considering the time in transit and are then set into relation to the reported total annual fuel consumption.

The results of the technical analysis are presented in the following tables in Section 2.7.2.3. The results are clustered according to vessel classes and grouped by vessel size. For each group, the following is stated:

- Number of vessels in this group.
- Average vessel speed [knots].
- Average net power gains in [kW] and [%].
- Average net fuel oil consumption gains [t/day] for vessels with shaft generator and auxiliary diesels.
- Average net fuel oil consumption gains [%] of the total annual fuel consumption.
- Number of vessels for which ALS provides average net savings at both drafts.
- Number of vessels for which ALS provides average net savings at ballast draft only.
- Number of vessels which appear to be not feasible for ALS (average negative savings).

Three result tables are shown: the first based on the actual average speed (Table 2-14), the second based on +10% increase (Table 2-15) and the third based on +20% increase (Table 2-16) of the average vessel speed.

2.7.2.2 Description of the technical analysis method and assumptions

Within the DNV Project “VERDE” (verification of decarbonization), a simplified method for estimating ALS power gains has been developed. The method has been validated against sea-trial results available to DNV at that time (2021) and against the predicted savings provided by the project partner, Silverstream Technologies (UK). The method is continuously being updated with new results from sea and service trials.

The technical analysis of the representative ship types is therefore based on predictions and assumptions derived from the simplified method developed in “VERDE,” in collaboration with vendors, along with the predictions provided by a vendor detailed in Appendix C.

Calculating the annual net fuel gains emission savings:

- The annual net fuel gains[t/year] are calculated from the average fuel gains [t/day] per ship type and size, multiplied by the number of expected installations in this vessel class. The average fuel gains per vessel class are summed up and multiplied by an average time in transit according to AIS data for each vessel, a similar investigation as described in Section 2.5.2.3. For converting the annual net fuel gains into emissions, a factor of 3,114 t CO_2/t HFOeq. is used for Tank-to-Wake.

$$\boldsymbol{Emission\ reduction}\ [\boldsymbol{t\ CO2/year}] \\ = \boldsymbol{Anual\ net\ fuel\ gain}\ [\boldsymbol{HFO\ t/day}] \times\ \boldsymbol{Emissions\ Conversion\ Factor}[\boldsymbol{3.114t\ CO_2/t}]$$

Where:

$$\boldsymbol{Annual\ net\ fuel\ gain}\ [\boldsymbol{t/year}] = \boldsymbol{Net\ Fuel\ Gains}[\boldsymbol{t/day}]\ \times \boldsymbol{Time@Sea}[\%\ \boldsymbol{per\ year}]$$

- **Net Fuel Gains** are calculated for two different machinery options as below and an average time in transit according to AIS data per each vessel.

$$\boldsymbol{Net\ Fuel\ Gains}[\boldsymbol{mt}] = \boldsymbol{Net\ Power\ Gain}\ [\boldsymbol{kW}] \times \boldsymbol{SFOC}\ [\boldsymbol{g/kWh}]$$

- **Calculating the net fuel gains for vessels with shaft generator:** Net fuel gains are calculated from the hydrodynamic gross power gains [kW] multiplied by SFOC (assumed to be 180 g/kWh based on HFO) of the main engine, subtracted by the average compressor power [kW] multiplied by SFOC (assumed to be 193.5 g/kWh based on HFO). The higher SFOC accounts for electrical/mechanical losses between the shaft generator and the consumer.

- **Calculating the net fuel gains for vessels with auxiliary diesels:** Net fuel gains are calculated from the hydrodynamic gross power gains [kW] multiplied with SFOC (assumed to be 180 g/kWh based on HFO) of the main engine, subtracted by the average compressor power [kW] multiplied with SFOC (assumed to be 215 g/kWh based on HFO) of the auxiliary engines.

- **The net power gains** are calculated as the difference between the "Hydrodynamic gross power gains" and the "Compressor power". Net power gains are calculated separately for the laden and ballast conditions, according to the defined operational profile for each vessel type.

$$\boldsymbol{Net\ Power\ Gain}[\boldsymbol{kW}] = \boldsymbol{Hydrodynamic\ gross\ power\ gain}[\boldsymbol{kW}] - \boldsymbol{Compressor\ power}[\boldsymbol{kW}]$$

- **Methods and assumptions for calculating the hydrodynamic gross power gains[4].** The following formula is to be used to estimate the gross power gains in kW:

$$\boldsymbol{Gross\ Power\ Gains}[\boldsymbol{kW}] = \boldsymbol{rho/2} \times \boldsymbol{v}^3 \times \boldsymbol{cf} \times \boldsymbol{etaALS} \times \boldsymbol{Effective\ air\ area}\ [\boldsymbol{m}^2]\ /\ \mathbf{1000}\ /\ \boldsymbol{etaD}$$

Where:

- Rho[t/m³]: the density of the seawater.
- v[m/s]: the vessel's speed .
- cf [-]: the frictional resistance coefficient as per Hughes friction line.
- etaALS [-]: ALS efficiency .
- Effective air area [m²] = Effective air length [m] * Effective air width [m] * $\sqrt[2]{CB}$.
- EtaD[-]: the total efficiency in calm water from model test report or CFD etc. is assumed to be 0.75 Tfor all vessel type and sizes throughout (for the purpose of this study).
- The effective air length [m] is assumed to be:
  - The minimum of : 0.4 x LOA [m] and 75 [m] for vessel length below 240 m.
  - The minimum of : 0.5 x LOA [m] and 130 [m] for vessel length above 240 m.
- The effective air width [m] is assumed to be:
  - Breadth moulded [m] – 2 x Bilge radius [m] for vessel length below 200 m.
  - Breadth moulded [m] – 2 x Bilge radius [m] for vessel length above 200 m (for Gas carriers).
  - Breadth moulded [m] – 4 x Bilge radius [m] for vessel length above 200 m (all other vessel types).
- CB[-] is the block coefficient at scantling draft referring to LPP.
- Efficiency of the air layer reducing the frictional resistance (EtaALS) to be:
  - EtaALS = 0.705 for vessel length below 240 m.
  - EtaALS = 0.585 for vessel length above 240 m.

- **Calculating the compressor power[5].** The compressor power is estimated based on the following formula:

$$\boldsymbol{Compressor\ P}\ [\boldsymbol{kW}] = \mathbf{0.00026} \times \boldsymbol{Effective\ air\ width}\ [\boldsymbol{m}] \times \boldsymbol{v} \times (\boldsymbol{T}/\mathbf{10}) \times \boldsymbol{Effective\ air\ length\ ratio}\ [-]$$

[4] Formula was developed using vendor-provided inputs (see Appendix A and C) and DNV's experience to estimate Gross power gain[kW] across various ship types and sizes.
[5] Formula was developed using vendor-provided inputs (see Appendix A and C) and DNV's experience to estimate Compressor power[kW] across various ship types and sizes.

Where:

- 0,00026 is a factor developed based on inputs of compressor power and net saving potential etc. from vendors.
- Effective air length ratio [-] = Effective air length [m] / 70 [m].
- v [m/s]: the vessel's speed .
- T [m]: the actual draft for laden and for ballast condition.

2.7.2.3 Result tables of the technical analysis

Table 2-14 Technical analysis based on the actual speed of vessels

Row Labels	Count of IMO_No	Average of vessel speed [knots]	Average of P gains [kW]	Average of P gains [%]	Average of FOC gains shaft gen [t/day]	Average of FOC gains shaft gen [%]	Average of FOC gains aux eng [t/day]	Average of FOC gains aux eng [%]	No of ALS for all drafts [---]	No of ALS for ballast [---]	No of ALS not suited [---]
Bulk carrier	**2.374**	**11,4**	**93**	**1,6%**	**0,35**	**1,4%**	**0,28**	**1,1%**	**1.702**	**650**	**22**
Handysize (10-40k dwt)	492	11,5	113	2,5%	0,45	2,3%	0,40	2,0%	491	1	0
Handymax (40-65k dwt)	703	11,5	118	2,1%	0,45	1,9%	0,37	1,6%	693	10	0
Panamax (65-100k dwt)	591	11,4	82	1,2%	0,30	1,1%	0,23	0,8%	476	114	1
Capesize (100-210k dwt)	479	11,1	55	0,6%	0,18	0,4%	0,10	0,2%	3	466	10
MR GDCS (6-9k dwt)	2	11,1	55	1,7%	0,23	1,6%	0,21	1,5%	2	0	0
LR GDCS (>9k dwt)	6	10,6	65	1,6%	0,26	1,5%	0,23	1,3%	6	0	0
Liner MPP (>25t SWL / >22k dwt)	21	11,5	115	2,3%	0,46	2,1%	0,40	1,8%	21	0	0
VLBC (>210k dwt)	70	11,4	58	0,4%	0,18	0,3%	0,08	0,1%	0	59	11
Light MPP (25-100t SWL)	1	11,7	80	2,6%	0,33	2,4%	0,30	2,3%	1	0	0
Open Hatch Carrier	3	12,0	120	2,0%	0,48	1,8%	0,42	1,6%	3	0	0
Minibulker (<10k dwt)	6	10,3	40	2,4%	0,16	2,2%	0,15	2,0%	6	0	0
Container ship	**2.185**	**14,3**	**101**	**1,1%**	**0,33**	**0,9%**	**0,19**	**0,6%**	**1.936**	**223**	**26**
<3k TEU	1.003	13,2	79	1,6%	0,30	1,4%	0,24	1,1%	927	67	9
3-8k TEU	587	15,1	98	0,8%	0,31	0,6%	0,15	0,3%	518	66	3
8-12k TEU	345	16,0	167	0,8%	0,52	0,6%	0,24	0,3%	328	15	2
12-15k TEU	169	15,2	106	0,5%	0,28	0,3%	0,03	0,0%	115	51	3
15-20k TEU	52	13,9	78	0,3%	0,19	0,2%	-0,03	0,0%	29	15	8
>20k TEU	29	14,8	112	0,3%	0,28	0,2%	-0,01	0,0%	19	9	1
Tanker (chemical)	**1.204**	**11,6**	**96**	**1,9%**	**0,38**	**1,7%**	**0,32**	**1,5%**	**1.185**	**18**	**1**
Handysize (10-55k dwt)	1.133	11,6	99	1,9%	0,39	1,7%	0,33	1,5%	1.116	16	1
Panamax (55-85k dwt)	12	12,1	128	1,5%	0,49	1,4%	0,40	1,1%	12	0	0
Small Tanker (2-10k dwt)	59	10,8	44	1,7%	0,18	1,6%	0,17	1,4%	57	2	0
Tanker (oil)	**1.233**	**11,4**	**69**	**0,8%**	**0,24**	**0,7%**	**0,17**	**0,5%**	**249**	**956**	**28**
Handysize (10-55k dwt)	116	11,3	97	1,9%	0,38	1,7%	0,32	1,5%	107	9	0
Panamax (55-85k dwt)	130	11,5	84	1,1%	0,31	1,0%	0,24	0,7%	109	19	2
Aframax Crude (85-125k dwt)	219	10,9	62	0,8%	0,23	0,7%	0,17	0,5%	11	205	3
Coated Aframax (85-125k dwt)	196	11,4	77	0,9%	0,29	0,8%	0,22	0,6%	6	189	1
Suezmax (125-200k dwt)	260	11,4	71	0,6%	0,26	0,5%	0,18	0,4%	0	257	3
UL/VLCC (>200k dwt)	295	11,6	50	0,2%	0,14	0,2%	0,04	0,0%	0	276	19
Small Tanker (2-10k dwt)	17	10,7	46	1,8%	0,19	1,7%	0,17	1,6%	16	1	0
Tanker (shuttle)	**63**	**10,2**	**33**	**0,3%**	**0,11**	**0,3%**	**0,07**	**0,1%**	**4**	**44**	**15**
Shuttle Tanker	63	10,2	33	0,3%	0,11	0,3%	0,07	0,1%	4	44	15
Tanker (other liquids)	**7**	**16,1**	**213**	**2,1%**	**0,84**	**2,0%**	**0,72**	**1,7%**	**6**	**1**	**0**
Handysize (10-55k dwt)	7	16,1	213	2,1%	0,84	2,0%	0,72	1,7%	6	1	0
General cargo ship	**610**	**11,6**	**92**	**2,0%**	**0,37**	**1,9%**	**0,33**	**1,7%**	**599**	**8**	**3**
Handysize (10-40k dwt)	1	12,0	148	2,8%	0,60	2,6%	0,54	2,4%	1	0	0
MR GDCS (6-9k dwt)	39	11,0	50	1,6%	0,21	1,6%	0,19	1,4%	38	1	0
LR GDCS (>9k dwt)	5	8,1	21	1,0%	0,08	0,9%	0,07	0,8%	3	1	1
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	51	12,6	113	2,0%	0,46	1,9%	0,42	1,7%	51	0	0
Liner MPP (>25t SWL / >22k dwt)	66	12,0	119	2,3%	0,47	2,1%	0,42	1,9%	64	2	0
Light MPP (25-100t SWL)	155	10,9	51	1,7%	0,21	1,6%	0,19	1,5%	153	1	1
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	39	12,3	87	1,9%	0,36	1,8%	0,33	1,7%	39	0	0
Open Hatch Carrier	191	11,9	120	2,2%	0,47	2,0%	0,40	1,7%	190	0	1
Deck Carrier	12	8,6	47	1,2%	0,18	1,1%	0,15	0,8%	12	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	41	13,0	115	2,5%	0,47	2,3%	0,43	2,2%	41	0	0
Other Misc.	2	14,9	281	4,1%	1,16	3,9%	1,08	3,6%	2	0	0
Short Sea GDCS (4-6k dwt)	1	12,6	49	2,2%	0,20	2,1%	0,18	1,9%	1	0	0
Other OSV	7	10,0	65	0,7%	0,24	0,6%	0,18	0,4%	4	3	0
Gas carrier	**419**	**13,6**	**177**	**2,2%**	**0,71**	**2,0%**	**0,63**	**1,8%**	**415**	**2**	**2**
LPG <5k cbm	9	11,2	39	1,8%	0,16	1,7%	0,14	1,6%	9	0	0
LPG 5-30k cbm	157	12,8	93	2,0%	0,38	1,9%	0,34	1,7%	157	0	0
LPG 30-60k cbm	68	14,0	205	2,6%	0,83	2,5%	0,75	2,2%	68	0	0
LPG >60k cbm	178	14,3	251	2,2%	1,00	2,0%	0,88	1,8%	174	2	2
LNG <40k cbm	7	13,0	90	1,9%	0,37	1,8%	0,34	1,7%	7	0	0
LNG carrier	**335**	**15,0**	**487**	**2,4%**	**1,91**	**2,2%**	**1,64**	**1,9%**	**325**	**9**	**1**
LNG 100-200k cbm	280	14,9	469	2,4%	1,84	2,2%	1,58	1,8%	271	8	1
LNG >200k cbm	45	16,1	676	2,7%	2,67	2,5%	2,31	2,1%	45	0	0
LNG <40k cbm	5	13,2	150	2,9%	0,62	2,7%	0,57	2,5%	5	0	0
LNG 40-100k cbm	4	10,5	71	1,5%	0,27	1,3%	0,21	1,0%	3	1	0
FSRU	1	14,5	388	2,0%	1,51	1,8%	1,26	1,5%	1	0	0
RoRo cargo ship (vehicle carrier)	**289**	**14,9**	**191**	**2,5%**	**0,76**	**2,3%**	**0,68**	**2,1%**	**279**	**10**	**0**
Vehicle Carrier	289	14,9	191	2,5%	0,76	2,3%	0,68	2,1%	279	10	0
RoRo cargo ship	**153**	**14,8**	**167**	**2,0%**	**0,67**	**1,9%**	**0,61**	**1,7%**	**153**	**0**	**0**
Ro-Ro Cargo	153	14,8	167	2,0%	0,67	1,9%	0,61	1,7%	153	0	0
RoRo passenger ship	**160**	**16,5**	**249**	**2,0%**	**1,01**	**1,9%**	**0,93**	**1,7%**	**160**	**0**	**0**
RoPax	142	17,0	270	2,0%	1,10	1,9%	1,00	1,7%	142	0	0
Shuttle Ferry	18	13,0	83	1,9%	0,34	1,8%	0,32	1,7%	18	0	0
Cruise passenger ship	**243**	**13,7**	**205**	**1,2%**	**0,82**	**1,1%**	**0,72**	**1,0%**	**230**	**3**	**10**
Cruise	242	13,7	206	1,2%	0,82	1,1%	0,72	1,0%	229	3	10
Other Pass./Ferry	1	11,2	50	2,5%	0,20	2,3%	0,19	2,2%	1	0	0
Refrigerated cargo carrier	**35**	**14,7**	**128**	**2,4%**	**0,51**	**2,2%**	**0,46**	**2,0%**	**35**	**0**	**0**
Refrigerated Cargo Ship	35	14,7	128	2,4%	0,51	2,2%	0,46	2,0%	35	0	0
Combination carrier	**19**	**11,5**	**83**	**1,4%**	**0,30**	**1,2%**	**0,23**	**0,9%**	**16**	**3**	**0**
Handymax (40-65k dwt)	1	11,2	108	2,4%	0,41	2,2%	0,34	1,8%	1	0	0
Panamax (65-100k dwt)	17	11,6	83	1,4%	0,30	1,2%	0,23	0,9%	15	2	0
Capesize (100-210k dwt)	1	10,6	48	0,8%	0,17	0,6%	0,11	0,4%	0	1	0
Grand Total	**9.329**	**12,7**	**120**	**1,5%**	**0,45**	**1,4%**	**0,36**	**1,1%**	**7.294**	**1.927**	**108**

Table 2-15 Technical analysis based on a +10% speed increase compared to the actual speed

Row Labels	Count of IMO_No	Average of vessel speed [knots]	Average of P gains [kW]	Average of P gains [%]	Average of FOC gains shaft gen [t/day]	Average of FOC gains shaft gen [%]	Average of FOC gains aux eng [t/day]	Average of FOC gains aux eng [%]	No of ALS for all drafts [---]	No of ALS for ballast [---]	No of ALS not suited [---]
Bulk carrier	**2.374**	**12,5**	**154**	**2,0%**	**0,60**	**1,8%**	**0,52**	**1,6%**	**1.832**	**541**	**1**
Handysize (10-40k dwt)	492	12,6	171	2,8%	0,70	2,6%	0,64	2,4%	492	0	0
Handymax (40-65k dwt)	703	12,7	189	2,6%	0,75	2,4%	0,67	2,1%	702	1	0
Panamax (65-100k dwt)	591	12,5	139	1,6%	0,53	1,4%	0,44	1,2%	578	13	0
Capesize (100-210k dwt)	479	12,2	109	0,9%	0,40	0,7%	0,31	0,6%	21	457	1
MR GDCS (6-9k dwt)	2	12,2	71	1,6%	0,29	1,6%	0,27	1,4%	2	0	0
LR GDCS (>9k dwt)	6	11,6	96	1,8%	0,39	1,7%	0,36	1,6%	6	0	0
Liner MPP (>25t SWL / >22k dwt)	21	12,7	173	2,6%	0,70	2,4%	0,64	2,2%	21	0	0
VLBC (>210k dwt)	70	12,6	124	0,7%	0,45	0,6%	0,32	0,4%	0	70	0
Light MPP (25-100t SWL)	1	12,9	103	2,5%	0,42	2,4%	0,39	2,2%	1	0	0
Open Hatch Carrier	3	13,2	182	2,3%	0,74	2,1%	0,68	2,0%	3	0	0
Minibulker (<10k dwt)	6	11,3	54	2,5%	0,22	2,4%	0,20	2,2%	6	0	0
Container ship	**2.185**	**15,8**	**131**	**1,1%**	**0,43**	**0,9%**	**0,24**	**0,6%**	**1.952**	**215**	**18**
<3k TEU	1.003	14,5	104	1,6%	0,39	1,4%	0,32	1,2%	899	95	9
3-8k TEU	587	16,6	123	0,7%	0,38	0,5%	0,18	0,3%	502	82	3
8-12k TEU	345	17,6	206	0,8%	0,62	0,5%	0,23	0,2%	340	4	1
12-15k TEU	169	16,7	151	0,6%	0,41	0,4%	0,06	0,1%	141	27	1
15-20k TEU	52	15,3	146	0,5%	0,40	0,3%	0,08	0,1%	42	6	4
>20k TEU	29	16,3	165	0,4%	0,39	0,2%	-0,05	0,0%	28	1	0
Tanker (chemical)	**1.204**	**12,7**	**147**	**2,1%**	**0,59**	**2,0%**	**0,53**	**1,8%**	**1.197**	**6**	**1**
Handysize (10-55k dwt)	1.133	12,7	151	2,2%	0,61	2,0%	0,54	1,8%	1.127	5	1
Panamax (55-85k dwt)	12	13,3	188	1,7%	0,73	1,5%	0,63	1,3%	12	0	0
Small Tanker (2-10k dwt)	59	11,9	58	1,7%	0,24	1,6%	0,22	1,4%	58	1	0
Tanker (oil)	**1.233**	**12,5**	**124**	**1,0%**	**0,46**	**0,9%**	**0,36**	**0,7%**	**462**	**760**	**11**
Handysize (10-55k dwt)	116	12,4	150	2,3%	0,60	2,1%	0,54	1,9%	113	3	0
Panamax (55-85k dwt)	130	12,7	131	1,3%	0,50	1,2%	0,41	1,0%	126	2	2
Aframax Crude (85-125k dwt)	219	12,0	110	1,1%	0,40	0,9%	0,31	0,7%	75	143	1
Coated Aframax (85-125k dwt)	196	12,6	137	1,2%	0,49	1,0%	0,36	0,7%	111	84	1
Suezmax (125-200k dwt)	260	12,6	127	0,8%	0,48	0,7%	0,38	0,6%	21	238	1
UL/VLCC (>200k dwt)	295	12,7	112	0,4%	0,40	0,4%	0,28	0,2%	0	289	6
Small Tanker (2-10k dwt)	17	11,7	60	1,8%	0,25	1,7%	0,23	1,6%	16	1	0
Tanker (shuttle)	**63**	**11,3**	**67**	**0,5%**	**0,24**	**0,4%**	**0,16**	**0,3%**	**11**	**47**	**5**
Shuttle Tanker	63	11,3	67	0,5%	0,24	0,4%	0,16	0,3%	11	47	5
Tanker (other liquids)	**7**	**17,7**	**272**	**2,0%**	**1,07**	**1,9%**	**0,91**	**1,7%**	**6**	**1**	**0**
Handysize (10-55k dwt)	7	17,7	272	2,0%	1,07	1,9%	0,91	1,7%	6	1	0
General cargo ship	**610**	**12,8**	**130**	**2,1%**	**0,53**	**2,0%**	**0,48**	**1,8%**	**604**	**4**	**2**
Handysize (10-40k dwt)	1	13,2	218	3,1%	0,90	3,0%	0,83	2,8%	1	0	0
MR GDCS (6-9k dwt)	39	12,1	66	1,7%	0,27	1,6%	0,25	1,5%	38	1	0
LR GDCS (>9k dwt)	5	8,9	32	1,2%	0,13	1,1%	0,12	1,0%	3	2	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	51	13,8	149	2,0%	0,61	1,9%	0,55	1,7%	51	0	0
Liner MPP (>25t SWL / >22k dwt)	66	13,2	172	2,6%	0,69	2,4%	0,63	2,2%	66	0	0
Light MPP (25-100t SWL)	155	12,0	68	1,8%	0,28	1,7%	0,26	1,5%	153	1	1
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	39	13,5	113	1,9%	0,46	1,8%	0,42	1,6%	39	0	0
Open Hatch Carrier	191	13,0	177	2,5%	0,71	2,3%	0,63	2,1%	190	0	1
Deck Carrier	12	9,4	75	1,5%	0,30	1,4%	0,27	1,2%	12	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	41	14,3	150	2,4%	0,61	2,3%	0,56	2,1%	41	0	0
Other Misc.	2	16,4	363	4,0%	1,49	3,8%	1,38	3,5%	2	0	0
Short Sea GDCS (4-6k dwt)	1	13,8	63	2,2%	0,26	2,0%	0,23	1,8%	1	0	0
Other OSV	7	11,0	115	0,9%	0,43	0,8%	0,35	0,7%	7	0	0
Gas carrier	**419**	**15,0**	**229**	**2,1%**	**0,92**	**2,0%**	**0,81**	**1,8%**	**417**	**1**	**1**
LPG <5k cbm	9	12,3	50	1,8%	0,20	1,7%	0,18	1,5%	9	0	0
LPG 5-30k cbm	157	14,1	121	1,9%	0,49	1,8%	0,44	1,6%	157	0	0
LPG 30-60k cbm	68	15,3	266	2,6%	1,07	2,4%	0,97	2,2%	68	0	0
LPG >60k cbm	178	15,7	325	2,2%	1,29	2,0%	1,13	1,7%	176	1	1
LNG <40k cbm	7	14,3	116	1,9%	0,47	1,8%	0,43	1,6%	7	0	0
LNG carrier	**335**	**16,5**	**742**	**2,9%**	**2,99**	**2,7%**	**2,68**	**2,4%**	**332**	**2**	**1**
LNG 100-200k cbm	280	16,4	718	2,9%	2,89	2,6%	2,59	2,3%	277	2	1
LNG >200k cbm	45	17,7	1.010	3,1%	4,07	2,8%	3,67	2,6%	45	0	0
LNG <40k cbm	5	14,5	198	2,9%	0,81	2,7%	0,75	2,5%	5	0	0
LNG 40-100k cbm	4	11,6	120	2,0%	0,47	1,7%	0,40	1,4%	4	0	0
FSRU	1	16,0	617	2,4%	2,48	2,2%	2,21	2,0%	1	0	0
RoRo cargo ship (vehicle carrier)	**289**	**16,4**	**245**	**2,4%**	**0,97**	**2,2%**	**0,86**	**2,0%**	**280**	**9**	**0**
Vehicle Carrier	289	16,4	245	2,4%	0,97	2,2%	0,86	2,0%	280	9	0
RoRo cargo ship	**153**	**16,3**	**216**	**2,0%**	**0,87**	**1,9%**	**0,78**	**1,7%**	**153**	**0**	**0**
Ro-Ro Cargo	153	16,3	216	2,0%	0,87	1,9%	0,78	1,7%	153	0	0
RoRo passenger ship	**160**	**18,2**	**321**	**1,9%**	**1,30**	**1,8%**	**1,19**	**1,7%**	**160**	**0**	**0**
RoPax	142	18,6	348	1,9%	1,41	1,8%	1,28	1,7%	142	0	0
Shuttle Ferry	18	14,4	109	1,9%	0,45	1,8%	0,42	1,7%	18	0	0
Cruise passenger ship	**243**	**15,0**	**280**	**1,2%**	**1,12**	**1,2%**	**0,99**	**1,0%**	**235**	**4**	**4**
Cruise	242	15,0	281	1,2%	1,12	1,2%	0,99	1,0%	234	4	4
Other Pass./Ferry	1	12,3	64	2,4%	0,26	2,3%	0,25	2,1%	1	0	0
Refrigerated cargo carrier	**35**	**16,1**	**164**	**2,3%**	**0,66**	**2,1%**	**0,58**	**1,9%**	**35**	**0**	**0**
Refrigerated Cargo Ship	35	16,1	164	2,3%	0,66	2,1%	0,58	1,9%	35	0	0
Combination carrier	**19**	**12,7**	**138**	**1,8%**	**0,53**	**1,6%**	**0,44**	**1,3%**	**18**	**1**	**0**
Handymax (40-65k dwt)	1	12,4	175	3,0%	0,70	2,7%	0,61	2,4%	1	0	0
Panamax (65-100k dwt)	17	12,8	139	1,7%	0,53	1,5%	0,44	1,3%	17	0	0
Capesize (100-210k dwt)	1	11,6	88	1,1%	0,33	0,9%	0,27	0,8%	0	1	0
Grand Total	**9.329**	**13,9**	**176**	**1,7%**	**0,68**	**1,5%**	**0,56**	**1,3%**	**7.694**	**1.591**	**44**

Table 2-16 Technical analysis based on a +20% speed increase compared to the actual speed

Row Labels	Count of IMO_No	Average of vessel speed [knots]	Average of P gains [kW]	Average of P gains [%]	Average of FOC gains shaft gen [t/day]	Average of FOC gains shaft gen [%]	Average of FOC gains aux eng [t/day]	Average of FOC gains aux eng [%]	No of ALS for all drafts [---]	No of ALS for ballast [---]	No of ALS not suited [---]
Bulk carrier	**2.374**	**13,7**	**217**	**2,1%**	**0,86**	**2,0%**	**0,74**	**1,7%**	**1.989**	**385**	**0**
Handysize (10-40k dwt)	492	13,8	227	2,9%	0,93	2,7%	0,86	2,5%	492	0	0
Handymax (40-65k dwt)	703	13,8	261	2,8%	1,05	2,6%	0,95	2,3%	703	0	0
Panamax (65-100k dwt)	591	13,7	186	1,7%	0,72	1,5%	0,60	1,2%	589	2	0
Capesize (100-210k dwt)	479	13,3	184	1,1%	0,68	1,0%	0,52	0,7%	154	325	0
MR GDCS (6-9k dwt)	2	13,3	90	1,6%	0,37	1,5%	0,34	1,4%	2	0	0
LR GDCS (>9k dwt)	6	12,7	125	1,8%	0,51	1,7%	0,48	1,6%	6	0	0
Liner MPP (>25t SWL / >22k dwt)	21	13,8	232	2,7%	0,95	2,6%	0,88	2,4%	21	0	0
VLBC (>210k dwt)	70	13,7	215	1,0%	0,79	0,8%	0,61	0,6%	12	58	0
Light MPP (25-100t SWL)	1	14,1	130	2,4%	0,53	2,3%	0,49	2,1%	1	0	0
Open Hatch Carrier	3	14,4	238	2,3%	0,97	2,2%	0,89	2,0%	3	0	0
Minibulker (<10k dwt)	6	12,3	70	2,5%	0,28	2,4%	0,26	2,2%	6	0	0
Container ship	**2.185**	**17,2**	**157**	**1,1%**	**0,50**	**0,9%**	**0,26**	**0,6%**	**1.853**	**311**	**21**
<3k TEU	1.003	15,8	130	1,5%	0,49	1,4%	0,40	1,1%	842	150	11
3-8k TEU	587	18,1	146	0,7%	0,45	0,5%	0,19	0,2%	471	110	6
8-12k TEU	345	19,2	240	0,7%	0,68	0,5%	0,19	0,1%	333	11	1
12-15k TEU	169	18,2	176	0,5%	0,45	0,3%	0,02	0,0%	132	36	1
15-20k TEU	52	16,6	178	0,5%	0,46	0,3%	0,02	0,0%	47	3	2
>20k TEU	29	17,8	185	0,3%	0,38	0,2%	-0,20	-0,1%	28	1	0
Tanker (chemical)	**1.204**	**13,9**	**194**	**2,2%**	**0,78**	**2,0%**	**0,70**	**1,8%**	**1.201**	**3**	**0**
Handysize (10-55k dwt)	1.133	13,9	199	2,2%	0,80	2,1%	0,72	1,9%	1.130	3	0
Panamax (55-85k dwt)	12	14,5	235	1,6%	0,92	1,5%	0,77	1,2%	12	0	0
Small Tanker (2-10k dwt)	59	13,0	74	1,7%	0,30	1,6%	0,27	1,4%	59	0	0
Tanker (oil)	**1.233**	**13,6**	**201**	**1,3%**	**0,76**	**1,1%**	**0,60**	**0,9%**	**763**	**465**	**5**
Handysize (10-55k dwt)	116	13,6	202	2,4%	0,82	2,2%	0,73	2,0%	114	2	0
Panamax (55-85k dwt)	130	13,8	168	1,3%	0,64	1,2%	0,53	1,0%	128	1	1
Aframax Crude (85-125k dwt)	219	13,1	189	1,5%	0,70	1,3%	0,54	1,0%	162	56	1
Coated Aframax (85-125k dwt)	196	13,7	240	1,6%	0,90	1,4%	0,70	1,1%	180	15	1
Suezmax (125-200k dwt)	260	13,7	216	1,1%	0,79	0,9%	0,59	0,7%	159	101	0
UL/VLCC (>200k dwt)	295	13,9	191	0,6%	0,73	0,5%	0,60	0,4%	3	290	2
Small Tanker (2-10k dwt)	17	12,8	77	1,8%	0,31	1,7%	0,29	1,6%	17	0	0
Tanker (shuttle)	**63**	**12,3**	**119**	**0,7%**	**0,44**	**0,6%**	**0,33**	**0,4%**	**21**	**41**	**1**
Shuttle Tanker	63	12,3	119	0,7%	0,44	0,6%	0,33	0,4%	21	41	1
Tanker (other liquids)	**7**	**19,4**	**339**	**2,0%**	**1,32**	**1,8%**	**1,12**	**1,6%**	**6**	**1**	**0**
Handysize (10-55k dwt)	7	19,4	339	2,0%	1,32	1,8%	1,12	1,6%	6	1	0
General cargo ship	**610**	**14,0**	**168**	**2,1%**	**0,68**	**2,0%**	**0,62**	**1,8%**	**605**	**4**	**1**
Handysize (10-40k dwt)	1	14,4	276	3,0%	1,13	2,9%	1,05	2,7%	1	0	0
MR GDCS (6-9k dwt)	39	13,2	84	1,7%	0,35	1,6%	0,32	1,5%	38	1	0
LR GDCS (>9k dwt)	5	9,8	42	1,4%	0,17	1,3%	0,16	1,1%	4	1	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	51	15,1	189	2,0%	0,77	1,8%	0,70	1,7%	51	0	0
Liner MPP (>25t SWL / >22k dwt)	66	14,4	223	2,6%	0,90	2,5%	0,82	2,2%	66	0	0
Light MPP (25-100t SWL)	155	13,1	87	1,7%	0,35	1,6%	0,33	1,5%	153	2	0
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	39	14,8	142	1,8%	0,58	1,7%	0,53	1,6%	39	0	0
Open Hatch Carrier	191	14,2	231	2,5%	0,93	2,3%	0,84	2,1%	190	0	1
Deck Carrier	12	10,3	110	1,7%	0,45	1,6%	0,41	1,5%	12	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	41	15,6	189	2,4%	0,77	2,2%	0,71	2,0%	41	0	0
Other Misc.	2	17,9	459	3,9%	1,88	3,7%	1,74	3,4%	2	0	0
Short Sea GDCS (4-6k dwt)	1	15,1	80	2,1%	0,32	2,0%	0,29	1,8%	1	0	0
Other OSV	7	12,0	171	1,1%	0,67	1,0%	0,57	0,9%	7	0	0
Gas carrier	**419**	**16,3**	**288**	**2,1%**	**1,15**	**1,9%**	**1,01**	**1,7%**	**417**	**1**	**1**
LPG <5k cbm	9	13,4	62	1,7%	0,25	1,6%	0,23	1,5%	9	0	0
LPG 5-30k cbm	157	15,4	152	1,9%	0,61	1,8%	0,55	1,6%	157	0	0
LPG 30-60k cbm	68	16,7	335	2,5%	1,35	2,3%	1,21	2,1%	68	0	0
LPG >60k cbm	178	17,1	408	2,1%	1,61	1,9%	1,40	1,7%	176	1	1
LNG <40k cbm	7	15,6	146	1,8%	0,59	1,7%	0,54	1,6%	7	0	0
LNG carrier	**335**	**18,0**	**984**	**3,0%**	**3,98**	**2,8%**	**3,60**	**2,5%**	**334**	**0**	**1**
LNG 100-200k cbm	280	17,9	962	3,0%	3,89	2,8%	3,53	2,6%	279	0	1
LNG >200k cbm	45	19,3	1.277	3,0%	5,13	2,8%	4,60	2,5%	45	0	0
LNG <40k cbm	5	15,8	254	2,8%	1,04	2,7%	0,96	2,5%	5	0	0
LNG 40-100k cbm	4	12,7	171	2,2%	0,68	2,0%	0,59	1,7%	4	0	0
FSRU	1	17,4	894	2,7%	3,65	2,5%	3,36	2,3%	1	0	0
RoRo cargo ship (vehicle carrier)	**289**	**17,8**	**307**	**2,4%**	**1,22**	**2,2%**	**1,06**	**1,9%**	**275**	**14**	**0**
Vehicle Carrier	289	17,8	307	2,4%	1,22	2,2%	1,06	1,9%	275	14	0
RoRo cargo ship	**153**	**17,8**	**272**	**2,0%**	**1,09**	**1,8%**	**0,98**	**1,7%**	**153**	**0**	**0**
Ro-Ro Cargo	153	17,8	272	2,0%	1,09	1,8%	0,98	1,7%	153	0	0
RoRo passenger ship	**160**	**19,8**	**405**	**1,9%**	**1,64**	**1,8%**	**1,48**	**1,6%**	**160**	**0**	**0**
RoPax	142	20,3	439	1,9%	1,77	1,8%	1,60	1,6%	142	0	0
Shuttle Ferry	18	15,7	139	1,9%	0,57	1,8%	0,53	1,7%	18	0	0
Cruise passenger ship	**243**	**16,4**	**360**	**1,3%**	**1,44**	**1,2%**	**1,27**	**1,0%**	**239**	**2**	**2**
Cruise	242	16,4	362	1,3%	1,44	1,2%	1,28	1,0%	238	2	2
Other Pass./Ferry	1	13,5	81	2,3%	0,33	2,2%	0,31	2,1%	1	0	0
Refrigerated cargo carrier	**35**	**17,6**	**206**	**2,2%**	**0,82**	**2,1%**	**0,73**	**1,8%**	**35**	**0**	**0**
Refrigerated Cargo Ship	35	17,6	206	2,2%	0,82	2,1%	0,73	1,8%	35	0	0
Combination carrier	**19**	**13,8**	**179**	**1,8%**	**0,69**	**1,6%**	**0,57**	**1,3%**	**18**	**1**	**0**
Handymax (40-65k dwt)	1	13,5	256	3,4%	1,04	3,2%	0,95	2,9%	1	0	0
Panamax (65-100k dwt)	17	13,9	177	1,7%	0,68	1,5%	0,56	1,2%	17	0	0
Capesize (100-210k dwt)	1	12,7	137	1,3%	0,54	1,2%	0,48	1,0%	0	1	0
Grand Total	**9.329**	**15,2**	**235**	**1,8%**	**0,91**	**1,6%**	**0,75**	**1,4%**	**8.069**	**1.228**	**32**

2.7.2.4 Conclusions from the technical analysis

From the technical analysis, it can be concluded that installing an ALS on board ships appears feasible for almost 99% of the vessels analyzed in the Section and provides net power gains. It is expected that ALS is effective in approximately 78% of cases across all drafts (laden and ballast), and in about 20% of cases at ballast draft only. In roughly 1% of cases, ALS has been found to be unfeasible from a technical perspective.

