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RETROFIT SOLUTIONS TO ACHIEVE 55% GHG REDUCTION BY 2030

Framework for Safe and Sustainable Shipping Operations

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Abbreviations

ALS	Air Lubrication System
AWS	Advanced Wing Systems
BDN	Bunker Fuel Delivery Note
B.L.	Boundary Layer
CH_4	Methane
CDP	Carbon Disclosure Project
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
CML	Committee Maritime International
CO_2	Carbon Dioxide
CO_{2e}	CO_2 Equivalent
COSWP	Code of Safe Working Practices for Merchant Seafarers
DC	Direct Current
DCS	Data Collection Systems
EU	European Union
ECA	Export Credit Agency
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EESM	Electrically Excited Synchronous Machines
EEXI	Energy Efficiency Existing Ship Index
EPS	Environmental Priority Strategies
ETC	Energy Transitions Commission
ETS	Emission Trading Scheme
FOC	Fuel Oil Consumption
GHG	Green House Gas
GT	Gross Tonnage
HMI	Human Machine Interface
ICCT	International Council on Clean Transportation
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISM	International Safety Management
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life cycle impact assessment
LCG	Longitudinal Centre of Gravity
MRV	Monitoring, Reporting and Verification
NPV	Net Present Value
NO_x	Nitrogen Oxides
OJEU	Official Journal of the European Union
PALS	Passive Air Lubrication System
PIDO	Process Integration and Design Optimisation
PLC	Programmable Logic Controller
PM	Permanent Magnet
PRB	Principles for Responsible Banking
PV	Photovoltaic
SC	Short Circuit

SEEMP	Ship Energy Efficiency Management Plans
SO_x	Sulphur Oxides
TCFD	Task Force on Climate-Related Financial Disclosure
VFD	Variable Frequency Drive
WASP	Wind Assisted Propulsion
ZEWT	Zero – Emission Waterborne Transport

Executive Summary

As the maritime industry navigates the transition towards a greener future, stakeholders require a deep understanding of the evolving regulatory landscape and available options. This report aims to address a framework for safe and sustainable shipping, by providing a comprehensive overview of current challenges, key regulations such as Poseidon principles, EU and IMO requirements, potential solutions, and crucial considerations for achieving safe and sustainable operations.

The framework acknowledges the hurdles hindering the industry's transition, such as ownership structures, diverse insurance policies, and high upfront costs. To navigate these challenges, the framework delves into critical regulations and policy drivers, including the roles of the International Maritime Organization (IMO), Poseidon Principles, Zero-Emission Ship Technology (ZEWT), Carbon Intensity Index (CII), and Emissions Trading Schemes (ETS). These entities establish environmental standards and incentivize sustainable practices.

Furthermore, the framework introduces the Life Cycle Analysis (LCA) methodology with an example of work done in the maritime industry, equipping stakeholders with a valuable tool to evaluate and compare different retrofit options. This model assesses emissions not only during operation but also during installation, providing a comprehensive picture of environmental impact. Additionally, the report explores the potential return on investment achievable through Emissions Trading Schemes (ETS) credits, offering further financial incentives for adopting sustainable solutions.

The framework also explores promising technologies and methodologies for a greener future, such as Air Lubrication Systems (ALS) and Wind-Assisted Propulsion (WASP) technologies. These advancements have the potential to significantly reduce emissions. Recognizing the critical importance of safety, the report emphasizes the need to address the safety aspects associated with these innovative technologies.

In conclusion, this framework serves as a valuable resource for maritime stakeholders by providing a holistic view of the changing regulatory landscape, available options for achieving sustainability, and crucial considerations for navigating this transition in a safe and sustainable manner. By understanding these factors, stakeholders can make informed decisions, adapt their operations, and contribute to a greener future for the maritime industry.

1 Introduction

The shipping industry plays a crucial role in global trade and commerce. Shipping is the backbone of international trade as around 80% of all global trade by volume and 70% by value are transported via shipping [1].To put shipping Green House Gas (GHG) emissions into perspective, the fuel consumption of ships excluding the military in the year 2016 was around 250 mt. Considering that for every ton of Carbon Dioxide (CO_2) produced, there is an increase of 5×10^{-12} °C, one billion tons of CO_2 raises the temperature by 0.005 °C every year [1], [2]. These numbers are estimated to increase exponentially by 150 – 250% by 2050 if no action is taken [3].

Monitored waterborne CO_2 emission in Europe from shipping emitted 144.6 million tons of emissions and inland waterway transport in the European Union (EU) results in around 3.8 million tons of CO_2 emissions per year. Shipping is responsible for 24% of the EU's Nitrogen Oxides (NO_x) and Sulphur Oxides (So_x) emissions, with very high amounts found in coastal and port areas. With the current regulations, after 2030, NOx emissions from the maritime industry are expected to exceed the EU's land-based sources [2].

Whilst inland waterway transport is not covered by the IMO, it is covered by EU and regional legislation which may differ from city to city. As it passes through city and town centres, emissions from inland waterways are quite visible. One large inland water way vessel may produce around 11,000 kg of NO_x per year [2].

The IMO has proactively established regulations to address emissions, such as the Carbon Intensity Indicator (CII), which is a rating system that measures how efficiently goods are transported as expressed as grams of CO_2 per cargo-carrying capacity [3], the Energy Efficiency Existing Ship Index (EEXI), a single lifetime rating assigned to a ship which indicates its efficiency in terms of CO_2 emission transport per work [4], and the Ship Energy Efficiency Management Plan (SEEMP), navigating the path towards significant reduction presents ongoing challenges. Despite this, the path forward for shipowners and stakeholders can be quite unclear.

However, addressing the environmental challenges imposed by emissions from shipping vessels is paramount. This framework aims to contribute to this journey by exploring practical and sustainable approaches to implementing these, regulations, safety measures, and technological innovations. Additionally, it will provide insights and best practices for achieving emission reduction targets set for the year 2030, which is 40% reduction of CO_2 per transport work, 5% uptake of zero-emission fuels, striving for 10% and an indicative checkpoint of 20% reduction of the total annual GHG emissions, striving for 30% as can be seen in **Error! Reference source not found.** [5].

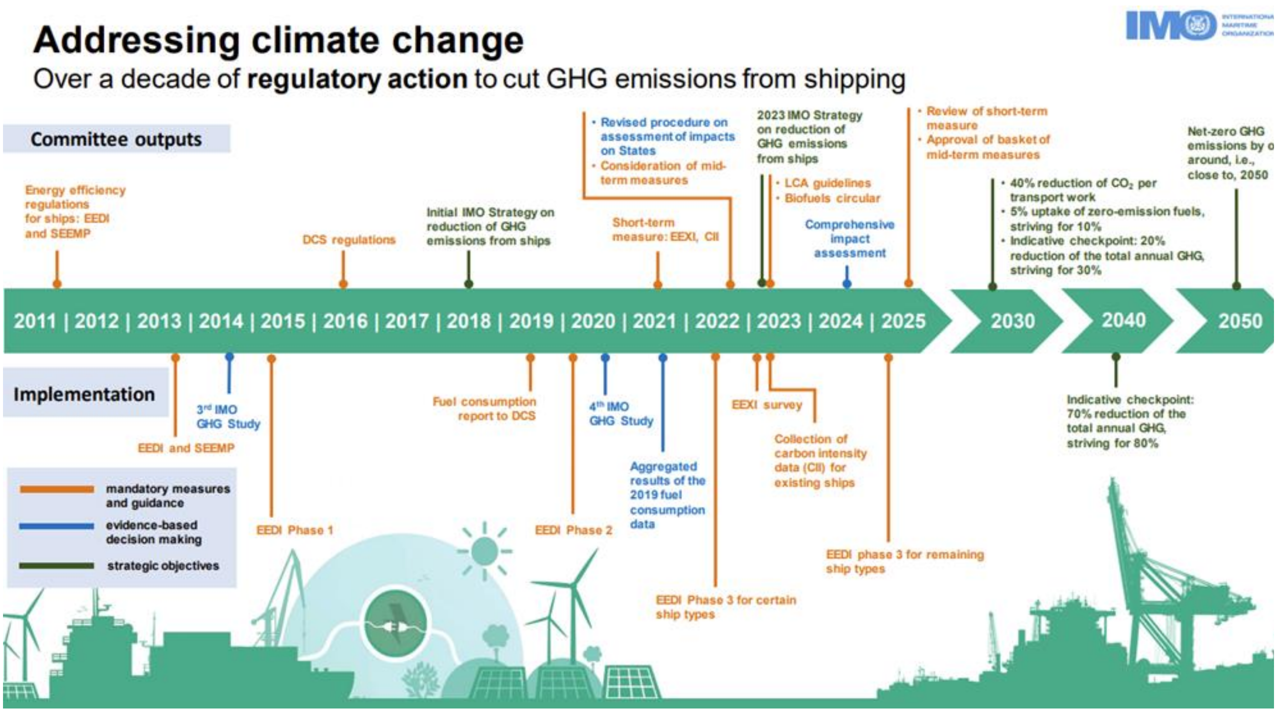

Figure 1: IMO Timeline for cutting GHG from Shipping [5]

1.1 Aims and Objectives

The aim of this framework is to equip stakeholders with a comprehensive framework for achieving safe and sustainable shipping by providing insights into current challenges, key regulations, potential solutions, and crucial considerations through the lens of the Poseidon Principles, EU, and IMO requirements.

To achieve the aim of the framework the following objectives have been developed:

- To lay out and explain the regulations and policies in a way that can be understood by all maritime stakeholders.
- Explain the Life Cycle Analysis (LCA) methodology.
- Introduce several technologies that can help ships achieve their emission goals.

1.2 Structure of Report

This report is divided into five chapters, including this chapter, which is a brief introduction to the background, aims and objectives.

- Chapter 2 is dedicated to highlighting and explaining the factors affecting the change area. This goes through different problems such as ownership, technology problems and financial problems. The aim of this chapter is to give the reader an understanding of problems that are not normally highlighted when it comes to adopting new technology.
- Chapter 3 tackles the legislation and policy drivers that are forcing the change for the 2030 and 2050 goals. Several policies, regulations, and environmental indexes such as IMO,

ZEWT and the CII are explained. The aim of this chapter is to give the reader a clearer understanding of the targets to be reached.

- Chapter 4 explains what the LCA is, how it works within the maritime industry, a cost benefit analysis and a small case study. The aim of this chapter is to show maritime stakeholders that, when choosing a technology, it is not just for the achieved savings, but also for the emissions during the installation and its use phase.
- Chapter 5 gives maritime stakeholders a general overview of what technologies exist and which ones can be adapted for different ships. This includes the technology working principles, safety and hazards that could come with an installation. The aim of this chapter is to give a better understanding of not only the technologies and their savings but also of the safety hazards that could come with the technology and how these could be mitigated.
- Chapter 6 is the final chapter of this report, and it provides a summary of the work done in this framework.

2 Factors Effecting Change

Shipping is a multi-faceted business, therefore there are several contributing factors that will slow down any changes. Some of these factors are overlapping and make it even more difficult to enforce any development, due to technological, infrastructure and legislation challenges.

2.1 International Sector

Shipping is an international business, in fact, over 80% of all trade is done via shipping [1]. However, this poses quite the problem. Ships will sail in international waters, this means that one voyage of ship will pass through different regions, national and local policies, and regulations. Every change needs to be agreed upon by different levels, therefore only incremental changes are in practice made. To put this problem into context, the following quote from the *Zero- Emission Waterborne transport (ZEWT) – Strategic Research and Innovation Agenda* [2] is here reported:

“A container ship, built in China, equipped with European engines, might be sailing from Shanghai to Rotterdam. The ship is flagged in Panama, insured in London and sails with crew from the Philippines and officers from Russia. The ship is managed from Liberia, chartered from France, owned by a German shipowner, and fuelled in Singapore” [2].