Especially for container vessels, bulk carriers, and tankers, it is advisable to investigate whether ALS is expected to be effective at all drafts or only at ballast conditions. According to the technical analysis, ALS appears feasible at all drafts for 90% of container vessels and 73% of bulk carriers, but only for 22% of tankers.

The expected net power gains are larger when the electric power to serve the compressors is generated by a shaft generator. The expected net power gains are lower when the electric power is generated by the auxiliary diesel engines. This is due to the higher specific fuel oil consumption of the auxiliary diesel engines compared with the main engine driving the shaft generator. Increasing the average service speed by 10% or 20% slightly increases the number of vessels for which ALS appears feasible.

Based on the 9,329 vessels in the dataset, fitting or retrofitting an ALS where technically feasible could save 1.1 million tonnes of fuel annually, equivalent to 3.5 million tonnes of CO2. The potential savings will increase as the average service speed increases.

2.7.3 Economic analysis of ALS

The economic analysis focuses on identifying when ALS installation is financially viable across ship types and operating conditions, examining its strong dependence on current and future fuel prices as well as on operational areas and sea states. The study also compares the greater economic benefits for newbuilds, owing to lower CAPEX and access to shaft-generator power, with the generally less favourable economics of retrofits.

2.7.3.1 Overview of the economic analysis workflow

The economic analysis comprises the following steps:

- Estimating the CAPEX and OPEX of the system, as per the technical assumptions (ALS suitable for all drafts or suitable for ballast draft only). For CAPEX, it is further differentiated between newbuilds (assuming the compressors are served by a shaft generator) and retrofit cases (assuming the compressors are served by auxiliary engines).
- The economic suitability is demonstrated by calculating the NPV (net present value) of the incoming and outgoing costs over a payback period of 15 years[6].
- Incoming costs are the saved penalties from EU ETS and Fuel EU and saved fuel costs.
- Outgoing costs are the operating and maintenance costs of the ALS, annual instalment payments, and Interest (assumed 8% interest rate[7]).

The incoming and outgoing costs for calculating the NPV are discounted by 8%[8]. When the NPV is positive at the end of the assumed 15-year payback period, it is concluded that the investment in an ALS is economically feasible.

The economic analysis is performed under different scenarios, and the results of the economic analysis are presented in the following tables in Section 2.7.3.3:

- The operating capability of the ALS is independent of the sea state.
- The operating capability of the ALS is reduced if the significant wave height exceeds 1% of the vessel's length.
- The reduced operating capability is estimated for the following operation areas:
    - Tropical conditions.

[6] The assumptions applied are consistent with the EMSA study (WAPS for Shipping). As ALS is an emerging energy-efficiency technology, its capital costs are expected to decrease over time, driven by higher order volumes and increasingly stringent environmental regulations.
[7] The interest rate between 5-10% is commonly using. e.g. Maritime Forecast for 2030-2050" (edition 2024) used 7%
[8] The discount rate between 5-10% is commonly using.

  - North Sea area.
  - Nordic Oceans (like North Atlantic or North Pacific).
- The NPV is calculated for different fuel cost scenarios:
  - Current fuel costs as per the fuel mix reported to the verified in-service database.
  - Scenario 2030: assuming a share of 30% carbon neutral and 70% fossil fuel.
  - Scenario 2050: assuming a 100% application of carbon-neutral fuel.
- For the scenarios 2030 and 2050, a “low” and a “high” cost level have been assumed:
  - Scenario 2030: low 400 EUR/t and high 1,000 EUR/t cost level.
  - Scenario 2050: low 700 EUR/t, medium 1,350 EUR/t and high 2,000 EUR/t cost level.

2.7.3.2 Description of the economic analysis method and assumptions

Calculating the payback time: On the basis of the NPV, the payback time is calculated. It is assumed that if the payback time is below threshold (15 years) then ALS will be installed. Due to different CAPEX for newbuilds and retrofit the number of the expected installations is different in both cases.

- **Net Present Value (NPV):** NPV calculates the present value of all future cash flows discounted back to today and deducts the initial investment as follows.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1-i)^t} - C_0$$

Where:

  - Rt = Net cash flow at time t = OPEX + Interest for loan (8%) in Amortization period of 5 years + Cost for EU ETS and FuelEU– Cost of fuel reduction from the net gains.
  - i = Discount rate (8%, referring to DNV Maritime Forecast 2050).
  - t = Number of years after ALS installation.
  - C0 = Initial investment at t=0 (CAPEX).
  - n = Lifetime of vessels.

- **Cost Estimation:** Overview (budgetary) CAPEX and OPEX, newbuilding and retrofit applications. The cost estimation is used for payback calculations. The cost estimation is based on information received from one vendor. The other vendors did not provide any input on the costs. The above-mentioned CAPEX includes the vendor scope for the system only, i.e. engineering, parts and components, documentation, and commissioning costs for integrator engineering.

  For yards costs (installation, piping, valves and possible docking costs) in China a markup of +40% is considered in case of a newbuilding, and a markup of +80% is considered in case of a retrofit. The relationship of yards costs in China, Singapore and Europe can be assumed to be 100%, 140% and 170% respectively.

  For the economic analysis the following equation[9] applies for estimating the CAPEX.

$$\boldsymbol{CAPEX}[€] = \boldsymbol{k1} \times \boldsymbol{k2} \times \boldsymbol{k3} \times \boldsymbol{effective\ air\ width}\ [\boldsymbol{m}] \times \boldsymbol{sqrt}(\boldsymbol{T}\ [\boldsymbol{m}]\ + \mathbf{12}) \times \sqrt[2]{\boldsymbol{V}\ [\boldsymbol{kn}]}) \times\ \mathbf{1,000}$$

  - With factor k1 depending on the ship type and size:
    - k1 = 1.20 for vessel length below 240 m.
    - k1 = 1.65 for vessel length above 240 m, vessel type : Container vessel.
    - k1 = 1.75 for vessel length above 240 m, vessel type : Gas carrier including LNGC, LPGC, etc.
    - k1 = 2.20 for vessel length above 240 m, all other vessel types.
  - With factor k2 depending on system layout:
    - k2 = 1.00 for system layout for laden & ballast draught.
    - k2 = 0.75 for system layout for ballast draught only.

[9] Formula was developed using vendor-provided inputs (see Appendix C) to estimate CAPEX across various ship types and sizes.

- With factor k3 accounting for yards costs for new building or retrofit:
    - k3 = 1.40 for newbuilds.
    - k3 = 1.80 for retrofit.
- T: Summer load draft in meter.
- V: Design speed in knots.
- CAPEX is rounded to the next € 50,000.
- OPEX10 annually is assumed to be 0.90% of the system costs and is rounded to the next € 50.

- **Fuel costs:** Three fuel cost alternatives in Table 2-17 Scenarios of fuel costs are applied in the economic analysis. The estimated fuel cost for future blended and carbon neutral fuel costs are aligned with the projection in DNV's "Maritime Forecast for 2030-2050" (edition 2024), page 65, figure A-2, as updated projections in 2025 edition were not available at the time of writing.

Table 2-17 Scenarios of fuel costs

Fuel alternatives	HFO[EUR/t]	MDO[EUR/t]	LNG[EUR/t]
Current fuel costs	357	480	728
2030 Scenario: 30/70% share carbon neutral / fossil	min 400 EUR/t, max. 1,000 EUR/t		
2050 Scenario: 100% carbon neutral fuel	min 700 EUR/t, mean 1,350 EUR/t, max. 2,000 EUR/t		

- **EU ETS and FuelEU Maritime :** The estimation considers vessels operating between EU and non-EU waters. For simplicity, 50% of total emissions, including transit and port operations, are assumed to be EU-liable under the EU ETS. The FuelEU Maritime Regulation[11] accounts for all fuel/electricity consumptions used on voyages involving at least one EU/EEA port of call toward a ship's annual GHG intensity, with 100% or 50% applicability depending on the voyage.

  'No biofuels' and 'shore power' are included in the analysis, and no correction factors are applied. The analysis uses annual fuel consumption data reported to the EU MRV system for reference vessels. Net savings from ALS apply directly to the annual consumption, thus estimating the EU ETS and FuelEU Maritime cost with and without ALS.

  The EU ETS: Assumed at EUR 91 (abt. USD 100) per tonne of CO2 equivalent (TtW) from 2025 onward, while DNV's Energy Transition Outlook 2050[12] projects carbon pricing to range from EUR 64 to EUR 238/tCO2eq (USD 70 to USD 250/tCO2eq) depending on regional and market conditions from 2025 onward. Surrender percentage of 70% in 2025, 100% from 2026 onward were used, which reflect the phased implementation of EU ETS for maritime emissions. 50% of total CO2 emissions are considered liable under EU ETS due to the vessel's operation in the EU and non-EU waters.

  FuelEU Maritime penalties are calculated using a penalty rate of 2,400 EUR per tonne of VLSFO-equivalent excess emissions. The analysis assumes no banking, borrowing, or pooling of compliance deficits or surpluses. Each vessel is assessed independently. Total annual energy consumption is derived from fuel use and converted using the lower calorific value of VLSFO (41,000 MJ/tonne). Methane (CH4) slip for LNG-fuelled vessels from an internal combustion engine depends on engine type (two- or four-stroke, gas turbine, or boiler), fuel (mono- or dual-fuel), and the combustion cycle (Otto or Diesel). Details of the methane slip coefficients for the combustion cycle can be found in the Guidance on the FuelEU Maritime Regulation, Annex I.

  In this high-level analysis, the current model does not distinguish between engine types (main or auxiliary) or combustion cycles (e.g., Otto or Diesel) to simplify the analysis. Instead, therefore, it was assumed a methane slip assumption of 1%[13] of the fuel's amount [% of the mass of LNG used by the engine] being slipped as methane. This unburnt methane amount is then converted to CO2 equivalent emissions using the Fuel EU formula for GHG intensity and a Global Warming Potential (GWP100) factor of 25, in line with Intergovernmental

[10] OPEX primarily consists of compressor maintenance costs.
[11] Guidance on the FuelEU Maritime Regulation https://transport.ec.europa.eu/document/download/d4426ccc-ef46-4292-8b6d-5bf7a620f5ba_en?filename=fueleu_guidance_document_for_shipping_companies.pdf
[12] DNV Energy Transition Outlook (2024 edition) https://www.dnv.com/energy-transition-outlook/
[13] A conservative value of 1% is applied, calculated as an average of Otto-cycle and diesel-cycle slow-speed engines, assuming a 50% contribution from diesel-cycle engines in both the existing and future fleet.

Panel on Climate Change Fourth Assessment Report (IPCC AR4) and EU regulatory standards (RED Annex V for Fuel EU).

For HFO and MDO fuels, it is assumed that CH4 and nitrous oxide (N2O) emissions are taken into consideration by increasing about 2%[14] more the CO2 emissions calculated with an emission factor (for HFO equal to 3,114 g CO2/g HFO and for MDO equal to 3,206 gCO2/g fuel – See Table Annex II Fuel EU Maritime Regulation - HFO and MDO fuel types).

For HFO and MDO, calculating only CO2 emissions and then increasing them by 2% is a reliable estimate of the contribution of CH4 and N2O for engines with no methane slippage.

If a vessel exceeds the GHG intensity target, the excess emissions are converted into VLSFO-equivalent tonnes and multiplied by the penalty rate. It is assumed that the vessels are operating as incoming or outgoing of the EU/EEA voyage area, and therefore, only 50% of the energy used on voyages is in scope. The formula and details of FuelEU Maritime can be found in Section 3.2.3

- **Ship service speeds and weather impact:** The procedure for determining ALS operating capability, as outlined in Section 2.5.2.6, was applied in the analysis.

[14] Assumed based on emission factors for HFO for CH_4 and N_2O from FuelEU maritime regulation, with Global Warming Potentials according to IPCC AR GWPs

2.7.3.3 Result tables of the economic analysis

Table 2-18 Economic analysis based on **current fuel cost**, considering different weather impact

		No weather impact		Tropical Conditions		North Sea		Nordic Oceans	
Row Labels	**Average of fuel price over lifetime [EUR/t]**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**
Bulk carrier	**381**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Handysize (10-40k dwt)	394	0	0	0	0	0	0	0	0
Handymax (40-65k dwt)	383	1	1	1	1	1	1	1	1
Panamax (65-100k dwt)	383	0	0	0	0	0	0	0	0
Capesize (100-210k dwt)	363	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	425	0	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	413	0	0	0	0	0	0	0	0
Liner MPP (>25t SWL / >22k dwt)	413	0	0	0	0	0	0	0	0
VLBC (>210k dwt)	358	0	0	0	0	0	0	0	0
Light MPP (25-100t SWL)	381	0	0	0	0	0	0	0	0
Open Hatch Carrier	388	0	0	0	0	0	0	0	0
Minibulker (<10k dwt)	424	0	0	0	0	0	0	0	0
Container ship	**388**	**89**	**7**	**50**	**4**	**11**	**0**	**5**	**0**
<3k TEU	386	89	7	50	4	11	0	5	0
3-8k TEU	392	0	0	0	0	0	0	0	0
8-12k TEU	389	0	0	0	0	0	0	0	0
12-15k TEU	383	0	0	0	0	0	0	0	0
15-20k TEU	377	0	0	0	0	0	0	0	0
>20k TEU	372	0	0	0	0	0	0	0	0
Tanker (chemical)	**392**	**11**	**0**	**5**	**0**	**0**	**0**	**0**	**0**
Handysize (10-55k dwt)	390	11	0	5	0	0	0	0	0
Panamax (55-85k dwt)	365	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	435	0	0	0	0	0	0	0	0
Tanker (oil)	**383**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Handysize (10-55k dwt)	394	2	0	0	0	0	0	0	0
Panamax (55-85k dwt)	387	0	0	0	0	0	0	0	0
Aframax Crude (85-125k dwt)	405	1	0	0	0	0	0	0	0
Coated Aframax (85-125k dwt)	375	0	0	0	0	0	0	0	0
Suezmax (125-200k dwt)	375	0	0	0	0	0	0	0	0
UL/VLCC (>200k dwt)	372	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	408	0	0	0	0	0	0	0	0
Tanker (shuttle)	**400**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Shuttle Tanker	400	0	0	0	0	0	0	0	0
Tanker (other liquids)	**352**	**4**	**1**	**3**	**0**	**1**	**0**	**0**	**0**
Handysize (10-55k dwt)	352	4	1	3	0	1	0	0	0
General cargo ship	**397**	**20**	**3**	**7**	**2**	**2**	**2**	**2**	**1**
Handysize (10-40k dwt)	354	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	427	0	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	420	0	0	0	0	0	0	0	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	396	3	0	0	0	0	0	0	0
Liner MPP (>25t SWL / >22k dwt)	383	5	1	3	1	1	1	1	1
Light MPP (25-100t SWL)	395	1	0	1	0	0	0	0	0
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	370	0	0	0	0	0	0	0	0
Open Hatch Carrier	395	0	0	0	0	0	0	0	0
Deck Carrier	424	0	0	0	0	0	0	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	420	9	1	1	0	0	0	0	0
Other Misc.	402	2	1	2	1	1	1	1	0
Short Sea GDCS (4-6k dwt)	448	0	0	0	0	0	0	0	0
Other OSV	407	0	0	0	0	0	0	0	0
Gas carrier	**398**	**100**	**9**	**62**	**5**	**11**	**3**	**7**	**1**
LPG <5k cbm	539	0	0	0	0	0	0	0	0
LPG 5-30k cbm	388	13	2	3	1	1	1	1	1
LPG 30-60k cbm	366	26	2	12	0	0	0	0	0
LPG >60k cbm	411	61	5	47	4	10	2	6	0
LNG <40k cbm	444	0	0	0	0	0	0	0	0
LNG carrier	**592**	**191**	**91**	**178**	**84**	**147**	**61**	**141**	**57**
LNG 100-200k cbm	623	141	57	130	53	101	38	95	34
LNG >200k cbm	405	45	33	45	30	44	23	44	23
LNG <40k cbm	595	2	1	1	1	1	0	1	0
LNG 40-100k cbm	524	2	0	2	0	1	0	1	0
FSRU	603	1	0	0	0	0	0	0	0
RoRo cargo ship (vehicle carrier)	**397**	**176**	**93**	**151**	**65**	**102**	**20**	**77**	**5**
Vehicle Carrier	397	176	93	151	65	102	20	77	5
RoRo cargo ship	**392**	**71**	**27**	**54**	**21**	**29**	**5**	**23**	**2**
Ro-Ro Cargo	392	71	27	54	21	29	5	23	2
RoRo passenger ship	**421**	**105**	**60**	**88**	**49**	**57**	**26**	**47**	**21**
RoPax	404	105	60	88	49	57	26	47	21
Shuttle Ferry	557	0	0	0	0	0	0	0	0
Cruise passenger ship	**408**	**105**	**28**	**93**	**22**	**57**	**11**	**49**	**8**
Cruise	408	105	28	93	22	57	11	49	8
Other Pass./Ferry	448	0	0	0	0	0	0	0	0
Refrigerated cargo carrier	**352**	**14**	**9**	**12**	**5**	**8**	**4**	**5**	**1**
Refrigerated Cargo Ship	352	14	9	12	5	8	4	5	1
Combination carrier	**358**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Handymax (40-65k dwt)	386	0	0	0	0	0	0	0	0
Panamax (65-100k dwt)	352	0	0	0	0	0	0	0	0
Capesize (100-210k dwt)	425	0	0	0	0	0	0	0	0
Grand Total	**396**	**890**	**329**	**704**	**258**	**426**	**133**	**357**	**97**

Table 2-19 Economic analysis for **2030 Scenarios, low fuel cost level** (400 EUR/t), different weather impact

		No weather impact		Tropical Conditions		North Sea		Nordic Oceans	
Row Labels	**Average of fuel price over lifetime [EUR/t]**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**
Bulk carrier	**400**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Handysize (10-40k dwt)	400	0	0	0	0	0	0	0	0
Handymax (40-65k dwt)	400	1	1	1	1	1	1	1	1
Panamax (65-100k dwt)	400	0	0	0	0	0	0	0	0
Capesize (100-210k dwt)	400	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	400	0	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	400	0	0	0	0	0	0	0	0
Liner MPP (>25t SWL / >22k dwt)	400	0	0	0	0	0	0	0	0
VLBC (>210k dwt)	400	0	0	0	0	0	0	0	0
Light MPP (25-100t SWL)	400	0	0	0	0	0	0	0	0
Open Hatch Carrier	400	0	0	0	0	0	0	0	0
Minibulker (<10k dwt)	400	0	0	0	0	0	0	0	0
Container ship	**400**	**55**	**4**	**25**	**0**	**5**	**0**	**0**	**0**
<3k TEU	400	55	4	25	0	5	0	0	0
3-8k TEU	400	0	0	0	0	0	0	0	0
8-12k TEU	400	0	0	0	0	0	0	0	0
12-15k TEU	400	0	0	0	0	0	0	0	0
15-20k TEU	400	0	0	0	0	0	0	0	0
>20k TEU	400	0	0	0	0	0	0	0	0
Tanker (chemical)	**400**	**6**	**0**	**2**	**0**	**0**	**0**	**0**	**0**
Handysize (10-55k dwt)	400	6	0	2	0	0	0	0	0
Panamax (55-85k dwt)	400	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	400	0	0	0	0	0	0	0	0
Tanker (oil)	**400**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Handysize (10-55k dwt)	400	1	0	0	0	0	0	0	0
Panamax (55-85k dwt)	400	0	0	0	0	0	0	0	0
Aframax Crude (85-125k dwt)	400	0	0	0	0	0	0	0	0
Coated Aframax (85-125k dwt)	400	0	0	0	0	0	0	0	0
Suezmax (125-200k dwt)	400	0	0	0	0	0	0	0	0
UL/VLCC (>200k dwt)	400	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	400	0	0	0	0	0	0	0	0
Tanker (shuttle)	**400**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Shuttle Tanker	400	0	0	0	0	0	0	0	0
Tanker (other liquids)	**400**	**4**	**1**	**3**	**0**	**1**	**0**	**0**	**0**
Handysize (10-55k dwt)	400	4	1	3	0	1	0	0	0
General cargo ship	**400**	**7**	**2**	**4**	**2**	**2**	**1**	**1**	**1**
Handysize (10-40k dwt)	400	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	400	0	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	400	0	0	0	0	0	0	0	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	400	0	0	0	0	0	0	0	0
Liner MPP (>25t SWL / >22k dwt)	400	2	1	1	1	1	1	1	1
Light MPP (25-100t SWL)	400	1	0	0	0	0	0	0	0
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	400	0	0	0	0	0	0	0	0
Open Hatch Carrier	400	0	0	0	0	0	0	0	0
Deck Carrier	400	0	0	0	0	0	0	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	400	2	0	1	0	0	0	0	0
Other Misc.	400	2	1	2	1	1	0	0	0
Short Sea GDCS (4-6k dwt)	400	0	0	0	0	0	0	0	0
Other OSV	400	0	0	0	0	0	0	0	0
Gas carrier	**400**	**70**	**5**	**36**	**3**	**5**	**1**	**1**	**1**
LPG <5k cbm	400	0	0	0	0	0	0	0	0
LPG 5-30k cbm	400	9	1	2	1	1	1	1	1
LPG 30-60k cbm	400	21	1	9	0	0	0	0	0
LPG >60k cbm	400	40	3	25	2	4	0	0	0
LNG <40k cbm	400	0	0	0	0	0	0	0	0
LNG carrier	**400**	**63**	**34**	**63**	**30**	**57**	**17**	**37**	**13**
LNG 100-200k cbm	400	17	3	17	2	13	0	3	0
LNG >200k cbm	400	45	30	45	28	44	17	34	13
LNG <40k cbm	400	1	1	1	0	0	0	0	0
LNG 40-100k cbm	400	0	0	0	0	0	0	0	0
FSRU	400	0	0	0	0	0	0	0	0
RoRo cargo ship (vehicle carrier)	**400**	**159**	**61**	**130**	**26**	**75**	**1**	**6**	**0**
Vehicle Carrier	400	159	61	130	26	75	1	6	0
RoRo cargo ship	**400**	**63**	**21**	**42**	**14**	**23**	**5**	**8**	**1**
Ro-Ro Cargo	400	63	21	42	14	23	5	8	1
RoRo passenger ship	**400**	**90**	**50**	**76**	**39**	**45**	**19**	**25**	**11**
RoPax	400	90	50	76	39	45	19	25	11
Shuttle Ferry	400	0	0	0	0	0	0	0	0
Cruise passenger ship	**400**	**83**	**18**	**70**	**10**	**42**	**3**	**15**	**0**
Cruise	400	83	18	70	10	42	3	15	0
Other Pass./Ferry	400	0	0	0	0	0	0	0	0
Refrigerated cargo carrier	**400**	**14**	**8**	**12**	**5**	**8**	**4**	**4**	**0**
Refrigerated Cargo Ship	400	14	8	12	5	8	4	4	0
Combination carrier	**400**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Handymax (40-65k dwt)	400	0	0	0	0	0	0	0	0
Panamax (65-100k dwt)	400	0	0	0	0	0	0	0	0
Capesize (100-210k dwt)	400	0	0	0	0	0	0	0	0
Grand Total	**400**	**616**	**205**	**464**	**130**	**264**	**52**	**98**	**28**

Table 2-20 Economic analysis for **2030 Scenarios, high fuel cost level** (1,000 EUR/t), different weather impact

		No weather impact		Tropical Conditions		North Sea		Nordic Oceans	
Row Labels	**Average of fuel price over lifetime [EUR/t]**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**
Bulk carrier	**1.000**	**303**	**25**	**148**	**9**	**20**	**2**	**4**	**1**
Handysize (10-40k dwt)	1.000	181	17	97	4	12	0	0	0
Handymax (40-65k dwt)	1.000	104	6	43	5	7	2	4	1
Panamax (65-100k dwt)	1.000	7	0	4	0	0	0	0	0
Capesize (100-210k dwt)	1.000	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	1.000	0	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	1.000	1	0	1	0	0	0	0	0
Liner MPP (>25t SWL / >22k dwt)	1.000	7	1	2	0	1	0	0	0
VLBC (>210k dwt)	1.000	0	0	0	0	0	0	0	0
Light MPP (25-100t SWL)	1.000	1	0	0	0	0	0	0	0
Open Hatch Carrier	1.000	0	0	0	0	0	0	0	0
Minibulker (<10k dwt)	1.000	2	1	1	0	0	0	0	0
Container ship	**1.000**	**554**	**222**	**428**	**140**	**227**	**57**	**85**	**10**
<3k TEU	1.000	482	221	375	139	211	57	84	10
3-8k TEU	1.000	47	1	36	1	10	0	1	0
8-12k TEU	1.000	25	0	17	0	6	0	0	0
12-15k TEU	1.000	0	0	0	0	0	0	0	0
15-20k TEU	1.000	0	0	0	0	0	0	0	0
>20k TEU	1.000	0	0	0	0	0	0	0	0
Tanker (chemical)	**1.000**	**348**	**73**	**199**	**30**	**60**	**6**	**14**	**0**
Handysize (10-55k dwt)	1.000	338	72	196	30	60	6	14	0
Panamax (55-85k dwt)	1.000	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	1.000	10	1	3	0	0	0	0	0
Tanker (oil)	**1.000**	**46**	**11**	**25**	**6**	**10**	**0**	**2**	**0**
Handysize (10-55k dwt)	1.000	36	10	19	5	8	0	1	0
Panamax (55-85k dwt)	1.000	2	0	1	0	1	0	0	0
Aframax Crude (85-125k dwt)	1.000	1	1	1	1	1	0	1	0
Coated Aframax (85-125k dwt)	1.000	1	0	1	0	0	0	0	0
Suezmax (125-200k dwt)	1.000	0	0	0	0	0	0	0	0
UL/VLCC (>200k dwt)	1.000	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	1.000	6	0	3	0	0	0	0	0
Tanker (shuttle)	**1.000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Shuttle Tanker	1.000	0	0	0	0	0	0	0	0
Tanker (other liquids)	**1.000**	**7**	**5**	**7**	**5**	**7**	**4**	**5**	**1**
Handysize (10-55k dwt)	1.000	7	5	7	5	7	4	5	1
General cargo ship	**1.000**	**272**	**75**	**188**	**38**	**59**	**9**	**10**	**3**
Handysize (10-40k dwt)	1.000	1	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	1.000	6	4	5	0	0	0	0	0
LR GDCS (>9k dwt)	1.000	0	0	0	0	0	0	0	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	1.000	23	17	19	11	16	0	0	0
Liner MPP (>25t SWL / >22k dwt)	1.000	51	16	41	8	14	4	5	1
Light MPP (25-100t SWL)	1.000	40	10	22	1	4	0	0	0
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	1.000	29	2	17	0	1	0	0	0
Open Hatch Carrier	1.000	87	4	56	2	5	0	1	0
Deck Carrier	1.000	0	0	0	0	0	0	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	1.000	32	20	26	14	17	3	2	1
Other Misc.	1.000	2	2	2	2	2	2	2	1
Short Sea GDCS (4-6k dwt)	1.000	1	0	0	0	0	0	0	0
Other OSV	1.000	0	0	0	0	0	0	0	0
Gas carrier	**1.000**	**297**	**205**	**260**	**177**	**212**	**95**	**138**	**21**
LPG <5k cbm	1.000	0	0	0	0	0	0	0	0
LPG 5-30k cbm	1.000	84	40	54	28	33	10	12	1
LPG 30-60k cbm	1.000	61	46	55	41	46	26	31	6
LPG >60k cbm	1.000	148	115	147	106	131	59	95	14
LNG <40k cbm	1.000	4	4	4	2	2	0	0	0
LNG carrier	**1.000**	**261**	**182**	**256**	**169**	**233**	**140**	**189**	**102**
LNG 100-200k cbm	1.000	209	133	206	121	184	93	140	56
LNG >200k cbm	1.000	45	45	45	45	45	45	45	45
LNG <40k cbm	1.000	4	1	2	1	1	1	1	1
LNG 40-100k cbm	1.000	2	2	2	2	2	1	2	0
FSRU	1.000	1	1	1	0	1	0	1	0
RoRo cargo ship (vehicle carrier)	**1.000**	**251**	**216**	**247**	**203**	**222**	**166**	**187**	**105**
Vehicle Carrier	1.000	251	216	247	203	222	166	187	105
RoRo cargo ship	**1.000**	**127**	**106**	**124**	**94**	**109**	**66**	**77**	**36**
Ro-Ro Cargo	1.000	127	106	124	94	109	66	77	36
RoRo passenger ship	**1.000**	**135**	**122**	**128**	**114**	**122**	**91**	**98**	**65**
RoPax	1.000	133	122	128	114	122	91	98	65
Shuttle Ferry	1.000	2	0	0	0	0	0	0	0
Cruise passenger ship	**1.000**	**169**	**141**	**162**	**127**	**149**	**105**	**120**	**74**
Cruise	1.000	169	141	162	127	149	105	120	74
Other Pass./Ferry	1.000	0	0	0	0	0	0	0	0
Refrigerated cargo carrier	**1.000**	**28**	**16**	**21**	**15**	**15**	**13**	**14**	**12**
Refrigerated Cargo Ship	1.000	28	16	21	15	15	13	14	12
Combination carrier	**1.000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Handymax (40-65k dwt)	1.000	0	0	0	0	0	0	0	0
Panamax (65-100k dwt)	1.000	0	0	0	0	0	0	0	0
Capesize (100-210k dwt)	1.000	0	0	0	0	0	0	0	0
Grand Total	**1.000**	**2.798**	**1.399**	**2.193**	**1.127**	**1.445**	**754**	**943**	**430**

Table 2-21 Economic analysis for **2050 Scenarios, low fuel cost level** (700 EUR/t), different weather impact

		No weather impact		Tropical Conditions		North Sea		Nordic Oceans	
Row Labels	**Average of fuel price over lifetime [EUR/t]**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**
Bulk carrier	**700**	**36**	**3**	**11**	**1**	**3**	**1**	**1**	**1**
Handysize (10-40k dwt)	700	27	0	6	0	0	0	0	0
Handymax (40-65k dwt)	700	7	3	5	1	3	1	1	1
Panamax (65-100k dwt)	700	0	0	0	0	0	0	0	0
Capesize (100-210k dwt)	700	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	700	0	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	700	0	0	0	0	0	0	0	0
Liner MPP (>25t SWL / >22k dwt)	700	1	0	0	0	0	0	0	0
VLBC (>210k dwt)	700	0	0	0	0	0	0	0	0
Light MPP (25-100t SWL)	700	0	0	0	0	0	0	0	0
Open Hatch Carrier	700	0	0	0	0	0	0	0	0
Minibulker (<10k dwt)	700	1	0	0	0	0	0	0	0
Container ship	**700**	**282**	**77**	**178**	**37**	**77**	**5**	**17**	**0**
<3k TEU	700	278	77	175	37	76	5	17	0
3-8k TEU	700	4	0	3	0	1	0	0	0
8-12k TEU	700	0	0	0	0	0	0	0	0
12-15k TEU	700	0	0	0	0	0	0	0	0
15-20k TEU	700	0	0	0	0	0	0	0	0
>20k TEU	700	0	0	0	0	0	0	0	0
Tanker (chemical)	**700**	**96**	**11**	**41**	**5**	**11**	**0**	**2**	**0**
Handysize (10-55k dwt)	700	94	11	41	5	11	0	2	0
Panamax (55-85k dwt)	700	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	700	2	0	0	0	0	0	0	0
Tanker (oil)	**700**	**15**	**2**	**9**	**0**	**2**	**0**	**0**	**0**
Handysize (10-55k dwt)	700	11	2	8	0	1	0	0	0
Panamax (55-85k dwt)	700	1	0	0	0	0	0	0	0
Aframax Crude (85-125k dwt)	700	1	0	1	0	1	0	0	0
Coated Aframax (85-125k dwt)	700	0	0	0	0	0	0	0	0
Suezmax (125-200k dwt)	700	0	0	0	0	0	0	0	0
UL/VLCC (>200k dwt)	700	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	700	2	0	0	0	0	0	0	0
Tanker (shuttle)	**700**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Shuttle Tanker	700	0	0	0	0	0	0	0	0
Tanker (other liquids)	**700**	**7**	**4**	**7**	**3**	**5**	**1**	**3**	**0**
Handysize (10-55k dwt)	700	7	4	7	3	5	1	3	0
General cargo ship	**700**	**97**	**20**	**43**	**5**	**9**	**3**	**3**	**1**
Handysize (10-40k dwt)	700	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	700	4	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	700	0	0	0	0	0	0	0	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	700	18	2	13	0	0	0	0	0
Liner MPP (>25t SWL / >22k dwt)	700	20	5	11	1	4	1	1	1
Light MPP (25-100t SWL)	700	14	1	1	0	0	0	0	0
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	700	8	0	0	0	0	0	0	0
Open Hatch Carrier	700	9	1	2	0	1	0	0	0
Deck Carrier	700	0	0	0	0	0	0	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	700	22	9	14	2	2	1	1	0
Other Misc.	700	2	2	2	2	2	1	1	0
Short Sea GDCS (4-6k dwt)	700	0	0	0	0	0	0	0	0
Other OSV	700	0	0	0	0	0	0	0	0
Gas carrier	**700**	**218**	**95**	**184**	**64**	**113**	**9**	**37**	**3**
LPG <5k cbm	700	0	0	0	0	0	0	0	0
LPG 5-30k cbm	700	41	16	30	8	10	1	1	1
LPG 30-60k cbm	700	48	28	41	18	28	2	8	0
LPG >60k cbm	700	126	51	111	38	75	6	28	2
LNG <40k cbm	700	3	0	2	0	0	0	0	0
LNG carrier	**700**	**173**	**91**	**164**	**87**	**127**	**69**	**94**	**57**
LNG 100-200k cbm	700	124	45	116	41	79	24	48	19
LNG >200k cbm	700	45	45	45	45	45	44	45	38
LNG <40k cbm	700	1	1	1	1	1	1	1	0
LNG 40-100k cbm	700	2	0	2	0	2	0	0	0
FSRU	700	1	0	0	0	0	0	0	0
RoRo cargo ship (vehicle carrier)	**700**	**224**	**175**	**208**	**150**	**175**	**97**	**121**	**19**
Vehicle Carrier	700	224	175	208	150	175	97	121	19
RoRo cargo ship	**700**	**116**	**77**	**100**	**58**	**72**	**32**	**39**	**13**
Ro-Ro Cargo	700	116	77	100	58	72	32	39	13
RoRo passenger ship	**700**	**124**	**102**	**115**	**86**	**97**	**59**	**70**	**37**
RoPax	700	124	102	115	86	97	59	70	37
Shuttle Ferry	700	0	0	0	0	0	0	0	0
Cruise passenger ship	**700**	**144**	**99**	**140**	**86**	**113**	**51**	**85**	**26**
Cruise	700	144	99	140	86	113	51	85	26
Other Pass./Ferry	700	0	0	0	0	0	0	0	0
Refrigerated cargo carrier	**700**	**18**	**14**	**15**	**13**	**13**	**10**	**12**	**5**
Refrigerated Cargo Ship	700	18	14	15	13	13	10	12	5
Combination carrier	**700**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Handymax (40-65k dwt)	700	0	0	0	0	0	0	0	0
Panamax (65-100k dwt)	700	0	0	0	0	0	0	0	0
Capesize (100-210k dwt)	700	0	0	0	0	0	0	0	0
Grand Total	**700**	**1.550**	**770**	**1.215**	**595**	**817**	**337**	**484**	**162**