2.1.1 High Energy Demand

Shipping is the most energy-efficient mode of transport per ton- kilometre. This is only because of the economy of scale, as ships are much larger and are only getting bigger. However, this growth in ships comes with its problems, as the energy needed to move them is very high. For the larger ships, 4 weeks of sailing, which is the equivalent of a trip from China to Europe, would require around 50 GWh of energy [2],[6].

2.1.1.1 Lack of Alternative Fuel

As of now, there is no full-scale, widely available and cost-effective alternative fuel. This is due to several reasons, such as technology constraints, infrastructure and supply problems, leading to higher uncertainty levels, as can be seen in **Error! Reference source not found.**. It must be kept in mind that. whilst shipping does contribute to 3% of all the world's trade, there are other industries such as cement and chemical production that contribute more. Therefore, there need for alternative fuel will be higher. Additionally, some of the alternative fuels are hazardous to humans if consumed. The feature and characteristics of these fuels can be seen in **Error! Reference source not found.** [7]. This poses safety questions and even more difficult technology problems. The biggest problem of alternative fuel is the energy density, since ammonia and methanol have about one third the energy density of marine fuel, this would result in either more bunkering stops or else less carrying capacity for ships as more space is needed to carry the fuel [2],[8],[9].

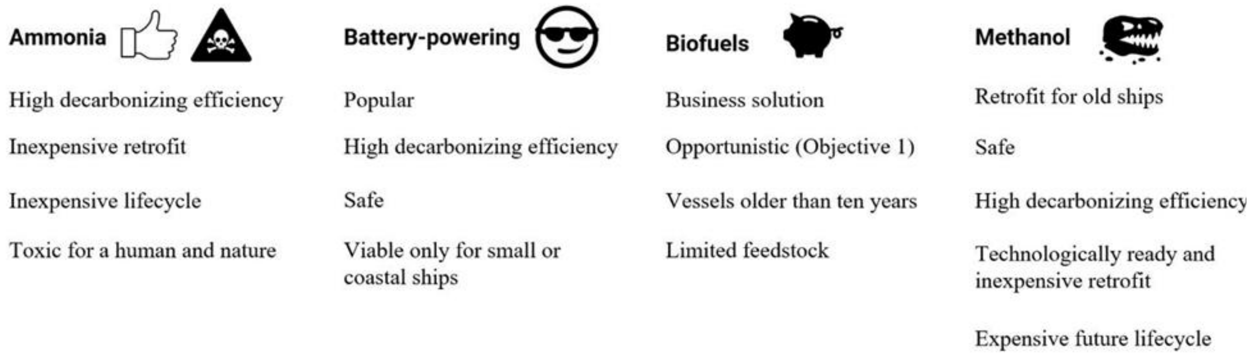

Figure 2: Feature of Energy Sources for Ship Retrofitting [7].

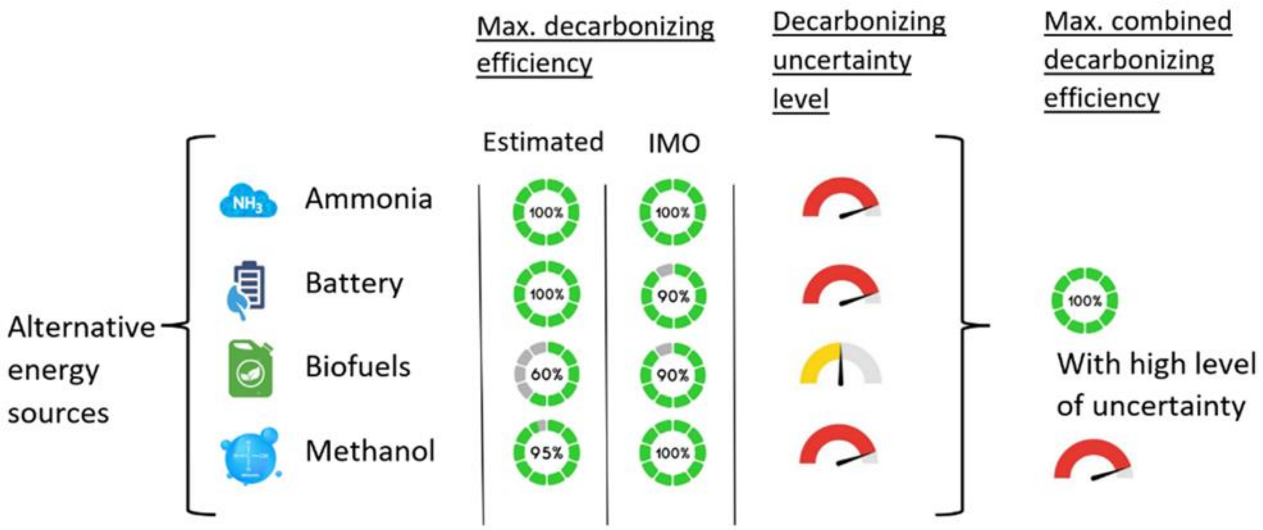

Figure 3: Uncertainty Levels of Alternative Fuels [7].

2.1.2 Lack of Infrastructure

Ports are crucial for ship operations, and refuelling typically happens via dedicated vessels called "bunker ships." However, the maritime industry is moving towards cleaner options like alternative fuels and electrification. This transition demands advancements in bunkering infrastructure, both within ports and along European waterways.

Each alternative fuel presents unique challenges. Cryogenic fuels like liquefied hydrogen require specialized technology and stricter safety protocols, due to their extremely low temperatures. Other options might share similar bunkering processes to traditional fossil fuels, with ammonia being a notable exception [8].

Electrification brings its own set of needs, including powerful charging facilities and backup power systems. Battery swapping technology could also play a role. Currently, most ports offer limited "cold ironing" capabilities, which involves using shore-based electricity while docked. While regulations mandate improvement, charging massive onboard batteries for seafaring necessitates much higher power supplies. Technologies for rapid high-power charging are under development, but integrating them safely and reliably with portside grids remains a hurdle [2].

2.1.3 Diversity of The Sector

The diversity of the waterborne transport sector, encompassing various players like shipbuilders, owners, operators, authorities, and even citizens' groups, presents a major complication in transitioning to zero-emission solutions. While numerous initiatives are underway, solutions developed for one ship type might not work for another.

A key missing piece is a unified innovation agenda that considers the varied needs and capabilities across the industry. Each segment, from shipyards to port authorities, has its own internal variations and business models, which can act as drivers or barriers to adopting new technologies. Sharing both the financial burden and potential profits of green solutions throughout the supply chain is crucial.

However, the traditional chartering model in shipping, where ownership and operation are separate, creates disincentives for implementing new technologies. The split incentives between owner and operator lead to conflicting priorities, making it difficult to justify investments in green solutions with short-term profit cycles [2],[10].

2.1.4 Age of Vessels

With the average seagoing ship having a life span of 25 years radically different, zero-emission designs are essential within just 10 years. Technologies developed under Horizon Europe hold the key. However, new builds alone will not be enough. This is especially critical for inland waterways, where older, less efficient ships dominate. On average inland vessels last 40-60 years, leading to many outdated, polluting ships. Western Europe has a massive aging fleet, with half (Germany, Netherlands, Belgium) and 80% (France) built over 50 years ago, whilst 15% even exceed 75 years (Netherlands). Switzerland boasts a newer fleet (87% built in the last 35 years) due to their inland cruise focus [2],[11].

2.1.5 Financial and Contractual Hurdles

The transition of the maritime industry to cleaner vessels faces significant financial and contractual challenges. Implementing emissions-reducing technologies, like scrubbers or electric motors on existing ships, requires substantial upfront investment, often exceeding available financial support programs. The complex contractual landscape involving ship owners, operators, and charterers presents challenges in cost-sharing due to conflicting incentives and short-term agreements. The rapidly evolving technological landscape poses a risk of stranded assets, as older vessels or "non-green" vessels will lose their value faster [12]. Finally, the lack of standardized solutions and the uncertainty surrounding insurance requirements and regulatory changes contribute further to the complexity and financial burden of retrofitting existing vessels. Addressing these multifaceted financial and contractual hurdles is crucial for paving the way for the widespread adoption of green technologies in the maritime sector and achieving emission reduction goals [13].

3 Legislation and Policy Drivers

At the helm of this shift stands a complex web of legislation and policy drivers, both international and regional, pushing for significant reductions in shipping emissions. From the ambitious IMO strategy of setting net-zero targets by 2050, to emerging market-based measures and innovative port regulations, these forces are reshaping the industry landscape. This chapter delves into the specific legislative and policy drivers impacting the maritime sector, analysing their impact on key stakeholders and their potential to unlock a future of cleaner seas.

3.1 IMO Strategy on Reduction of GHG Emissions from Ships

The IMO plays a multifaceted role in driving the industry towards cleaner practices. Firstly, it acts as the architect of global regulations and standards governing safety, security, and environmental protection. These regulations span all aspects of maritime operations, from ship construction and fuel standards to operational practices and pollution prevention [5].

Beyond setting targets, the IMO actively develops and enforces these regulations. Initiatives like the Energy Efficiency Design Index (EEDI) for new ships and guidelines for Ship Energy Efficiency Management Plans (SEEMPs) translate global ambitions into concrete actions. The organization also facilitates international agreements like the International Convention for the Prevention of Pollution from Ships (MARPOL) convention (addressing pollution prevention) and the Kyoto Protocol (targeting greenhouse gas reduction), creating a comprehensive framework for environmental protection [5].

However, the IMO's influence extends beyond the theoretical. It fosters cooperation and technical assistance among member states, ensuring widespread understanding and implementation of regulations. This collaborative approach is crucial for addressing the global nature of maritime operations and fostering consistent enforcement across diverse regions.

3.1.1 2023 IMO Strategy

The 2023 IMO GHG Strategy unveils a transformative roadmap for decarbonizing international shipping. It articulates a clear vision for the future, demanding significant reductions in greenhouse gas emissions aligned with the Paris Agreement. This ambition translates into a concrete 40% carbon intensity reduction target by 2030. The guiding principles and potential mid- and long-term measures are outlined, addressing potential challenges through capacity building, technical cooperation, and R&D initiatives. Recognizing the crucial role of innovation, the strategy mandates the uptake of zero or near-zero GHG technologies, fuels, and energy sources for at least 5% (striving for 10%) of international shipping energy consumption by 2030. Significantly, the strategy acknowledges the long-term goal of complete decarbonization, explicitly calling for "phasing them out" in accordance with the Paris Agreement temperature targets. This multifaceted framework, demanding collaboration and innovation, lays the foundation for a cleaner and more sustainable maritime future [14].

Recognizing the ongoing evolution of the sector, the strategy mandates reviews that incorporate:

- Updated emission estimates, ensuring accurate data guides decision-making.
- Emissions reduction options, exploring emerging technologies and solutions.
- Intergovernmental Panel on Climate Change (IPCC) reports and IMO studies, leveraging expert assessments and data.

These review elements will assess progress towards achieving net-zero GHG emissions, a crucial ambition outlined in the strategy. Furthermore, the levels of ambition and indicative checkpoints are explicitly linked to the life cycle GHG emissions of well-to-wake marine fuels, within the boundaries of the energy system of international shipping.

The level of ambition for the 2023 IMO GHG strategy is as follows:

- Carbon intensity of the ship to decline through further improvement of the energy efficiency for new ships.
- Carbon intensity of international shipping to decline by at least 40 % by 2030 compared to 2008.
- Uptake of zero or near-zero GHG emissions technologies, fuels and/or energy sources to increase by at least 5% to 2030 and if possible 10%.
- GHG emissions from international shipping to reach net zero by or around 2050.

Along the process, indicative checkpoints have been set up as follows:

- To reduce the total GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008.
- To reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008 as seen in **Error! Reference source not found.**.

3.2 Zero Emission Waterborne Transport– Strategic Research and Innovation Agenda

The Zero Emission Waterborne Transport Partnership (ZEWT) is a European initiative aimed at accelerating the development and deployment of technologies and solutions for clean and sustainable waterborne transport, with the goal to achieve zero emission waterborne transport in Europe by 2050. ZEWT brings together various stakeholders from across the maritime and inland waterborne transport sector, including shipbuilders, shipping companies, port authorities, technology providers, research institutions, and policymakers' regulations. ZEWT sets the agenda for maritime research in Europe [2].

The ZEWT Objectives include several measures to reduce greenhouse gas emissions from ships, such as:

- To provide and demonstrate zero-emission solutions for all main ship types and services before 2030, which will enable zero-emission waterborne transport before 2050.

- To develop and demonstrate deployable technological solutions, which will be applicable for the decarbonisation and the elimination of other harmful emissions of main ship types and services.
- By 2030, the implementation of economically viable European new technologies and concepts regarding zero-emission waterborne transport, to strengthen the competitiveness of European industries in growing greenship technology markets and provide the capability to re-enter markets presently dominated by Europe's competitors.The regulations would require ships to meet certain energy efficiency standards.
- To facilitate the development and implementation of regulations and policies at the national and international level, including the development of standards to enable the implementation of technological solutions for ZEWT by 2030 at the latest.
- To facilitate the uptake of innovative zero emission waterborne transport technologies and solutions within the European waterborne sector, supporting economic growth and European employment.

Error! Reference source not found. shows the operational objectives of the partnership.

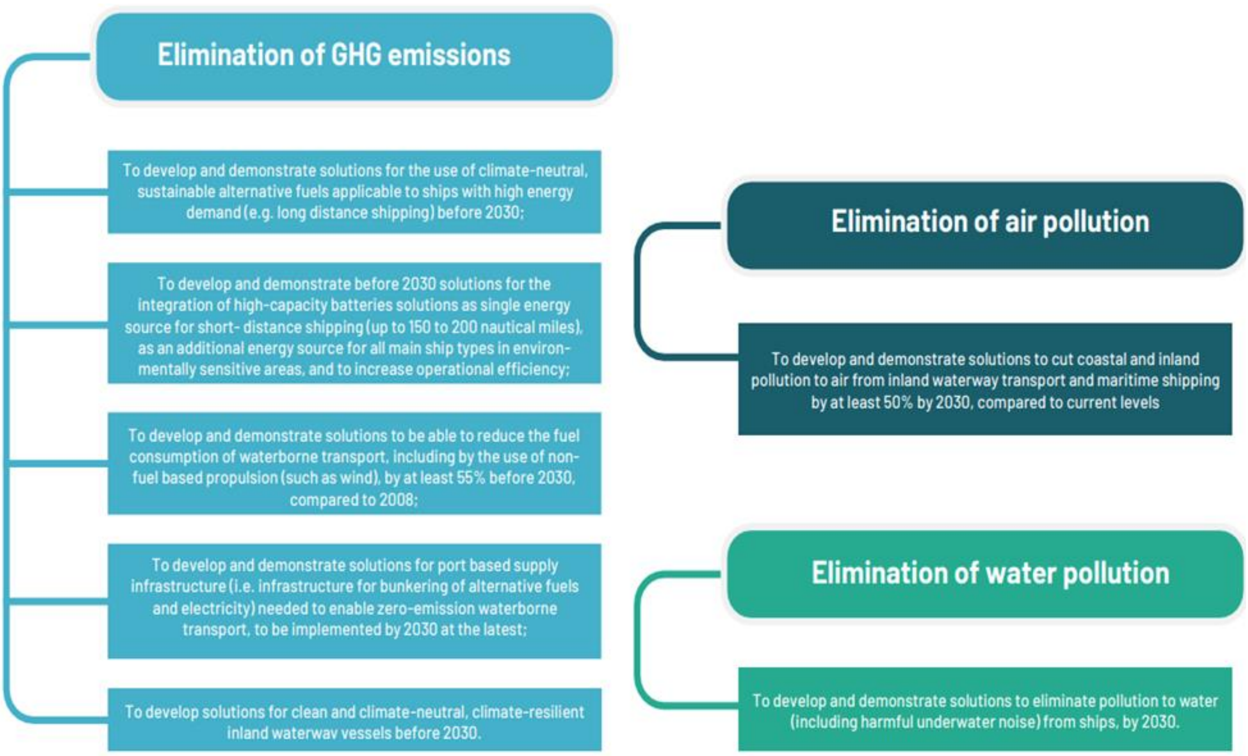

Figure 4: Operational Objectives of ZEWT [2].

3.3 Poseidon Principles

The Poseidon Principles serve as a framework for creating common, global baselines that are consistent with and supportive of society's goals.

The Poseidon Principles are consistent with the policies and ambitions of the IMO, including its ambition for GHG emissions to peak as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008. They are also intended to support other initiatives, such as the Principles for Responsible Banking (PRB), Carbon Disclosure Project (CDP), Energy Transitions Commission (ETC), Task Force on Climate-Related Financial Disclosures (TCFD), and many others that are developing to address adverse factors [13].

The Poseidon Principles serve as a voluntary framework for financial institutions involved in the maritime sector, specifically lenders, lessors, and guarantors including export credit agencies. Signatories adhere to these principles when engaging in specific financing activities related to the shipping industry.

Firstly, the principles apply to all credit products – encompassing bilateral loans, syndicated loans, club deals, and guarantees – secured by a vessel mortgage, finance lease title, or unmortgaged Export Credit Agency (ECA) loan directly tied to a specific vessel. This ensures that financing decisions consider the environmental impact of the vessel itself [10].

Secondly, the scope extends to vessels exceeding 5,000 Gross Tonnage (GT) that operate under the IMO. Notably, these vessels must have an established "Poseidon Principles trajectory," meaning that their carbon intensity can be effectively measured using data from the IMO Data Collection System (DCS). This ensures accountability and transparency in assessing the climate alignment of financed vessels.

It is crucial to note that the scope of the financial products covered by the Poseidon Principles is subject to future review and potential expansion by signatories. This demonstrates the evolving nature of the framework and its adaptability to incorporate new developments in the financial and maritime landscapes.

Currently, the sole environmental factor considered by the Poseidon Principles is climate alignment. However, the scope regarding environmental factors is also susceptible to review and potential expansion at the discretion of signatories. This reflects the ongoing commitment to address broader environmental concerns within the maritime sector.

In essence, the Poseidon Principles define a clear yet flexible framework for financial institutions to contribute to greener shipping practices. By focusing on vessels with measurable carbon footprints and considering the potential expansion of both financial product coverage and environmental factors, the framework encourages responsible financing decisions that can ultimately contribute to a more sustainable maritime future.

3.3.1 Principle 1: Assessment of Climate Alignment

Signatories will, on an annual basis, measure the carbon intensity and assess climate alignment (carbon intensity relative to established decarbonisation trajectories) of their shipping portfolios. This requirement takes effect for each Signatory in the following calendar year after the calendar year in which it became a Signatory. In the context of the Poseidon Principles, climate alignment refers to the extent to which a vessel, product, or portfolio's carbon intensity aligns with a defined decarbonization trajectory. This trajectory specifically adheres to the IMO's ambitious goal of reducing total annual greenhouse to net zero by 2050. This metric serves as a benchmark for assessing and comparing the climate impact of shipping activities within the framework of the Poseidon Principles [13].

Carbon intensity is a key metric used to assess the environmental impact of vessel operations. It defines the total emissions (grams of CO_2 per tonne-nautical mile, gCO_2/tnm) associated with producing a specific amount of transport work. Crucially, this quantification considers multiple voyages over a representative period (e.g., a year) to capture the performance of the vessel under real-world conditions. This comprehensive approach is vital for an accurate climate impact assessment, surpassing the limitations of design specifications like the EEDI. By focusing on actual operational data, carbon intensity provides a more realistic and actionable measure of a vessel's contribution to greenhouse gas emissions [13].

The IMO DCS defines the data that the IMO has mandated for shipowners to collect and report per calendar year. The IMO DCS is an amendment to MARPOL Annex VI which entered into force in March 2018. The IMO DCS specifies the data to be collected and reported for each calendar year, for ships which are vessels 5,000 GT and above, not solely engaged in voyages within waters subject to the sovereignty or jurisdiction of the State the flag of which the ship is entitled to fly:

- The amount of fuel consumption for each type of fuel in metric tonnes
- Distance travelled
- Hours underway
- Technical characteristics of the ship including DWT at maximum summer draught.

3.3.2 Principle 2: Accountability

For each step in the assessment of climate alignment, Signatories will rely exclusively on the data types, data sources, and service providers identified in the Technical Guidance [13].

3.3.3 Principle 3: Enforcement

Signatories will agree to work with clients and partners to covenant the provision of necessary information to calculate carbon intensity and climate alignment [13].

3.3.4 Principle 4: Transparency

Upon becoming a Signatory, the Signatory will publicly acknowledge that it is a Signatory of the Poseidon Principles. On an annual basis, each Signatory will report the overall climate alignment of its shipping portfolio and supporting information, as per the Accountability requirements, to the Secretariat no later than 15 November, this work flow can be seen in **Error! Reference source not found.**. This requirement takes effect for each Signatory in the calendar year after the calendar year in which it became a Signatory. On an annual basis, each Signatory will publish the overall climate alignment of its shipping portfolio in relevant institutional reports on a timeline that is appropriate for that Signatory. This requirement takes effect for each Signatory in the calendar year after the calendar year in which it became a Signatory MRV [13].

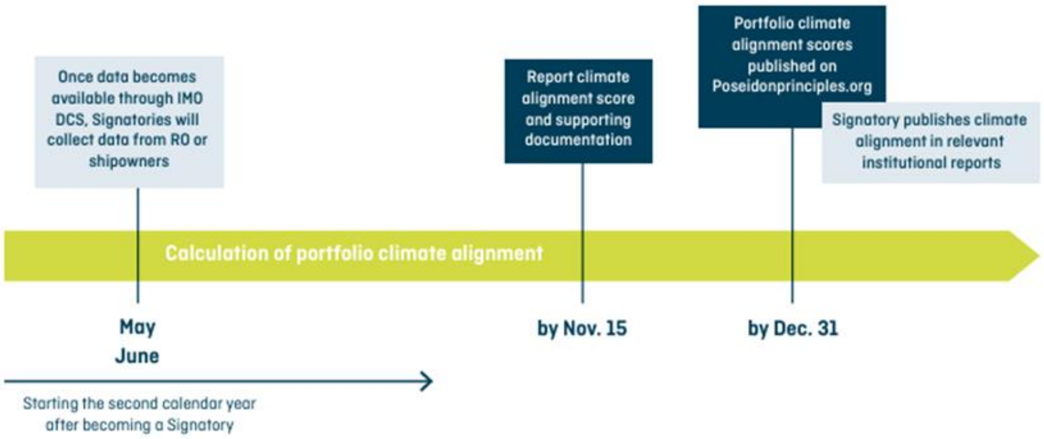

Figure 5: Timeline of Workflow [13].

3.4 MRV – Monitoring, Reporting and Verification

The Monitoring, Reporting and Verification (MRV) is a policy approach commonly used in the context of climate change mitigation, including decarbonization efforts. MRV policies are designed to track and assess greenhouse gas emissions and the progress of decarbonization initiatives. These policies are important for ensuring transparency, accountability, and effective reduction of emissions, which came into place on July 1st 2015 [15].