Table 2-22 Economic analysis for **2050 Scenarios, mean fuel cost level** (1,350 EUR/t), different weather impact

		No weather impact		Tropical Conditions		North Sea		Nordic Oceans	
Row Labels	**Average of fuel price over lifetime [EUR/t]**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**	**No of Newbuilds Payback NPV <15y**	**No of Retrofits Payback NPV <15y**
Bulk carrier	**1.350**	**786**	**165**	**570**	**79**	**197**	**11**	**21**	**2**
Handysize (10-40k dwt)	1.350	350	120	263	59	120	5	13	0
Handymax (40-65k dwt)	1.350	343	39	244	17	66	5	7	2
Panamax (65-100k dwt)	1.350	74	0	48	0	7	0	0	0
Capesize (100-210k dwt)	1.350	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	1.350	1	0	0	0	0	0	0	0
LR GDCS (>9k dwt)	1.350	3	1	1	0	1	0	0	0
Liner MPP (>25t SWL / >22k dwt)	1.350	11	3	10	2	2	1	1	0
VLBC (>210k dwt)	1.350	0	0	0	0	0	0	0	0
Light MPP (25-100t SWL)	1.350	1	1	1	0	0	0	0	0
Open Hatch Carrier	1.350	1	0	1	0	0	0	0	0
Minibulker (<10k dwt)	1.350	2	1	2	1	1	0	0	0
Container ship	**1.350**	**831**	**395**	**729**	**295**	**493**	**147**	**244**	**59**
<3k TEU	1.350	605	390	532	291	387	146	213	59
3-8k TEU	1.350	150	5	128	4	60	1	20	0
8-12k TEU	1.350	76	0	69	0	46	0	11	0
12-15k TEU	1.350	0	0	0	0	0	0	0	0
15-20k TEU	1.350	0	0	0	0	0	0	0	0
>20k TEU	1.350	0	0	0	0	0	0	0	0
Tanker (chemical)	**1.350**	**735**	**230**	**537**	**127**	**221**	**36**	**61**	**7**
Handysize (10-55k dwt)	1.350	699	223	521	126	218	36	61	7
Panamax (55-85k dwt)	1.350	3	0	2	0	0	0	0	0
Small Tanker (2-10k dwt)	1.350	33	7	14	1	3	0	0	0
Tanker (oil)	**1.350**	**114**	**30**	**84**	**17**	**31**	**7**	**10**	**0**
Handysize (10-55k dwt)	1.350	71	22	57	13	24	6	8	0
Panamax (55-85k dwt)	1.350	25	1	14	1	2	0	1	0
Aframax Crude (85-125k dwt)	1.350	2	1	2	1	1	1	1	0
Coated Aframax (85-125k dwt)	1.350	4	0	4	0	1	0	0	0
Suezmax (125-200k dwt)	1.350	0	0	0	0	0	0	0	0
UL/VLCC (>200k dwt)	1.350	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	1.350	12	6	7	2	3	0	0	0
Tanker (shuttle)	**1.350**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Shuttle Tanker	1.350	0	0	0	0	0	0	0	0
Tanker (other liquids)	**1.350**	**7**	**7**	**7**	**7**	**7**	**5**	**7**	**4**
Handysize (10-55k dwt)	1.350	7	7	7	7	7	5	7	4
General cargo ship	**1.350**	**389**	**212**	**317**	**139**	**200**	**42**	**58**	**8**
Handysize (10-40k dwt)	1.350	1	0	1	0	0	0	0	0
MR GDCS (6-9k dwt)	1.350	10	6	6	4	5	0	0	0
LR GDCS (>9k dwt)	1.350	0	0	0	0	0	0	0	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	1.350	35	20	26	19	19	11	16	0
Liner MPP (>25t SWL / >22k dwt)	1.350	54	43	53	30	43	12	15	4
Light MPP (25-100t SWL)	1.350	69	32	43	17	21	1	2	0
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	1.350	35	28	33	11	17	0	0	0
Open Hatch Carrier	1.350	144	50	118	33	66	2	7	0
Deck Carrier	1.350	1	0	1	0	0	0	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	1.350	37	30	33	23	27	14	16	2
Other Misc.	1.350	2	2	2	2	2	2	2	2
Short Sea GDCS (4-6k dwt)	1.350	1	1	1	0	0	0	0	0
Other OSV	1.350	0	0	0	0	0	0	0	0
Gas carrier	**1.350**	**354**	**281**	**317**	**244**	**266**	**191**	**218**	**113**
LPG <5k cbm	1.350	2	0	0	0	0	0	0	0
LPG 5-30k cbm	1.350	121	74	93	47	55	29	33	10
LPG 30-60k cbm	1.350	64	58	63	52	57	44	47	28
LPG >60k cbm	1.350	161	145	157	141	150	116	136	75
LNG <40k cbm	1.350	6	4	4	4	4	2	2	0
LNG carrier	**1.350**	**300**	**247**	**298**	**240**	**280**	**212**	**256**	**170**
LNG 100-200k cbm	1.350	248	195	246	190	228	163	206	123
LNG >200k cbm	1.350	45	45	45	45	45	45	45	45
LNG <40k cbm	1.350	4	4	4	2	4	1	2	1
LNG 40-100k cbm	1.350	2	2	2	2	2	2	2	1
FSRU	1.350	1	1	1	1	1	1	1	0
RoRo cargo ship (vehicle carrier)	**1.350**	**268**	**237**	**258**	**230**	**248**	**205**	**222**	**170**
Vehicle Carrier	1.350	268	237	258	230	248	205	222	170
RoRo cargo ship	**1.350**	**137**	**125**	**129**	**123**	**125**	**98**	**110**	**67**
Ro-Ro Cargo	1.350	137	125	129	123	125	98	110	67
RoRo passenger ship	**1.350**	**142**	**134**	**137**	**124**	**128**	**115**	**121**	**94**
RoPax	1.350	134	130	133	124	128	115	121	94
Shuttle Ferry	1.350	8	4	4	0	0	0	0	0
Cruise passenger ship	**1.350**	**192**	**162**	**183**	**154**	**171**	**141**	**151**	**111**
Cruise	1.350	191	162	183	154	171	141	151	111
Other Pass./Ferry	1.350	1	0	0	0	0	0	0	0
Refrigerated cargo carrier	**1.350**	**33**	**25**	**28**	**19**	**21**	**15**	**15**	**13**
Refrigerated Cargo Ship	1.350	33	25	28	19	21	15	15	13
Combination carrier	**1.350**	**5**	**0**	**3**	**0**	**0**	**0**	**0**	**0**
Handymax (40-65k dwt)	1.350	1	0	1	0	0	0	0	0
Panamax (65-100k dwt)	1.350	4	0	2	0	0	0	0	0
Capesize (100-210k dwt)	1.350	0	0	0	0	0	0	0	0
Grand Total	**1.350**	**4.293**	**2.250**	**3.597**	**1.798**	**2.388**	**1.225**	**1.494**	**818**

Table 2-23 Economic analysis for **2050 Scenarios, high fuel cost level** (2,000 EUR/t), different weather impact

		No weather impact		Tropical Conditions		North Sea		Nordic Oceans	
Row Labels	Average of fuel price over lifetime [EUR/t]	No of Newbuilds Payback NPV <15y	No of Retrofits Payback NPV <15y	No of Newbuilds Payback NPV <15y	No of Retrofits Payback NPV <15y	No of Newbuilds Payback NPV <15y	No of Retrofits Payback NPV <15y	No of Newbuilds Payback NPV <15y	No of Retrofits Payback NPV <15y
Bulk carrier	**2.000**	**1.429**	**687**	**1.291**	**485**	**889**	**185**	**380**	**27**
Handysize (10-40k dwt)	2.000	444	341	420	256	353	121	190	20
Handymax (40-65k dwt)	2.000	603	286	551	193	374	55	152	6
Panamax (65-100k dwt)	2.000	348	41	291	22	144	4	29	0
Capesize (100-210k dwt)	2.000	0	0	0	0	0	0	0	0
MR GDCS (6-9k dwt)	2.000	2	1	1	1	1	0	0	0
LR GDCS (>9k dwt)	2.000	4	2	3	1	1	1	1	0
Liner MPP (>25t SWL / >22k dwt)	2.000	18	12	17	8	12	3	7	1
VLBC (>210k dwt)	2.000	1	0	1	0	0	0	0	0
Light MPP (25-100t SWL)	2.000	1	1	1	1	1	0	0	0
Open Hatch Carrier	2.000	3	1	3	1	1	0	0	0
Minibulker (<10k dwt)	2.000	5	2	3	2	2	1	1	0
Container ship	**2.000**	**1.145**	**634**	**1.098**	**557**	**923**	**379**	**666**	**204**
<3k TEU	2.000	701	564	676	505	588	361	448	200
3-8k TEU	2.000	274	51	259	39	201	12	134	4
8-12k TEU	2.000	148	19	143	13	125	6	84	0
12-15k TEU	2.000	20	0	18	0	8	0	0	0
15-20k TEU	2.000	1	0	1	0	0	0	0	0
>20k TEU	2.000	1	0	1	0	1	0	0	0
Tanker (chemical)	**2.000**	**1.047**	**654**	**932**	**475**	**698**	**201**	**326**	**66**
Handysize (10-55k dwt)	2.000	988	619	882	458	674	198	322	66
Panamax (55-85k dwt)	2.000	10	3	10	1	6	0	1	0
Small Tanker (2-10k dwt)	2.000	49	32	40	16	18	3	3	0
Tanker (oil)	**2.000**	**229**	**100**	**199**	**69**	**127**	**25**	**55**	**9**
Handysize (10-55k dwt)	2.000	97	68	91	51	70	19	35	8
Panamax (55-85k dwt)	2.000	78	14	66	7	38	1	11	0
Aframax Crude (85-125k dwt)	2.000	15	2	9	1	5	1	2	1
Coated Aframax (85-125k dwt)	2.000	19	3	14	2	4	1	4	0
Suezmax (125-200k dwt)	2.000	7	0	6	0	1	0	0	0
UL/VLCC (>200k dwt)	2.000	0	0	0	0	0	0	0	0
Small Tanker (2-10k dwt)	2.000	13	13	13	8	9	3	3	0
Tanker (shuttle)	**2.000**	**4**	**0**	**2**	**0**	**1**	**0**	**0**	**0**
Shuttle Tanker	2.000	4	0	2	0	1	0	0	0
Tanker (other liquids)	**2.000**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**
Handysize (10-55k dwt)	2.000	7	7	7	7	7	7	7	7
General cargo ship	**2.000**	**515**	**388**	**450**	**318**	**362**	**199**	**251**	**64**
Handysize (10-40k dwt)	2.000	1	1	1	1	1	0	1	0
MR GDCS (6-9k dwt)	2.000	29	12	15	6	6	5	5	0
LR GDCS (>9k dwt)	2.000	2	0	1	0	0	0	0	0
Semi-Liner MPP (>25t SWL / 16.5k-22k dwt)	2.000	39	34	38	27	33	19	19	16
Liner MPP (>25t SWL / >22k dwt)	2.000	61	53	59	53	54	44	50	18
Light MPP (25-100t SWL)	2.000	121	75	86	50	54	25	27	3
Heavy Lift MPP (100-250t SWL / <16.5k dwt)	2.000	35	35	35	34	35	19	24	1
Open Hatch Carrier	2.000	177	135	169	110	142	58	94	5
Deck Carrier	2.000	4	1	2	1	1	0	0	0
Premium Project Carrier (>250t SWL / <16.5k dwt)	2.000	41	39	39	33	33	27	29	19
Other Misc.	2.000	2	2	2	2	2	2	2	2
Short Sea GDCS (4-6k dwt)	2.000	1	1	1	1	1	0	0	0
Other OSV	2.000	2	0	2	0	0	0	0	0
Gas carrier	**2.000**	**385**	**354**	**371**	**323**	**336**	**276**	**289**	**217**
LPG <5k cbm	2.000	5	3	4	0	0	0	0	0
LPG 5-30k cbm	2.000	147	122	134	99	105	64	67	34
LPG 30-60k cbm	2.000	64	64	64	63	64	58	62	47
LPG >60k cbm	2.000	162	159	162	156	162	150	156	134
LNG <40k cbm	2.000	7	6	7	5	5	4	4	2
LNG carrier	**2.000**	**313**	**289**	**312**	**288**	**308**	**275**	**303**	**250**
LNG 100-200k cbm	2.000	260	237	259	236	256	223	251	200
LNG >200k cbm	2.000	45	45	45	45	45	45	45	45
LNG <40k cbm	2.000	4	4	4	4	4	4	4	2
LNG 40-100k cbm	2.000	3	2	3	2	2	2	2	2
FSRU	2.000	1	1	1	1	1	1	1	1
RoRo cargo ship (vehicle carrier)	**2.000**	**278**	**254**	**278**	**246**	**271**	**239**	**252**	**218**
Vehicle Carrier	2.000	278	254	278	246	271	239	252	218
RoRo cargo ship	**2.000**	**144**	**136**	**139**	**129**	**134**	**124**	**126**	**112**
Ro-Ro Cargo	2.000	144	136	139	129	134	124	126	112
RoRo passenger ship	**2.000**	**148**	**145**	**146**	**139**	**139**	**131**	**132**	**120**
RoPax	2.000	137	135	136	133	134	127	129	120
Shuttle Ferry	2.000	11	10	10	6	5	4	3	0
Cruise passenger ship	**2.000**	**209**	**184**	**207**	**177**	**193**	**168**	**179**	**153**
Cruise	2.000	208	183	206	177	193	168	179	153
Other Pass./Ferry	2.000	1	1	1	0	0	0	0	0
Refrigerated cargo carrier	**2.000**	**35**	**34**	**35**	**28**	**30**	**21**	**24**	**16**
Refrigerated Cargo Ship	2.000	35	34	35	28	30	21	24	16
Combination carrier	**2.000**	**10**	**3**	**10**	**0**	**7**	**0**	**1**	**0**
Handymax (40-65k dwt)	2.000	1	1	1	0	1	0	0	0
Panamax (65-100k dwt)	2.000	9	2	9	0	6	0	1	0
Capesize (100-210k dwt)	2.000	0	0	0	0	0	0	0	0
Grand Total	**2.000**	**5.898**	**3.869**	**5.477**	**3.241**	**4.425**	**2.230**	**2.991**	**1.463**

2.7.3.4 Conclusions from the economic analysis

The economic analysis indicates that installing an ALS on ships is highly sensitive to current and future fuel prices, as well as to the operational area and sea conditions. Retrofits seem to be less economically viable compared to new builds.

Based on a dataset of 9,329 vessels, the percentage of the total fleet that is expected to be economically feasible for fitting an ALS at a new building and for retrofit is shown in the following table.

Table 2-24 Percentage of the total economic fleet feasibility for fitting an ALS, at newbuilds and retrofits

Operational area & Scenarios	Fuel cost	Percentage of newbuilds, payback NPV <15y	Percentage of retrofits, payback NPV <15y
Weather impact neglected	Current as per DCS	10%	4%
2030 Scenario	Low 400 EUR/t	7%	2%
	High 1,000 EUR/t	30%	15%
2050 Scenario	Low 700 EUR/t	17%	8%
	Medium 1,350 EUR/t	46%	24%
	High 2,000 EUR/t	63%	42%
Tropical conditions	Current as per DCS	8%	3%
2030 Scenario	Low 400 EUR/t	5%	1%
	High 1,000 EUR/t	24%	12%
2050 Scenario	Low 700 EUR/t	13%	6%
	Medium 1,350 EUR/t	39%	19%
	High 2,000 EUR/t	59%	35%
North Sea area	Current as per DCS	5%	1%
2030 Scenario	Low 400 EUR/t	3%	1%
	High 1,000 EUR/t	16%	8%
2050 Scenario	Low 700 EUR/t	9%	4%
	Medium 1,350 EUR/t	26%	13%
	High 2,000 EUR/t	47%	24%
Nordic Oceans	Current as per DCS	4%	1%
2030 Scenario	Low 400 EUR/t	1%	0%
	High 1,000 EUR/t	10%	5%
2050 Scenario	Low 700 EUR/t	5%	2%
	Medium 1,350 EUR/t	16%	9%
	High 2,000 EUR/t	32%	16%

Most economically viable ship types (newbuilds and retrofits)

The tables below present the percentage of vessels in the top 5 vessel classes identified as the most economically feasible under the current fuel cost scenario, the 2030 low fuel cost level (400 EUR/t), and the 2050 high fuel cost level (2,000 EUR/t).

ALS are best suited for:

- Newbuilds equipped with shaft generator: CAPEX of the system is less at newbuilds, and OPEX is less when the electric power for the compressors is provided by a shaft generator.
- Ships featuring low operating drafts like LNG carriers, gas carriers, all kinds of RoRo-vessels and cruise passenger vessels.
- To a certain extent, these systems appear to be feasible at smaller-sized vessel classes, such as Handysize tankers and Handysize bulk carriers, Liner MPP (Multi-Purpose) carriers and container vessels below 3000 TEU.

ALS are less suited for:

- Retrofits where the power supply is typically provided by diesel generators. CAPEX for the system is higher than for newbuilds, and OPEX is higher when electric power is provided by diesel generators rather than a shaft generator.
- Ships with high operating drafts like bulk carriers, tankers and large container vessels.

Economic success is highly dependent on the vessel's operational profile, the operational sea area, and the typical significant wave height relative to the vessel's size. The decision to install such a system should be made on a case-by-case basis, taking into account the constraints outlined above.

Table 2-25 Percentage of **newbuilds** with payback time of less than 15 years at **current fuel prices**

	Not restricted due to weather	Operating in "Tropical Seas"	Operating in "North Sea" area	Operating in "Nordic Oceans"
LNG carrier	57%	53%	44%	42%
Gas carrier (LPG)	24%	15%	3%	2%
RoRo (vehicle carrier)	61%	52%	35%	27%
RoRo cargo	46%	35%	19%	15%
RoRo passenger	66%	55%	36%	29%
Cruise passenger	43%	38%	23%	20%

Table 2-26 Percentage of **retrofits** with payback time of less than 15 years at **current fuel prices**

	Not restricted due to weather	Operating in "Tropical Seas"	Operating in "North Sea" area	Operating in "Nordic Oceans"
LNG carrier	27%	25%	18%	17%
Gas carrier (LPG)	2%	1%	1%	0%
RoRo (vehicle carrier)	32%	22%	7%	2%
RoRo cargo	18%	14%	3%	1%
RoRo passenger	38%	31%	16%	13%
Cruise passenger	12%	9%	5%	3%

Table 2-27 Percentage of **newbuilds** with payback time of less than 15 years at an **assumed fuel price of 400 EUR/t**

	Not restricted due to weather	Operating in "Tropical Seas"	Operating in "North Sea" area	Operating in "Nordic Oceans"
LNG carrier	19%	19%	17%	11%
Gas carrier (LPG)	17%	9%	1%	0%
RoRo (vehicle carrier)	55%	45%	26%	0%
RoRo cargo	41%	27%	15%	1%
RoRo passenger	56%	48%	28%	7%
Cruise passenger	34%	29%	17%	0%

Table 2-28 Percentage of **retrofits** with payback time of less than 15 years at an **assumed fuel price of 400 EUR/t**

	Not restricted due to weather	Operating in "Tropical Seas"	Operating in "North Sea" area	Operating in "Nordic Oceans"
LNG carrier	10%	9%	5%	4%
Gas carrier (LPG)	1%	1%	0%	0%
RoRo (vehicle carrier)	21%	9%	0%	0%
RoRo cargo	14%	9%	3%	1%
RoRo passenger	31%	24%	12%	7%
Cruise passenger	7%	4%	1%	0%

Table 2-29 Percentage of **newbuilds** with payback time of less than 15 years at an **assumed fuel price of 2000 EUR/t**

	Not restricted due to weather	Operating in "Tropical Seas"	Operating in "North Sea" area	Operating in "Nordic Oceans"
LNG carrier	93%	93%	92%	90%
Gas carrier (LPG)	92%	89%	80%	69%
RoRo (vehicle carrier)	96%	96%	94%	87%
RoRo cargo	94%	91%	88%	82%
RoRo passenger	93%	91%	87%	83%
Cruise passenger	86%	85%	79%	74%

Table 2-30 Percentage of **retrofits** with payback time of less than 15 years at an **assumed fuel price of 2,000 EUR/t**

	Not restricted due to weather	Operating in "Tropical Seas"	Operating in "North Sea" area	Operating in "Nordic Oceans"
LNG carrier	86%	86%	82%	75%
Gas carrier (LPG)	84%	77%	66%	52%
RoRo (vehicle carrier)	88%	85%	83%	75%
RoRo cargo	89%	84%	81%	73%
RoRo passenger	91%	87%	82%	75%

Cruise passenger	76%	79%	69%	63%

Potential for fuel and emission savings (newbuilds and retrofits)

Based on the economic analysis, it was concluded that installing ALS on board ships is highly sensitive to actual or expected future fuel prices and to the intended operational area and sea conditions. Retrofits appear to be less economically feasible than newbuilds.

On the basis of the 9,329 vessels in the dataset, fitting an ALS where this appears economically feasible for new builds, and assuming the 2030 low fuel cost level scenario (400 EUR/t) has the potential of saving up to 84,000 tons of fuel annually, corresponding to up to 262,000 tons of CO_2. Assuming the 2050 high-fuel-cost scenario (2,000 EUR/t), ALS could save up to 684,000 tons of fuel annually, corresponding to up to 2.1 Mio tons of CO_2.

3. Safety and environmental standards, regulations, and guidelines

The regulatory framework governing maritime GHG-emissions is undergoing significant transformation. The IMO has advanced its Net-Zero Framework (NZF) regulations, which could introduce a global marine fuel standard and a two-tier GHG intensity pricing mechanism.

In parallel, the European Union has already implemented key measures under the Fit for 55 package, extending the EU Emissions Trading System (EU ETS) and introducing the FuelEU Maritime Regulation.

Amid these developments, ALS is emerging as a promising technology for energy efficiency. While ALS does not directly alter fuel type or GHG intensity metrics, it contributes to reduced fuel consumption and emissions, thereby supporting compliance with both IMO and EU frameworks. ALS also plays a role in improving EEDI and EEXI requirements, although current verification standards and methodologies remain fragmented. This chapter outlines the regulatory context, the role of ALS in compliance, and the challenges associated with performance validation and integration across the maritime sector.

3.1 International Maritime Organization (IMO)

Reducing GHG emissions from ships is vital to global climate efforts, with multiple regulatory frameworks at international, regional, and national levels driving the sector's decarbonization.

Figure 3-1 illustrates the revised 2023 IMO strategy, which aims to significantly reduce GHG emissions from ships, targeting net-zero emissions by or around 2050. Concrete measures to achieve the goals are under discussion (IMO NZF). The IMO GHG strategy will be reviewed again in 2028, building on data and insights from previous studies and the IMO fuel consumption reporting system.

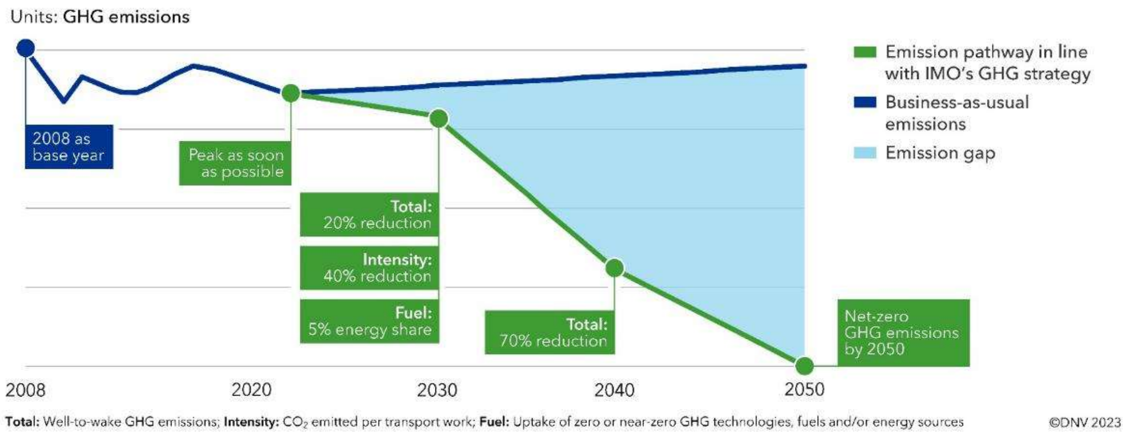


Figure 3-1 Revised 2023 IMO strategy on reduction of GHG from ships (Source: DNV)

3.1.1 Energy Efficiency Design Index and Energy Efficiency Existing Ship Index

The EEDI is a mandatory measure under MARPOL Annex VI, Chapter 4, applicable to new ships. It was adopted in 2011 and came into force in 2013. The regulation sets minimum energy-efficiency standards for newly built ships, expressed as grams of CO_2 per tonne-nautical mile (gCO_2/tonne-nm). The EEDI is calculated based on a ship's design parameters and is intended to promote the adoption of energy-efficient technologies and innovative ship designs. The required EEDI values become progressively stricter over time through phased reduction targets (Phase 0 to Phase 4), depending on ship type and size. Compliance is verified at the design stage and is a prerequisite for obtaining an International Energy Efficiency Certificate (IEEC).

The EEXI was introduced to extend similar efficiency requirements to existing ships. It was adopted in 2021 and entered into force on 1 January 2023. The EEXI applies to ships of 400 gross tonnage and above that fall under

MARPOL Annex VI and are engaged in international voyages. The EEXI is a technical measure that assesses the energy efficiency of ships already in operation, using a similar formula and approach as EEDI. Ships must demonstrate compliance by their first annual, intermediate, or renewal survey after 1 January 2023. If a ship does not meet the required EEXI, it must implement corrective measures such as engine power limitation (EPL), energy-saving devices (ESDs), or retrofitting of ESDs.

ALS can contribute to achieving improved EEDI and EEXI. The reduction in energy demand from ALS translates into lower fuel consumption and CO_2 emissions, thereby improving the ship's attained EEDI and EEXI. The MEPC.1/Cir.896 provides guidance on how to account for ALS in the EEDI and EEXI calculations.

MEPC.1/Circ.896, issued by the IMO in December 2021, provides guidance on how to treat innovative energy efficiency technologies when calculating and verifying a ship's EEDI and EEXI. It categorizes technologies into groups and outlines methodologies for assessing their impact on ship performance and emissions. The circular is intended for use by shipbuilders, owners, classification societies, and verifiers, and it complements existing EEDI and EEXI guidelines without replacing them.

Innovative energy efficiency technologies are allocated to category (A), (B) and (C), depending on the characteristics and effects on the EEDI formula. Category (A) is for technologies that shift the speed vs. power curve by reducing resistance or improving propulsion efficiency. As an example, low-friction coating system and propeller optimization. Category (B) is for technologies that reduce the propulsion power but need auxiliary power, such as ALS (Category B-1) and WAPS (Category B-2). Category (C) is the technology that generates electricity, such as WHRS (Category C-1) and Photovoltaic cells (Category C-2).

ALS is classified under Category B-1 in MEPC.1/Circ.896. It is recognized as an innovative energy efficiency technology that reduces a ship's frictional resistance by injecting air bubbles beneath the hull.

The guidance consists of two stages of EEDI verification for a vessel with ALS.

Preliminary verification at the design stage

The following should be prepared for preliminary EEDI verification during the design stage:

- Speed vs. power curve for both ALS ON and OFF conditions in both EEDI and Trial conditions.
- Additional power necessary for running the ALS in both EEDI draft and Trial conditions.

Final verification of the attained EEDI at sea trial

The final verification of EEDI for a vessel with installed ALS should be conducted during the sea trial. For dry cargo vessels and gas carriers, including LNG carriers, sea trials are typically performed at ballast draft. The results are then extrapolated to the EEDI draft, in accordance with ITTC and ISO sea-trial guidelines, using the speed-power curves from both the sea-trial draft and the EEDI draft derived from the model test. However, there are technical challenges to getting accurate results from the model test as described in Section 2. In addition, sea trials for the vessels are generally conducted under trimmed conditions, which do not represent the design condition for ALS. However, LNG carriers can achieve an even-keel condition that matches the ALS design conditions. Currently, there is no standardized methodology for extrapolating performance data from a trimmed ballast draft to the EEDI draft for both the propulsion power and the additional power necessary for running the system. This lack of established practice presents a challenge in ensuring consistency and accuracy in EEDI verification under these conditions.

The following are to be prepared for the final EEDI verification at sea trial:

- Speed vs. power curve for both ALS ON and OFF conditions in EEDI draft or Trial conditions.
- Determine the actual reduction rate (ADR_{Trial}) from the sea trial in case the trial was carried out at EEDI draft.
- To determine the propulsion power at the EEDI draft, the speed-power curve obtained at the trial draft should be extrapolated accordingly. The difference in propulsion power at the reference speed (Vref) between the estimated reduction rate(EDR_{Trial}), established during the preliminary verification phase, and the actual reduction rate (ADR_{Trial}) observed during the sea trial can be used to adjust the estimated propulsion power at the EEDI draft as expressed in the following formula, and illustrated in Figure 3-2.

$$ADR_{Full} = 1-(1- EDR_{Full}) \times (1- ADR_{Trial}) / (1- EDR_{Trial})$$

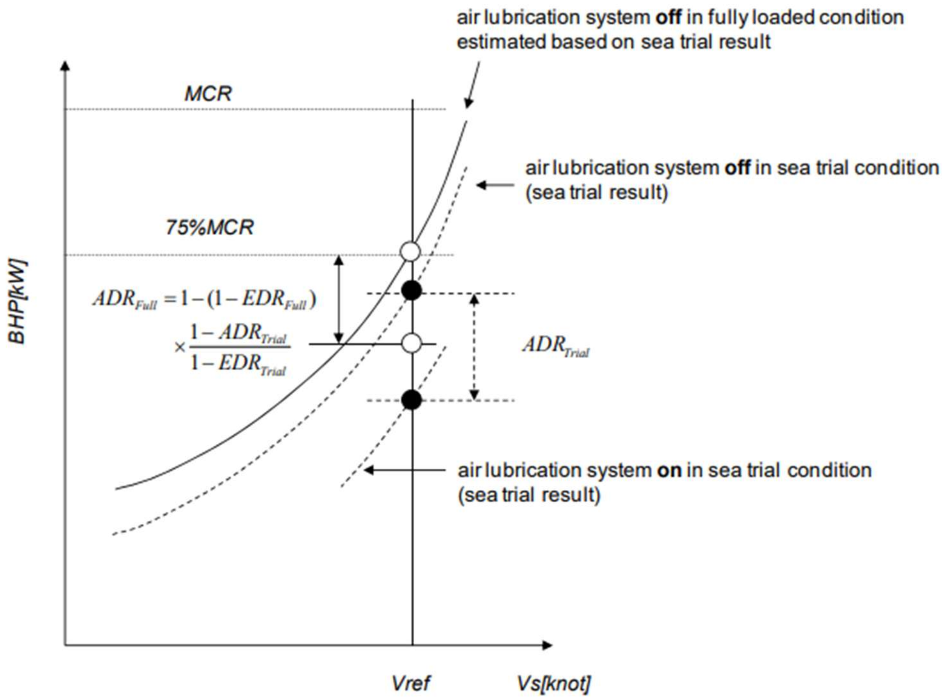


Figure 3-2 Calculation of the reduction rate of propulsion power due to ALS (Source: MEPC.1/Circ.896)

3.1.2 IMO Net Zero Framework for International Shipping

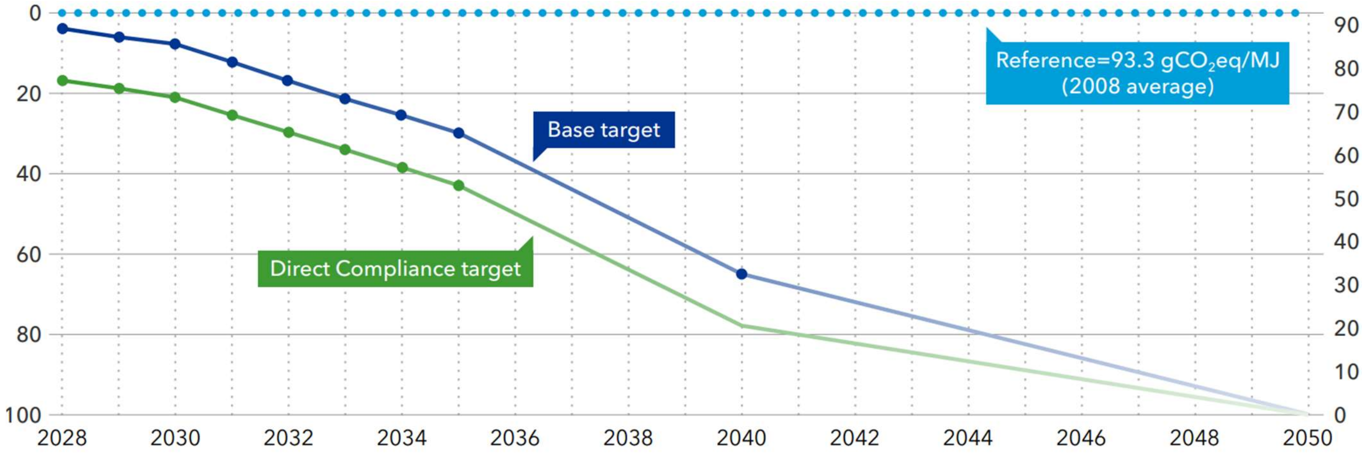
The IMO Net Zero Framework (NZF) is the IMO's regulatory response to the 2023 IMO GHG Strategy, which sets out the ambition to reach net-zero GHG emissions by or around 2050. The stated goal of the NZF is to ensure that international shipping can meet the strategy's GHG emission reduction targets, to accelerate the uptake of so-called zero or near-zero GHG fuels, technologies and energy sources (ZNZs), as well as to support a just and equitable transition of the maritime sector.