In its ongoing fight against greenhouse gas emissions, the European Union has implemented the MRV Regulation. This regulation mandates the monitoring, reporting, and verification of CO_2 emissions from large ships (above 5000 GT) operating within, arriving at, or departing from any port located in the EU or European Economic Area (EEA). This document serves as a guide for members, outlining the regulation scope and application in detail [15].

3.4.1 Monitoring

This involves the systematic collection of data on emissions and other relevant information. It will explain how CO_2 will be monitored. The monitoring plan should include the following:

- the name of the ship, its IMO identification number, its port of registry or home port, and the name of the shipowner.

- the name and address of the company, including telephone and e-mail details of a contact person
- the CO_2 emission sources on board, including main engines, auxiliary engines, gas turbines, boilers, and inert gas generators along with the fuel types used
- a description of the procedures, systems and responsibilities used to update the list of CO_2 emission sources over the reporting period
- a description of the procedures used to monitor the completeness of the list of voyages
- a description of the procedures for monitoring the fuel consumption of the ship, including the method used to calculate the fuel consumption of each CO_2 emission, the procedures for the measurement of fuel loaded tank contents, a description of the measuring equipment used, and the method used to determine density, where applicable. There should be a procedure to ensure that the total uncertainty of fuel measurements is consistent with the requirements of the MRV Regulation
- emission factors used for each fuel type, or the methodologies for determining the emission factors for alternative fuels, including details of sampling, methods, fuel analysis and the laboratories used along with the ISO 17025 accreditation of those laboratories, if any
- a description of the procedures used for determining activity data per voyage, including the procedures to determine and record distance travelled, formulae and data sources to determine and record cargo carried and the number of passengers carried, the time spent at sea between the port of departure and the port of arrival.
- a description of the method to be used to determine surrogate data for closing data gaps.
- a revision record sheet to record all the details of the revision history.

A standard monitoring plan exists that is based on one of the following monitoring methods:

- Method A: Bunker Fuel Delivery Noted (BDN) and periodic stock take of fuel tanks.
- Method B: Bunker fuel tank monitoring on board.
- Method C: Flow meters for applicable combustion processes.
- Method D: Direct CO_2 emission measurements.

3.4.2 Reporting

Companies or entities subject to MRV policies are required to submit regular reports detailing their emissions data and other relevant information. These reports are often submitted to relevant authorities or international organizations. The annual report should include the following:

- quantity of fuel used, type of fuel used and emission factor for each type of fuel.
- total aggregated CO_2 emitted within the scope of this regulation.
- aggregated CO_2 emissions from all voyages between ports under a Member State's jurisdiction.
- aggregated CO_2 emitted within the scope of this Regulation aggregated CO_2 emissions from all voyages between ports under a Member State's jurisdiction.
- CO_2 emissions which occurred within ports under a Member State's jurisdiction at berth
- total distance travelled.

- total time spent at sea.
- total transport work.
- average energy efficiency.
- information relating to the ship's ice class and to navigation through ice, where applicable.

3.4.3 Verification

The verification process under the MRV Regulation ensures the accuracy and integrity of reported emissions data. Verifiers first assess the submitted monitoring plan for compliance with the regulatory requirements. Identified nonconformities require the company to revise the plan and re-submit it for approval before the reporting period begins. Following data collection, the verifier scrutinizes the completed emissions report, comparing it with the approved monitoring plan. If their assessment, conducted with "reasonable assurance", finds no material misstatements, they issue a verification report confirming the satisfactory completion of the emissions report. This rigorous process guarantees reliable data, crucial for combating greenhouse gas emissions within the maritime sector. In addition, verifiers must assess the accuracy and credibility of the following data points:

- attribution of fuel consumption to voyages.
- reported fuel consumption data and related measurements and calculations.
- choice and employment of emission factors.
- CO_2 emission calculations.
- energy efficiency calculations.
- reported data correlates with estimated data based on ship tracking data and characteristics such as the installed engine power.
- reported data is free of inconsistencies when comparing the total volume of fuel purchased annually by each ship and the aggregate fuel consumption during voyages.
- data has been collected in accordance with applicable rules.
- relevant records are complete and consistent.

3.4.4 Compliance

Following a successful verification of the emissions report, the verifier grants a "document of compliance" signifying the report adherence to MRV Regulation requirements. This document details the specific ship (name, identification number, home port), shipowner information, verifier identity, and the document's validity period (ending 18 months after the reporting period). Notably, the verifier informs both the European Commission and the ship's Flag Administration upon issuing the document of compliance. This transparent process ensures accountability and promotes data integrity within the regulation's framework [15].

3.5 Environmental Sustainability Indexes

With the Paris agreement aiming to keep the global average temperature below 2°C from pre-industrial levels, and to cap the overall temperature increase to 1.5°C, there has been a lot of work and effort to reduce GHG on all fronts [16]. Since international shipping is excluded from the Paris

Agreement, the IMO has set up its strategy [12]. This strategy aims to reduce annual international shipping GHG emissions to half of what they were in 2008 by 2050 and later phase out GHG emissions by 2100 as can be seen in **Error! Reference source not found.** [6],[7]. To help achieve this IMO has come up with three different indexes which are EEDI, Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII) [4].

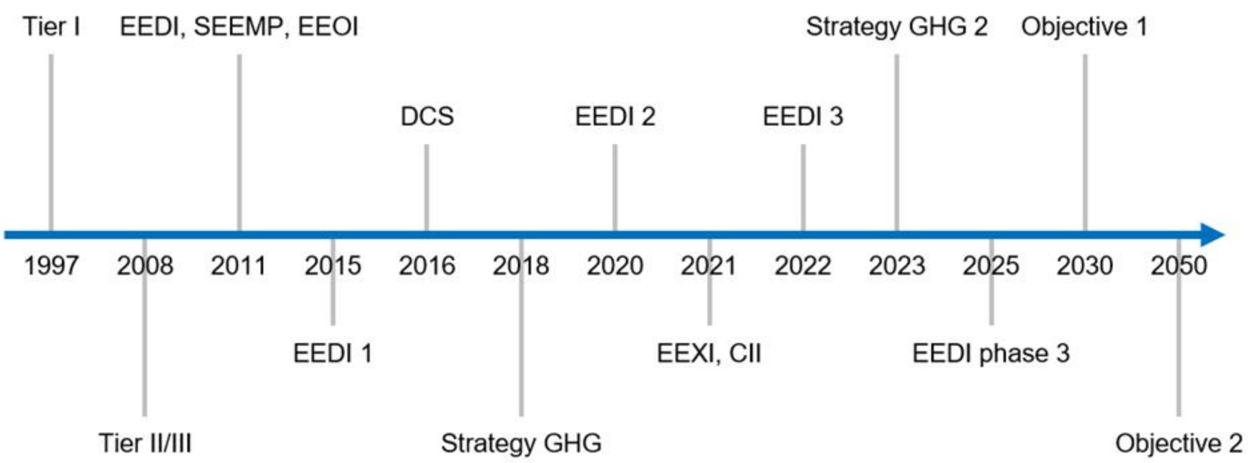

Figure 6: IMO Decarbonisation Strategy for 2050.

3.5.1 EEXI – Energy Efficiency Existing Ship Index

The EEXI is related to the technical design of a ship and i measures the energy efficiency of existing ships. A ship must attain an EEXI approval once in its lifetime till 2023. In 2026 the EEXI will be reviewed on its effectiveness and, if changes are needed, there will be further development and amendments. The EEXI Value is determined by the type of ship, its capacity, and its propulsion: The concept formula is shown in Equation 1 and

Table 1. More information can be found in "Outlines of EEXI regulation" [17], and "Implementing Energy Efficiency Design Index (EEDI)" [18].

$$EEXI\left[\frac{g}{ton}.mile\right]=\frac{CO_2 Conversion\ Factor\ x\ SFC\left[\frac{g}{Kw}.h\right]x\ Engine\ Power\ [kW]}{Capacity\ [ton]x\ Speed\ [knots]} \quad \text{Eq.1}$$

Table 1: EEXI inputs.

CO_2 Conversion Factor	Corresponds to fuel used
SFC	Specific fuel consumption at 75% maximum continuous rating (MCR) of the main engine or 50% of the auxiliary engine
Engine Power	75% of the rated installed power (MCR)
Capacity	Deadweight, for container ships (70% of the deadweight)
EEXI Speed	Ship speed at 75% MCR under the draught condition corresponding to the capacity

If the ship is not within the EEXI calculated value, then a number of mitigation actions are required [4]. Both the EEDI and EEXI apply for ships over 400 GT.

3.5.2 EEDI

The Energy Efficiency Design Index (EEDI) focuses on the environmental impact of a ship during the design phase. It is a function of the installed power, speed of the vessel and cargo carried. It acts as a rating system, assessing how efficiently the design of a ship utilizes fuel, ultimately aiming to reduce greenhouse gas emissions. Ships built after 2013 must meet an EEDI level and every five years this level is increased. After the year 2025, all ships must have a reduction of 30% from an average of between 2000 and 2010 [19].

The EEDI incorporates various special design features and considerations, including the use of energy recovery technologies, compatibility with low-carbon fuels, performance in waves, and ice-strengthening for specific ships. Equation 2 is a simplified version of the actual More information can be found in the following document “55% GHG REDUCTION BY 2030 Characterization of the ship systems and Electric Load Analysis (ELA)” [20].

$$\text{EEDI} = \frac{\text{Main Engine Emissions} + \text{Auxiliary Engines} + \text{Shaft Generator Emissions} - \text{Efficiency Technologies}}{\text{Trasnport Work}} \quad \text{Eq.2}$$

3.5.3 CII – Carbon Intensity Indicator

CII is intended to measure how efficiently a ship can transport its goods or passengers in a year. The value is calculated as CO_2 emitted per cargo-carrying capacity and nautical mile, gCO_2/dwt.nmile. Equation 3 is a simplified version of the actual CII equation. The full Ships internationally trading cargo, RoPax and cruise ships over 5,000 GT will have CII enforced and will be given a rating from A-E (A = best, E=poor) and the rating threshold will become more and more difficult going on to 2030 as can be seen in **Error! Reference source not found.** and **Error! Reference source not found.**.

$$\text{CII} = \frac{\text{Annual } CO_2 \text{ Emissions}}{\text{Deadweight} * \text{Distance Sailed}} \quad \text{Eq.3}$$

Based on ship data from 2019, 35% of all ships would have a D or E rating and if nothing changes by 2030, around 70% of all ships will have a D or E rating, as can be seen in **Error! Reference source not found.** and **Error! Reference source not found.**.

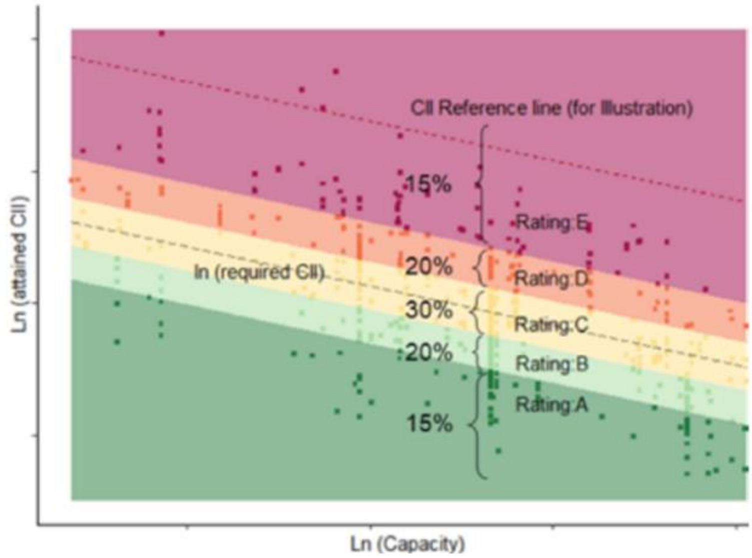

Figure 7: CII Reference 2019 Ship Data [22].

The CII will also tackle consumption of fuel without distanced travelled i.e., when anchored. Therefore, long waiting times at ports, or long port stays will impact the result of the CII. Therefore, the importance of ports being incorporated in the CII will further develop port logistics and efficiency. In fact, there are 8 suggested measures for ports and terminals to help in improving CII score [21].

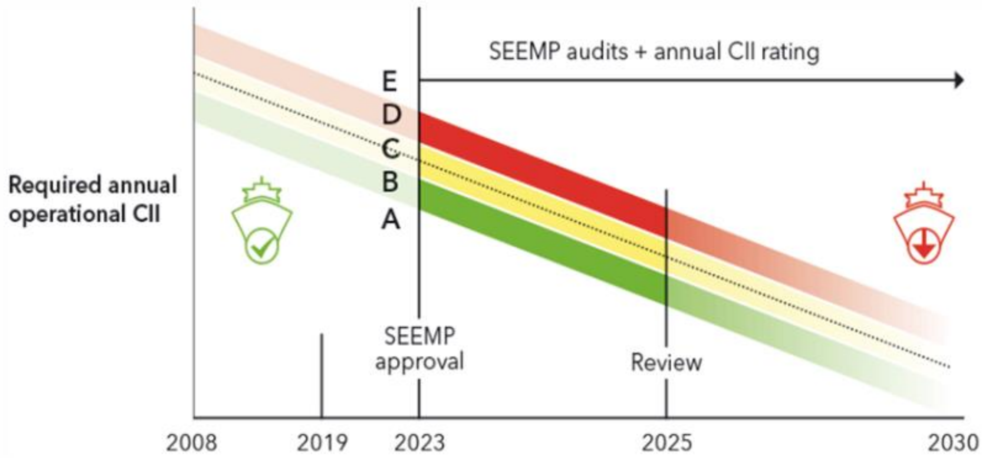

Figure 8: CII Rating [22].

The CII will become stricter by 2% every year [22]. More information on CII can be found in "55% GHG REDUCTION BY 2030 Characterization of the ship systems and Electric Load Analysis (ELA)" [20], "CII- Carbon Intensity Indicator" [22], "MEPC.336(76) - 2021 Guidelines on Operational Carbon Intensity Indicators and the Calculation Methods (CII Guidelines, G1)" [23].

3.6 Emission Trading Scheme

A significant step towards greener maritime transport has been taken by the European Union with the agreement to incorporate shipping into its ETS. This move signifies a commitment to reducing carbon dioxide emissions within the sector, aiming to create a more sustainable industry [24],[20].

An ETS for the shipping industry is a market-based mechanism designed to curb greenhouse gas emissions from vessels while promoting environmental sustainability and regulatory compliance. This innovative approach represents a significant step toward addressing the maritime sector's substantial carbon footprint.

This directive will mandate commercial cargo and passenger vessels exceeding 5,000 GT operating within the EU to acquire and surrender emission allowances for their CO_2 emissions starting in 2024. The scope will further expand in 2027 to encompass offshore ships. This decision represents a crucial milestone in aligning maritime transport with the EU's broader climate goals [20].

The EU ETS scheme will apply to 100% of voyages and port calls within the EU/EEA area and 50% of emissions on trips in and out of the EU/EEA area. To prevent circumvention of the system, specific measures are implemented for container ships making transhipment stops outside the EU/EEA. If a transhipment port is located within 300 nautical miles of an EU/EEA port, 50% of the emissions associated with the entire voyage to the EU/EEA port must be reported, not just the short leg from the transhipment point. This deters "flag hopping" strategies aimed at avoiding emissions reporting. The EU will provide a readily accessible list of transhipment ports falling under this regulation. This ensures clarity and consistency for shipping companies, facilitating compliance and mitigating confusion [25].

Under this ETS, participating shipowners and operators are assigned an annual emissions cap, which limits the amount of greenhouse gases their vessels can release into the atmosphere. These caps are based on historical emissions and are gradually reduced over time, driving industry-wide emission reductions. The EU ETS, established in 2005, is a cornerstone policy instrument that caps greenhouse gas emissions from specific sectors and incentivizes emissions reduction through a market-based mechanism. By integrating shipping into this system, the EU aims to leverage the economic forces of supply and demand to drive industry-wide decarbonization efforts [24].

3.6.1 Scope

From 2024 ships exceeding 5,000 GT engaged in commercial cargo or passenger transport within the EU will be included in the EU ETS. These companies will be required to acquire and surrender emission allowances corresponding to their reported greenhouse gas emissions [24].

From 2025 the EU MRV system will be expanded to encompass offshore ships exceeding 400 GT General cargo ships between 400 and 5,000 GT engaged in commercial cargo transport. These ships will be required to report their CO_2 emissions under the MRV system. From the beginning of 2024, only CO_2 emissions will be included in the report, however by the end of 2024 Methane (CH4) and N2O will be included in the EU MRV and later in 2026 they will be included in the ETS scheme as can be seen in Table 2 [26].

Table 2: Emission Reporting Dates.

GHG	EU MRV	EU ETS
CO_2	In force	2024
CH_4 and (N_2O)	2024	2026

From 2027 Offshore ships exceeding 5,000 GT will be incorporated into the EU ETS as can be seen in Table 3.

Table 3: ETS Dates.

Type	Size (GT)	EU MRV	EU ETS
Ships transporting cargo or passengers	5000+	In force	2024
General cargo and offshore ships	400-5000	2025	To be evaluated
Offshore ships	5000+	2025	2027

3.6.2 Working Principle

Any shipping company operating within the EU/EEA, regardless of the flag state of their vessels, comes under the directive. This includes shipowners, managers, bareboat charterers, or any entity assuming operational responsibility according to the International Safety Management Code (ISM Code).

Shipowners and operators are initially granted a specific number of emission allowances, which represent the permissible reported level of greenhouse gas emissions for their vessels within a year. These allowances are typically based on historical emissions and may decline over time to encourage progressive emission reductions. Participants can buy, sell, or trade these allowances within the regulated market. This mechanism incentivizes companies to invest in cleaner technologies, energy-efficient engines, and operational improvements, allowing them to stay within their allocated caps. It creates a competitive marketplace for emissions, fostering innovation and driving the maritime industry towards greater environmental sustainability.

Emissions will be reported and verified through the existing EU MRV system. This established system currently tracks CO_2 emissions from large ships (>5,000 GT) operating within the EU/EEA [24].

To accommodate the EU ETS, the MRV system will be revised and expanded. This could involve adjustments to cover additional greenhouse gases, ship types, and size categories as needed [20].

4 Life Cycle Analysis

4.1 What is Life Cycle Analysis?

A Life Cycle Analysis (LCA), also known as Life Cycle Assessment, is a comprehensive and systematic methodology used to evaluate the environmental impacts of a product, process, or service over its entire life cycle, from raw material extraction to disposal. It is a powerful tool for assessing the sustainability and environmental performance of various systems and helps in making informed decisions to reduce their environmental footprint [17].

LCA considers various environmental factors, such as energy consumption, greenhouse gas emissions, resource depletion, air and water pollution, and other relevant environmental indicators. The results of an LCA can help identify areas in the life cycle where environmental improvements are most needed and guide decision-makers in making more sustainable choices, whether it is in product design, process optimization, or policy development. It is widely used in environmental management, sustainability assessment, and eco-design to support more environmentally responsible practices and decision-making.

The LCA has evolved from a theoretical framework for environmental assessment into a powerful tool for evaluating the environmental, economic, and social impacts of products and systems throughout their entire life cycle. LCA helps stakeholders to identify potential improvements across different life cycle stages, informing product and process design or redesign efforts. It further enables the selection of appropriate environmental performance indicators, alongside relevant measurement techniques and critical evaluation methods [22].

In terms of life cycle modelling or assessment, the pioneering methodologies can be traced back to before 1992:

- The Environmental Priority Strategies (EPS) methodology based on endpoint modelling expressing results in monetary values.
- Swiss Ecoscarcity (or Ecopoints) based on the distance to target principle.
- The Comitee Maritime International (CML) 1992 (Dutch guidelines) methodology based on midpoint modelling.

These three methodologies were further developed and widely adopted for LCA assessments today in various fields, since the early nineties, many attempts have been made to harmonise approaches. This is partly to avoid having several methodologies which provide potentially different results (depending on the methodology chosen). Due to this standardisation, there are two current LCA Models ISO standard 14040 (2006) [27] and 14044(2006) [28].

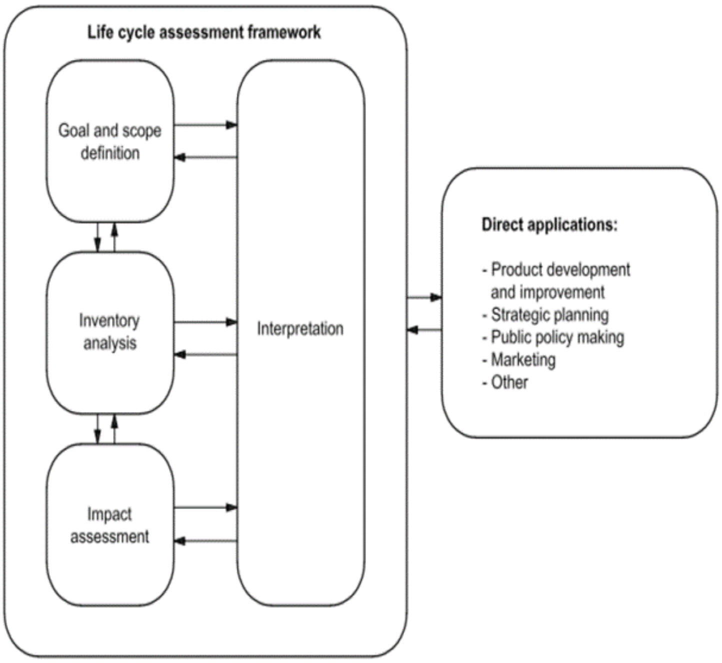

Figure 9: ISO representation for an LCA [27].

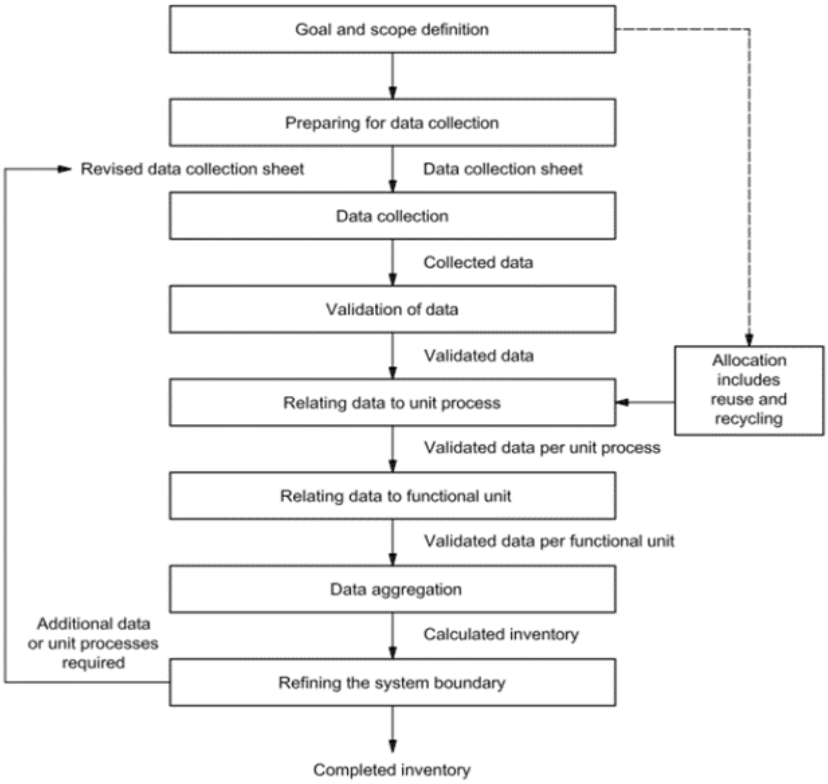

Figure 10: LCA progression [27].