The IMO has advanced its NZF regulations, which introduced a global marine fuel standard and a two-tier GHG-intensity pricing mechanism. The framework sets progressive GHG intensity reduction targets and allows for banking and transfer of surplus compliance units, reinforcing IMO's commitment to decarbonizing international shipping.

The regulatory framework comprises two primary components: a mandatory global marine fuel standard and a two-tiered GHG-intensity pricing mechanism. The fuel standard mandates a gradual reduction in the annual GFI of ships, calculated on a WtW basis. This includes emissions from all onboard energy sources, such as conventional fuels, electricity, wind propulsion, and solar power. The regulation applies to all ships with a gross tonnage exceeding 5,000, with exceptions for vessels engaged solely in domestic trade, offshore platforms, drilling rigs, and semi-submersible vessels.

Each ship will be required to meet a Direct Compliance target for its annual GFI, as illustrated in Figure 3-3. The regulation defines two performance thresholds: a Base target and a more stringent Direct Compliance target. Ships that achieve GFI levels below the Direct Compliance target will be eligible to generate surplus compliance units, which can be banked or traded. Conversely, ships that exceed the Direct Compliance target will be subject to financial penalties.

The economic element introduces a two-tiered pricing mechanism for GHG emissions that exceed the regulatory thresholds. Ships that do not meet the Direct Compliance target must purchase Remedial Units (RUs), with penalty rates ranging from \$100 to \$380 (approximately €85 to €321 at the 12.4 exchange rate) per tonne of CO_2e, depending on the level of non-compliance. The proceeds from RU purchases will be directed into the IMO Net-Zero Fund. This fund will provide financial incentives for ships using zero- or near-zero GHG-emission technologies (ZNZs), fuels, and energy sources, and will also support the implementation of the NZF in developing countries. The pricing mechanism for RUs will be finalized by 2028, with implementation beginning in 2031. To support implementation, the IMO will develop detailed guidelines to ensure readiness for the operationalization of the NZF. Although adoption of the IMO NZF regulation was adjourned for one year, development of these detailed guidelines is proceeding as originally planned.



Year	2028	2029	2030	2031	2032	2033	2034	2035	...	2040
Base	4%	6%	8%	12.4%	16.8%	21.2%	25.6%	30%	...	65%
Direct	17%	19%	21%	25.4%	29.8%	34.2%	38.6%	43%	...	-

Figure 3-3 GFI trajectory and targets (Source: DNV, 2025)

The initial GFI thresholds for reward eligibility are set at a maximum of 19.0 gCO_2eq/MJ until the end of 2034, and 14.0 gCO_2eq/MJ from 2035 onward. These thresholds will be reviewed every five years. Ships that utilize ZNZs, which are defined broadly to include not only alternative fuels but also technologies such as wind propulsion, solar energy, and onboard carbon capture and storage, will be eligible for financial rewards. The methodology for determining the type and size of these rewards will be finalized by 1 March 2027 and administered through the IMO Net-Zero Fund.

Ongoing work to support the implementation of the IMO NZF includes several key initiatives as follow:

- Development of a detailed methodology for calculating GFI, including the integration of wind propulsion and electricity use, which will ensure consistent and accurate accounting of energy contributions from non-traditional propulsion systems.
- Establishment of default emission factors under the IMO's Life-Cycle Assessment (LCA) Guidelines, covering well-to-tank and tank-to-wake emissions for all marine fuels. These factors are being developed by the GESAMP-LCA Working Group.
- Creation of a Sustainable Fuels Certification Framework by 2027, which will require fuels to be certified by recognized Sustainable Fuel Certification Schemes (SFCS) and documented via Fuel Lifecycle Label (FLL).
- Operationalization of the GFI Registry and the IMO Net-Zero Fund, which will manage compliance data, surplus and remedial units, and financial flows related to rewards and penalties.
- Development of a reward mechanism for Zero or Near-Zero GHG (ZNZ) technologies, with the methodology for determining reward size and eligibility.
- Establishment of a regulatory framework for Onboard Carbon Capture and Storage (OCCS), with safety and operational guidelines under development. This will address technical, economic, and safety considerations for integrating OCCS into ship operations.

Use of ALS is not expected to influence a vessel's GFI, as it does not alter the type of fuel and energy used by the vessel. However, since ALS can reduce a vessel's fuel consumption, it can reduce the Tier 2 compliance deficit for a vessel with a GFI above the Base target, or the Tier 1 compliance deficit for a vessel with GFI between the Base and Direct Compliance Target, thereby reducing compliance costs. In addition, using ALS will reduce the amount of low-GHG fuel required to meet the targets.

3.1.3 IMO Carbon Intensity Indicator (CII)

The Carbon Intensity Indicator (CII) is a mandatory operational efficiency measure adopted under MARPOL Annex VI, aimed at reducing the carbon intensity of international shipping. It forms part of the IMO's broader strategy to achieve a 40% reduction in CO2 emissions per transport work by 2030, relative to 2008 levels.

CII applies to ships of 5,000 gross tonnage and above operating on international voyages. The regulation entered into force on 1 January 2023, with the first annual ratings issued in 2024 based on 2023 performance data. The indicator is calculated as grams of CO_2 emitted per deadweight ton-nautical mile (gCO_2/dwt-nm), using fuel consumption data reported under the IMO Data Collection System (DCS). Adjustments are made using correction factors to account for operational conditions such as ice-class operations, wind propulsion, and alternative energy use.

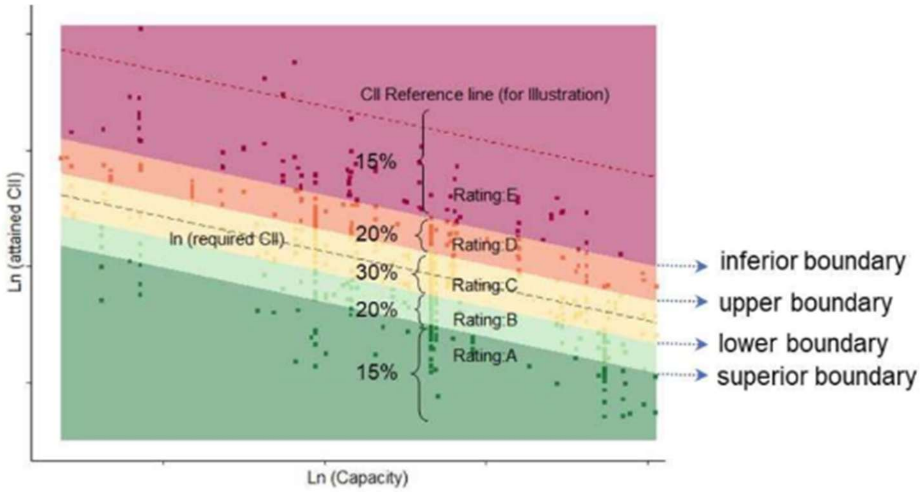


Figure 3-4 CII rating scale (Source: MEPC 78)

As illustrated in Figure 3-4, each vessel is assigned an annual rating from A to E, where A indicates superior performance and E indicates inferior performance. A rating of C is considered compliant. Ships rated D for three consecutive years or E in any single year are required to submit a corrective action plan as part of their Ship Energy Efficiency Management Plan (SEEMP) Part III.

The required CII becomes progressively more stringent through annual reduction factors. These began at 5% in 2023 and are scheduled to increase to 11% by 2026.

The MEPC Committee completed Phase 1 of the review of short-term GHG reduction measures in April 2025, including the CII. Reduction factors were agreed through to 2030, providing regulatory certainty for shipowners and operators. The Committee also initiated Phase 2 of the review, which will focus on enhancing the SEEMP framework, refining CII metrics, and ensuring alignment with the IMO NZF.

The MEPC emphasized the importance of data transparency and approved regulations to improve fuel oil reporting. The Committee also reviewed the annual carbon intensity and energy efficiency of the global fleet, covering developments from 2019 to 2023. These insights will inform future amendments to the CII framework and support the IMO's decarbonization goals.

3.2 Regulations for EU member states

The European Union has set ambitious climate targets as part of its commitment to achieving climate neutrality by 2050. Central to this vision is the European Green Deal, which outlines a comprehensive roadmap for reducing GHG emissions across all sectors of the economy. The EU aims to cut net GHG emissions by at least 55% by 2030 compared to 1990 levels, an objective that underpins the legislative package known as Fit for 55. Additionally, EU ETS has been extended to cover CO_2, CH4 and N2O emissions from ships entering EU ports, and the FuelEU

Maritime Regulation mandates the uptake of renewable and low-carbon fuels, with a goal to reduce the GHG intensity of energy used on board ships by 80% by 2050 compared to 2020 levels.

3.2.1 EU Fit for 55 – Maritime and Energy-Related Regulations

The Fit for 55 package, adopted by the European Commission in July 2021, is a cornerstone of the European Green Deal and outlines the European Union's legislative roadmap toward achieving climate neutrality by 2050. Central to this package is the legally binding objective of reducing net GHG emissions by at least 55% by 2030, compared to 1990 levels. The package integrates maritime transport into the EU's climate policy framework, which had previously been excluded from binding EU-level emissions regulations.

The Fit for 55 package strengthens existing climate instruments and introduces new regulatory mechanisms. Key components include the revision of the EU Emissions Trading System (EU ETS), the establishment of the FuelEU Maritime Regulation, the revision of the Renewable Energy Directive (RED II/III), and a proposal to revise the Energy Taxation Directive (ETD). Collectively, these measures aim to reduce emissions, accelerate the deployment of clean energy technologies, and establish a fair and efficient carbon pricing system across the EU single market.

3.2.2 EU Emissions Trading System (EU ETS)

The EU ETS is the cornerstone of the EU's climate policy and operates as a cap-and-trade system for GHG emissions. Initially focused on stationary installations and aviation, the system was expanded under the EU Fit for 55 packages to include maritime transport, making it one of the most significant regulatory changes for the shipping sector in recent years. Under the revised ETS, from 1 January 2024, shipping companies are required to monitor, report, and verify their GHG emissions (CO2, CH4, N2O) and surrender allowances (EUAs) annually to cover these emissions.

This market-based instrument now applies to cargo and passenger ships of 5,000 gross tonnage and above, covering emissions from 100% of voyages within the EEA, 50% of voyages between EEA and non-EEA ports, and 100% of emissions occurring at EEAU ports. Offshore ships with a GT above 5000 will be included in the scope of the ETS from 2026 onward.

The maritime extension took effect on 1 January 2024, with a phase-in compliance schedule as follows:

- Allowances must be surrendered for 40% of reported emissions in 2024.
- This increased to 70% in 2025.
- 100% compliance is required from 2026 onwards.
- From 2027, CH_4 and N_2O emissions will be included in the scope of EUA surrendering obligations.

The ETS introduces direct carbon cost into shipping operations and is expected to significantly influence ship design, fuel strategies, and voyage planning. Operators who reduce fuel consumption or adopt emission-reducing technologies will benefit from lower compliance costs. Thus, systems that enhance hydrodynamic efficiency, such as ALS, are increasingly relevant. ALS can reduce hull friction and thus fuel consumption by 5–10%, translating directly into lowered CO2 emissions, EU ETS obligations, GHG emissions and number of EUAs.

Emissions reductions achieved from ALS can be verified from the MRV system, which is directly linked to EU ETS compliance costs. However, it must ensure that the system remains operationally effective across diverse operational conditions, including ships' operational profiles and environmental factors.

3.2.3 FuelEU Maritime Regulation

The FuelEU Maritime Regulation sets limits on the GHG intensity of energy used onboard ships operating within the EU or EEA, complementing the EU ETS, which targets ships' GHG emissions. Effective from 1 January 2025, it applies to vessels over 5,000 GT calling at EU ports, that serve the purpose of transporting passengers or cargo, irrespective of their flag, with some ship types exempted, and requires a progressive reduction in WtW GHG intensity compared to 2020 levels, covering emissions from fuel extraction, production, transport, and onboard combustion, including methane slip and nitrous oxide emissions.

The EU has clarified that all fuel/electricity consumption on voyages that include at least one EU/EEA port of call can contribute to the total annual GHG intensity, even though only 50% of the energy is included in the total energy in scope. This implies a prioritized allocation of fuels, starting with the fuels with the lowest GHG intensity, until the total energy in scope is covered. This includes any renewable, biogenic and low-carbon fuels, as well as fossil fuels such as liquefied natural gas (LNG) and liquefied petroleum gas (LPG).

As illustrated in Figure 3-5 , the required reductions start at 2% in 2025 and increase incrementally to reach 80% by 2050. The regulation considers emissions of CO2, methane (CH4), and nitrous oxide (N2O) and is structured to allow shipowners flexibility in how they comply. Compliance can be achieved by switching to low- or zero-carbon fuels or by adopting technological solutions, such as wind propulsion. FuelEU Maritime also introduces a compliance pooling mechanism, allowing overperforming vessels to offset underperforming vessels within a fleet, and imposes penalties for non-compliance based on the degree of deviation from targets.

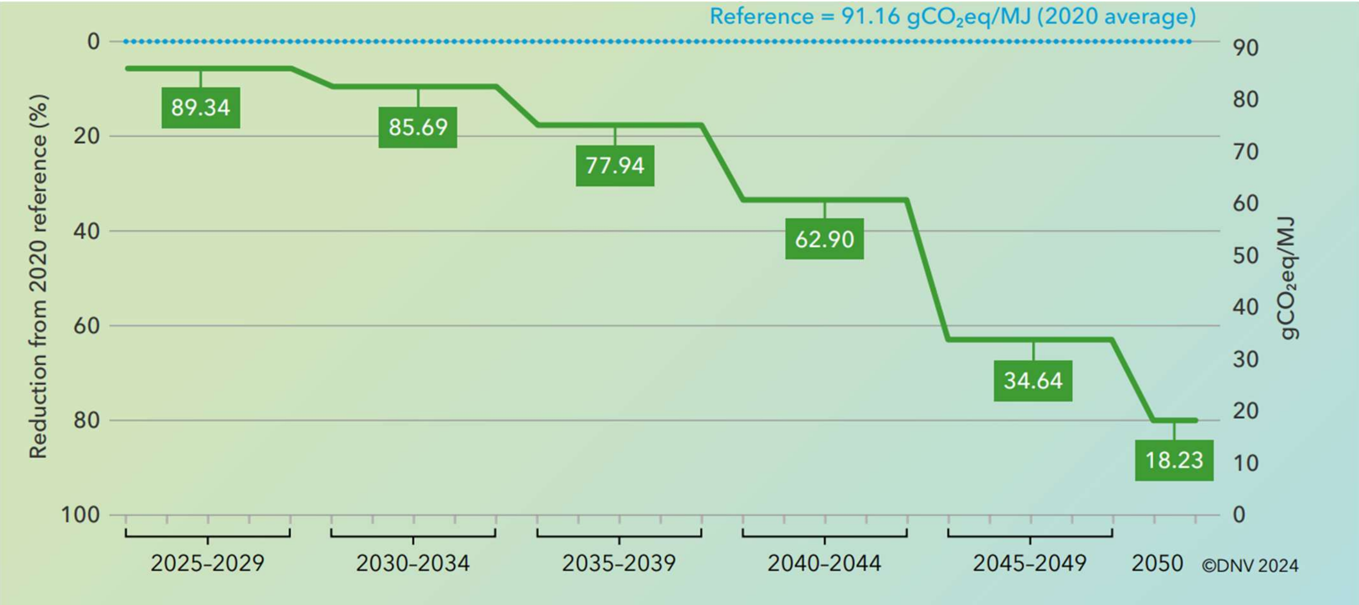


Figure 3-5 FuelEU Maritime GHG intensity requirements from 2025 to 2050.(Source: DNV)

Unlike wind-assisted propulsion systems (WAPS), which are eligible for specific incentives under the FuelEU Maritime Regulation and can reduce the annual WtW GHG intensity by a factor, ALS are not directly rewarded because they may lower fuel consumption rather than affect the type of fuel or energy used. ALS will, however, as is the case for several other energy efficiency measures, reduce the compliance deficit (or surplus) of a vessel with a WtW GHG intensity higher (or lower) than the FuelEU Maritime GHG intensity target, by reducing the actual final fuel consumption/energy demand of the ship when at sea.

The FuelEU Maritime Regulation imposes penalties on vessels that exceed the prescribed GHG intensity threshold after pooling, banking, and borrowing. These penalties are calculated based on the compliance balance, defined as the difference between the target and actual GHG intensity, multiplied by the vessel's total energy consumption, including fuel use and shore power. By lowering fuel consumption, ALS reduces total energy use and WtW GHG emissions. If a vessel exceeds the GHG intensity target, the use of ALS can reduce the compliance deficit, potentially resulting in lower financial penalties.

The penalty mechanism under FuelEU Maritime is calculated by converting the deficit of the Compliance Balance into an equivalent quantity of conventional marine fuel (VLSFO) and applying a fixed rate of 2,400 EUR per tonne. The calculation involves determining the actual GHG intensity of the ship's energy use, calculating the compliance balance, and converting this excess into VLSFO-equivalent tonnes using a standard energy content value of 41,000 MJ per tonne VLFSO. The final penalty is then derived by multiplying the VLSFO-equivalent excess by the fixed rate.

$$GHG\ Penalty[€] = \frac{Compliance\ balace[tCO_2eq]}{Actual\ GHG\ intensity[{}^{gCO_2eq}/_{MJ}]} \times \frac{2{,}400\ [{}^{€}/_{tVLSFOeq}]}{41{,}000\ [{}^{\mathrm{MJ}}/_{tVLSFOeq}]} \times (1 + \frac{Consequtive\ periods - 1}{10})$$

The penalty can also be calculated per tonne GHG compliance deficit basis. This is done by dividing the standard penalty rate by the vessel's actual GHG intensity, as shown below. This calculation excludes any additional penalties applied for consecutive non-compliance periods.

$$Penalty\ per\ tonne\ GHG\ compliance\ deficit\left[{€}/{tCO_2eq}\right] = \frac{58{,}537\ [{€}/{TJ}]}{Actual\ GHG\ intensity[{gCO_2eq}/{MJ}]}$$

Even if the following does not currently affect the Fuel EU cost estimation of Section 2.6.3.2, it is important to highlight for the sake of clarity that from 2030, container ships and passenger vessels over 5,000 GT moored for more than two hours at Trans-European Transport Network (TEN-T) core maritime ports (i.e. ports covered by this requirement are those which meet the criteria of Article 9 of the Alternative Fuels Infrastructure Regulation (AFIR)) must connect to shore power, or an equivalent zero-emission technology to meet all onboard electrical demand. Shore Power is considered to have zero GHG intensity under FuelEU, even if the electricity grid is partially fossil-fueled. Vessels not complying with the shore power or zero-emission technology requirement will need to pay a penalty, which is determined as 1.50 €/kWh multiplied by the established total electrical power demand of the ship at berth in kW and by the total number of rounded-up hours spent at berth in non-compliance, as follows:

$$OPS\ Penalty[€] = 1.50\ [{€}/{kWh}] \times Electrical\ power\ demand[kW] \times Time\ at\ berth\ not\ compliant[hrous]$$

3.3 International Association of Classification Societies (IACS)

The International Association of Classification Societies (IACS) was established in 1968 and is a leading global organization that brings together the world's major classification societies. IACS plays a crucial role in promoting maritime safety and environmental protection, and in developing technical standards for the design, construction, and maintenance of ships and offshore structures. IACS contributions include advancing rules that support energy efficiency improvements, enabling the safe use of alternative fuels such as LNG, hydrogen, ammonia, and methanol, and providing technical input to IMO frameworks, including EEDI, EEXI, and CII. By combining technical expertise with a focus on safety, IACS helps ensure that regulatory goals for reducing GHG emissions are translated into practical, reliable solutions for the global shipping industry.

IACS PR38_Rev5. - Procedure for calculation and verification of the EEDI

The IACS PR38 outlines the standardized procedure for calculating and verifying the EEDI for new ships. This industry guideline ensures a consistent and standardized approach among IACS members for calculating and verifying the EEDI, which is a measure of a ship's energy efficiency, and includes detailed methodologies, required documentation, and verification procedures to ensure compliance with IMO regulations. This latest revision aligns with the latest IMO guidelines and aims to enhance clarity and consistency in EEDI assessments. When it comes to innovative energy-efficient technologies, the industry guidelines refer to MEPC.1/Cir.896.

IACS NO.172_Rev.1 EEXI Implementation Guidelines

IACS Rec. 172 provides comprehensive technical guidelines for the implementation, calculation, and verification of the Energy Efficiency Existing Ship Index. It aligns with IMO resolutions MEPC.350(78), MEPC.351(78), MEPC.335(76), and their amendments, and is intended for use by classification societies during surveys and certification, and to ensure uniform application of EEXI regulations across classification societies. ALS is not explicitly mentioned in this guideline; however, it refers to the MEPC.1 Circ.878.

Provide technical guidance on:

- Approval of the EEXI Technical File
- Non-overridable power limitation systems
- EEXI calculation for LNG carriers
- Ship type applicability
- Selection of Specific Fuel Consumption (SFC) values
- Numerical validation of the reference speed (Vref)

IACS NO.173 Guidelines on Numerical Calculations for t1he purpose of deriving the Vref in the framework of the EEXI Regulation

IACS NO.173 provide a standardized methodology for using Computational Fluid Dynamics (CFD) to derive the reference speed (Vref) for ships under the EEXI regulation. ALS (Category B-1 under MEPC.1/Circ.896) is explicitly excluded from the guideline including Hull painting and coatings.

Three-step methodology for CFD-based Vref derivation as below.

Qualification:

- CFD providers must demonstrate capability using ITTC guidelines or equivalent.
- Validation against public benchmark hulls (e.g., KCS, KVLCC2) is encouraged.

Validation/Calibration:

- Calibration factor: ratio of sea trial/model test power to CFD-predicted power from the target ship.
- Acceptable calibration factor range: 0.95 -1.05 (up to 0.90 -1.10 with justification).
- If no direct data is available, use similar ships or a comparable ship database.

IACS NO.175 SEEMP/CII Implementation Guidelines

IACS Recommendation No. 175, first published in April 2023 and updated in June 2025, provides guidance to support the implementation of the IMO's CII regulations. It is designed to assist shipowners, operators, and charterers in meeting the requirements of the IMO's energy efficiency framework, particularly in relation to SEEMP Part III.

The recommendation outlines the methodology for calculating the attained CII, incorporating correction factors and voyage adjustments to account for operational variances, with integration of IMO resolutions. It also details the procedures for verifying and rating the CII values, ensuring consistency with IMO reference lines and rating thresholds. Verification includes documentation standards and data validation processes. In addition to technical guidance, the document addresses company-level audits and compliance checks. It specifies the actions required when a vessel receives a D rating for three consecutive years or an E rating for a single year, including the mandatory development and approval of a corrective action plan.

3.3.1 Rules in Classification societies

Major classification societies established rules to facilitate the application of ALS.

3.3.1.1 American Bureau of Shipping (ABS):

- Scope and Application section outlines the purpose, applicability, and general principles of the ALS rules. It defines typical ALS arrangements, including their role in enhancing vessel stability, manoeuvrability, and safety under dynamic conditions. The Section also clarifies the types of vessels and offshore units to which the rules apply, and the conditions under which compliance is mandatory or recommended.

- ALS Machinery and Systems section provide detailed technical requirements for the mechanical and electrical components of ALS systems. It includes:
    - Piping systems: Specifications for pipes, joints, value, and shell vales in connection with Marine vessel rules (ABS rule 4-6-2).
    - Air compressors and reservoirs: Design criteria, redundancy requirements, and integration with control systems.
    - Main power and electrical systems: Power supply reliability, emergency backup provisions, and compatibility with vessel-wide electrical architecture.

- Control, Monitoring, Alarm, and Safety Systems section focuses on the automation and safety infrastructure of ALS. It includes:

    - Automatic control systems: Requirements for manual and automatic control modes, fail-safe mechanisms, and user interface standards.
    - Monitoring and alarms: Real-time data acquisition, fault detection, and alert protocols.
    - Safety systems: limit the consequences of failure, human safety and the vessel.
- Survey and Certification During Construction section outlines the survey procedures and documentation requirements during the construction and installation phases. It includes:
    - Inspection checkpoints for ALS components.
    - Testing protocols for system functionality and integration.

3.3.1.2 Bureau Veritas (BV)

The specific rules and guidelines for ALS from Bureau Veritas (BV) weren't listed in their Guidance Notes or Rule Notes. While BV awarded Approval in Principle to the GILLS Air Lubrication System, which demonstrates how BV evaluates ALS technologies for safety, performance, and compliance.

3.3.1.3 China Classification Society (CCS)

CCS issued guidelines in 2020 for the design, installation, and survey of ALS used for dragging reduction on sea-going ships. These guidelines aim to ensure the safety, effectiveness, and regulatory compliance of ALS technologies.

- General Provisions section defines the scope, terminology, and applicability of the guidelines which apply to sea-going ships equipped with ALS for drag reduction. Recognizes various ALS technologies, including Air layer drag reduction, Microbubble drag reduction, Air cavity drag reduction, Air supply device, and Air supply piping system. Allows for alternative systems if supported by theoretical analysis, testing, or recognized standards.

- Construction and Systems section outlines technical requirements for ALS components:
    - Longitudinal strength: minimize the effect on longitudinal strength from the openings for ALS.
    - Subdivision and stability: the intact and damage stability with ALS are to meet the CCS Rules for Classification of Sea-Going Steel Ships.
    - Air supply devices: Compressors or blowers with redundancy and capacity standards.
    - Piping systems: Materials, layout, and pressure containment.
    - Air layer/bubble generators: Devices that disperse air under the hull.
    - Air escape protectors: Prevent unintended air release or system failure.
    - Power and electrical systems: Integration with shipboard power, including emergency power.
    - Monitoring and control systems: Real-time performance tracking and safety interlocks.

- EEDI Calculation and Verification section outlines the methodology for calculating the EEDI for ships equipped with ALS and details the procedures for verifying the system's contribution to drag reduction and energy savings. In alignment with IMO MEPC.1/Circ.896, the CCS guidelines emphasize the importance of empirical validation. For the preliminary EEDI phase, CCS requires comparative model testing, with and without the ALS installed, to determine the propulsion power reduction rate, expressed through the parameters EDR_{Full} and EDR_{Trial}, during the preliminary verification phase. Additionally, numerical simulations (e.g., CFD analysis) may be accepted as an alternative to model tests, provided they are conducted using validated methods and yield results consistent with CCS standards. For the final EEDI verification phase, sea trial verification is required in order to estimate the reduction ratio of the propulsion power due to the ALS.

3.3.1.4 Class NK

ClassNK does not currently publish a dedicated standalone rulebook specifically for ALS.

3.3.1.5 Det Norske Veritas (DNV)

DNV (Det Norske Veritas) does not currently publish a standalone rulebook specifically for ALS. DNV issues RPs that provide guidance on performance verification based on in-service measurement.

3.3.1.6 The Korean Register (KR)

The Korean Register (KR) includes ALS as a recognized energy-saving and pollution prevention technology and has ES-ALS and ES-ALS1 notations. The guideline outlines the following:

- General section defines the purpose of ALS as a drag-reduction system that improves fuel efficiency and reduces GHG emissions. Recognizes ALS as part of the ship's environmental protection system.

- Basic Requirements section provides requirements on technical and design to mitigate risks from flooding and fire and to enhance the crew's safety, caused by the installation of the ALS. This Section outlines technical requirements:
  - Strength and Structure: The hull structure and openings for air injection are to be designed in accordance with KR Rules for the Classification of Steel Ships.
  - Stability: new and existing ships to be in accordance with KR Rules for the Classification of Steel Ships.
  - Auxiliaries and Piping Arrangement describes requirements for pipes, valves, and air chamber etc.
  - Electrical Equipment and Control gears for Motors where request to account additional electrical loads from ALS in the electrical load analysis.
  - Control, Alarm and Safety Systems: Control, alarm and safety systems are to be designed to avoid a single failure event leading to a potentially dangerous situation for human safety and/or the ship.
  - Ventilation and Fire safety.

- Additional Requirements section: The ships complied with this Section can be assigned a notation ES-ALS1, in addition to the Sec 2. The Section emphasizes redundancy, fail-safe design, and emergency shutdown features. KR requires real-time monitoring of air pressure, flow rate, and system status. Integration with the ship's automation and safety systems is mandatory.

- Survey section outlines the survey and certification process, including design approval, installation inspection, operational testing, and periodic surveys to ensure continued compliance.

3.3.1.7 Registro Italiano Navale (RINA)

The specific rules and guidelines for ALS from RINA were not listed in their rules.

Lloyd's Register (LR): LR provides detailed guidance for the integration and operation of ALS through its document LR-GN-017: Guidance Notes for Air Lubrication Systems. The purpose of the guidance is to support shipowners, designers, and builders in integrating ALS into new or existing vessels. It ensures ALS installations align with LR's safety, structural, and operational standards under the approval process, as shown in Figure 3-6.

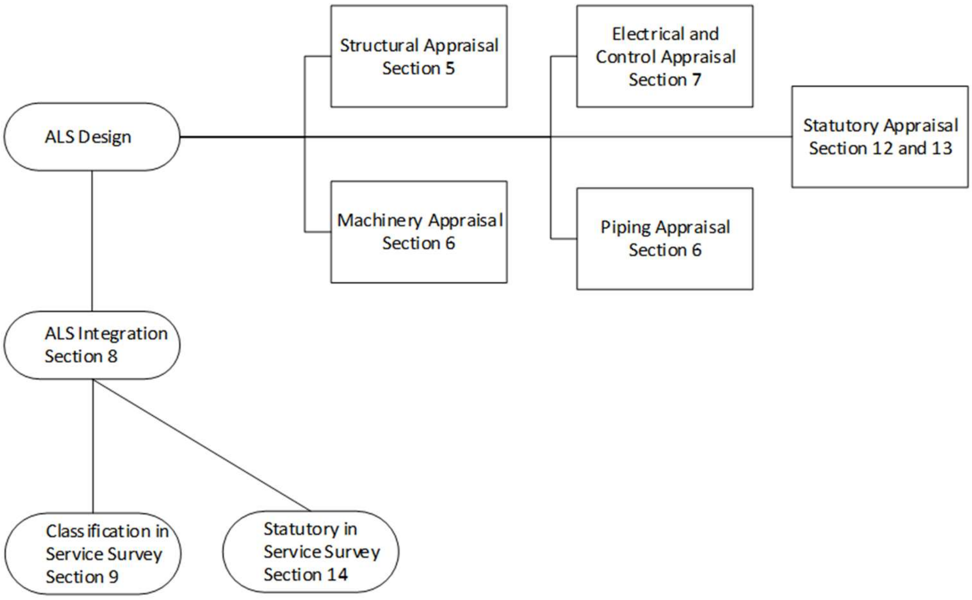


Figure 3-6 The approval process, captured from LR-GN-017(Source: LR)

- Structural Design section outlines global and local hull strength, dynamic loading, and maximum ship speed for a vessel with ALS. ADUs (Air Delivery Units) are treated as shell plating and must meet equivalent material and thickness standards.

- Machinery and Piping section focuses on:
    - Consider pipe materials, valve design, routing, pressure relief, and corrosion protection.
    - Ensure personnel safety from pressure and temperature hazards.
    - Electrical and Control Systems.
    - Maintain power balance and electrical protection.
    - Ensure remote and local shutdown capabilities.
    - Avoid placing components in hazardous areas unless properly certified.

- Survey and Certification section focuses on:
    - Integration Survey: Includes hull, machinery, and electrical inspections.
    - Installation Plan: Must include approved drawings, certificates, and NDE plans.
    - Sea Trials: May be required to verify system performance and ensure no adverse effects on other systems.
- Statutory Compliance section described that ALS must not interfere with statutory equipment (e.g., echo sounders). Considerations include:
    - SOLAS: Fire protection, stability, and electrical safety.
    - MARPOL: EEDI compliance and pollution prevention.
    - Load Line Convention: Design of air inlets and vents.
    - Tonnage Measurement: Impact on ITC and canal certificates.

- In-Service and Periodic Surveys section describes:
    - ALS components may become surveyable items under statutory regimes.
    - LR surveyors will inspect hull penetrations, coatings, and sea connections during periodic surveys.

3.4 International Organization for Standardization (ISO)

ISO provides two standard procedures for assessing a ship's speed vs. power performance. ISO 15016 is based on speed trial, and ISO 19030 assesses performance based on in-service data. Further details are provided in the Section.

ISO 15016 Ships and marine technology-specifications for the assessment of ship and power performance by analysis of speed trial data

ISO 15016 provides standardized procedures for assessing a ship's speed and power performance through the analysis of speed trial data. The first standard was published in 2002 and amended in 2015. The latest standard is ISO 15016:2025, which incorporates the STA-Group's work and ITTC guidelines. The standard outlines how to prepare, execute, and analyse sea trials to determine a vessel's performance under specific conditions. It is particularly relevant for verifying compliance with contractual speed requirements and EEDI regulations.

Key aspects covered include:

- Responsibilities of involved parties.
- Trial preparation and execution.
- Limits for environmental and operational conditions.
- Data measurement, correction, and analysis methods.

The standard ensures consistent, accurate evaluation of ship performance, particularly for displacement-type vessels, by accounting for variables such as wind, waves, current, and water depth. The result is a speed/power curve for clean hull conditions in calm weather. It is compared with model test results and provides a calibration of the model test curves. At the same time, model test results (propulsive efficiency and overload factors) are used to analyse the measured data.

The standard does not include special procedures or guidelines for vessels with ALS.

ISO 19030 - Ships and marine technology - Measurement of changes in hull and propeller performance

ISO 19030 provides standardized methods for measuring changes in a ship's hull and propeller performance over time. The standard is designed to help ship operators monitor and improve fuel efficiency by assessing the impact of hull fouling, propeller degradation, and maintenance activities. It is intended to analyse and track the performance of an individual ship over time, but it is not established for comparative analysis between different ships.

The standard is divided into two parts: Part 1 outlines general principles and performance indicators, and Part 2 details default methods for data collection and analysis. It applies to ships with conventional fixed-pitch propellers and supports performance comparisons before and after dry-docking or retrofitting.

Key aspects covered include:

- Quantify performance degradation.
- Evaluate the effectiveness of maintenance.
- Support decisions on hull cleaning and propeller polishing.
- Improve operational efficiency and reduce emissions

The standard does not include special procedures and guidelines for a vessel with ALS.

3.5 International Towing Tank Conference (ITTC)

ITTC 7.5-04-01-01.1 – Preparation, Conduct and Analysis of Speed/Power Trials

Like the ISO 15016 standard, the ITTC procedure is widely used to verify contractual speed and power performance and to support compliance with IMO energy-efficiency regulations, such as EEDI. The procedure does not include special guidelines for a vessel with ALS.

This guideline outlines procedures for:

- Preparing and conducting full-scale speed/power trials.
- Ensuring accurate and repeatable measurements.
- Correcting for environmental influences (wind, waves, current).