4.2 LCA within the maritime industry

Within the shipping and shipbuilding industry, LCA finds relevance in various stages:

1. Process or product design: LCA can inform the design of ships and related processes, considering the environmental footprint of materials, manufacturing methods, and energy consumption.
2. Construction and repair: Applying LCA during construction and repair phases helps optimize resource utilization, minimize waste generation, and assess the environmental impact of associated activities.
3. Retrofitting: LCA can be employed to evaluate the environmental benefits of retrofitting existing ships with cleaner technologies or efficiency improvements [25].

MEPC 80 adopted the "Guidelines on Life Cycle GHG Intensity of Marine Fuels" (LCA Guidelines), establishing standardized methods for calculating well-to-wake and tank-to-wake emissions for all marine fuels and energy sources. These guidelines, recognizing the evolving landscape, are undergoing continuous review and development, focusing on – (MEPC):

- Default emissions factors: Refining data for accurate assessments.
- Sustainability criteria: Ensuring environmental considerations beyond GHG emissions.
- Fuel certification and handling: Promoting transparency and responsible practices.

The 2023 IMO GHG Strategy recognizes the diverse environmental footprints of potential low- and zero-carbon fuels for shipping. Recognizing these differences, the strategy underscores the need for a robust international framework to assess their greenhouse gas intensity and overall sustainability in a scientific and holistic manner [5].

This framework hinges on the LCA methodology, which evaluates GHG emissions from production Well-to-Tank to shipboard use Tank-to-Wake. This comprehensive approach acknowledges both upstream (production and delivery) and downstream (shipboard combustion) emissions it also ensures informed decision-making and fosters the use of truly sustainable fuel alternatives in international shipping [8].

Table 4 offers a range of LCA studies within the maritime industry on different aspects such as reviews, fuel, recycling, and retrofits.

Table 4: LCA maritime studies.

Reference	Title
[29]	Life Cycle Assessment and Life Cycle Costing for assessing maritime transport: a comprehensive literature review
[30]	Maritime Transport in Life Cycle Perspective: How Fuels, Vessel Types, and Operational Profiles Influence Energy Demand and Greenhouse Gas Emissions
[31]	A method for analysis of maritime transportation systems in the life cycle approach – The oil tanker example
[32]	Environmental impacts of steel ship hulls building and recycling by life cycle assessment (LCA)
[33]	LCA as a tool to aid in the selection of retrofitting alternatives
[34]	Life-cycle energy and environmental emissions of cargo ships
[35]	How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study

4.3 Goal and Scope

The overarching goal of the LCA within the project Retrofit55 is to gain a comprehensive understanding of the environmental impact associated with the implementation and utilisation of the various developed technologies. This assessment focuses specifically on the installation and use phases of each technology, aiming to shed light on the environmental footprint associated with their deployment and operation.

The scope of the LCA encompasses:

- **Material resources**: This includes a detailed evaluation of the materials required for installation, such as bolts, welding consumables, and grinding materials. Additionally, the assessment will delve into the materials utilized in the technology itself, encompassing components like metal, plastic, and other relevant materials.

- **Energy consumption during installation**: The LCA will meticulously analyse the energy expenditure associated with the installation process, including energy utilized for welding, grinding, and any other relevant activities.

- **Operational energy consumption:** This crucial aspect focuses on understanding the energy consumption of each technology during its use phase. It acknowledges that different technologies may have varying operational requirements, with some potentially requiring compressors, blowers, or relying on a more passive approach.

Through this collaborative approach, the LCA fosters transparency and informed decision-making, equipping maritime stakeholders with the necessary knowledge to actively contribute to a more sustainable maritime industry. The assessment will provide quantified insights into the CO_2 and

Carbon Dioxide equivalent (CO_{2e}) emissions associated with the installation of each technology and use phases, alongside the timeframe for these emissions to be offset by the operational benefits of technology. Ultimately, stakeholders will gain a comprehensive understanding of the total emission savings achieved through the implementation of each technology, enabling them to make informed choices that contribute to a greener future for the maritime sector.

4.4 System Boundaries

The baseline model for the LCA includes the installation and operation of the technologies on board a ship. The reason behind this logic, aside from the inherited necessity of simplifying some data due to the holistic nature of the LCA, is also to take into consideration the most relevant systems, while ignoring the ones that are considered trivial.

Additionall with a lack of information about the part lists and the installation process, therefore keeping a system boundary between installation and operation ensures the highest level of accuracy when it comes to procuring data.

4.5 Data Gathering

Data was gathered using different surveys, as shown in Table 5, Table 6 and

Table 7. For this example data is given on an Air Lubrication System (ALS) and a Wind Assisted Ship Propulsion (WASP) system.

Table 5: Material specification for LCA.

Outfitting Material Specification			
Component	Material	Quantity	Weight (kg) per Unit
Metal Sheets	Aluminium	10	50
Outlet	Aluminium	5	25
Inlet	Aluminium	5	25
Piping For Inlet	Aluminium	3	15
Piping For Outlet	Aluminium	3	15

Table 6: Table of Installation Energy Processes

Processes			
Denomination/Type	Consumables	Time of Use (hr)	Energy Rating (kWh)
Tig Welding	5 m of Weld	2	20

Table 7: Energy use phase for LCA.

Processes	
Type of process	Energy Use (kWh)
Lifting of sail	10
Use of compressor	23

A small part of the data was derived from estimations and calculations, where no data was publicly available.

4.6 LCA – Sample

For the LCA sample, the details and parameters for the bulk carrier M/V KASTOR, owned by LASKARIDIS SHIPPING CO, LTD, a project partner in RETROFIT 55 have been used, as can be seen in **Error! Reference source not found.**.

Figure 11: M/V KASTOR.

A user would first start by inputting the characteristics of the vessel, as well as the fuels used over a voyage or period, as shown in Table 8 and Table 9.

Table 8: Ship specification Inputs for the LCA.

Specification	
Ship Type	Bulk Carrier
Condition	Ballast
Length of Ship (m)	229
Length Perpendicular (LBP) (m)	225

Breadth (m)	32.3
Depth (m)	20.05
Deadweight Tonnes	81,600
Gross Tonnage	43,939
Distance Travelled (nm)	6,251

Table 9: Fuels.

Fuel Used Tons	
Heavy Fuel Oil (ISO 8217 Grades RME, RMG and RMK, 0.10 < S ≤ 0.50%)	327.76
Light Fuel Oil (ISO 8217 Grades RMA, RMB and RMD maximum 0.10% S)	0
Marine Gas Oil (ISO 8217 Grades DMX, DMA, DMZ and DMB maximum 0.10% S)	15.71
Marine Diesel (ISO 8217 Grades DMX, DMA, DMZ and DMB maximum 0.10% S)	60.91
Liquefied Natural Gas (Methane)	0

This information will then feed into an emission calculator and the CO_2 equivalent will be calculated. The calculation can be seen in Equation 4. The CO_2 equivalent is a metric used to understand the emissions from a number of GHGs on the basis of the Global Warming Potential (GWP). It is based on the conversion of other gases such as methane and nitrous oxide to an equivalent of CO_2 [36]

$$CO_{2_{Equivalent}} = CO_2 Factor * Fuel\ amount \qquad \text{Eq. 4}$$

The emissions factors are gathered data from the IMO “Guidelines on life cycle GHG intensity of marine fuels” [5] and the International Council on Clean Transportation (ICCT) “Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies “ [37]. The CO_2 equivalent can be seen in Table 10.

Table 10: CO_2 factors.

Fuel	**CO_2 Factor (Tons of CO_2/Ton of Fuel)**
Heavy Fuel Oil	3.114
Light Fuel Oil	3.151
Marine Diesel	3.206
Marine Gas Oil	3.206
Liquified Natural Gas	2.75

For this case study the fuel produced will create 1266.29 Tons of CO_2 equivalent as can be seen in Table 11.

Table 11: Calculated CO_2 equivalent for fuel.

Fuel	Amount	CO_2 Factor	CO_2 Equivalent Tons
Heavy Fuel Oil	327.76	3.114	1,020
Marine Diesel	15.71	3.206	50.36
Marine Gas Oil	60.91	3.206	195.28
			1266.29

The user would then decide on the technology that they wish to use as can be seen in Table 12

Table 12: Technology selection for LCA.

Retrofitted Technologies	
Air Lubrication System	Yes
Wind Assisted Propulsion	No
Wind Assisted Propulsion	No
Electrification	No

Once these decisions are made, the digital twin will work out how many systems will fit on the ship. For example, it may assess that 8 ALS outlets can be installed, as well as 2 wing-sails. In addition, the digital twin will feed into the LCA, and it will calculate the parts needed for 8 outlets. For this case study, it is assumed that 5 outlets and a 5% fuel savings will be achieved.

The LCA will then workout the CO_2 equivalent for the material and installation process, which equates to 13.52 tonnes of CO_2 equivalent, as shown in Table 13.

Table 13: CO_2 equivalent for installation.

Components	Material	Quantity	Weight (kg)/ Unit	Total Weight Tons	CO_2 Factor	Tons of CO_2e
Metal Sheets	Aluminium	10	50	0.5	16	8.05
Outlet	Aluminium	5	25	0.125	16	2.0125
Inlet	Aluminium	5	25	0.125	16	2.0125
Piping	Aluminium	3	15	0.045	16	0.7245
Piping for Outlet	Aluminium	3	15	0.045	16	0.7245
						13.52

Finally, the LCA will calculate the savings in terms of CO_2 equivalent, ETS as described in the previous chapter and the savings in fuel. For this case study, it is assumed that the installed ALS will provide a 5% reduction in fuel consumption. The prices of the ETS and the fuel are based on [38] and [39] respectively. The results of this case study are summarized in Table 14.

Table 14: LCA results.

LCA	
Tons of CO_2e Before Retrofit	1,266.29
Tons of CO_2e of Retrofit	13.52
Tons CO_2e After Retrofit	1,202.97
Tons Savings of CO_2e	63.31
Savings in ETS (Euro)	4,021.10
Saving in Fuel (Tons)	311.37
Saving In Fuel (Euro)	155,686.00

4.7 Cost Benefit Analysis

In addition to the environment assessment method, Retrofit55 will also work to conduct a cost-benefit analysis, using the Net Present Value (NPV) method, which can be seen in Eq. 5 . In this way, anyone interested in acquiring a technology can understand the cost effectiveness of its installation.

The Cost-Benefit Analysis (CBA) is a systematic method for evaluating the financial viability and overall value of a project, decision, or policy. It delves into both the positive and negative financial implications. This analysis considers all the potential costs associated with the project, including initial investment, ongoing operational expenses, maintenance requirements, and even potential risks that could translate into financial losses. On the flip side, it also meticulously examines the expected benefits, such as increased revenue, improved efficiency, reduced costs in other areas, or even intangible benefits like environmental improvements or social impact (though these might require qualitative assessments). By meticulously comparing these quantified costs and benefits, a CBA helps decision-makers to understand the project's overall value proposition. Ideally, the expected benefits outweigh the projected costs, indicating a worthwhile investment. However, a CBA does not guarantee a definitive answer – it provides a framework for informed decision-making, considering both the financial implications and potential broader impacts 59[40],[41].