3.6 Gap Analysis

The objective of this gap analysis is to assess uncertainties and the lack of dedicated guidelines and regulations for implementing ALS in industry. Colour coding of the identified gaps is shown in Table 3-1. The summary of these gaps is seen in Table 3-2.

Table 3-1 Colour coding of gap analysis

Gap assessment	Colour status
No gap or changes	●
Small gaps / minor changes	●
Medium gaps / few changes	●
Large gaps / many changes	●

Table 3-2 Comparison of regulations, guidance, and Class rules for ALS applications

Subject	Code	Comments
Safety **ALS technology**	Classification societies from IACS members	■ Classification societies refer to existing rules, while some members have developed detailed rules or guidance for ALS installation, safety, and performance verification; some refer to the existing rules.
Safety **ALS operation**	Industry guidelines	■ Operational experience with the system remains limited, as do vessel designs and their operational profiles. Vendors are refining their systems based on feedback from vessels in service, addressing issues such as the location and geometry of the sea chest to mitigate the risk of air ingress. ■ Regarding performance verification, uncertainties persist regarding the system's actual effectiveness in real-world conditions, particularly regarding the risks associated with ALS during operation. One of the most critical challenges lies in the complexity of understanding and controlling the multiphase turbulent boundary layer beneath the hull, which is fundamental to achieving reliable and quantifiable drag reduction. Successful integration of ALS into ship design demands sophisticated control systems and responsive feedback mechanisms to ensure consistent performance across a range of operating conditions.
GHG Emissions verification	IMO	■ EEDI verification methods for both preliminary and final verification are available. ■ The guideline needs to be improved to account the following aspects. ■ Method and procedure for establishing the speed–power curve with ALS on and off during preliminary verification at the design stage. ■ Procedure for extrapolating from trial conditions to alternative loading drafts, such as the EEDI draft, or from even keel conditions to trimmed conditions.
	ISO	■ Vessel's speed vs. power performance with ALS installation can be investigated from the current procedure from the test with ALS on and off conditions in case the trial is carried out at EEDI draft.

		■ It is necessary to measure the compressor power consumption in addition associated with ALS, as well as quantify the energy losses occurring between the generators and compressors. ■ There are currently no established guidelines for extrapolating performance from trial conditions to alternative loading drafts, such as the EEDI draft. ■ To address this gap, a new ISO guideline is presently under development.
	ITTC	■ Same comment as ISO.
	IACS	■ All IACS members refer to MEPC.1/Circ.896.
	EU	■ EU ETS: Emission reductions achieved from ALS can be verified from the MRV system, which is directly linked to EU ETS compliance costs.
		■ FuelEU Maritime: Unlike wind-assisted propulsion (WAP), which may receive specific incentives under FuelEU Maritime, ALS is not rewarded because it does not alter the type of fuel or energy used by the vessel.

3.7 Maritime Regulations conclusions

The IMO NZF regulatory framework consists of two primary components: a mandatory global marine fuel standard and a two-tiered GHG-intensity pricing mechanism. The fuel standard mandates a gradual reduction in the GFI of ships, calculated on a WtW basis. Use of ALS is not expected to influence a vessel's GFI, as it does not alter the type of fuel and energy used by the vessel.

Within the European Union, the Fit for 55 package has extended the EU Emissions Trading System (EU ETS) to maritime transport. From January 2024, ships over 5,000 gross tonnage must monitor and report CO2 emissions and surrender allowances accordingly. ALS can reduce vessel fuel consumption, GHG emissions, and the number of EUAs. The FuelEU Maritime Regulation, effective from January 2025, targets the GHG intensity of energy used onboard ships. ALS does not alter the type of fuel used and therefore does not directly affect a vessel's GHG intensity under FuelEU Maritime. However, ALS reduces total energy use and GHG emissions, which can mitigate financial impacts by either reducing compliance deficits or lowering the amount of low-GHG fuel required to meet targets. This contrasts with wind-assisted propulsion (WAP), which may qualify for specific regulatory incentives due to its direct influence on propulsion energy sources.

The Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index are key IMO measures for promoting energy efficiency in new and existing ships. ALS is classified as a Category B-1 technology under MEPC.1/Circ.896, which provides guidance on incorporating innovative technologies into EEDI and EEXI calculations. While the circular outlines preliminary and final verification procedures, it lacks standardized methods for extrapolating sea trial data to EEDI conditions, especially for ships operating under trimmed ballast drafts. The International Organization for Standardization (ISO) has developed standards such as ISO 15016 and ISO 19030, which provide methodologies for assessing ship speed-power performance and monitoring hull and propeller efficiency. Similarly, the International Towing Tank Conference (ITTC) guidelines support sea trial analysis, but ALS-specific provisions are not available. These standards do not include specific procedures for vessels equipped with ALS. ISO 25189, Air lubrication device sea trial test, is under development and recommends a test method for ALS during actual ship trial tests.

Classification societies have taken varied approaches to ALS. Some, such as ABS, CCS, KR, and LR, have developed detailed rules or guidance for ALS installation, safety, and performance verification. CCS and KR include ALS in EEDI calculation procedures, referencing IMO guidelines. Others, including BV, DNV, RINA, and ClassNK, have no standalone ALS-specific rules; instead, they refer to the existing safety rules.

A gap analysis reveals that while MEPC.1/Circ.896 provides a foundational framework for EEDI verification involving ALS, it lacks detailed procedures for deriving speed-power curves and extrapolating trial data. ISO and ITTC standards do not address ALS-specific performance verification, and classification societies primarily focus on installation and safety, deferring EEDI assessments to IMO. Combined with limited operational experience and variability in vessel design and behaviour, this absence of a unified methodology presents challenges to consistent and reliable verification. The complexity of managing the multiphase turbulent boundary layer beneath the hull further complicates performance validation, underscoring the need for advanced control systems and standardized approaches to ensure dependable integration of ALS across the industry.

4. Safety assessment

Currently, there are no specific international safety regulations that apply solely to ALS. Nonetheless, the installation and operation of ALS are governed by a variety of established requirements set by major classification societies (see Section 3.3). Classification societies provide detailed guidance on integrating ALS into newbuilds and retrofits, covering aspects such as hull penetrations, machinery, piping, electrical systems, and control and monitoring infrastructure.

While ALS technology primarily utilizes proven marine equipment and does not introduce novel active components, it is important to recognize that system integration can present unique operational and safety considerations. For example, classification society guidelines require that all hull modifications, penetrations, and associated machinery installations comply with existing structural and safety standards. Additionally, the automation, monitoring, and alarm systems for ALS should adopt fail-safe and redundancy criteria to ensure vessel safety under both normal and fault conditions.

Although mainly addressing performance criteria such as DNV-RP-0695 emphasize the importance of robust installation procedures, long-term in-service measurements, and regular maintenance to ensure the continued safe operation of ALS. Furthermore, while ALS is generally not considered to introduce significant new safety risks when properly designed and installed, potential hazards—such as water ingress through hull penetrations, electrical faults, or unintended interactions with other onboard systems—should be systematically assessed through risk identification workshops (e.g., HAZID) and addressed with appropriate safeguards.

4.1 HAZID Workshop

This Section explains the common objectives, methods, and scopes used in the HAZID workshop.

4.1.1 Objectives

A HAZID aims to assess the overall safety risks associated with the design and implementation of an ALS. Results from the analysis will be used for decision-making purposes to ensure a safe design and operation of the system.

Main objectives of the HAZID are to:

- Identify potential safety hazards.
- Identify related causes and associated consequences.
- Review the existing/planned risk-reducing measures.
- Identify and propose additional risk-reducing measures where required (recommendations).
- Increase understanding among key stakeholders of the design, risks and challenges to be managed.

Results from the hazard identification will be recorded in a log sheet/risk register.

4.1.2 Scope

A general assumption for the HAZID is that all vessels to be fitted with ALS are approved according to applicable Class and Statutory requirements, as indicated in the introduction to this chapter. Thus, the workshop's scope would be the integration of the ALS into the vessel and its normal operation, and the identification of any safety-related hazards associated with this integration.

Retrofitting an ALS into an existing vessel may require hull modifications, whereas in a new vessel, it will be an integral part of the hull design. In both cases, approval from relevant regulatory bodies is necessary.

Aside from the hull modifications, ALS does not require extensive support systems beyond control-system and power-supply integration. The principles for ALS are largely the same across system types, though they may vary slightly by ship type and size.

4.1.3 Assumptions and limitations

The workshop focused on safety hazards associated with the normal operation of the ALS and the risks they may pose to personnel and third parties. Risks described and their related qualification of likelihood and consequence are provided as expert judgements by the HAZID workshop team.

General assumptions summarized:

- The focus for the workshop is on safety (for personnel and potential third parties).
- The system is installed and approved according to applicable Class and Statutory Rules & Regulations.
- The frequency & severity rating considers safeguards implemented to mitigate risk (i.e. residual risk).
- The severity rating considers a credible and worst-case consequence under the current conditions. If multiple final credible outcomes are identified, the worst one is selected.
- The frequency index selected is the likelihood of the final outcome, not the likelihood of the cause or the initial event.
- HAZID considers single failures only, which means simultaneous events or failures (i.e. double jeopardy) are not considered when they do not have any common failure.
- Hazards related to the operation of common shipboard equipment (e.g. compressors).

4.1.4 HAZID workshop methodology

The detailed procedure applied in this HAZID workshop followed the steps outlined below and the procedure is represented as a flow chart in Figure 4-1.

- Identification of HAZID Nodes: To assess the specifics of each individual area or operation, the areas and operations associated with a system are usually broken down into a series of nodes. In the case of ALS, however, the area of operation and system operation is limited to the extent that a decomposition into separate nodes was deemed not necessary.

- System (Node) Briefing: For all HAZID team members to obtain a common understanding of the design and intended operation of a node, an introductory presentation giving a brief introduction of a node is held. In this case, this was covered by a presentation of the system from the vendors participating in the workshop, as well as operational experiences shared by the ship owner.

- Identification of Hazards, their Causes, and Consequences:
    - In order to commence discussion on potential hazards associated with the utilities and equipment of the ALS, hazard sources should be identified. The HAZID team considered each node in turn to identify potential hazards associated with the system.
    - For each hazard identified, all potential causes of the hazard occurring were identified and discussed where relevant.
    - For each hazardous event, all possible health and safety consequences were identified and discussed, without taking credit for safeguards. Consequence was not limited by the HAZID node definitions or scope boundaries in evaluating the consequences of a given event.

- Identification of Safety Measures: The next part of the HAZID was for each hazardous event to identify existing or planned safety measures expected to prevent an incident from occurring, as well as those measures intended to control the incident development or mitigate its consequences.

- Determination of Severity, Frequency, and Risk: Risk ranking is the categorization of the identified hazards rather than the estimation of their associated risks. This allows to undertake the relevant risk analysis.

- Identification of Recommendations (Action Items): If the current provision of preventive or mitigating measures was identified to be insufficient to manage the hazard, or if further assessments are required to obtain a better understanding of the hazard, recommendations were raised during the workshop.

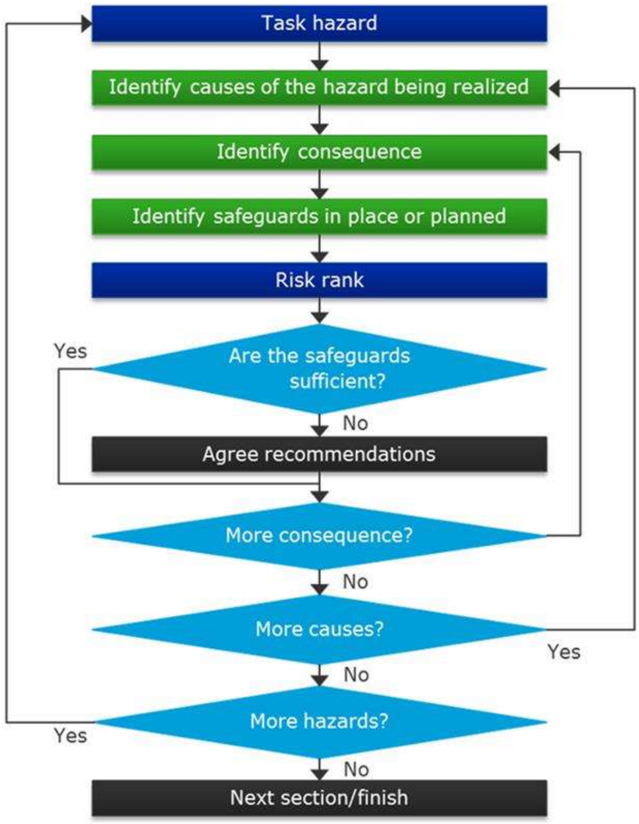


Figure 4-1 HAZID Procedure (Source: DNV)

4.1.5 Risk Ranking

Risk ranking was performed using the risk matrix shown in

Figure 4-2. Risk ranking was focused on the safety aspect.

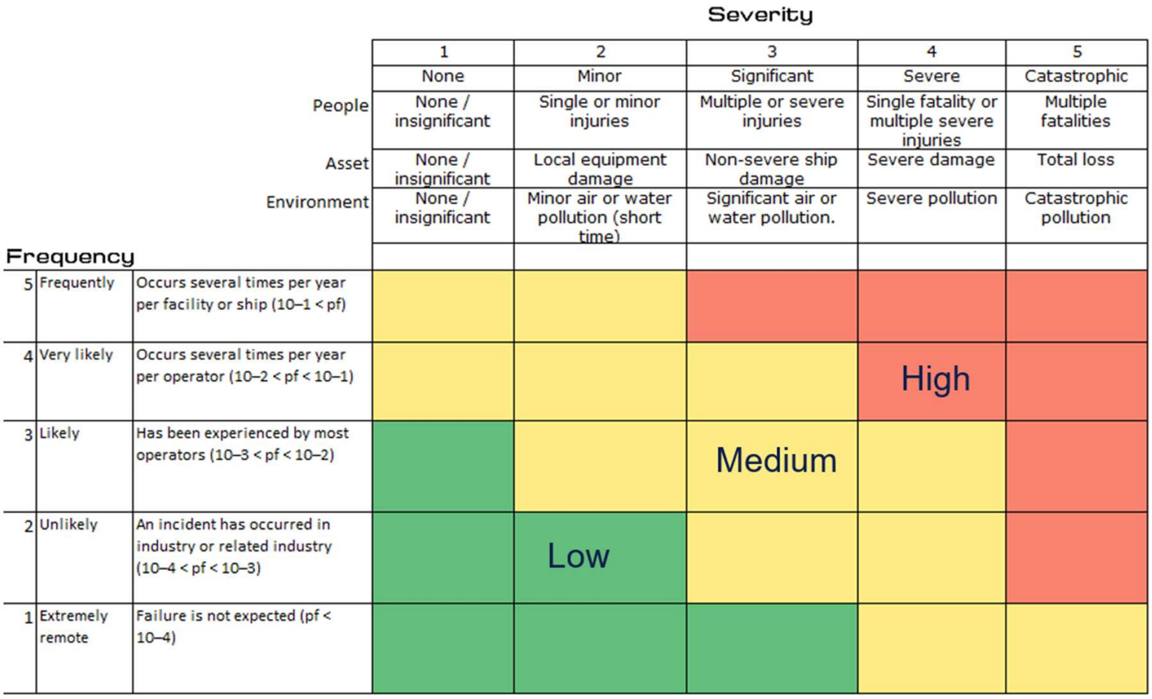


Figure 4-2 Risk Matrix (Source: DNV)

The risk matrix classifies hazardous events by their severity and frequency into low-risk hazardous events (Low, green region), which can be considered broadly acceptable, and high-risk hazardous events (High, red region), which are not acceptable unless additional safeguards are provided to reduce the risk. For medium-risk hazardous events (Medium, yellow region), it should be demonstrated that all reasonable, practical measures to reduce risk are in place. The information is summarized in Table 4-1 below.

Table 4-1 Risk acceptance criteria

Risk	Acceptance criteria
High Risk	Action must be taken to reduce risk to at least the medium level.
Medium Risk	Risk reduction measures must be taken if their respective costs are not disproportionately high as compared to their attained benefits (ALARP principal); actions need to be taken to manage and measure risk.
Low Risk	Monitoring actions required to identify whether the risk rises to medium level.

For each hazard identified, the following was discussed and recorded:

- Hazardous event.
- Causes.
- Consequences.
- Existing (or planned) safety measures.
- Risk ranking.
- Ship type specificity.
- Proposed Additional Safety Measures (Actions/Recommendations).
- Comments and Notes.

All the HAZID recommendations and relevant discussion were recorded in the HAZID log sheets (Appendix D) The HAZID worksheet was altered after the workshop session to incorporate comments to the log, including editorial updates.

The item “Ship type specificity” is meant to indicate whether a hazard would be specific for certain types of ships, in order to capture if there are any challenges concerning ALS tied to specific ship types.

4.1.6 Hazards

In terms of safety, typical hazards associated with ALS are primarily tied to the watertight integrity of the hull, as there will be additional hull penetrations to release air bubbles along the bottom of the hull.

Another characteristic that could be affected is the vessel's stability; reduced friction along the hull could lead to increased rolling. However, it is assumed that this effect would have a marginal impact on stability.

In general, ALS has not been reported to be subject to any specific safety concerns beyond those associated with operating general onboard equipment, which is outside the scope of this analysis.

4.1.7 HAZID Approach

In the workshop, representatives from two ALS vendors and a shipowner in the container vessel segment participated. One of the vendors has designed an active ALS, whereas the other has designed a passive system. System descriptions summarized in Table 4-2 from Section 2.2. Together, their systems are represented across a range of different vessel types, e.g. Cruise vessel, RoRo, Gas carriers, Chemical tankers, Bulk carriers as well as Multi-purpose vessel (MPV) for coastal trade/inland waterways.

In the opening part of the workshop, the vendors presented their respective systems to support assessment during the HAZID sessions. Furthermore, the shipowner provided an account of operational experience with ALS, primarily related to performance issues, performance measurement, and integration. However, no safety-related issues were encountered.

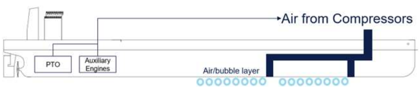
To identify hazards specific to certain ship types, the hazardous events were assessed to determine whether potential consequences would differ depending on their installation on different ship types. This was documented by adding a column to the HAZID log sheet indicating whether the hazard was ship-type-specific. The ship types used to benchmark these assessments were:

- Cargo and passenger ship: Cruise vessel and RoRo.
- Deep sea operation: Gas Carrier, Mega container vessel, Bulk Carrier, Chemical tanker.
- Coastal operation: Container feeder vessel, MPV.

The three ALS (ref.Table 4-2) under evaluation in the HAZID were:

- Active ALS - using onboard compressors to generate a continuous flow of air that is pumped through piping to ARUs located along FoB of a vessel’s hull.
- Passive ALS - creates air/bubble layer under a ship’s hull without relying on large compressors. Instead, it uses the vessel’s forward motion to drive water through venturi-based inlets, which naturally draw in air from deck level. The resulting air-water mixture is then released beneath the hull to reduce drag.
- Air Cavity System - decreases friction by creating stable pockets of air beneath a ship’s FoB, preventing large parts of the hull from coming into direct contact with water. Air is injected behind a cavitator, establishing a continuous cavity that is maintained with longitudinal skegs to stop air from escaping. By significantly reducing the wetted surface area, the system lowers hydrodynamic resistance and decreases fuel consumption.

Table 4-2 Description of different ALS

<table>
<tr><th>System</th><th>Description</th><th colspan="2">Hardware & arrangement</th><th>Vendors</th><th>Ship types</th><th>Remarks</th></tr>
<tr><td>Active ALS (Compressor-driven)</td><td>Compressors inject air via ARUs forming bubbles/air layer</td><td>No. of compressors are different depending on vendors, ARUs, piping</td><td>
</td><td>Alfa Laval, Silverstream, Samsung, Hanwha, Hyundai, etc.</td><td>LNG Carriers, Cruise Ships, RoRo and RoPax Ferries, Container vessels (feeders & ULCVs), VLCC/LR Tankers, Bulk</td><td>Refer to Section 2.3.2</td></tr>
</table>

					Carriers (ballast mode)	
Passive ALS (Venturi-driven air-water mix.)	Hull motion draws air via venturi pods/inlets	No compressors		Armada	Limited number of pilot installations (e.g. LNG Carrier for Armada PALS).	Refer to Section 2.3.3
Air Cavity System (Air pockets reduce wetted area)	Air cavities maintained by hull geometry + air feed	Cavity geometry + air supply		Damen (DACS)	Applied mainly in experimental cargo vessels, smaller high-speed craft, specialized hull designs (e.g., Damen DACS applications).	Refer to Section 2.3.1

4.2 HAZID results

During the HAZID workshop, 15 hazards were identified and logged. Of these 15, however, only 4 were somewhat linked to safety issues; the rest had no safety consequences. For ease of reference, the safety-related findings have been repeated in Table 4-3.

Table 4-3 Excerpt of risk-ranked hazards from HAZID log sheets

ID	Hazardous event	Potential causes	Potential consequences	Existing or planned safety measures	F1	Ss1	R1	Ship type specific?
1	Layer of air entering sea chests	- Hull and ALS design - Sea conditions	- SW pump cavitation - Loss/reduction of cooling water supply (operational) - Engine/Equipment trips - loss of propulsion/manoeuvrability - Grounding or collision - Issues with reverse osmosis plant/FW generation	- Changeover to different SW intake (usually both low- and high-level intakes are available) - Sea chest de-aeration vent - Cooling water temperature alarms	2	2	1	No
4	Cavitation	- Air from ALS affecting the cavitation properties of the propeller	- Erosion of propeller blades	- Periodic surveys of the propeller - ALS design/integration CFD simulation	2	1	1	No
10	ALS control system complexity	- Integration errors	- Damage to associated systems - Ship blackout - Equipment damage	- Class approval process (electrical systems)	2	2	1	No
14	Echo sounder interference (aft sensor)	Air boundary layer of ALS disturbing the Echo sounder	- Unable to assess depth in shallow waters in case of aft trim - Grounding or contact damage	- Double set of sensor(s), fore and aft, fore sensors should be able to get an accurate reading of depth - Mostly used during maneuvering where ALS would normally not be in operation	2	3	2	No

None of the identified hazards were found to be tied to particular ship types.

No high-risk hazards were identified, and only one was categorized as medium risk. When operating the ALS, air bubbles may interfere with data from the aft echosounder, resulting in false readings and potentially increasing the risk of contact damage to the sea bottom. This issue, however, is not considered very likely, as most vessels have a redundant fore echosounder that would provide a reliable result. In addition, the echosounder would be most relevant to use when maneuvering at lower speeds, i.e., when ALS is not operational.

Figure 4-3 gives a visual representation of the risk distribution resulting from the HAZID.

Frequency		Severity 1 None	2 Minor	3 Significant	4 Severe	5 Catastrophic
5	Frequently					
4	Very likely					
3	Likely					
2	Unlikely	2	1 10	14		
1	Extremely remote					

Figure 4-3 Distribution of risks in the risk matrix (numbers refer to hazard ID, Source: DNV)

In conclusion, the HAZID findings indicate that installing ALS does not significantly raise the risk level of a ship. Considering the relatively simple installation, the use of standard machinery and piping components, and the established regulatory regime of class rules that have covered this type of installation for many decades, the result is not surprising.

Compressing and distributing gases on board ships is done on almost every ship in the world fleet, from compressing flammable gases in cargo systems on gas carriers to compressing toxic refrigerants for processing, to compressing air for control systems and starting air.

Watertight integrity of hull penetrations is strictly regulated by Class Rules and Load Line regulations, ensuring proper pipe thickness and welding of pipes to the hull, while also requiring barriers against influx of seawater through the ALS piping system.

As a result, it can be concluded that ALS does not present any additional safety risk. Watertight integrity was likely considered the primary concern initially, but this is already addressed by the hull approval process with the Classification societies. Any penetrations from ALS would maintain the same level of integrity as other hull penetrations and the rest of the hull structure.

4.2.1 Recommendations

Although no high-risk hazards were identified, some recommendations were made, see Table 4-4. Please note that these recommendations should be considered fairly general, and to a large extent already part of good engineering/design- and operational practice.

Table 4-4 HAZID recommendations

Hazard ID	Recommendation
1	1. Consider locating the air release such that the likelihood of air accumulation in sea chests is as low as possible.
3	2. Consider disabling ALS when maneuvering in ports/narrow waters to reduce the likelihood for grounding or collision scenarios
4	3. If cavitation may be a concern, consider carrying out acoustic emission tests to determine if this is a problem and prevent subsequent propeller damage.
10	4. Ensure that the integration of ALS covers a discrimination study (electrical & Instrumentation) to ensure that switching on the ALS system will not draw power from the system to such an extent that the vessel may experience a blackout
14	5. Ensure crew training and knowledge sharing that the crew are aware not to pay attention to aft echo sounder when ALS is in operation
14	6. Consider if there is a possibility to integrate an alarm/alert for aft echo sounder if the ALS is operational and fore echo sounder measures depth below keel to be reduced below an applicable threshold, to make crew aware that aft echo sounder is not providing reliable data and prevent potential groundings.

4.2.2 Conclusive remarks

Based on the risk assessment, ALS may be perceived as a relatively low-risk system. This could potentially be a result of being based on well-known equipment, and subject to approval within well-established disciplines of naval architecture. No risks were identified as being specific to particular ship types. Although no representatives from the passenger vessels segment were present, contacts in the industry report that the main concerns within this segment are related to performance as well as noise and vibration, the latter as a result of passenger comfort being of vital importance.

5. Conclusions

ALS represents a promising but still maturing approach to improving energy efficiency and reducing emissions in maritime shipping, particularly for vessels with substantial flat-bottom areas, such as LNG carriers. With more than three hundred vessels already equipped and several hundred more on order. The resulting decrease in fuel consumption directly reduces GHG emissions and other air pollutants, including NO_x, SO_x, and particulate matter.

Across vessel types, verified net energy savings generally fall between 2% and 5%, although vendors have reported higher percentages for LNG carriers, RoRo and RoPax vessels, and cruise ships. The performance of ALS is closely linked to vessel design characteristics, particularly the size and continuity of the flat-bottom region and machinery system for compressor power supply, as well as operational factors such as speed, draft, and prevailing sea states. These sensitivities mean that the magnitude and consistency of potential savings vary across the fleet.

Predicting full-scale ALS behaviour remains challenging due to limitations in computational fluid dynamics and physical model testing, both of which struggle to accurately capture multiphase flow and the transition between bubble regimes and air-layer formation. As a result, full-scale trials and long-term operational monitoring remain essential for reliable performance verification.

Compressor power consumption is a significant determinant of net savings for active ALS systems, and vessels capable of supplying compressor loads through shaft generators demonstrate a clear advantage over those reliant on auxiliary diesels. Although passive ALS and Air Cavity Systems offer interesting potential, their lower levels of technological maturity and limited operational evidence introduce greater uncertainty.

While ALS can contribute to sustainability by reducing fuel consumption and associated GHG emissions, its effectiveness depends heavily on vessel type, operational profile, draft, and environmental conditions. Economic feasibility likewise varies, with newbuilds and vessels featuring low operating drafts and shaft-generator power systems benefiting the most, whereas retrofits and high-draft ship types tend to see less favourable effects.

Safety assessments indicate that ALS does not introduce any high-risk hazards when well designed and approved according to applicable rules for the classification of ships. A medium-risk item identified in the safety assessment, interference with aft echo-sounders, is manageable through operational measures. Additional risks related to potential air ingestion, cavitation behaviour, noise, and control systems can be effectively mitigated through engineering design and operational procedures.

From a regulatory perspective, ALS aligns with IMO decarbonization objectives and is recognized within the EEDI and EEXI frameworks, but it is not yet directly incentivized under the FuelEU Maritime Regulation. Given its proven ability to reduce fuel consumption and emissions, there is a strong basis for regulators to consider more explicit acknowledgement of ALS within future revisions. Looking ahead, increased transparency in vendor reporting, standardized performance-verification protocols, and the development of ALS-specific testing standards within ISO and ITTC will be essential to further improving confidence and facilitating wider adoption across the global fleet.

Table 5-1 summarizes the main observations, mitigations/suggestions for different categories described in the study.

Table 5-1 Main observations, mitigations, and suggestions

Category	Main Observations	Mitigations / Suggestions
ALS Technology	■ ALS reduces hull friction by injecting air (air/bubble layer, cavities). ■ Active systems use compressors; passive systems use the venturi effect. ■ >300 vessels in service and ~300 on order. ■ Performance prediction difficult due to two-phase flow and scale effects.	■ Apply DNV-RP-0695 and emerging ISO 25189 verification when it is available. ■ Investigate full-scale trials and a long-term assessment. ■ Strengthen collaboration among vendors, shipyards, and class societies.
Sustainability	■ Reduces fuel use and GHG, NOx, SOx, PM.	■ Conduct long-term in-service measurements.

	■ Expected savings depend on ship type, operational pattern, machinery and systems onboard, etc. ■ Possible URN reduction. ■ Savings depend on vessel type, draft, weather, and compressor load.	
Suitability	■ Depends on lubricated area, draft, speed, hull geometry, compressor load, weather. ■ Low-draft ships (LNGC, RoRo, cruise) show higher benefit. ■ High-draft vessels show reduced benefit.	■ Investigate the vessel's operational profile, hull characteristics, and machinery configuration before deciding on ALS installation. ■ Calibrate ALS separately for ballast/laden and make an operational guideline for different weather conditions. ■ Use adaptive control for varying conditions.
Availability	■ Widely available from multiple vendors globally. ■ System variants (ALS, Passive ALS, ACS) differ in maturity. ■ Not sufficient operational experience and verified performance of different systems.	■ Strengthen collaboration among vendors, shipyards, and class societies.
Techno-Economic Aspects	■ Newbuilds with shaft generators give better economics than a vessel with Gensets. ■ Retrofits are less attractive due to both higher CAPEX and OPEX. ■ Economics are influenced by fuel price, weather, and utilisation.	■ Account for route, sea state, and operational profile in payback analysis. ■ Consider hybrid measures for retrofits, such as PTO.
Regulations	■ ALS reduces fuel use, but no effect on GFI. ■ Category B-1 under MEPC.1/Circ.896 for EEDI/EEXI. ■ Lacks standardized method for extrapolating sea-trial data. ■ ETS reductions via lower fuel use.	■ Strengthen collaboration among vendors, shipyards, and class societies to develop an agreed procedure. ■ Support ISO/ITTC standardization efforts.
Risk Assessment	■ 15 hazards identified; none high risk. ■ One medium risk: echo-sounder interference. ■ Other concerns: noise/vibration from pipes from the compressed air flow, air in sea chests, added drag.	■ Disable ALS in shallow waters. ■ Improve sea chest design. ■ Use vibration-damping mounts and flexible supports to isolate the piping from the hull structure. ■ Design piping layouts to minimize sharp bends, sudden expansions, and contractions. ■ Mount compressors on vibration-isolating bases.
Performance Uncertainty & Verification	■ CFD/model tests limited for the two-phase flow and scale effects. ■ Full-scale data essential. ■ ISO 25189 is under development and DNV-RP-0695 is currently applicable for verification.	■ Strengthen collaboration among vendors, shipyards, and class societies to develop an agreed procedure.

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Appendix A Interviews with ALS vendors and Model basins

Background to this study

There are previous studies on ALS, such as the 2020 study by DNV, “Building knowledge base and assessment of ALS,” conducted for a large energy supplier. The project consisted of three main parts:

- Liaison with model basins about the state-of-the-art of experimental and numerical performance prediction methods for ALS.
- Literature review on the working principles of ALS and the performance prediction methods for ALS.
- Liaison with vendors and shipyards to understand their specific technologies for ALS, to learn from their experience on experimental and numerical performance prediction methods, and to hear their feedback from sea trials with ALS.

Since 2020, research on ALS has increased, more vendors have entered the market, and various technologies with different operating principles have been proposed.

To understand the working principles, the underlying physical principles and the technical maturity of a vendor's ALS, the following questionnaire covering typical challenges in the design and operation of ALS was discussed with the vendor's specialists during a workshop:

1. How do you optimise the shape of the nozzle designs resp. the air release units?
2. How do you optimise the placement/arrangement of the nozzles resp. the air release units?
3. What is the added resistance due to air release units (ALS not in operation)?
4. How do you ensure that no air is accumulated in the sea chests?
5. How do you ensure that there is no increased risk for cavitation/erosion?
6. How do you optimise the air flow rate for different ship speeds and drafts?
7. How do higher sea states affect the performance of the ALS bubble layer?
8. What do you implement in the control system of the ALS?
9. What is the expected power consumption for the air compressors, and how do you measure it during the trials?
10. How do you verify the savings during the sea trials?
11. Is there a pilot installation with the vendor ALS, and what are the verified savings?
12. Are there installations on various types and sizes of ships with the vendors ALS, and what is the feedback on the power and fuel savings from service measurements?

Liaison with model basin RISE (formerly SSPA)

The main goal of this initial meeting with RISE was to understand RISE's current 'best practice" for testing ALS, whether by EFD (experimental fluid dynamics), CFD (computational fluid dynamics), or full-scale measurements on ships, and to learn about their plans for future development.

Speed-Power Prediction

Towing tank resistance and self-propulsion tests with ALS in principle do not differ from typical towing tank tests. Initial tests for ALS are conducted at various air flow rates to determine the optimal balance between air flow and energy savings. Final tests are carried out at different draughts and across a range of speeds, both with ALS switched on and off.

The scaling from the model test figures to full-scale remains unresolved. RISE did not comment on the relevant ITTC Recommended Procedure 7.5-02-02google-03 "R&P Tests with Skin Friction Drag Reduction".

To scale the gains within an R&D project, RISE has conducted resistance tests on large plates (7m long) at various speeds and air flow rates. The resistance measurements are supported by visual observations and video recordings of the air sheet forming along the length of the plate.

In the RISE test setup, micro air bubbles are generated by pressing air through a sinter metal split with an average porous diameter of 20 microns. In an alternative test setup, an air film is generated by pressing air through a narrow gap. Both the air bubbles and the air film led to similar decreases in skin friction resistance in the case of the 7 m plate (depending on the air flow rate, gains of up to 20-25% have been found for the micro bubbles and up to 15-18% for the air film).

It could be noticed that resistance reduction with ALS is small once the flow rate is higher than a certain rate (in calm water conditions). Hence, it is DNV's opinion that a systematic air flow rate study can be useful to balance between compressor load and shaft power reduction in order to decrease overall consumption.

To better understand what the difference in observed air flow pattern along the plate means for the gains, repeat tests have been performed with a so-called split-plate. This means that the 7 m plate was divided into a 1 m long forward part and 6 m long aft part, for which the resistance has been measured individually. It turned out that from the 20-25% gains of the total plate, the aft 6 m contribute with just 5-6% to the total gains.

This concludes that just the most forward 1 m part of the 7 m plate is sufficiently covered by air bubbles so that the skin friction resistance is reduced to approximately zero. The air coverage of the remaining 6 m part of the plate is just suited to reduce the skin friction resistance of the aft part by 5-6%.

For scaling the results of towing tank tests with ALS RISE suggests performing resistance tests with a 10 m split plate, consisting of 10 segments with length 1 m each. With such a test setup RISE expects to better understand the reduction of the skin friction reduction over the length of a submerged flat plate. The scaling from 10 m model plate to the length of the full-scale FoB shall be supported by CFD.

Computation fluid dynamics (CFD)

It is RISE's opinion that CFD can give answers only in combination with model tests in the design and optimization of ALS. CFD typically applied for naval architects' problems cannot dissolve the microbubbles sufficiently.

Furthermore, unrealistic air entrainment at the hull fluid intersection is often an issue in 'normal' VoF (Volume of Fluid) calculations and the codes have been developed to avoid this. This handling is of course problematic when using the same CFD tools to assess the reduction of the skin friction by an air sheet layer.