The cost benefit analysis takes in to account the capital expenditure (CAPEX) and operating expenditure (OPEX):

- The **CAPEX** focus on the price for the purchase of the asset, in this case, the energy efficient technology. This includes any costs incurred during the acquiring phase, such as insurance, days installing etc. However, in the maritime industry, installation is generally aligned with dry docks to avoid any extra costs. Generally, for CAPEX, this will be an upfront cost that is associated with purchase and installation.
- The **OPEX** is the price of operation of the acquired technology across the lifetime of the vessel. This will include maintenance, fuel to run (if necessary) and crew re-training [40].

The CAPEX and OPEX will affect the final payback period of the installed technology, this is important as in the shipping industry the pay back tends to be quite short eg 12-18 months [42].

The CBA can be calculated using Equation **Error! Reference source not found.**.

$$PV = PV_o + FV(1 - (1 + i)^{-n}/i \qquad \text{Eq. 5}$$

Where PV_o is the capital expenses, FV is the cost of operative expenses,I is the interest rate and N is the lifetime of the vessel.

4.7.1 Assumptions and Limitations

As with any LCA model, some of the data must be estimated, to add to the complexity of this work, most technology providers are startups. Hence, they had limited data when it came to the number of parts, installation process and energy of the use phase.

5 Technologies

This section will explain the different technologies, their working principles and techniques that are available to relevant maritime stakeholders can use to reduce their CO_2 emissions and footprint. This list is not exhaustive as there are different technologies and methodologies that are outside of the remit of Retrofit55.

5.1 Air Lubrication Systems - ALS

5.1.1 General introduction

Air lubrication is a technology that can be used to reduce the drag on ships, which can help to improve their fuel efficiency and reduce their environmental impact. It works by using a system of air blowers and nozzles to blow a thin layer of air bubbles onto the hull of the ship, which creates a layer of air between the hull and the water. This layer of air acts as a lubricant, reducing the friction between the ship and the water, modifying the turbulence in the boundary layer (BL) and thereby reducing the overall ship drag. There are several different types of air lubrication systems, including surface effect air lubrication, submerged air lubrication, and hybrid air lubrication. Each of these systems has its own unique set of advantages and disadvantages, and the most suitable option for a particular ship will depend on a variety of factors. The working principle for ARMADA, the ALS partner in the RETROFIT 55 Consortium can be seen in **Error! Reference source not found.**.

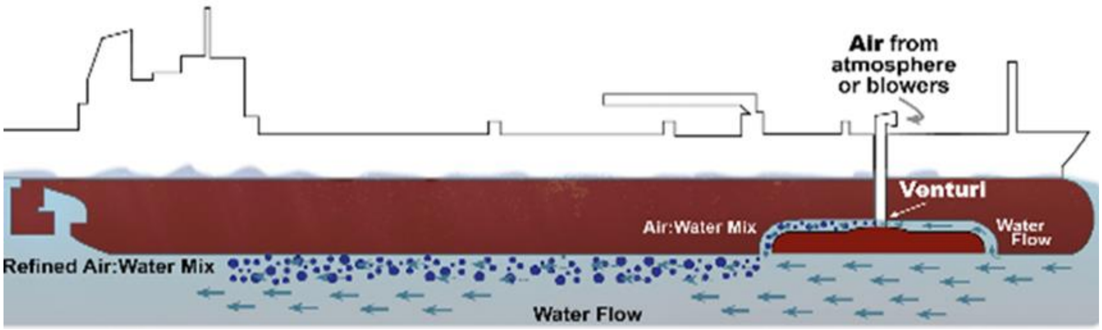

Figure 12: ALS Working Principles.

5.1.1.1 Operation Principles

The Passive Air Lubrication System (PALS) considered in the Retrofit55 project is provided by Armada Technologies. The system can be monitored and controlled from one of the duplicate Human Machine Interfaces (HMI) panels located onboard The HMI screens will enable the user to interact with the system whilst in operation, during system commissioning or testing.

The PALS is designed to be a plug-and-play solution, requiring minimal to no human intervention to be operated. At any point in time, the PALS will function in one of the several predefined operating modes. A PALS functional description and control philosophy has been developed and underpins the system Programmable Logic Controller (PLC) operation. The PLC provides the monitoring and control function of the system and ensures system set points are optimal for the prevailing vessel operating condition. The PLC will control the general isolation and flow control to ensure that the mass flow and pressure settings are acceptable for the optimal operation of the ejectors. The PLC will take inputs from pressure and flow indicating transmitters within the system and couple this with general ship information (e.g. speed, draft, global ship dynamics) to ensure successful start-up/ shut down sequencing and make necessary system adjustments in real time.

The PLC continuously captures data from all the valves and instruments, generating operational logs of each journey allowing for analysis and performance improvement over time. These operational logs can be easily exported and sent to the technology providers for processing in our bespoke machine learning software, where assessment may lead to small changes to improve the overall system performance.

5.1.1.2 ALS Safety and Hazards

The PALS spaces are to be designated as remotely operated and thus 'not normally manned' spaces, meaning access into these spaces is reserved for abnormal events requiring physical close-up inspection and diagnostics, or from irregular planned maintenance of the pump motors/ valve inspection.

ALS spaces are categorized as confined spaces and, as such, confined space entry risks and requirements need to be managed and properly complied with.

In general, compliance with the Code of Safe Working Practices for Merchant Seafarers (COSWP) should be incorporated within risk assessments and the completion of it permits to work prior to ALS space entry. Similarly, each PALS installation will be designed to class design requirements, subject to any applicable statutory regulations, plan review and ultimate class approval. Installation of PALS on the vessel will be overseen and approved by the local class surveyor.

In particular, it is essential to ensure:

I. a breathable atmosphere:
   a. ALS spaces are equipped with forced ventilation to ensure an ongoing breathable atmosphere whilst operators are present.
   b. Atmospheric testing within ALS spaces is performed and throughout.
   c. A standby person is equipped with the necessary rescue equipment, including a self-contained breathing apparatus and radio for communication with the bridge and/ or ECR.
II. safe access/ egress to/from the double bottom and ALS spaces:
   a. If required, and aligned with the vessel's existing safety plan, safe access arrangements shall be provided e.g. latter cages and/ or fall arrest lines will be provided to prevent/ arrest a fall from height.
   b. Vessel pre-existing PPE requirements to be complied with.
III. vessel hydrostatics and intact/ damage stability:
   a. The enclosed volume of the ALS spaces is minimal in comparison to the ballast volume. Similarly, the net weight differential between ALS spaces fitted and the water weight of those spaces is minimal – a reassessment of the inclining experiment is not

required for PALS installation as a change to deviation in lightship longitudinal centre of gravity (LCG) is < 1%.

b. a stability assessment is completed as part of the PALS integration design, engineering, and approval.

IV. fire control and suppression:

a. ALS spaces are to be kept free of combustible materials.
b. A fire detection system provided within ALS spaces and interconnected with the ship's global fire detection system.

5.2 Wind Assisted Propulsion (WASP)

5.2.1 What is Wind Assisted Propulsion

The collapsible wing sail system in this project is provided by Advanced Wing Systems (AWS) and is based on experience in soft wing-sail development and testing over many years. To date, this wing sail technology has been used on craft from 2 to 22 m. It has been used in competitive sailing, including the 36th America's Cup, and a 7,500 nautical mile ocean voyage. The technology allows aerodynamically efficient wing sails with variable geometry, to be produced using existing materials and construction methods. The working principle can be seen in **Error! Reference source not found.**.

Figure 13: WASP working principle.

The innovation applied here is to make the wing-sail system completely collapsible, such that a large wing-sail can be stowed to a small deck footprint. This allows larger wing-sails to be deployed while having minimal impact on docking and loading operations. Further, the AWS wing-sails can be designed to collapse into a housing that is a suitable size and weight for transport as container cargo. This coupled with the ability to make the WASP system completely self-contained simplifies production and optimises maintenance operations.

A deck mounting frame is the only part customised to the vessel. With appropriate design, the deck mounting frame can be fitted to the vessel without the need for dry docking and welding.

The AWS wing sail technology allows large cross section mast sections to be used with little or no aerodynamic penalty. The resulting wing sections can produce very high lift and excellent lift-to-drag characteristics.

5.2.2 Operation Principles

The AWS wing-sail is a variable geometry (morphing), semi-rigid wing. Camber, asymmetry, thickness and twist of the aerofoil profile can be varied quickly to optimise the wing-sail for the operating conditions. Configuration changes require three main control inputs to vary the shape of the wing. The wing consists of rigid battens, which support sail fabric membranes. Unlike conventional sails, the wing sail can be set to be symmetrical to allow feathering to the wind with no flapping or flogging. The fabric membranes allow the wing sail to be collapsed. The structural mast can then be folded to allow the entire system to be covered by a storage housing.

5.2.3 Wasp Safety and Hazards

Risks associated with the WASP system can be classified as follows:

- Equipment Risks such as operational failures, component failures, power loss, etc. can be mitigated by design analysis, redundancy in key systems, and control limitations to reduce failure risks.
- Location Risks, such as interference with other equipment and operations. They can mitigated by a careful selection of the installation location. The ability to stow the system for port operations reduces the interaction risk during port operations.
- Environmental Risks such as weather conditions. They can be mitigated by the ability to stow the system when operating conditions fall outside acceptable parameters. The AWS system has been tested in very strong wind conditions and proven to be stable. For operational purposes, wind conditions are limited to 45 knots of apparent wind speed. This wind speed represents more than 98% of expected wind conditions.
- Operational Risk, such as failure condition. They can be mitigated by redundancy in systems and training of crew to manage exceptional circumstances.
- Structural Failure Risk. They can be mitigated by structural design and by control systems and sensing to ensure that extreme load scenarios are not encountered.
- Impact on vessel stability. It can be mitigated by control systems and sensing to ensure that extreme load scenarios are not encountered. The system allows for a very rapid response to inputs such as heeling force.

5.3 Hydrodynamic Optimisation

As part of the RETROFIT55 project, further to the new technologies like WASP and PALS which shall be investigated for the benefits they provide by way of reduction in fuel consumption, separate studies shall also be carried out on the subject vessel to optimize the hydrodynamic performance. While the existing hull shape and propulsion system may have been derived from an optimization process, after many years in service the following factors justify the need for such a re-assessment:

- Change in mission and/or loading conditions of the vessel.
- Change in operational conditions (e.g., slow steaming).

More representative weather conditions can also be considered during this optimization process.

As a first step, bow retrofitting and propeller retrofit have been considered as two indicative solutions. For the bow retrofit, a new hull form with a bulbous bow has been studied. Using a parametric model, the region of interest in the bow area has been transformed using the Free Form Deformation method in CAESES as can be seen in **Error! Reference source not found.**. Parameters such as bulb length, width, upward and downward vertical extension were defined as the design variables.

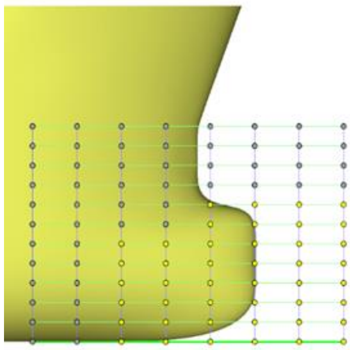

Figure 14: Free-Form deformation box defined in CAESES.

Calm water resistance calculation is to be carried out using SHIPFLOW and a global optimization study will be carried out for minimization of resistance using a weighted objective function based on a matrix of loading conditions and speeds as can be seen in **Error! Reference source not found.**.

Table 15: Resistance calculations.

Load. Cond.	Name	T_M [m]	TRIM [degree]	V_1 [kn]	V_2 [kn]
1	Homog. Light Cargo (0.804T/m^3) departure	14.45	0	11.5	13.5
2	Normal ballast at departure	6.35	-3	12.5	14.75

The existing propeller of the subject vessel has also been studied in detail to optimize the propulsion system for lower operating speeds and lower thrust requirements, due to the installation of other energy saving technologies. Modifications of the original propeller have been considered by modifying the tip rake distribution, to increase efficiency and by adjusting the blade roughness to control blade tip cavitation as can shown in **Error! Reference source not found.**.