However, if the local skin friction resistance reduction is known (from model tests), CFD can be used to simulate the effect of the ALS flow around the hull by modifying the boundary layers where ALS is present. This will increase the confidence in full scale speed/power predictions both in terms of improving resistance estimates and delivered power (i.e. effect on viscous pressure resistance and propulsive efficiency).

Performance in a seaway

To assess the performance of ALS in a seaway RISE suggests performing resistance tests with the 10m split plate but inclined to the horizontal plane corresponding to typical roll and pitch angles. The change of the surface area covered by the air layer should give an indication how much the performance in a seaway might be reduced in the worst case.

Full-scale measurements

To verify the predicted savings RISE suggests just performing trial measurements with ALS switched on and off. When performed directly after each other, the results can be compared even without the need to correct for the effect of wind, waves and current.

To support the design and optimisation process, RISE does not see the need for observations (e.g., near the air outlets or below the ship's bottom) because they cannot be quantified. The visual impression may not even indicate whether an air layer of bubbles is attached to the bottom surface (reducing skin friction) or detached from it (having no effect on skin friction).

Records for ALS model test

The Air Cavity System, which requires a chamber to capture the air cavity, has been investigated in collaboration with Stena. A prototype model vessel, about 15m in length has been tested for an Aframax tanker. However, it seems the actual ship has not been designed and ordered.

A full-scale test for a nozzle or an air outlet was conducted in a cavitation tunnel. Due to the cavitation tunnel's water circulation, there is limited time to observe and measure without air in the tunnel, and RISE prefers to conduct the ALS model test in a towing tank.

RISE has conducted several research projects on ALS, as reported in the “Speed-power prediction” section. RISE has also conducted several commercial tests with air-cavity systems and some air-film/air-bubble systems, both in the towing tank and the cavitation tunnel.

Tests in the cavitation tunnel might be difficult, but can be very rewarding, and to our knowledge, the latest tests done there have been implemented on board. It is correct that there are limitations to the cavitation tunnel, but with good measurement and video systems, the full-scale capability is very interesting. For performance determination, a combination of model testing in a towing tank, cavitation tunnel and CFD is the best approach.

Availability on ALS model test

RISE is flexible and can execute ALS model tests on short notice.

Liaison with model basin HSVA

The main aim of this initial meeting with HSVA was to learn what HSVA's "best practice" is today for testing ALS, either by EFD (experimental fluid dynamics), by CFD (computational fluid dynamics) or by full-scale measurements on board ships, and what their plans are for future development.

Speed-Power Prediction

Following the ITTC proposal, towing tank resistance and self-propulsion tests with ALS essentially do not differ from "normal" towing tank tests. Initial tests for ALS are conducted at various air flow rates to identify the optimal ratio between air flow and savings. Final tests are carried out at different draughts and across a range of speeds, both with ALS switched on and off, as is standard.

However, HSVA does not support this view. HSVA would not recommend performing such kind of tests.

Not yet solved is the scaling from the model tests figures to full-scale. HSVA commented on the ITTC Recommended Procedure 7.5-02-02-03 "R&P Tests with Skin Friction Drag Reduction" as following:

- From scientific point of view correct, but the change from "ITTC 57 Correlation Line" to "ATTC Friction Line" does not allow using the established extrapolation procedures of each model basin and the proposed Geosim model tests to determine alpha(full-scale) is a "killer" for commercial projects and thus practically not usable.

HSVA suggests a "hybrid" approach as outlined below:

- Performing 1:1 full-scale test in HYKAT as described below. Determine the potential for friction reduction with several air concentrations.
- Performing CFD calculations applying HSVA's FreSCo+ implementation of an additional transport equation for air bubble concentration. Derive the reach of air bubble carpet and concentration.
- Performing resistance and self-propulsion tests as usual (without ALS).
- Applying alpha-reduction rates (depending on bubble-concentration) based on HYKAT results to the areas identified in 2.

HSVA would use ITTC57 correlation line for consistency reasons.

Optimization (shape and placement of nozzles)

HSVA recently has been in charge for similar investigations for a major mining company as required by DNV GL's customer.

HSVA has performed a combination of tests and calculations with the ALS supplier being involved. Heart of the test campaign were 1:1 full-scale test with an original air release unit installed in HYKAT (large cavitation tunnel) to investigate air carpet behaviour and influence on resistance. The latter with air supply being switched on and off.

Further tests were carried out with a normal scale ship model in HYKAT to investigate side effects on sea chests as well as on cavitation, noise and pressure pulse generation.

It was an idea discussed in the meeting that side effects on sea chests can be dealt by finding a location where is safe from bubbles or special design to prevent air into sea chests such as blowing water from sea chest to change flow around inlet area. It has been applied to vessels operating in Ice condition for similar reasons.

Performance in a seaway

HSVA recently has tested research vessels in a seaway to assess the "bubble sweep down" performance of these vessels. The process of generating the bubbles is completely different, but the problem (tracking the bubbles along the ship's hull) is somewhat similar. In case of the research vessels the bubbles are generated by breaking waves at the water surface. The breaking of the wave can either be the bow wave itself or can be breaking waves of the seaway. The bubbles are transported in huge clouds below the hull, and it is intention of the tests to verify that the bubbles do not compromise the effect of sonars and transducers until a certain sea state.

The “model bubbles” are known to be too large and having a relative bigger buoyancy than the full-scale “bubbles”. Thus, the “bubble sweep down” tests have been performed with ink instead. The assessment of the “full-scale” ship has been done by comparing corresponding CFD both in model-scale and in full-scale.

It could be noticed that CFD results showed good agreement with the test results.

As the CFD typically applied for naval architects’ problems cannot dissolve the micro-bubbles sufficiently the CFD was performed not considering bubbles at all.

Instead, after having calculated the flow field around the hull in a second step a scalar transport equation for an introduced artificial air bubble - water concentration is solved, indicating the amount of air bubbles at any point in the flow field around the ship relative to its source, e.g. breaking bow wave. This method is preferably applied in the scope of hull form modification with respect to bubble sweep down or the optimization of the alignment of the sonar devices.

Similar approach HSVA suggests for assessing the air-coverage of a ships bottom equipped with ALS, both for calm water and in a seaway. The different air-coverage in model-scale and in full-scale should be used to decide on a suitable alpha(full-scale) for extrapolating the savings.

Liaison with the model basin MARIN

The main aim of this initial meeting with MARIN was to understand what constitutes MARIN's "best practice" today in testing ALS, whether through EFD (experimental fluid dynamics), CFD (computational fluid dynamics), or full-scale measurements aboard ships, and to learn about their plans for future development.

How to predict the savings due to ALS best?

In principle, there are different options to perform the predictions, but all have their drawbacks:

- Model tests suffer from large-scale effects, and the correlation is difficult to verify.
- Typical CFD (RANSE) cannot handle bubbles in a suitable way.
- Specialized CFD using two-phase models (water and air) are extremely sensitive to numerical settings and can produce any results.
- Most reliable method today is probably extrapolating from known full-scale data from vessel(s) in operation to a new project.

There is no standard method to estimate the savings from ALS yet. However, neither the savings in [kW] nor the savings in [%] of a parent vessel can be directly applied to a target vessel. Compressor power depends on the operating parameters of the compressed air system (pressure loss, compressor efficiency), the air flow rate, and the ship's actual draught and speed. The hydrodynamic savings depend on the area of the bottom effectively covered by air, the thickness of the air layer, and again, the ship's speed. Shipyards and/or vendors will need to disclose their method for transferring results from a parent vessel to a new target vessel if ALS is to be considered in EEDI.

The unresolved issue today is the scaling of the savings resulting from ALS. Injecting gas (air) causes two distinct drag-reduction phenomena: air-layer drag reduction (ALDR) and bubble drag reduction (BDR). The air-layer flow offers friction drag reduction of over 80%, while bubble flow provides only about 20% or less friction drag reduction.

It remains unclear which effects predominantly influence the stability of the air layer and how the transition from air layer to bubbles is initiated. The primary effect is probably simply the length downstream of injection, but the stability of the air layer likely depends on many other factors: salinity and temperature of the fluid (seawater), pressure distribution and pressure gradient (draft, trim, ship motions such as heave, pitch, trim), surface roughness (deteriorated coating, fouling), etc.

How to optimize the shape of the nozzle designs resp. the air release units?

The best way to test and optimise the shape of the nozzles or the air release units is through full-scale tests in high-speed facilities, such as the "Bill Morgan Tunnel" in the United States or the HYKAT at HSVA.

However, these tests are still somewhat limited as they can only be performed in fresh water. The salinity of the water is known to affect the stability of the air-layer.

Full-scale CFD serves as an alternative, provided that results can be validated against full-scale measurements.

How to optimize the placement / arrangement of the nozzles resp. the air release units?

Full-scale CFD is suggested to optimise the placement or arrangement of nozzles or air release units. Avoid positioning the units in areas with large pressure gradients or low-pressure zones, and align the units with the main flow direction.

What is the added resistance due to air release units (ALS not in operation)?

The additional resistance for a single opening is small compared to the total resistance of a ship. Full-scale CFD can be utilised to determine the added resistance of the units when ALS is not in operation.

How to ensure that no air is accumulated in the sea chests?

This depends on the ship's design. It is advisable not to place sea chests in the path of the bubbles. If this cannot be avoided, fitting deflectors could be an option. Alternatively, increasing the size of the vent pipes may help to eliminate the air.

How to ensure that there is no increased risk for cavitation/erosion?

MARIN does not see this as a risk. On twin-screw cruise vessels with open shafts, the air passes between the propeller tips and the hull, and the airflow does not affect cavitation or erosion at all.

On twin-skeg LNGCs, this may differ slightly, but it might only cause minor changes to the wake field that can be addressed in the propeller design. This can be verified with CFD using different boundary conditions (no slip, no shear) on the hull to gain insight into a "worst case" scenario.

Air entering the propeller plane will decrease the severity of cavitation. The collapse of vapor bubbles ("normal" cavitation causing erosion) will be more violent than the collapse of air bubbles.

Another effect of air entering the propeller plane is the loss of forward thrust, and the propeller's operating point shifts slightly towards higher rpm.

How to optimize the air flow rate for different ship speeds and drafts?

The optimal air flow rate cannot be directly determined during scale model tests, as scaling laws are in effect.

MARIN expects that full-scale calibration tests before the speed trials are necessary to determine the optimal air flow rate for drag reduction. Ideally, the air flow rate should be calibrated for each unit or pair of units.

Calibrating the ALS could be aided by assessing the quality of the air layer at the location. MARIN has conducted measurements using sensors that detect air and water to differentiate between the air layer and bubbly flow. These measurements have been taken at six different locations, each within the boundary layer at three distances from the hull (3 cm, 6 cm, and 18 cm). The equipment and test setup remain experimental.

The question remains: When calibration is done at ballast draught, how should it be calibrated for the loaded condition? Since there is no agreed method for this yet, calibration (balancing the compressor load and shaft power reduction) must be performed at least twice—once at ballast draught and once at loaded condition.

How do higher sea states affect performance of the ALS?

Probably worsens the situation. The air-layer is highly sensitive to pressure variations and therefore to heave, pitch, and roll motions of the ship. Eventually, the air-layer may break into patches of air or bubbles, significantly reducing drag reduction.

The question is, at which sea-state should the ALS be switched off, because the drag reduction no longer outweighs the energy consumption of the compressors?

In principle, this could be measured during scale model tests, but there remains the unresolved issue of scaling the results to full-scale.

What parameters to implement in the control system of the ALS?

The optimal airflow rate depends on the length of the bottom surface intended to be covered by air, the actual draft and trim of the vessel, and the ship's speed. These are the minimum control parameters to be used. Additionally, water temperature, salinity, and any impurities in the seawater are likely to affect the stability of the air film and the transition from air layer to bubbles. In the long term, it may be advisable to include these as control parameters as well. The airflow rate should be monitored per air inlet on a short time-scale basis (order of seconds).

What is the expected power consumption for the air compressors and how to measure during the trials?

According to extrapolation from model tests and as per publicly available feedback from full-scale trials the power consumption of the air compressors ranges between 3-5% of the propulsion power. The percentage of the propulsion power depends on the actual speed of the vessel, e.g. 5% yields for lower speeds, while 3% yields for higher speeds (see paper of “Lee et al”, table 9).

For bubble flow systems (using less air compared to air layer/cavity systems), the power consumption is somewhat lower (approx. 1-2% of the propulsion power). However, as mentioned under question 1, the effectiveness of a bubble system is less compared to an air layer/cavity system.

The electric consumption of the compressors should be measured locally during the trials.

How to do verification of the savings during the sea trials?

Verification of savings during sea trials can easily be achieved by switching the system “on” and “off”. Preferably, the 'on/off' measurements are performed consecutively, starting with the “off” condition and then proceeding to the “on” condition in the same direction. Both “on/off' measurements should be carried out at the same power settings, against and with the wind condition.

Enough time must be allowed until the vessel has reached a steady condition again.

A sufficiently long measurement period with the system switched “on” is advised, as the measurement results may be influenced by low-frequency fluctuations of the air-film/air-bubble flow.

Damen Air Cavity System (DACS)

The following information on the Damen Air Cavity System (DACS) has been taken from Damen's homepage:

Next Generation Air lubrication

Damen Air Cavity System© (DACS) is a patented ALS. By generating cushions of air between the hull and the water beneath the FoB area, a substantial reduction in resistance can be achieved. This results in lower fuel consumption and emissions. DACS can reduce fuel use by up to 15% and has been verified by RINA and Lloyd's Register.

Damen Air Cavity System© at similar flow rates, an air cavity reduces the friction significantly more than the 1st generation bubble generating systems. The system aims to reduce resistance in the water, particularly for ships with a low Froude number ($Froude\ Number = Ship's\ Speed(V)/\sqrt[2]{g \times Ship\ Length}$). Such vessels are known to encounter the greatest resistance in the water. By reducing this, DACS achieves both lower both emissions and fuel consumption.

How DACS works

With DACS, an air cavity is formed by injecting air beneath the vessel behind a small cavitator that separates the water flow from the hull. To secure the cavity, longitudinal skegs are fitted to prevent the air from escaping sideways. The compressors only need to overcome the hydrostatic pressure caused by the vessel's draught. As a result, the air cavity method requires significantly less compressor power than competing first-generation systems. To maximise the hull area covered by the system, multiple cavities are created in series, separated by transverse skegs that help maintain seakeeping behaviour. Having a series of cavities also offers the advantage that any air escaping from one cavity is absorbed by the next.

Air cushions instead of air bubbles

Damen Air Cavity System© was developed in a collaboration with Delft University of Technology. The technology is patented worldwide. DACS is reducing the vessel's wetted area. This is done by creating stable pockets of air that separate the hull from the water. Damen Shipyard Group has commercialised the technology by using MARIN and HSVA to evaluate under real ship conditions.

Significant savings

Last year, Damen installed the DACS system on Amisco's cargo vessel Danita in Estonia. During Danita's sea trials, Damen gathered data on the vessel's performance. Independent verification by RINA confirmed that DACS allowed the vessel to achieve significant fuel savings (6-7%).

To strengthen the findings, Damen sought a second opinion. Its next step was to provide Lloyd's Register with the same data. With this, Lloyd's carried out an independent verification, using its own methodologies. Lloyd's results were similar to those of RINA, showing that at the vessel's typical operating speeds, DACS reduced fuel consumption by between 7-8%.

Silverstream Air Lubrication System

Silverstream Technologies provided the following responses to the questionnaire, which was distributed to the model basins and all vendors participating in this study.

How to predict the savings due to ALS best?

The projected savings associated with the potential deployment of the Silverstream® System are estimated, based on data provided by the ship owner, charterer, ship designer, and/or shipyard.

During the design phase, when complete documentation may not yet be available, performance estimates can be provided using reference hull forms with similar principal dimensions that have previously been analysed by the team.

As more detailed technical information becomes available, such as flow line data and other outputs of CFD analyses, a tailored Air Release Unit (ARU) arrangement is developed. This forms the basis for analysing the lubricated area and calculating potential fuel savings.

Silverstream's proprietary estimation tool is built on data from extensive full-scale testing conducted at the HSVA HYKAT (hydrodynamic and cavitation tunnel) facility, and real-world data from the installed fleet. These results have been carefully adjusted to reflect real-world conditions and operational profiles. Correlation factors are also applied to assess the lubricating effect of the technology.

As the Silverstream in-service fleet continues to grow, real-world operational data is integrated into the estimation tool, ensuring that savings projections remain as accurate and reliable as possible.

How do you optimise the shape of the nozzle designs resp. the air release units?

The design of the Air Release Unit (ARU) has been optimised through the conduct of extensive testing at HSVA. The shape of the ARU and its effectiveness in generating fluid shearing – the phenomenon that underpins the functionality of the Silverstream® System - has been tested at a wide range of speeds and draughts, to ensure all operating conditions of the ship could be verified in a controlled environment.

The primary elements of ARU shape have remained constant since inception and initial proving, however, further testing across multiple test campaigns contributed to the continued evolution of the ARU shape.

How do you optimise the placement/arrangement of the nozzles resp. the air release units?

As part of the initial estimation process, a preliminary Air Release Unit (ARU) arrangement is developed. The size of each ARU is selected based on the vessel's hull structure, while the overall system configuration (the number of ARUs and compressors) is determined by the extent of the FoB area. Where available, CFD analyses and flow regime data are incorporated to enhance the accuracy of this stage.

As the project progresses and more detailed inputs become available, Silverstream's structural engineering team collaborates closely with ship designers to ensure the ARU arrangement is structurally compatible and fully compliant with Class regulations.

Occasionally, this collaboration leads to minor adjustments to the most efficient configuration to align with structural constraints. However, Silverstream consistently engages in dialogue to reach mutually beneficial solutions, ensuring hull integrity is maintained without significantly compromising the system's performance or projected savings.

What is the added resistance due to air release units (ALS not in operation)?

The drag penalty associated with the ARUs inserted into the hull's FoB is considered to be negligible. The drag associated with a single ARU has been tested in HSVA, and the total drag associated with a full system deployment is a multiple of the drag associated with a single ARU. Any flow disturbance caused by the ARUs is negligible and does not significantly impact overall vessel performance.

How do you ensure that no air is accumulated in the sea chests?

In the design stage of the project, marine engineers provide recommendations to the yard on how to avoid air ingestion. Examples of how this risk can be mitigated include modifying the ARU arrangement slightly or adding additional venting in the sea chests. Insights from this are now part of Silverstream's detailed sea chest guidance which is provided to all customers across all ship segments.

How do you ensure that there is no increased risk for cavitation/erosion?

As per 'Ship Hull Air Lubrication: Aspects of Cavitation, Underwater Radiated Noise and Propulsion' by Prof J.S. Carlton, injected air can be used to reduce the probability of cavitation-induced erosion.

Whilst it is true that air in water will bring the onset of cavitation, the offloading of the propeller (due to reduced hull drag) outweighs this event. To date, no issues in respect to cavitation have been observed either in terms of operation of the vessel or visual inspection of the propeller or surrounding structure.

During the pilot, Silverstream deployed acoustic monitoring on the shaft to detect any change in propeller performance that could be associated with cavitation, and none was identified. Furthermore, anecdotal evidence suggests that the propeller shows no signs of cavitation as a result of operating the Silverstream® System than otherwise would have been anticipated on docking had the technology not been installed.

How do you optimise the air flow rate for different ship speeds and drafts?

The airflow rates required for a given ship speed and draught is determined in the estimation process using data from the experimental works completed at HSVA. Airflow rates vary depending on the ship's operational profile (speed and draught) and compressor sizing.

During vessel operations, data is gathered to deepen an understanding of the relationship between speed, draught and air flow, to optimise the technology to best suit the vessel operational profile.

In line with digitalisation trends in the maritime industry, Silverstream sees the potential of automating the optimisation of flow rates in real time, using artificial intelligence and machine learning.

How do higher sea states affect performance of the ALS bubble layer?

Fluid Shearing occurs on the hull of the ship in all sea states. Therefore, the bubble carpet will continue to reduce drag at any time the system is switched ON, regardless of weather conditions.

The Lloyd's register report on Sea Trials for MV Amalienborg, the Pilot vessel, states that positive performance was observed over a 3-day period and at different sea states.

The challenge in higher sea states is accurate and reliable system performance measurement and testing, rather than system functionality. At high sea states, the uncertainty of measurement increases, as such affecting the outcomes and observations. Furthermore, depending on the sea state, the captain might decide to reduce speed below the automatic minimum start-up speed of the system, which ranges between 9 and 11 knots depending on ship type. Additionally, the effects of weather on other control variables such as excessive rudder movement will have a negative effect on the overall reduction.

What do you implement in the control system of the ALS?

The primary control inputs required are ship speed and draught. However, the control system records a number of inputs for the purposes of performance assessment, system monitoring and maintenance, and performance optimisation. These include UTC timestamps, GPS position, wave data, wind data, current data, shaft torque and thrust information, vessel course data, and others.

The finalisation of the signal list will be ship specific. For example, data on stabiliser wings utilisation might be required from cruise ships and ferries, but not from other ship types.

The Silverstream® System also records its own functionality in terms of power consumption, warnings, alarms, compressor functionality, valve functionality, etc.

What is the expected power consumption for the air compressors and how do you measure during the trials?

The power necessary to operate the system is dependent on the number of compressors and the type of compressor deployed on the ship. The total power consumption and power requests for each compressor during ON states are monitored by the control system and displayed on the ICMS in the engine control room or on the bridge. This data is also recorded in the ALS data journals. Actual kW/fuel savings (and thus emission reduction) will be a function of the operating profile associated with the vessel to which the technology is fitted.

How do you verify the savings during the sea trials?

The testing methodology on ALS during Sea Trials consists in executing double runs. During the test, the system is switched ON and OFF in regular intervals. Once the data is collected, savings are calculated using the following formulas:

$$Gross\ Savings\ (kW) = P_{OFF} - P_{ON}$$

Where:

- P_{OFF} Delivered power with Silverstream® System OFF
- P_{ON} Delivered power with Silverstream® System OFF

$$Net\ Savings\ (kW) = Gross\ Savings\ (kW) - Compressor\ Power\ (kW)$$

Is there a pilot installation with the vendors ALS and what are the verified savings?

Silverstream Technologies first pilot was in 2015. So rather than use Pilot approach we have over 120 vessels operating for us to assess system performance. However, notable pilots where savings have been verified and publicly endorsed by shipowners include:

- Grimaldi Group: Achieving verified 5–6% net savings on a 7,800 LM RoRo, resulting in an orderbook of 40 RoRo, RoPax, and PCTC vessels, with independent verification by RINA.
- Carnival: Achieving verified 5% net savings on a 116k GT cruise vessel, resulting in an orderbook of 23 cruise vessels, with independent verification by LR and Wärtsilä.
- Shell: Achieving verified 5% net savings on a MR Tanker, resulting in an orderbook of 65 vessels across the gas and energy shipping segment, with independent verification by LR, HSVA, DNV, and the University of Southampton.

How is the radiated noise when the system is in operation a) affecting crew and passengers, and b) noise emissions into the ocean?

Silverstream Technologies categorises acoustic emissions into two types: onboard noise and vibrations, which refer to frequencies transmitted within the vessel, and underwater radiated noise (URN), which pertains to acoustic energy propagated from the hull and propeller into the surrounding marine environment. Extensive efforts have been undertaken to monitor and adapt onboard vibrations to minimise discomfort. While the Silverstream® System has consistently complied with DNV standards for noise and vibration, an additional product enhancement has been developed to further reduce these levels. Operational assessments confirm that the system has minimal to no acoustic impact on crew and passengers. With regard to URN, the application of air (in the form of bubbles) to reduce noise transmission into the ocean is well established in the underwater installation industry, particularly in activities such as pile driving. The potential to apply this principle directly to ships has gained increasing attention in both shipbuilding and academic literature, as highlighted in Professor J. Carleton's 2023 paper, Ship Hull Air Lubrication: Aspects of Cavitation, Underwater Radiated Noise and Propulsion. More recently, a study conducted by University College London (UCL) demonstrated that a layer of microbubbles beneath the hull can effectively shield vibrations from propagating into seawater. This acoustic shielding, combined with the bubbles' ability to reduce cavitation, contributes positively to the mitigation of underwater noise from both the hull and propeller. To further advance understanding of these effects, Silverstream Technologies continues to invest in both numerical and physical research, including in-service measurements, focused on underwater radiated noise.

Hanwha Ocean Air Lubrication System

Hanwha Ocean (HWO) provided the following replies to the questionnaire, sent out to the model basins and all vendors participating in this study:

How to predict the savings due to ALS best?

For the quantitative assessment of power saving due to ALS, full-scale trial measurements must be conducted under various operational and environmental conditions because many complexities and uncertainties are involved in evaluating the effect of ALS through model tests or CFD. In this regard, HWO has already carried out full-scale trial measurements for the quantitative assessment of ALS performance on a 173.4K cbm LNGC (Liquefied Natural Gas Carrier) equipped with HWO ALS during various operational and environmental conditions through sea trials and actual voyages.

Additionally, HWO employed a CFD approach with the full-scale ship to qualitatively predict the power savings due to ALS by simulating the air layer distribution on the hull surface. In a full-scale CFD simulation, the VOF method is used to model two-phase fluids based on the RANS equation, since the VOF method is a practical approach for predicting the behaviour of the air layer during the development stage. The EMP (Eulerian Multi Phase) method is also being developed to enhance the quantitative evaluation of CFD results through validation with full-scale trial measurement data.

HWO currently develops the quantitative assessment methodology to predict the power saving due to ALS based on the correlation between full-scale trial measurement and full-scale CFD calculation

How do you optimise the shape of the nozzle designs resp. the air release units?

HWO optimize the shape of the air release unit considering even air flow distribution, effective air layer formation, added resistance due to air release unit at ALS off condition and maintenance. The following performance of air release unit are verified through full scale CFD calculation and full-scale experiment in the cavitation tunnel. The cavitation tunnel is used to simulate full scale conditions experienced beneath the ship hull with the air release unit in full scale and real ship speeds.

- The air flow is evenly distributed at each air release unit.
- The air layer is generated effectively between the hull bottom and free stream liquid flow.
- The air release units have the minimum added resistance at ALS off condition.

How do you optimise the placement / arrangement of the nozzles resp. the air release units?

The positions of air release units are determined considering pressure distribution and streamline of the bare hull without air release units from the flow field at full-scale CFD calculation. Regarding the arrangement of air release units, a considerable number of cases which have the variation for the width of air release units and distance between FWD and AFT air release units are investigated by full scale CFD calculation To evaluate the drag reduction as per different arrangement of air release units density and volume ratio of the air on the hull surface as well as frictional drag are investigated for each case. The final arrangement of air release units is selected to have optimal point in the net power saving.

What is the added resistance due to air release units (ALS not in operation)?

Based on full scale CFD investigation for 173.4K LNGC equipped with HWO ALS, the hull drag at ALS off condition (with outlet holes) shows almost same level with bare hull (without outlet holes) due to the small size of air outlet hole and the low height of air release unit filled with water. It is evaluated that the drag increase by air outlet holes is negligible, which was also verified by comparing the speed power performance at the sea trial between a ship with ALS and sister ship without ALS.

How to ensure that no air is accumulated in the sea chests?

To prevent the adverse effect of the air bubbles being drawn into the sea chest, the structures of the sea chest are modified as follows:

- Internal volume increase.
- Inlet position upward.
- Suction pipe extension, w/ Baffle, w/ Air vent hole.

To investigate the effectiveness of the modified sea chest, air flow entering into the sea chest was simulated for the original and modified sea chest by CFD. Air bubbles flow from air outlets was also investigated by full scale CFD calculation in order to trace the path of air bubbles around the hull.

From the full-scale trial for 173.4K LNGC equipped with HWO ALS, it was confirmed that the air bubbles are not drawn into the suction pump in the sea chest through the check of sea chest ventilation system and sea water pump condition.

How to ensure that there is no increased risk for cavitation/erosion?

The cavitation observation and pressure pulse measurement were conducted during the full-scale trial for 173.4K LNGC equipped with HWO ALS. From the results of cavitation observation, ALS bubbles do not have a harmful effect on propeller cavitation as the collapse of cavitation bubble near blade can be suppressed by continuous supply of ALS bubbles. From the results of pressure fluctuation measurement, the pressure fluctuation with operation of HWO ALS is decreased about 30~40% compared to ALS OFF condition due to the pressure damping effect.

How to optimise the air flow rate for different ship speeds and drafts?

The following parameters are required to be optimised in order to establish the optimal air flow rate for different ship speeds and drafts:

- Total air supply ratio.
- Air supply ratio to the FWD and AFT air release units.
- Air supply ratio to each air release unit under the condition of the fixed FWD and AFT air supply ratio.

To investigate the optimal airflow rate, consecutive runs with ALS_OFF and ALS_ON for each air-supply condition must be conducted.

How do higher sea states affect performance of the ALS bubble layer?

To investigate the effect of ship motion on A LS performance, air bubble flow around the hull with the roll motion was simulated by full scale CFD calculation. Based on full scale CFD simulation with roll motion, it is estimated that power saving due to ALS can be effective up to Beaufort 5 condition. The effect of sea states on ALS performance was also investigated thro ugh full scale trial for 173.4K LNGC equipped with DS ME ALS From the numerous performance measurement at various sea environmental condition, ALS showed effective power saving performance up to Beaufort 5 condition, and the roll motion had more effect on ALS performance compared to other ship motion as heave and pitch. In the case that the vessel has excessive roll motion due to high wave from the side, the power saving due to ALS was not attainted

What do you implement in the control system of the ALS?

The control system of HWO ALS generates control commands based on the measurements from the vessel's instrument equipment. These control commands are transmitted to the flow control valves, blow off valves and auxiliary equipment so that the compressor operates safely and automatically

The following functions are implemented in the control system of HWO ALS:

- Start and stop of air compressor.
- Start and stop of FW/SW cooling pumps for air coolers.
- Control of air flow at each sub main line via flow control valve.
- Selection sailing mode as per speed and draft.
- Compressor status monitoring (power, rpm, etc?).
- Air temperature/pressure monitoring at discharge side of air compressors.
- Monitoring of bosun store air supply fan run/stop status.

- Monitoring of ship performance (ship speed, propulsion power, propulsion rpm, and navigation data d raft, rudder angle, wind speed & direction, etc.).

What is the expected power consumption for the air compressors and how do you measure during the trials?

Table A - 1 is the power consumption of the air compressors over the propulsion power as an averaged value at the operation speed range of HWO ALS. The relative ratio of the compressor power over the propulsion power reduces as the ship speed increases because the power consumption of the air compressor linearly increases as the ship speed increases to keep the same effective air thickness for the reduction of hull drag, while the propulsion power increases in proportion with several powers of the ship speed.

The control system of HWO (ex DSME) ALS provides the function to monitor and measure the power consumption of the air compressor.

Table A - 1 ALS Net saving and system power consumption for 174K LNGC from HWO

Speed (kns)	Ballast		Laden	
	ALS Net Saving (kW)	System Power (kW)	ALS Net Saving (kW)	System Power (kW)
15.0	643	394	561	465
17.5	956	452	826	534
19.5	1172	470	1021	556

How do you verify the savings during the sea trials?

The following test procedure for ALS optimization & performance evaluation are required to verify the power saving due to ALS.

- The consecutive runs with ALS_OFF and ALS_ON condition in the same direction at ballast draft during sea trial and laden draft during actual voyage trial.
- The consecutive runs alternating in direction, one up and one down for ALS_OFF and ALS_ON condition on the test course by double run at ballast draft during sea trial.
- Long term measurement for ALS performance during actual voyage.

Is there a pilot installation with the vendors ALS and what are the verified savings?

HWO (ex DSME) has delivered 174K LNGC with ALS to Maran in September 2019 and the vessel was fully verified by full scale measurements in sea trial and continuous monitoring in operations. Maran asked to install ALS on another 174K LNGC which has been delivered in 2021.

Are there installations on various types and sizes of ships with the vendors ALS and what is the feedback on the power and fuel savings from service measurements?

HWO has experience from LNGC's and 16K TEU Container Vessels.

How is the radiated noise when the system is in operation?

URN (Underwater Radiated Noise) measurement was conducted for ALS OFF & ON condition at the latest LNGC equipped with Hanwha Ocean ALS in December 2023. From the results of URN measurement in full scale, it was confirmed that URN level of ALS 'ON' condition is reduced overall across the entire frequency range compared to ALS 'OFF' condition due to masking effect of shipborne noise emitted through the FoB by ship machinery equipment and reducing noise levels generated by the propeller.

The Port of Vancouver Authority listed HWO's ALS as a 'Vessel Technologies to Reduce Underwater Noise.' after reviewing the technical report on ALS's underwater radiated noise reduction performance and the noise reduction performance when applied to actual ships. Hanwha Ocean's ALS is registered as Silver Level in the Port of Vancouver's EcoAction Program.

<u>HD Hyundai Air Lubrication System (Hi-ALS)</u>

HD Hyundai provided the following replies to the questionnaire, which was sent to the model basins and all vendors participating in this study.

How to predict the savings due to ALS best?

To predict the savings due to ALS, scale model tests and CFD analyses are conducted.

How do you optimise the placement / arrangement of the nozzles resp. the air release units?

CFD analysis is performed for optimal arrangement.

What is the added resistance due to air release units (ALS not in operation)?

The additional resistance caused by air release units is expected to be negligible.

How do you ensure that no air is accumulated in the sea chests?

We ensure that no air is accumulated by system control.

How do you ensure that there is no increased risk for cavitation/erosion?

HD Hyundai agrees model basins understanding of that increase in risk for cavitation and erosion by ALS is very limited considering the amount of air bubbles flowing into propeller plane is almost negligible.

In the case of propeller design, it is primarily based on the ALS-off condition. The propeller's operating point can be slightly altered in the ALS-on condition as mentioned; however, the impact is expected to be minimal because it would still fall within the engine's normal operating range.

How do you optimise the air flow rate for different ship speeds and drafts?

The optimisation test to be conducted for various ship speeds and drafts.

How do higher sea states affect performance of the ALS bubble layer?

Builder understands that ALS performance is highly affected by environmental sea condition. Generally, the ALS performance should be reduced as the sea conditions are getting worse.

What is the expected power consumption for the air compressors and how do you measure during the trials?

The expected power consumption is compressor power, which is measured by voltage and current.

How do you verify the savings during the sea trials?

Measurements are performed by switching the system "on/off".

Are there installations on various types and sizes of ships with the vendors ALS and what is the feedback on the power and fuel savings from service measurements?

There are installations on ships of various types and sizes.

How is the radiated noise when the system is in operation?

There is little information regarding radiated noise when the system is in operation.

Samsung Heavy industries (SHI) Air Lubrication System (SAFER-Air)

SHI provided the following replies to the questionnaire sent to the model basins and all vendors taking part in this study.

How do you optimise the shape of the nozzle designs resp. the air release units?

The air nozzle is refined using CFD to reduce energy loss in the internal flow.

How do you optimise the placement / arrangement of the nozzles resp. the air release units?

The air nozzles are arranged in a single row to make room such as a void space for maintenance. Depending on the hull shape, some of the nozzles located in the centre could be arranged toward the bow to form a separated 1 row.

What is the added resistance due to air release units (ALS not in operation)?

Samsung's ALS system adopts compact size nozzles with three circular holes (90mm diameter). Therefore, it does not deteriorate the performance or safety of the original ship when the ALS is not in operation.

How do you ensure that no air is accumulated in the sea chests?

It is recommended to use High Sea chest to prevent the accumulation of air when ALS is operated.

How do you ensure that there is no increased risk for cavitation/erosion?

The vessels equipped with ALS were recently redocked. The visual inspection of the vessel's propeller revealed no signs of cavitation or erosion.

How do you optimise the air flow rate for different ship speeds and drafts?

The optimum airflow rate is usually obtained via CFD simulations for each speed and draft, and the airflow rate corresponding to the maximum net power saving is determined.

How do higher sea states affect performance of the ALS bubble layer?

Generally, it is recommended to use up to BF5 (and sometimes up to BF6 depending on the situation).

What do you implement in the control system of the ALS?

The system is designed to operate automatically above a certain speed and controls the injection of air at a preset air flow rate as the speed changes.

What is the expected power consumption for the air compressors and how do you measure during the trials?

The power consumed by the compressor is measured through a power meter installed in each air compressor.

How do you verify the savings during the sea trials?

The speed-power curve is obtained by performing double run test according to ISO15016 under three load conditions during system operation. This speed-power curve is compared with the speed-power curve performed under non-operation condition to calculate the power saving rate at a certain speed.

Is there a pilot installation with the vendors ALS and what are the verified savings?

It is mainly applied to LNG ships, and a net power saving rate of 5-7% has been confirmed.

Are there installations on various types and sizes of ships with the vendors ALS and what is the feedback on the power and fuel savings from service measurements?

Total installations are: 52 newbuilds (119 on order):

- LNG Carrier: 34 delivered (82 on order).
- Container carrier: 18 delivered (37 on order).

Net fuel and emission savings assuming typical operational profile and utilization:

- Ship type: LNG Carrier.
- Capacity: 170-180k.
- Speed: 12-19 knots.
- Draught: laden & ballast.
- Net fuel: 5-7%.

Alfa Laval OceanGlide System

Alfa Laval provided the below replies to the questionnaire, sent out to the model basins all vendors participating in this study:

How to predict the savings due to ALS best?

Alfa Laval OceanGlide currently uses an empirical approach to predict savings based on sea-trial results from suitable reference vessels.

Based on long term measurements applying DNV's RP-0695 "Performance of air lubrication systems" with repeated ON/OFF cycles. Gross savings are calculated by comparing propulsion power and speed through water during each ON/OFF cycle. Net power savings are determined by subtracting the compressor power from the gross savings.

A drag reduction factor is determined based on the air covered area and the propulsion efficiency of the reference vessel. The gross savings of a project vessel are calculated by applying the same drag reduction factor and the specific air covered area and the propulsion efficiency of the target project vessel.

How do you optimise the shape of the nozzle designs resp. the air release units?

We rely on tow tank testing a 7m submerged flat plate fitted with a 1m wide Section of our full-scale design tested at speeds of up to 16 knots. We complement this with cavitation testing, offering better instrumentation but at reduced speed and flowrates. Finally, we are also developing a multiphase solver utilizing test results for validation to eventually address the shortcomings of experimental work. This is our current approach.

How do you optimise the placement / arrangement of the nozzles resp. the air release units?

We use the experimental and computational approach described above.

What is the added resistance due to air release units (ALS not in operation)?

This is vessel specific, but we have run several CFD cases with our system installed but turned off and we can present typical results.

How do you ensure that no air is accumulated in the sea chests?

This is typically not in our scope; we make the customer and integrator aware of this potential issue, and they design a solution according to their needs.

How do you ensure that there is no increased risk for cavitation/erosion?

There are papers concluding that this is not an issue (e.g. Study on Marine Propeller Running in Bubbly Flow by C. Kawakita). In addition, inspections of propeller have not shown any issues in our installed system.

How do you optimise the air flow rate for different ship speeds and drafts?

In the first instance we try to do that based on full scale data. We log our sensors and relevant vessel sensors and process that data accordingly. However, there is a challenge in isolating the performance of ALS using full scale data. Firstly, there are no sensors focused on capturing ALS (e.g. shear stress sensor on FoB), we rely at best on torque and STW sensors. Then there is the additional issue of the quality and availability of key vessel sensors (e.g. unreliable torque meters and STW sensors). Overall, it is a major challenge to measure the marginal gains on a vessel. There is a parallel modelling effort (combining experimental and CFD work) to pre-determine optimum settings and program them in.

How do higher sea states affect performance of the ALS bubble layer?

Although an effect is expected, it is harder to isolate individual parameters based on full scale data due to the reasons above. Experimentally, in a tow tank, we are still testing at idealized conditions. Adding other factors such as roll is a longer-term aspiration.

What do you implement in the control system of the ALS?

Now, we just set the flowrate distribution. Longer term we're working on active control.

What is the expected power consumption for the air compressors and how do you measure during the trials?

A variety of compressors is used depending on the specific application and their consumption is always measured in directly in kW.

How do you verify the savings during the sea trials?

Certification societies bring some of their instruments on board during trials but that does not result in comprehensive verification. It is an issue trying to measure marginal vessel gains using standard sea trial as the accuracy has shown to be inadequate (e.g. a paper by MARIN Quantifying the Uncertainty of High-Fidelity Speed/Power Trials reviewed accuracy of an ideal sea-trial, with all instrumentation etc up to standard. It concludes; "Based on the analysis conducted, it can be concluded that for the presented case, the overall uncertainty in shaft power - considering various sources of uncertainty such as shaft power measurements, wave correction, wind correction, and others - amounts to approximately 4 - 6%. This indicates that even with the implementation of rigorous and accurate sea trials, there will still be inherent uncertainties that can affect the estimation of performance gains." It also states that comparing sea trials of sister vessels resulted in 8-10% total error).

Is there a pilot installation with the vendors ALS and what are the verified savings?

There are installations and results are available and can be presented for discussion but comment above applies to verification.

Are there installations on various types and sizes of ships with the vendors ALS and what is the feedback on the power and fuel savings from service measurements?

As above.

How is the radiated noise when the system is in operation?

Affecting crew and passengers, and this is dependent on installation. In some instances, the compressor noise and associated vibration is a nuisance to the crew (e.g. when it is installed near sleeping quarters). In other instances, it has been noted that OceanGlide reduces overall vessel vibrations and improves conditions for crew.

Noise emissions into the ocean has not been measured. We are part of the Lownoiser consortium, aiming to measure just that (https://www.lownoiser.eu/)

Armada Passive Air Lubrication System (PALS)

Armada Technologies provided the responses below to the questionnaire, sent to the model basins and vendors:

How does the Armada Air Lubrication System work?

Armada's Passive ALS is illustrated in Figure A - 1 and transforms vessel efficiency by integrating specially designed pods into the double bottom tanks, flush with the vessel's baseline. Using the ship's own forward motion, water is driven into the system inlets and through specially designed venturis, this creates the required suction of air (from the deck level) to create a fine air-water mixture at system outlets.

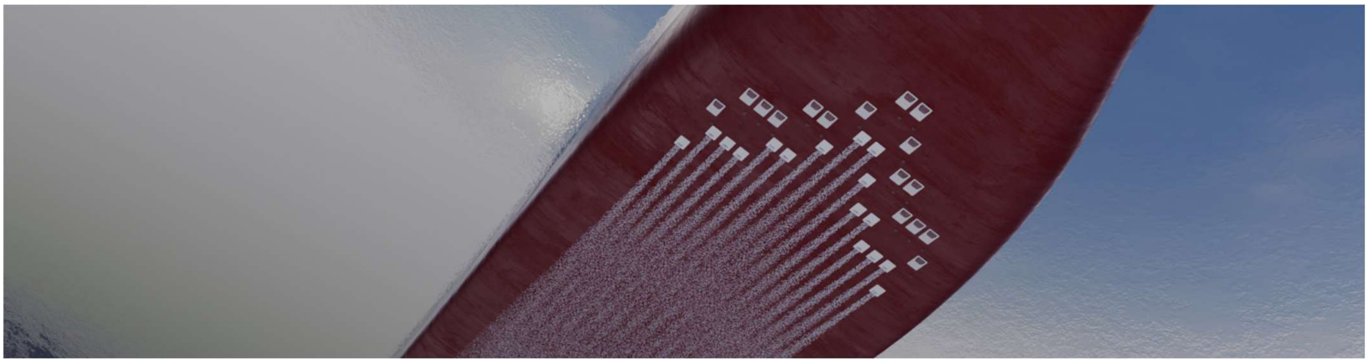

Figure A - 1 number of Armada pods arranged at the double bottom of a ship (Source: Armada Technologies)

As illustrated in Figure A - 2 , each pod can be independently tuned for optimal performance, ensuring reliable drag reduction even in rough sea states. The system maintains its effectiveness regardless of variable conditions, making it especially valuable as more vessels adopt slow steaming and engine power limitations for regulatory compliance. With more precise control of bubble creation and downstream boundary layer dynamics PALS sets a new standard for hull lubrication technology.

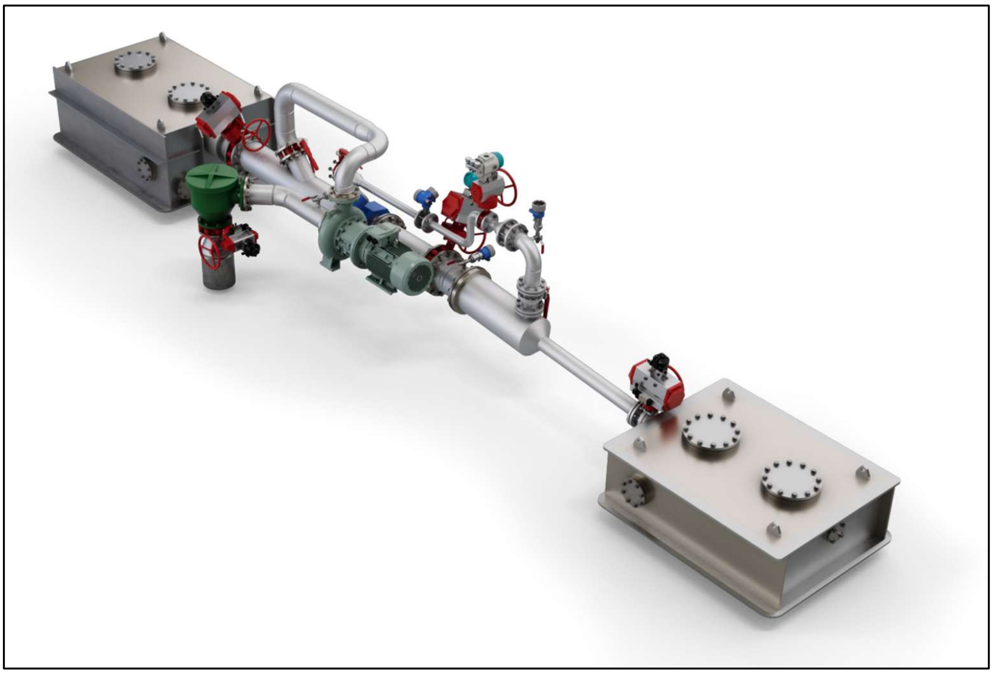

Figure A - 2 Single Armada pod with water inlet, venturis and system outlets (Source: Armada Technologies)

PALS utilizes a small number of low energy pumps to provide enough air-water flow to ensure ongoing optimal performance at deep drafts, slow vessel speeds and higher sea states. This allows better system control and drag reduction optimization that is aligned to the vessels speed, draft and the prevailing weather conditions.

How to predict the savings due to ALS best?

Good question, difficult to answer. The normal scale-model tests cannot be used as there is no established method for generating scale-model bubbles and for extrapolating the test results to full-scale. ITTC is proposing so-called Geosim tests (test with at least three different model scales and trying to extrapolate this to full-scale) but we consider this as a very theoretical exercise which has never reached practical relevance in terms of air lubrication.

The normal numerical methods (CFD) cannot model the injection of micro bubbles or, in case of our system, a thin layer of air and water, into the viscous sublayer of the boundary layer. With more complex CFD methods many control parameters must be set, for which reliable and relevant full-scale data would be necessary to validate the prediction results. Such full scale data as the size of the bubbles, air density, behaviour of the bubbles in the turbulent boundary layer as a function of time and distance from the air outlets, and the variations in shear stress between hull and seawater simply are not available.

Armada has decided not to dig deeper into scale model testing and/or advanced numerical methods but using the first installation on board of KOOL HUSKY as a test laboratory and predict the savings at new projects based on this reference case.

How do you optimise the shape of the nozzle designs resp. the air release units?

Armada does not have air release units, but instead outlet transition pieces that deliver a mix of air and water into the vessel boundary layer. The objective of the optimization of these fairly complex shapes is to deliver a thin layer of air and water into the viscous sublayer of the boundary layer. We aim to saturate the viscous sublayer with air and avoid the presence of a slip of water sitting between the steel of the ship and the developed air carpet. We use many optimization runs in CFD for our concept design and validated in HSVA HYKAT cavitation tunnel.

How do you optimise the placement / arrangement of the nozzles resp. the air release units?

We provide a computation model of the ship and run bare hull CFD assessment to identify the coefficients of pressure. This enables us to select the theoretical ideal location of the pod (inlets and) outlets - an area of laminar flow. The outlet positions are subject to change when we begin to assess structural integration where we must balance the optimal hydrodynamic positioning and configuration with the ease of integration around surrounding structures.

What is the added resistance due to air release units (ALS not in operation)?

In failsafe mode (all valves closed and no flow through the pod systems), for 14 pod installation, we estimate 0.3-0.7% of bare hull resistance. However, it has to be mentioned that we see drag reduction benefits that far outweigh the losses in a pure passive water lubrication mode.

How do you ensure that no air is accumulated in the sea chests?

We installed a permanent deaeration solution on sea chests during dry dock. We also injected significantly less air than our competitors. We have had experience of sea chest aeration issues, but these are resolved using our existing deaeration solution. We are also able to dynamically modify the trajectory of the air carpet using water deliver for different pods.

How do you ensure that there is no increased risk for cavitation/erosion?

Air developed in ALS is a structurally sound gaseous air bubble and not a vapor bubble susceptible to collapse when it reaches a higher-pressure domain - no ALS should be creating cavitation under this theory.

How do you optimise the air flow rate for different ship speeds and drafts?

We can control water flow and thus venturing pressure drop, we can also control blower delivery rate.

How do higher sea states affect performance of the ALS bubble layer?

We are still testing this, although the dynamic control of our developed air carpet enables us to over-lubricate the centre line of the vessel and use the rise of floor of the ship + the roll response of the vessel to maximize bubbles carpet retention.

What do you implement in the control system of the ALS?

We do have a control system that has been developed through considerable grant funding. The control system (once tuned) will control system set points (e.g. flow control valve position, blower RPM etc..) in line with real time operating conditions of draft, speed and sea conditions.

What is the expected power consumption for the air compressors and how do you measure during the trials?

Armada does not have air compressors. We have 3 blowers to support the Venturis (if required) - our blowers are on a 2x duty, 1x standby. Each blower is 11kW. So total rated power in operation is 22kW.

How do you verify the savings during the sea trials?

DNV sea trial attendance + DNV one-way long term performance monitoring.

Is there a pilot installation with the vendors ALS and what are the verified savings?

Yes, we have a pilot plant of KOOL HUSKY. The system was installed in Yui Lian Shipyard, China in October 2024. Savings are still be assessed over long term performance monitoring.

Are there installations on various types and sizes of ships with the vendors ALS and what is the feedback on the power and fuel savings from service measurements?

Armada currently has 1 pilot system in operation.

How is the radiated noise when the system is in operation?

We have not measured this directly. However, any radiated noise of the system is expected to be minimal given the location of our equipment and its mounting design. Given Armada does not have a bank of air compressors that may harmonize and vibrate with another vibration source, we see Armada being an overall lower noise solution - of course ALS is recognized as a noise suppression solution to avoid URN. There appears to be more and more attention at IMO of URN and thus an important factor for Armada as we continue to test and analyse data.

For a specified number, type and size of ships a technical, cost and economic analysis shall be performed. This includes estimation of the following:

- Hydrodynamic gross power savings at two draughts and for a range of speeds.
- Net power savings for typical compressor power demand.
- Net fuel savings assuming typical main engine and auxiliary generator arrangement [in t/day].
- Net fuel and emission savings assuming typical operational profile and utilization in [t/year].

Is this something where you could support and provide estimates for the expected savings and ballpark figures for the costs?

We are happy to support this from a cost perspective, please bear in mind that from a performance estimation perspective, we have only our one pilot as a reference case (160k cam LNG carrier).

Has Armada been engaged in any EU funded or other research for developing the system?

Armada has been associated with the RETROFIT55 project, which has received funding from the European Union's Horizon Europe Research & Innovation programme under Grant Agreement No. 101096068.

Aim of this research was optimizing the air carpet and to achieve the maximum consistent fuel savings at variable operational conditions and different vessel drafts. A systematic series of tank tests has been carried out and, simulations have supplemented these, to determine how the preliminary drag reduction achieved on a plate can be scaled up and reproduced on a full-sized vessel.

Regarding other research activities Armada has supported the building of a JDP led by model basin MARIN from The Netherlands.

Aim of this research was developing new sensors and performing full-scale measurements of micro bubble size, air density and reduction of shear stresses between a ship's hull and the seawater. Unfortunately, this JDP didn't materialize.

Appendix B Literature Review

Approach

To meet the objective of this work, a series of papers has been collected and reviewed. A selection of these is provided in the reference list at the end of this document. In addition, the interviews with the towing tanks, Silverstream and university personnel have provided valuable information that is reflected in the discussion.

Scaling issues for ALS model tests

Air lubrication by injection of micro-bubbles has been studied in scaled models in the laboratory, and the ability to use a traditional test set-up in a towing tank to estimate the savings from such a system would be most useful. But model testing to establish vessel propulsion power is already a challenging task due to the inability to follow both Reynolds number ($Re = vL/$v, where $v = velocity\ (m/s), L = Ship\ Lengh\ (m)$,and v= Kinematic viscosity(m^2/s)) and Froude number($Fn\ = Ship's\ Speed(V)/\sqrt[2]{g\ \times\ Ship\ Length}$)similarity. With micro-bubbles new physics is introduced and should be accounted for in prediction methods using scaled tests.

Physical effects governing air-induced drag reduction

When air is released into the boundary layer, the mixture of air and water influences the shear force on the wall. The reduction in shear depends on the volume fraction of air, how the air is distributed through the boundary layer, and the possible composition of air bubbles. Angular momentum exchange between the boundary layer and the bulk causes the emission of coherent structures that influence Reynolds stress. Air bubbles hinder this exchange, reduce Reynolds stress, and subsequently lead to drag reduction. The goal is usually to maintain an air layer over a significant downstream distance. The air layer drag reduction (ALDR) is much greater than that achieved by bubble drag reduction (BDR), where the boundary layer contains a volume fraction of air bubbles. A transitional regime exists between the air layer and bubble drag regimes.

Ruben A. Verschoof et al. (2016) concludes that the percentage reduction in drag (%DR) is sensitive to the bubble size for the BDL regime. The bubble deformability is crucial in the drag reduction mechanism. They explain that this is disputed by some authors but confirmed by others. They introduce the Weber number which dimensionless number used in fluid mechanics to describe the relative importance of a fluid's inertial forces compared to its surface tension forces($We = \rho v^2 L/\sigma$, where $\rho = fluid\ density(kg/m3)\ , v =\ characteristic\ velocity(m/s)\ , \boldsymbol{L} = characteristic\ length\ (m), \sigma\ =\ surface\ tension\ (N/m)$. Bradley C. Pfeifer (2020) also mentions in their discussion that the Weber number may be important for the ability to sustain an air layer. They are surprised to find that properties of the rigid surface affect the extent of the ALDR regime, even if the features (roughness or superhydrophobic properties) are on a physical scale much smaller than the thickness of the air layer. They postulate that this is due to turbulent effects causing the water to penetrate the air layer randomly, and that the local wall properties then decide if the water sticks or the air layer is sustained. This points to surface roughness as an important physical parameter.

Brian R. Elbing et al. (2013) examine how a critical air flux for ALDR can be determined by balancing shear-induced lift and buoyancy forces on a single bubble in a shear flow. They find a scaling of the air flux and find that this agrees with results covering different flow conditions and model test configurations. The transition to ALDR depends on the ratio of buoyancy and turbulent shear forces. Buoyancy promotes phase separation while turbulent fluctuations enhance flow dispersion.

A. Aliseda and J. C. Lasheras (2005) studies experimentally a turbulent boundary layer laden with micro-bubbles. They conclude that even for a high volume fraction, the logarithmic law characteristic for single-phase turbulent boundary layers is still valid. An offset in the distance from the wall determined by a new constant depending on bubble void fraction should be introduced. The bubble void fraction in the boundary layer should be preserved, and this is linked to buoyancy forces.

When studying the physical effects, it seems that scaled tests need to ensure similarity of the Reynolds number, the bubble void fraction in the boundary layer, and the surface roughness. Turbulence intensity may also be significant, along with the ambient pressure. The latter has a direct impact on the use of towing tanks or cavitation tunnels and warrants further investigation.

Numerical methods

Several methods exist to study the injection of air into the viscous boundary layer of a surface moving through water. The main categories are Euler-Lagrangian and Euler-Euler methods.

Two recent studies by X. Zhao et al. (2020) and Hee-Taek Kim et al. (2019) provide a good summary of current Eulerian-Eulerian methods, in which the water and air phases are solved for in a fixed reference frame. Hee-Taek Kim et al. study Eulerian multi-phase (EMP, interpenetration or mixing of phases) and Volume-of-Fluid (VOF, non-mixing fluid surfaces).

The EMP methodology requires estimating the drag, lift, and mass forces acting on air bubbles surrounded by water. In addition, coefficients need to be set to determine the bubble population, accounting for e.g. micro-bubble coalescence from random collisions due to turbulence. X. Zhao et al. (2020) provides details on how these have been determined. Hee-Taek Kim et al. (2019) report good agreement of their EMP results with experiments reported by Brian R. Elbing et al. (2008). However, the details of the coefficients that need to be set in the simulations are not provided.

The VOF method is reported to perform well in conditions where ALDR is observed experimentally. However, as the standard implementation of the VOF method does not permit mixing of fluid surfaces, this method is not suitable for modelling the transition from ALDS to BDL, nor the BDL regime.

Eulerian-Lagrangian methods are characterized by one of the phases being tracked by following the individual fluid parcel as it moves through space and time. The complexity in the lagrangian treatment of phase interaction may vary. It is possible to account for e.g. buoyancy, drag, lift and fluid mixing, see S. Rawat et al. (2019). However, for air lubrication studies, a simple use of tracer particles to approximate the amount and location of air seems most common. Drag reduction quantification requires a model for how the local drag coefficient varies with the estimated volume fraction and distribution of air in the boundary layer. Such a model needs calibration by more advanced simulation methods, model- or full-scale tests.

Industry experience on numerical methods

The towing tanks have experience in conducting tests on ALS, as detailed separately in Sections 3 and 6. These institutions have limited experience with numerical methods and have either proposed using tracer particles to understand how the air covers the hull surface (HSVA) or introduced the concept of a “moving boundary” to simulate the effect of air-lubrication in a simplified manner (RISE). Both proposed methods overlook real physics, such as the potential impact of air bubbles on the boundary layer and the buoyancy effect of the air bubbles.

Contrary to the European towing tanks, SHI has shown expertise and experience through Hee-Taek Kim et al. (2019). They have come quite far in development of an EMP numerical method.

Generally, the consensus is that full-scale trials are required for quantification of real energy saving, but SHI may be close in development of a numerical method using EMP that can predict performance of ALS on new vessels when validated against full-scale data from existing vessels.

In personal communication, Prof. Steen (2020) reports that there is limited experience with air lubrication at NTNU and SINTEF Ocean. They have had some collaboration with Simo Mäkiharju and his team at UC Berkeley, working on a superhydrophobic surface for frictional drag reduction. This is a promising technology that may work well together with e.g. micro-bubble drag reduction. The superhydrophobic surface helps reduce the required volume fraction of air to achieve and sustain an air layer.

New commercial tests are now planned at SINTEF Ocean to study air lubrication using their upgraded cavitation tunnel (new test Section). Prof. Sverre in NTNU agrees that air lubrication resistance tests should be at the correct Reynolds scale and that such studies are fit to understand the generation of the micro-bubbles and properties of the flow close to the body a short distance down-stream of the generation point.

Discussion

An optimal ALS should use a minimum of compressor power to achieve air layer drag reduction on as large an area as possible on the ship hull, in the forward area with the largest induced viscous share force.

Computational fluid dynamics in full-scale may be used to find a good placement of the air release units, and to check the coverage of air along the vessel bottom. Advanced and costly numerical models may be calibrated by full-scale measurements to provide a good guess on ALS savings on a new vessel. Further work is needed to get a good idea about the accuracy for different vessel types and operation.

The literature review did not come up with any systematic study on scale effects. Ideally, one should start with the governing physics and consider the range of nondimensional numbers between scaled tests and prototype. Relevant numbers include Reynolds number (inertia and viscosity), Euler number (pressure and inertia), Weber (inertia and surface tension), Grashof (buoyancy and viscosity), Bond (gravity and surface tension). The sensitivity to the results to the balance of these different forces may be determined from the change of the nondimensional parameter checked against data in literature.

It appears that scaled tests may struggle to capture the break-down and transition from an air layer to micro-bubbles. Local drag reduction of 80% is typical for a sustained air layer, while it is much lower (a few percent) for the BDL regime. Thus, the ability to predict the total area covered by an air layer is essential.

Current research shows good progress in quantification of the flux of air needed for a given ambient flow velocity to achieve ALDR.

Symposium on Air Lubrication Systems (SALT)

SALT'25 was held in Trondheim 2025, 16th/17th of June. SINTEF Ocean organized in cooperation with NTNU and UC Berkeley with sponsored by HR Wallingford and the research council of Norway. The followings are proposed topics.

- Numerical investigation of air lubrication.
- Experimental investigation of air lubrication.
- Full scale investigation of air lubrication.
- Effect of air lubrication on noise and vibrations.
- Air lubrication-propulsor interaction.
- Air lubrication-surface structure interaction.
- Air lubrication-coating interaction.
- Ship design considerations for air lubrication.
- Air compressor technologies.

Main ALS vendors recognized model basins and institutes, and universities participated in the SALT'25. Introduction of different ALS are discussed in the symposium. However, this is already touched in Appendix A, thus are not included in the Section.

The 1st International Symposium on Air Lubrication Technologies (SALT'25) provided a good overview of the current understanding of ALS within industry and academia. On-going research and development showed possible future direction of Air Lubrication Technologies (ALT) in the maritime industry. The symposium emphasized the urgent need to reduce the environmental impact of shipping, particularly its significant contributions to CO2 and particulate emissions.

Important discussion topics of the symposium were the challenges related to optimization of ALT and performance estimation/verification. One of the most critical issues is the difficulty in understanding and controlling the multiphase turbulent boundary layer (mpTBL) under the hull, which is essential for achieving consistent and measurable drag reduction.

Scaling ALT from laboratory experiments to full-scale vessels introduces further uncertainty, as air layers that appear stable in controlled environments may become unstable or patchy in real-world conditions. Additionally, the performance of ALT systems is highly sensitive to operational factors such as hull form, sea state, fouling, and maintenance practices. Effective integration of ALT into ship design requires advanced control systems and feedback mechanisms to ensure consistent performance across varying conditions. To address these challenges, the symposium highlighted the need for:

- Advanced numerical and experimental methods to simulate mpTBL with ALT.

- High-quality full-scale measurement data from vessels equipped with ALS, supported by sophisticated sensor technologies.
- Strong collaboration between research institutions and industry to bridge the gap between theoretical development and practical application.

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Appendix C Case Study by Alfa Laval – OceanGlide

Alfa Laval - OceanGlide

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Issued by Mehmet Kirmizi	**Date** 24/07/2025	
Recipients Marcel Somers		

Revision history

Rev. 1	16/06/2025	First issue	
Rev. 2	17/06/2025	Second issue	
Rev. 3	24/07/2025	Third issue	(Typo in speed column of Table 4 is corrected)

This report outlines the configuration, band arrangement, and performance indicators of the seven case vessels, as requested by DNV as part of a project for *European Maritime Safety Agency (EMSA) for Studies on promising technologies.*

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1. Introduction

This report outlines the configuration, band arrangement, and performance indicators of the seven case vessels, as requested by DNV as part of a project for *European Maritime Safety Agency (EMSA) for Studies on promising technologies*. The case vessels are listed below:

- MR Tanker
- Container Vessel (2200 TEU)
- RoRo Vessel
- LNG (Q-Flex)
- LR Tanker (Aframax)
- Container Vessel (23K TEU)
- Bulk Carrier (Capesize)

DNV has provided the following vessel information as input for the calculations:

- Operating Speed
- Delivered Power (P_D)
- Frictional to Total Resistance coefficient ratio (C_F/C_T)
- Wetted Surface Area
- Flat of Bottom – Area, Length and Width

The flat bottom shape was not provided and was therefore assumed based on the available area, length, and width data.

2. References

Ref 1: ALS Alfa Laval OceanGlide vEMSA.xlsx

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3. MR Tanker

3.1- Vessel Particulars

Ship Type	:	MR Tanker
Length, pp	:	180.0 m
Breadth, WL	:	32.2 m
Draft (Ballast)	:	7.08 m
Draft (Laden)	:	11.0 m
Wetted surface (Ballast)	:	6874.4 m^2
Wetted surface (Laden)	:	8444.9 m^2
Lubricated FoB Area	:	1877 m^2

3.2- ALS Configuration

OceanGlide air lubrication system consists of one V-shape air distribution band and one VML95 compressor type as seen from the Figure 1. The system has been optimized for a service speed of 15 knots.

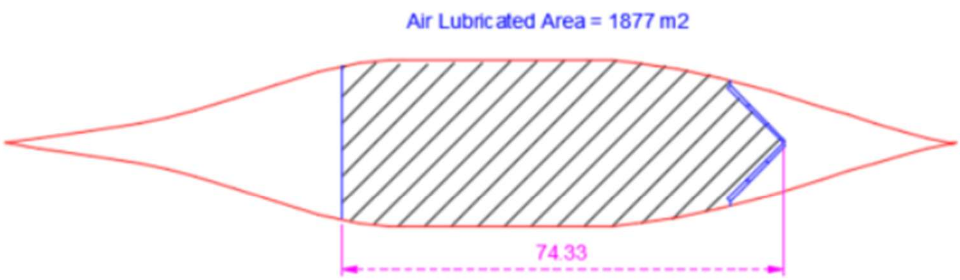

Figure 1 MR Tanker Band Arrangement

The mechanical design of the air lubrication configuration for MR Tanker is illustrated in Figure 2.

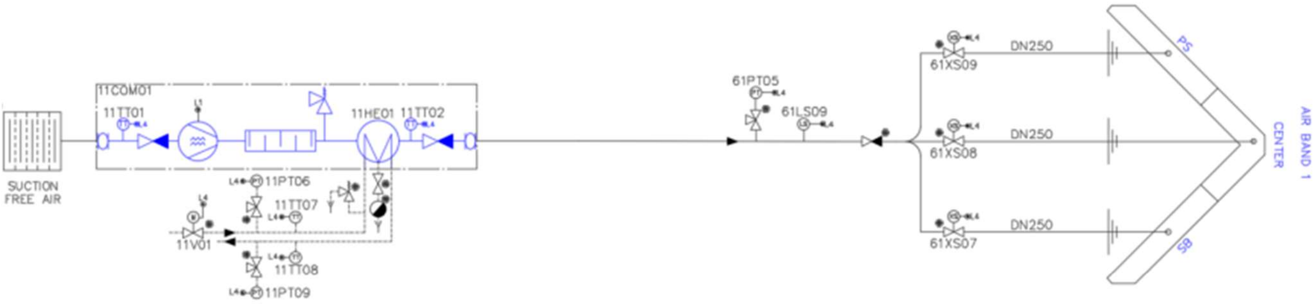

Figure 2 MR Tanker Air System P&I Drawing

3.3- Performance Indicators

Table 1 represents the performance indicators of MR Tanker with the assumptions mentioned in Section 10.

Table 1 MR Tanker Performance Indicators

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
7.08 m	0,549	0.273	13	2144	313	132	181
	0,524		14	2941	386	143	244
	0,514		15	3914	470	153	317
11.0 m	0,611	0.222	13	4142	331	211	120
	0,610		14	5142	409	227	182
	0,607		15	6365	499	243	255

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4. Container Vessel, 2200 TEU

4.1- Vessel Particulars

Ship Type	:	Container Vessel, 2200 TEU
Length, pp	:	168,60 m
Breadth, WL	:	32,20 m
Draft (Ballast)	:	7.50 m
Draft (Laden)	:	9.50 m
Wetted surface (Ballast)	:	5920 m^2
Wetted surface (Laden)	:	6738 m^2
Lubricated FoB Area	:	1350 m^2

4.2- ALS Configuration

OceanGlide air lubrication system consists of one V-shape air distribution band and one VML95 compressor type as seen from the Figure 3. The system has been optimized for a service speed of 18 knots.

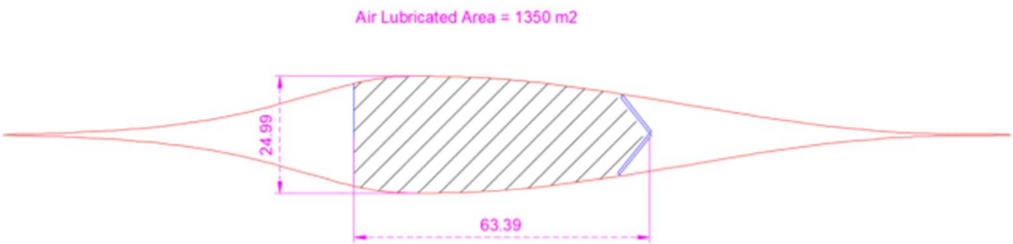

Figure 3 Container Vessel (2200 TEU) Band Arrangement

The mechanical design of the air lubrication configuration for container vessel (2200 TEU) is illustrated in Figure 4.

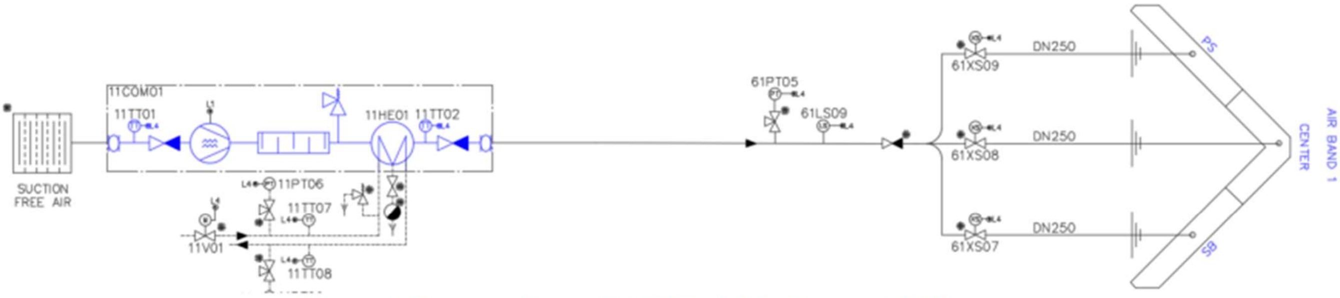

Figure 4 Container Vessel (2200 TEU) Air System P&I Drawing

4.3- Performance Indicators

Table 2 represents the performance indicators of Container Vessel (2200 TEU) with the assumptions mentioned in Section 10.

Table 2 Container Vessel (2200 TEU) Performance Indicators

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
7.5 m	0,555	0.228	13	3205	251	129	122
	0,566		14	3893	306	139	167
	0,569		15	4721	379	149	230
	0,564		16	5733	457	159	297
	0,545		17	7061	542	169	373
	0,515		18	8817	637	179	458
9.5 m	0,611	0.200	13	3365	254	164	90
	0,614		14	4145	310	177	133
	0,612		15	5073	384	190	194
	0,600		16	6226	461	202	259
	0,575		17	7736	548	215	333
	0,536		18	9775	642	228	415

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5. RoRo Vessel

5.1- Vessel Particulars

Ship Type	:	RoRo
Length, pp	:	225,60 m
Breadth, WL	:	32,0 m
Draft	:	6.40 m
Wetted surface	:	8050.1 m^2
Lubricated FoB Area	:	1290 m^2

5.2- ALS Configuration

OceanGlide air lubrication system consists of one V-shape air distribution band and one D98H blower type as seen from the Figure 5. The system has been optimized for a service speed of 20 knots.

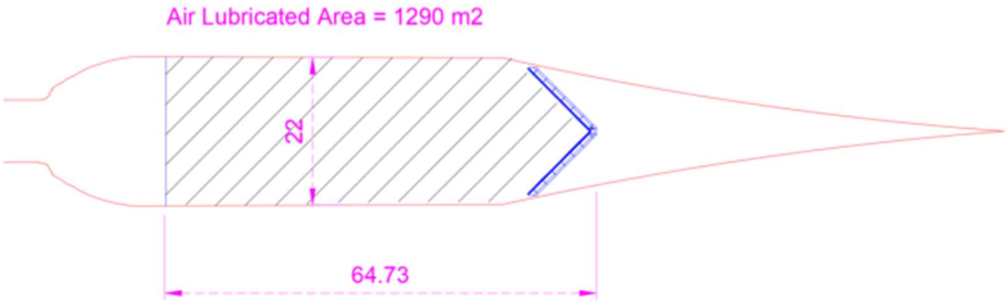

Figure 5 RoRo Vessel Band Arrangement

The mechanical design of the air lubrication configuration for RoRo vessel is illustrated in Figure 6.

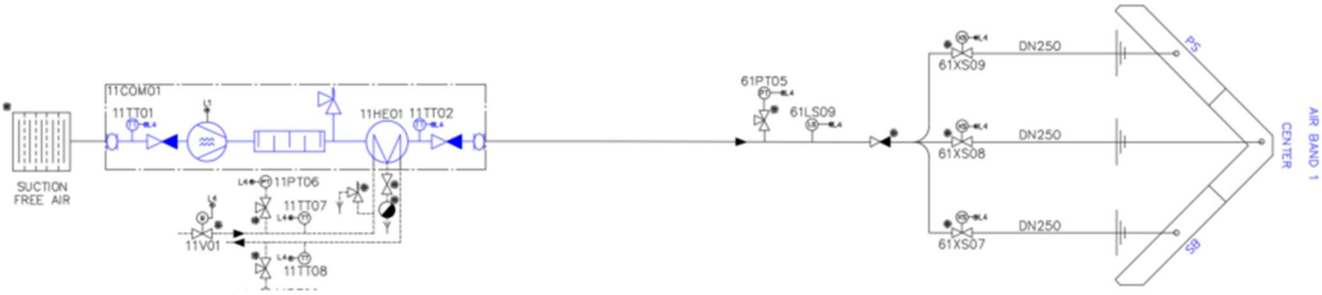

Figure 6 RoRo Vessel Air System P&I Drawing

5.3- Performance Indicators

Table 3 represents the performance indicators of RoRo Vessel with the assumptions mentioned in Section 10.

Table 3 RoRo Vessel Performance Indicators

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
6.4 m	0,675	0.15	15	6084	349	121	228
	0,670		16	7384	419	129	291
	0,665		17	8857	499	137	363
	0,658		18	10544	588	145	443
	0,647		19	12544	686	153	533
	0,632		20	14880	794	161	633

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6. LNG Carrier, Q-Flex

6.1- Vessel Particulars

Ship Type	:	LNG Carrier, Q-Flex
Length, pp	:	278,60 m
Breadth, WL	:	45,60 m
Draft (Ballast)	:	9.30 m
Draft (Laden)	:	11.70 m
Wetted surface (Ballast)	:	14884 m^2
Wetted surface (Laden)	:	16648 m^2
Lubricated FoB Area	:	4721 m^2

6.2- ALS Configuration

OceanGlide air lubrication system consists of one transverse-shape and one V-shape air distribution bands and three VML95 compressor type as seen from the Figure 7. The system has been optimized for a service speed of 18 knots.

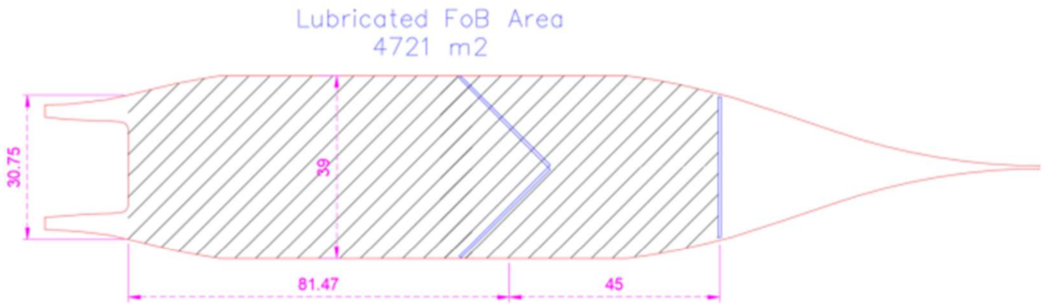

Figure 7 LNG Vessel (Q-Flex) Band Arrangement

The mechanical design of the air lubrication configuration for LNG Carrier (Q-Flex) is illustrated in Figure 8.

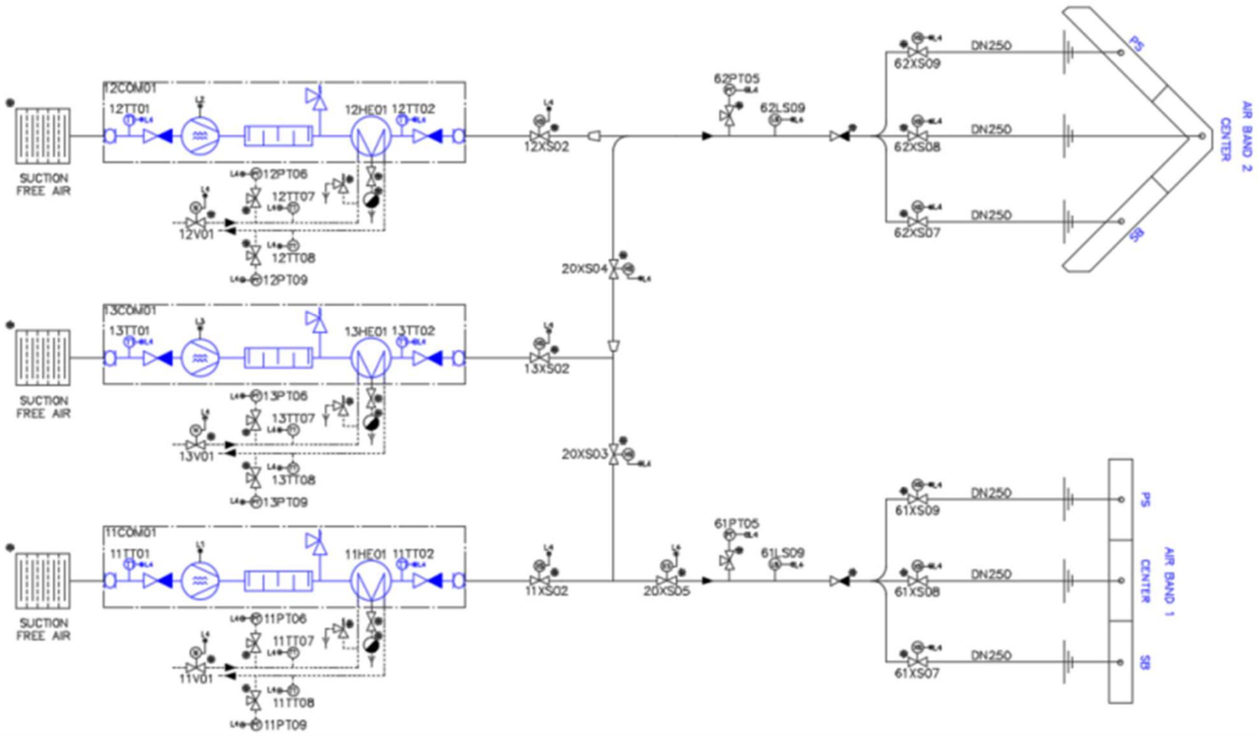

Figure 8 LNG Carrier (Q-Flex) Air System P&I Drawing

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6.3- Performance Indicators

Table 4 represents the performance indicators of LNG Carrier (Q-Flex) with the assumptions mentioned in Section 10.

Table 4 LNG Carrier (Q-Flex) Performance Indicators

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
9.3 m	0,588	0.3172	14	8754	898	525	373
	0,581		15	10807	1095	563	532
	0,589		16	12826	1319	601	719
	0,613		17	14683	1574	638	936
	0,649		18	16343	1861	676	1185
11.7 m	0,725	0.2836	14	8305	944	671	273
	0,744		14	9867	1152	719	434
	0,759		16	11653	1389	766	623
	0,769		17	13704	1655	814	841
	0,770		18	16119	1951	862	1089

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7. LR Tanker, Aframax

The performance evaluation of this case vessel is divided into two parts: one focusing on optimizing and configuring the system for the ballast condition, and the other for the laden condition. This separation is necessary because the system configuration—particularly the number and type of compressors—differs between the two loading conditions.

7.1- Vessel Particulars

Ship Type	:	LR Tanker, Aframax
Length, pp	:	240,0 m
Breadth, WL	:	42,0 m
Draft (Ballast)	:	7.45 m
Draft (Laden)	:	13.70 m
Wetted surface (Ballast)	:	11449 m^2
Wetted surface (Laden)	:	14717 m^2
Lubricated FoB Area	:	4053 m^2

7.2- ALS Configuration for Ballast only

OceanGlide air lubrication system consists of two transverse-shape air distribution bands and two D98H blower type as seen from the Figure 9. The system has been optimized for a service speed of 14.5 knots.

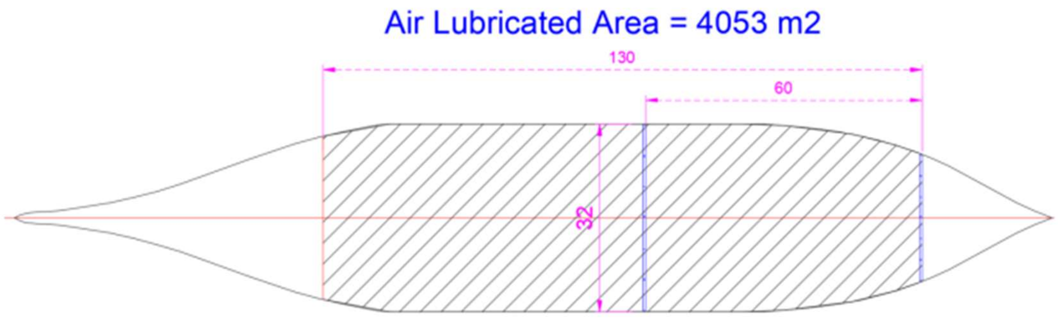

Figure 9 LR Tanker (Aframax) Band Arrangement FOR Ballast only

The mechanical design of the air lubrication configuration for LR Tanker (Aframax) is illustrated in Figure 10.

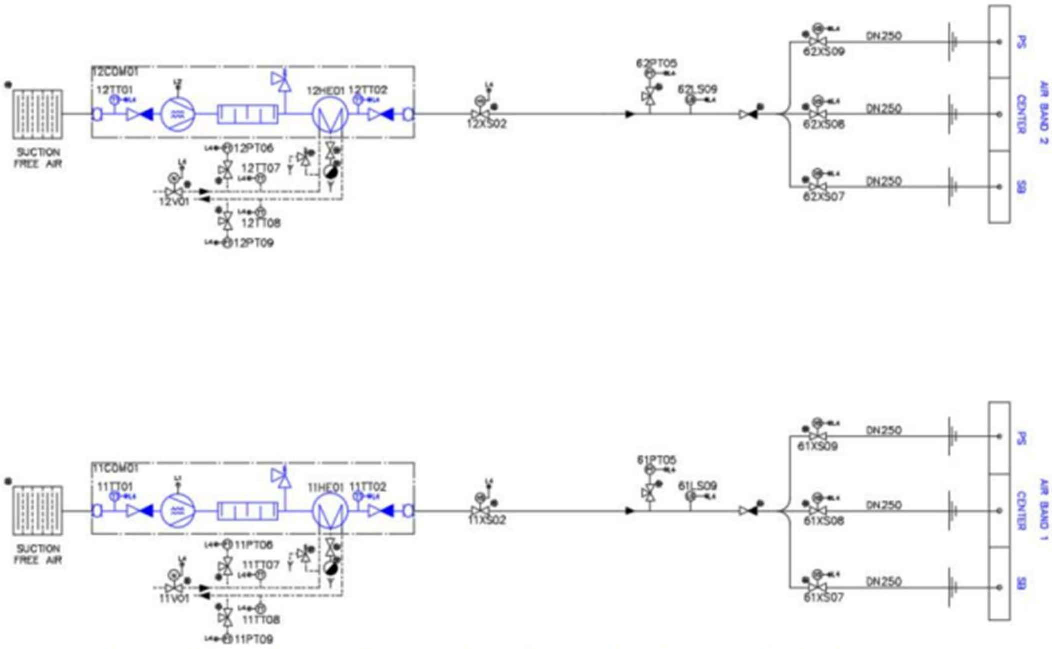

Figure 10 LR Tanker (Aframax) Air System P&I Drawing for Ballast only

7.3- Performance Indicators for Ballast only

Table 5 represents the performance indicators of LR Tanker (Aframax) with the assumptions mentioned in Section 10.

Table 5 LR Tanker (Aframax) Performance Indicators for Ballast only

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
7.45 m	0.6783	0.354	12	4.038	499	263	236
	0.6610		13	5.217	627	285	342
	0.6418		14	6.651	776	307	469
	0.6315		14.5	7.477	858	318	540

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7.4- ALS Configuration for Ballast and Laden

OceanGlide air lubrication system consists of two transverse-shape air distribution bands and three VML95 blower type as seen from the Figure 11. The system has been optimized for a service speed of 14.5 knots.

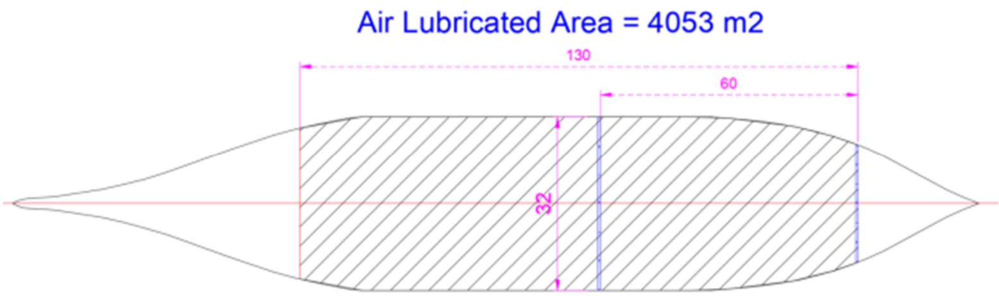

Figure 11 LR Tanker (Aframax) Band Arrangement for Ballast and Laden

The mechanical design of the air lubrication configuration for LR Tanker (Aframax) is illustrated in Figure 12.

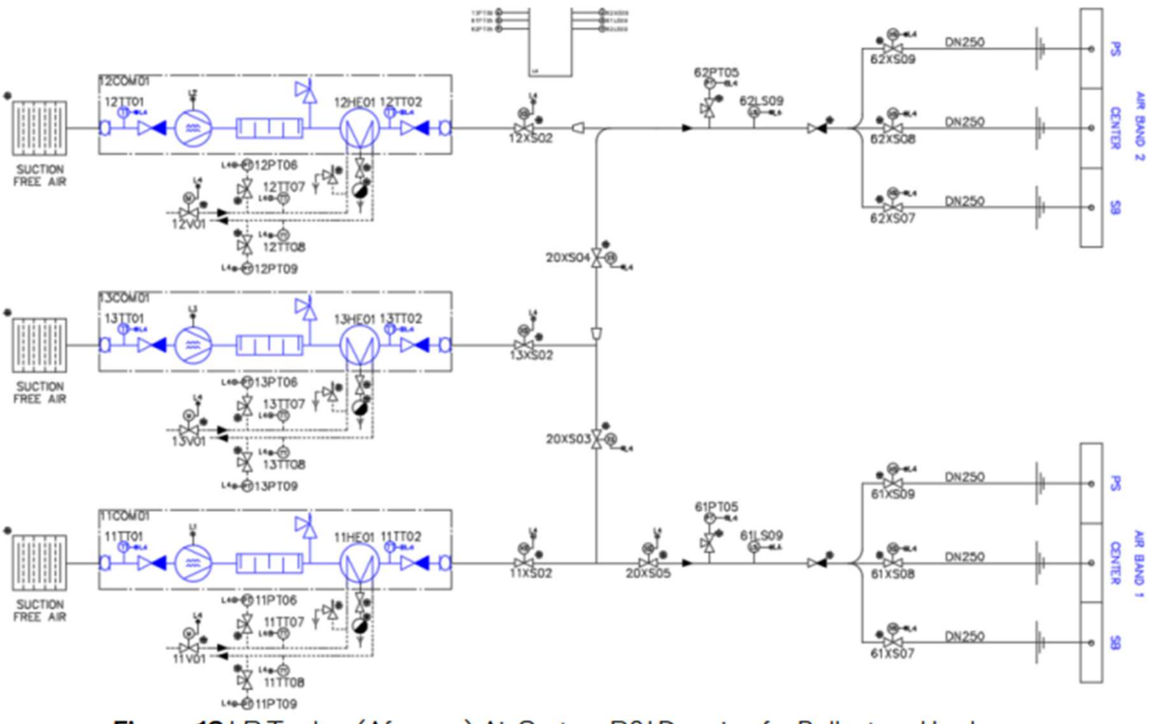

Figure 12 LR Tanker (Aframax) Air System P&I Drawing for Ballast and Laden

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7.5- Performance Indicators for Ballast and Laden

Table 6 represents the performance indicators of LR Tanker (Aframax) with the assumptions mentioned in Section 10.

Table 6 LR Tanker (Aframax) Performance Indicators for Ballast and Laden

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
7.45 m	0.6783	0.3540	12	4.038	489	276	213
	0.6610		13	5.217	615	299	316
	0.6418		14	6.651	760	322	438
	0.6315		14.5	7.477	841	334	507
13.70 m	0,6768	02754	12	5251	488	532	-44
	0,6822		13	6558	614	576	38
	0,6783		14	8165	760	620	140
	0,6729		14.5	9105	841	643	198

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8. Bulk Carrier, Capesize

8.1- Vessel Particulars

Ship Type	:	Bulk Carrier, Capesize
Length, pp	:	283,8 m
Breadth, WL	:	45,0 m
Draft (Ballast)	:	8.95 m
Wetted surface (Ballast)	:	15356 m^2
Lubricated FoB Area	:	4560 m^2

8.2- ALS Configuration

OceanGlide air lubrication system consists of two transverse-shape air distribution bands and two VML95 compressor type as seen from the Figure 13. The system has been optimized for a service speed of 13 knots.

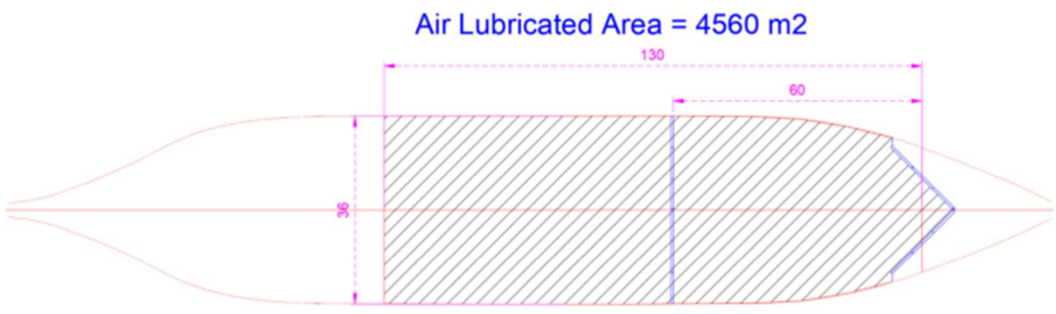

Figure 13 Bulk Carrier (Capesize) Band Arrangement

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The mechanical design of the air lubrication configuration for Bulk Carrier (Capesize) is illustrated in Figure 14.

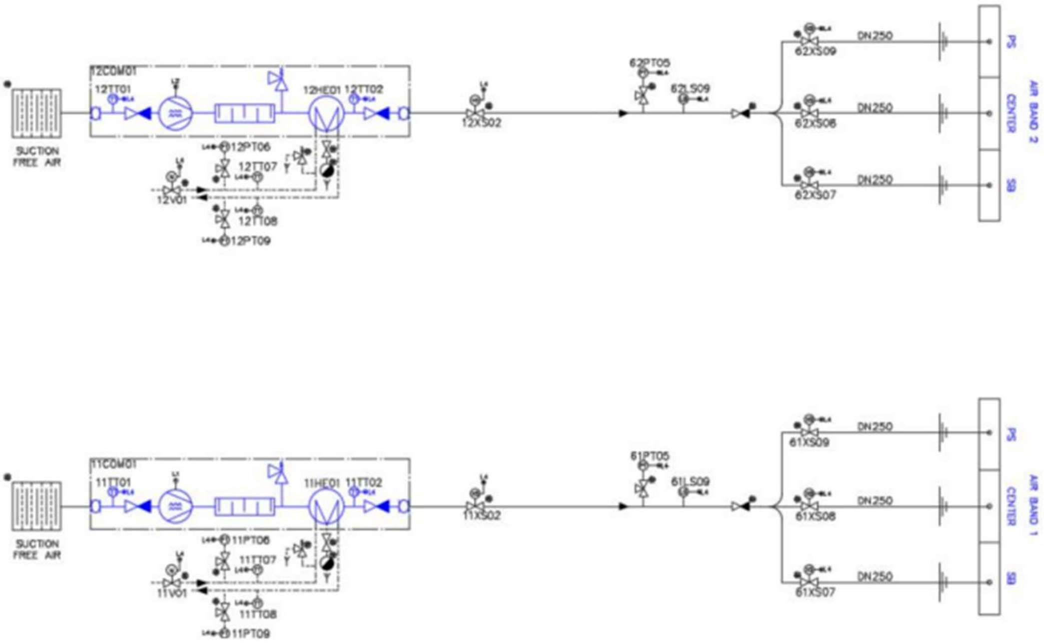

Figure 14 Bulk Carrier (Capesize) Air System P&I Drawing

8.3- Performance Indicators

Table 7 represents the performance indicators of Bulk Carrier (Capesize) with the assumptions mentioned in Section 10.

Table 7 Bulk Carrier (Capesize) Performance Indicators

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
8.95 m	0,7291	0.297	12,0	4476	579	405	174
	0,7155		12,5	5131	651	422	229
	0,6998		13,0	5873	728	439	290

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9. Container Vessel, 23k TEU

9.1- Vessel Particulars

Ship Type	:	Container, 23k TEU
Length, pp	:	393.9 m
Breadth, WL	:	63.3 m
Draft (Ballast)	:	14.5 m
Draft (Laden)	:	16.0 m
Wetted surface (Ballast)	:	15356 m^2
Wetted surface (Laden)	:	29515 m^2
Lubricated FoB Area	:	4648 m^2

9.2- ALS Configuration

OceanGlide air lubrication system consists of two transverse-shape air distribution bands and three VM85 compressor type as seen from the Figure 15. The system has been optimized for a service speed of 18 knots.

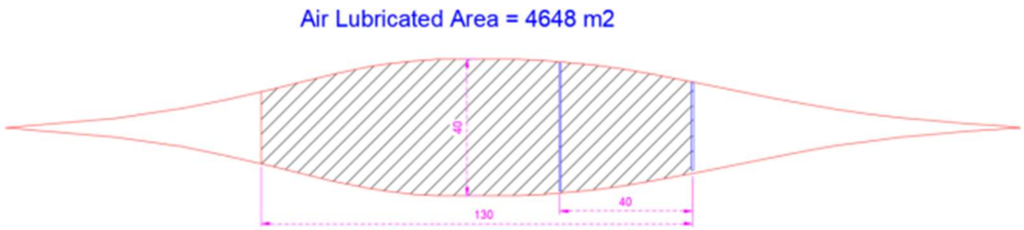

Figure 15 Container Vessel (23k TEU) Band Arrangement

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The mechanical design of the air lubrication configuration for Container Vessel (23k TEU) is illustrated in Figure 16.

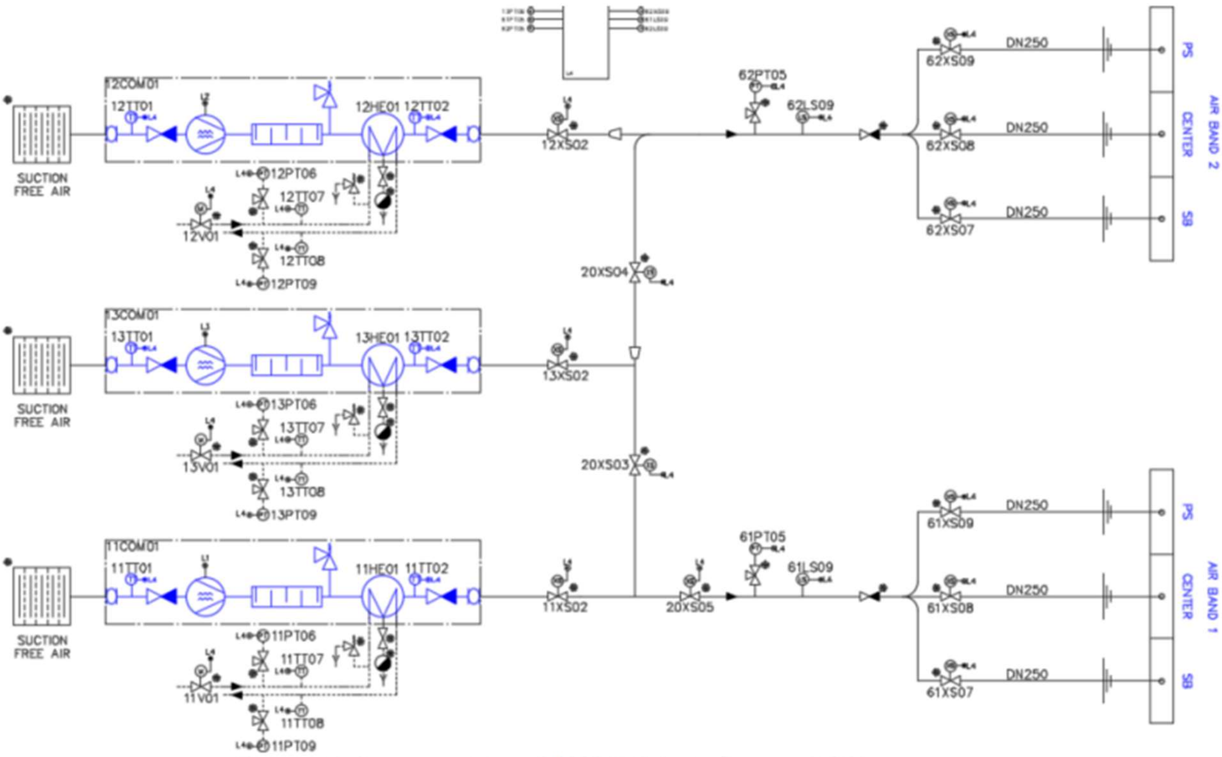

Figure 16 Container Vessel (23k TEU) Air System P&I Drawing

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9.3- Performance Indicators

Table 8 represents the performance indicators of Container Vessel (23k TEU) with the assumptions mentioned in Section 10.

Table 8 Container Vessel (23k TEU) Performance Indicators

Draught	Cf/Ct	Aa/Aw	Speed	Propulsion power before	Gross savings	Total compressor power	Net savings
	[-]	[-]	[kn]	[kW]	[kW]	[kW]	[kW]
14.5 m	0,7555	0.1645	16	18475	906	701	205
	0,7559		17	21993	1079	744	335
	0,7575		18	25879	1273	788	485
16.0 m	0,7825	0.1575	16	19405	942	790	153
	0,7728		17	23404	1121	839	282
	0,7654		18	27865	1321	888	432

10. Assumptions for Performance Indicators

The performance indicators calculated for case vessels are based upon information received in Ref (1). Additionally, it reflects the following specific notes and assumptions:

- The resistance ratio, wetted surface and propulsion power were used as received from the provided data.
- Flat of bottom shape was assumed based on the provided flat bottom dimensions.
- The indicative power savings are calculated at a given speed and draught, as per ISO 15016.
- The estimated power savings are calculated based on the system configuration as presented in this document.
- The indicative power savings are valid for even keel conditions.
- Compressor power is calculated with an internal piping pressure loss of 0.2 barg.

Appendix D HAZID Log Sheets

ID	Hazardous event	Potential causes	Potential consequences	Existing or planned safety measures	F1	Ss1	R1	Ship type specific?	Proposed additional safety measures (recommendations)	Comments and notes
1	Layer of air entering sea chests	- Hull and ALS design. - Sea conditions.	- SW pump cavitation. - Loss/reduction of cooling water supply (operational). - Engine/Equipment trips - loss of propulsion/ maneuverability - Grounding or collision. - Issues with reverse osmosis plant/FW generation	- Changeover to different SW intake (usually both low- and high-level intakes). - Sea chest de-aeration vent. - Cooling water temperature alarms.	2	2	1	No	- Consider locating the air release such that the likelihood of air accumulation in sea chests is as low as possible.	- Mostly considered an operational issue, likely it will first affect effectiveness of heat exchangers etc., and eventually see a degradation in system performances. - ALS normally disabled during maneuvering where other systems might need more power. - Structures to deflect or separate the air flow in front of the sea chest has previously been proposed, however, it is not certain if it would actually help or make matters worse in terms of air ingress to the sea chest.
2	Stability issues	- Large air cushions. - Rough Sea conditions.	- Larger dynamic transversal motions. - Potential water ingress in bad weather. - Progressively worsened stability. - Foundering.	- ALS design/integration CFD simulation. - Approval of stability booklet. - Sea trials. - *Not considered a credible scenario.*				No		- Potential change in weight distribution of the ship, primarily longitudinally, changing bending moment, etc. - ALS considered to have marginal impact on stability.
3	Directional control issues	- Air interference with course keeping abilities of vessel.	- Reduction in maneuvering control - Grounding or collision	- ALS design/integration CFD simulation. - Testing during sea trials.				No	- Consider disabling ALS when maneuvering in ports/narrow waters to reduce likelihood for grounding or collision scenarios.	- ALS is normally disabled during maneuvering where other systems might need more power. - Not considered a credible scenario.

ID	Hazardous event	Potential causes	Potential consequences	Existing or planned safety measures	F1	Ss1	R1	Ship type specific?	Proposed additional safety measures (recommendations)	Comments and notes
4	Cavitation	- Air from ALS affecting cavitation properties of the propeller.	- Erosion of propeller blades.	- Periodic surveys of the propeller. - ALS design/integration CFD simulation.	2	1	1	No	- If cavitation may be a concern, consider carrying out acoustic emission tests to determine if this is a problem, and prevent subsequent propeller damage.	- MSC have currently no experience with cavitation from ALS happening this far but is closely monitoring the situation - ALS creates a structurally sound air bubble, not caused by pressure differential across the propeller blade as for cavitation, thus it is less likely to implode and damage the blade.
5	Noise and vibration	- Noise/ vibrations generated from ALS system transmitted through vessel structure.	- Noise generated in accommodation. - Fatigue of crew.	- Vibration analysis. - Testing during sea trials. - Location of ALS-related equipment in relation to habitated areas. - Piping system design. - Vibration reduction measures for rotating equipment.				No		- No problems related to noise and vibrations experienced this far by MSC. - Examples have been shared from vessels that N&V has even been reduced in some cases. - Integrators of ALS should pay attention to this to prevent N&V from becoming a problem. - Not considered a safety issue.
6	Hull structural weakness	- Multiple hull penetrations for ALS air release. - Impact to protruding hull elements (grounding/ collision).	- Water ingress into hull. - Reduced stability.	- Statutory and Class Society requirements for hull penetrations. - Damage stability requirements. - NDT testing after installation. - Non-return valves and possible double block and bleed arrangement to reduce risk of down flooding. - Level switches in "dry" volumes.				No	-	- The general rule is that installation of ALS and any penetration in the hull, the structure should not be any weaker than before the installation. - Integrator's responsibility to ensure that the ALS is safely integrated into the vessel overall. - Boxes installed as hull replacement for Armada's system, is approved by Class societies in the same way as sea chests are approved. - **No difference in risk level as a result of introducing the ALS is perceived from the WS participants relating to this hazard.**

ID	Hazardous event	Potential causes	Potential consequences	Existing or planned safety measures	F1	Ss1	R1	Ship type specific?	Proposed additional safety measures (recommendations)	Comments and notes
7	Backflow through ALS outlets	- ALS damage (e.g. during hull cleaning). - Valve failure. - Assembly error.	- Water ingress to spaces with ALS related equipment and/or piping	- Class Society requirements for hull penetrations. - Piping system design. - Testing during sea trials.				No		- Scenario is considered similar to the previous scenario (ID 6). - Hull cleaning would normally not happen while ALS system in operation.
8	Added resistance when ALS not in use			No consequence for safety				No		
9	Reduced performance in high sea states			No consequence for safety				No		
10	ALS control system complexity	- Integration errors.	- Damage to associated systems. - Ship blackout. - Equipment damage.	- Class approval process (electrical systems).	2	2	1	No	- Ensure that the integration of ALS covers a discrimination study (electrical & Instrumentation) to ensure that switching on the ALS system will not draw power from the system to such an extent that the vessel may experience a blackout	
11	ALS energy expenditure		Total energy demand exceeding savings.	No consequence for safety				No		
12	Underwater radiated noise		Potential impact to marine underwater organisms.	No consequence for safety				No		- Noise travels faster in water than air, thus ALS should in theory reduce the underwater radiated noise. - Ejection of air on the other hand could represent a source generating radiated noise under water. - Separate research projects looking into this topic.

ID	Hazardous event	Potential causes	Potential consequences	Existing or planned safety measures	F1	Ss1	R1	Ship type specific?	Proposed additional safety measures (recommendations)	Comments and notes
13	Slamming in the fore part of the hull affects ALS	- Heavy seas.	- Damage to ALS. - Water ingress into the hull.	- Statutory and Class Society requirements for hull penetrations. - Damage stability requirements. - NDT testing after installation.				No		- Investigate with ship owners and Hull structures (Class) if any issues related to this have been experienced.
14	Echo sounder interference (aft sensor)	The air boundary layer of ALS is disturbing the Echo sounder.	- Unable to assess depth in shallow waters in case of aft trim. - Grounding or contact damage.	- Double set of sensor(s), fore and aft, fore sensor should be able to get an accurate reading of depth. - Mostly used during maneuvering where ALS would normally not be in operation.	2	3	2	No	- Ensure crew training and knowledge sharing that the crew are aware not to pay attention to aft echo sounder when ALS is in operation - Consider if there is a possibility to integrate an alarm/alert for aft echo sounder if the ALS is operational and fore echo sounder measures depth below keel to be reduced below an applicable threshold, to make crew aware aft echo sounder is not providing reliable data and prevent potential groundings.	- ALS is known to create this issue, however, ALS is not normally in operation in situations where the aft echo sounder is essential.
15	Oil carry-over	Oil carry-over from compressors.	Oil release to the sea.	- Most vendors seem to be using oil-free compressors for those systems relying on compressed air.				No		- Not a safety issue, potential environmental concern.

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