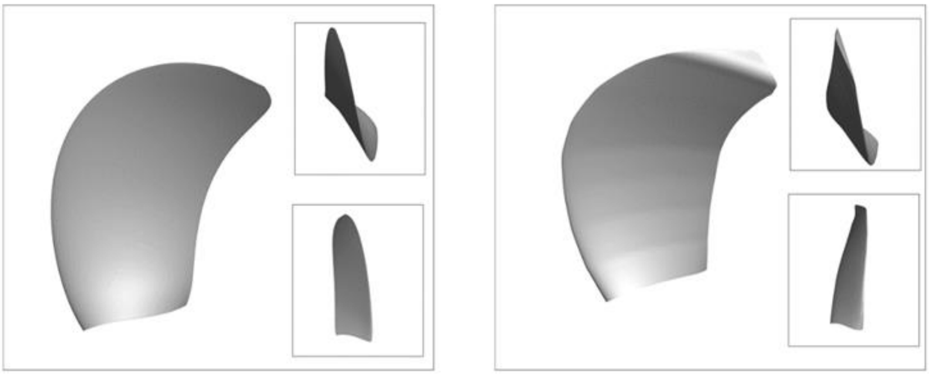

Figure 15: Hydrodynamic optimisation of the propeller.

5.4 Ship Electrification

5.4.1 Photo-Voltaic power generation

The primary role of Photo-Voltaics (PV) in the global transition towards a low carbon energy mix has been consolidated over the past two decades. PV power generation reached 945.7 GW at the end of 2021 and currently contributes to reducing annual global emissions by about 3% [43].

Despite such an extensive use of PV in terrestrial applications (e.g., at utility scale), the shipboard integration of PV generation systems is limited so far. Indeed, the requirement of a large surface area on board for installing PV panels has made the use of solar-assisted power generation on ships quite uncommon [27],[28].

Currently, the need for implementing mandatory measures encouraging the adoption of energy-saving technologies in ships, according to IMO GHG strategy to 2050 [44], is pushing players of the shipping industry toward considering the integration of on-board PV systems as a viable solution contributing to fuel consumption and pollutant emission reduction [28]. The reduction trend in PV capital costs is a further encouraging factor toward the use of this technology on board.

Research projects and ongoing scientific/industrial research demonstrate the interest in using PV generation onboard, also in hybrid configurations [45],[46],[47]. It is also worth noting that PV systems are explicitly contemplated within energy efficiency related technologies in the IMO document “2021 Guidance on the treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI” [48].

The photovoltaic technology is a suitable solution for ship retrofitting. In general, cargo vessels present at least two advantages that make them suitable for the implementation of PV modules:

- they have little equipment installed on top of their deck.

- they have a relatively large surface area that is only used to store goods, i.e., the hold, upon which PV modules can be smartly integrated [49].

PV systems can operate as an ideal auxiliary power source since they feature the following properties [27]:

- electrical power production does not involve the transfer of gas or liquid fuel.
- electrical power production does not imply gas and noise emissions.
- practical absence of mechanical moving parts.
- simplicity (they consist of a few parts), easy installation and fast replacement in case of aging or degradation.
- satisfactory lifetime (usually not less than 80% of the nominal one after 25 years of operation).
- possible installation on surfaces with no practical use and/or on preexisting structures such as roofs, walls, funnels, hold covers etc.
- low maintenance cost.

In the area of ocean-going vessels, the application of solar photovoltaic technology is not yet mature, and many countries are committed to the development and improvement of this technology. In this area, much work still needs to be done. In addition, due to the differences in the structure, mission, and applicable routes of different ship types, it is not possible to arbitrarily select a ship as a bare loading platform. The target ship type should be selected through appropriate evaluations and analyses, including safety regulations, area maximization, and aesthetic issues. At the same time, the stability, manoeuvrability, and aerodynamic characteristics of the ship should be considered. Finally, the PV generator efficiency, and reliability, including anti-corrosion problems and vibration impacts for solar panels used in marine environments, should be accounted for [27].

5.4.2 Shaft Generator Systems

The concept of shaft generators was introduced around the 60's. The pushing reason had been the better fuel economy of a two-stroke engine technology compared to four-stroke technology [50]. When electric power is produced with a slow-speed main engine instead of medium- or high-speed gensets, this results in significant fuel savings.

Shaft generators have been installed on small and medium-sized ships since the beginning of the Direct Current (DC) era, while they have become 'standard' equipment in larger merchant ships, especially container ships, only in the past few years.

Its structure is relatively simple. In its simplest form, the generator is mechanically connected to the main engine, typically by a gearbox and operates at a fixed speed to produce a constant frequency to the electric on-board plant. As the main engine typically has a lower specific fuel consumption than the smaller auxiliary engines, there is a margin for improving the overall fuel efficiency.

In the case of fixed-pitch propeller propulsion, the frequency of the shaft generator inherently changes with the speed variations of the main engine. This implies either different design requirements of the on-board electric grid or just the limitation in the use of the shaft generator. On the contrary, a constant on board frequency can be produced by adopting a controllable-pitch propeller propulsion, where the engine speed is maintained constant. The cost to be paid is that the propeller will not work in the most efficient way, particularly during low-thrust operations.

In consideration of the limitations arising from the direct mechanical connection of shaft generators, variable speed shaft generator systems have been preferred. Such an improvement has been permitted by the evolution of power electronics technology and generator design, of permanent magnet (PM) machines, enabling enhanced versatility and performance control. The overall setup consists of the shaft generator, frequency converter, transformer (if applicable), and control system.

At the beginning, shaft generators were based on Electrically Excited Synchronous Machines (EESMs), whose main drawback was a rather low efficiency. Especially in slow-speed applications, where the primary power must come from the main engine, this led to increased fuel consumption. Nowadays, as the comparison shows, PM generators have technical advantages compared to synchronous excitation generators and are today the most used type.

The frequency converter supplying the electric machine is configurable either as a single- or as a multi-drive system, permitting the connection of several energy sources and loads to the same DC link. This allows designs where auxiliary engines may easily be integrated with other power sources that produce electricity like fuel cells, solar panels, shore connection, wind power, or energy storage.

Variable speed shaft generators can be used operationally as a power generator (PTO) for the vessel’s electrical network, optimizing the use of the large engine, while reducing the need to run auxiliary generators; booster motor (PTI) for the main propulsion shaft, to cover peak power or ‘worst-case scenario’ needs; or alternative propulsion system (PTH) providing redundancy and safety for unexpected situations.

It is also worth noting that shaft generator is explicitly contemplated within energy efficiency related technologies in the IMO document “2021 Guidance on the treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI” [48].

As for the security and safety issues, the following considerations could be made. One of the most critical situations in terms of both safety and security is the presence of a short circuit (SC) in the AC power grid on board. In this case, the power source must be designed to provide enough current to last for a certain time to secure that the grid SC protection system functions, selectively according to the current protection principle. The same applies to shaft generator applications. Industrial solutions already fulfil this task. For example, ABB frequency converters can deliver the defined SC current for up to four seconds to serve this purpose as seen in **Error! Reference source not found.**, showing a record of a real-life on-site test where the shaft generator converter supplies nearly two times the rated current (as required for this specific installation) for two seconds for the grid SC protection, to clear the fault. It is to be noted that the DC voltage of the converter is stable during the significant grid disturbance with only a minor fluctuation. Reliable SC protection is required to protect the system and personnel from physical damage and to prevent total system blackout [51].

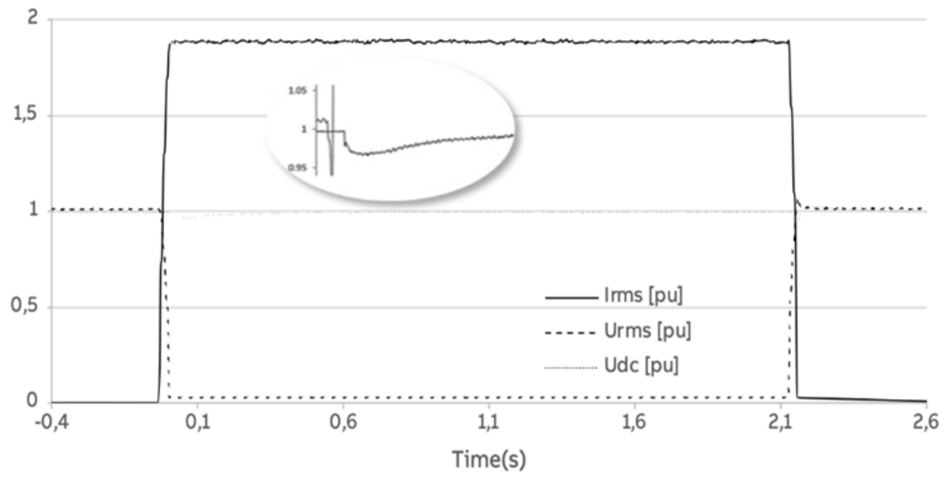

Figure 16: DV voltage performance during short circuit [51].

Power converters for large electric motors

On board vessels, there are a number of so-called large electric motors which absorb high active and reactive powers and moreover are characterized by high inrush currents during their starting up, if directly supplied by the on-board power grid.

The ship electric energy efficiency can be, for example, significantly improved by acting on large pumps and fans, driven by electric motors, not running continuously and at full capacity. Target ships for such a kind of retrofitting solution are basically all types of vessels, including bulk carriers, container ships, cruise ships, LNG carriers, drilling rigs, offshore support vessels, icebreakers and special purpose vessels.

As for the pumps, for example, a diesel-powered cargo ship needs almost 36-50 pumps of various types accounting for 20-30% of the total mechanical equipment of the ship. Among all, the seawater pump system is among the most power demanding.

Ship electric energy efficiency can be further improved by acting on room engine fans. A proper engine room ventilation system serves two purposes:

- providing sufficient oxygen for fuel combustion.
- cooling the room by dissipating the heat radiated from propulsion and auxiliary engines.

Besides the engine room fans, cargo ships present specific ventilation requirements for:

- minimizing the formation of sweat by dew point control.
- removing hazardous gases which may be emitted by the cargo.
- preventing excessive heating of the cargo.
- removing taint.

The standard ways to modify the duty point of a pump are:

- Bypassing.

- Throttling.
- On - Off control.
- Variable Frequency Drive (VFD) pumps.

Among the above solutions, the VFD pumps reveal the most interesting solution from the project perspective. They change the pump speed in accordance with the affinity laws. If the pump impeller speed is reduced, the pump curve moves downwards. If the speed is increased, it moves upwards. They permit the pumping capacity to be exactly matched to the process requirements. VFD motor drives operate pumps and fans more efficiently in partial loads: during slower sailing speeds (seawater pumps) or with reduced ventilation requirements (engine room fans). In pump and fan applications on board vessels, using VFDs can cut energy consumption by 60%.

It is to be noted that inverter-fed drives are not explicitly contemplated within energy efficiency related technologies in the IMO document “2021 Guidance on the treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI” (MEPC.1/Circ.896) [48]. It implies that different suitable metrics for the evaluation of their impact in terms of efficiency improvement must be still found.

As for the safety issues of the variable speed drives installed on-board, the following considerations could be made. As the use of a drive in a machine can impact its safety performance, it is necessary to first consider the overall requirements for machinery safety [52].

Machinery that is supplied within the European Economic Area must comply with the Machinery Directive [53] and other applicable European Directives. This can be achieved by complying with relevant harmonized European standards listed in the Official Journal of the European Union (OJEU) because these grant a presumption of conformity with the requirements of a European Directive. In accordance with the breadth of their scope, harmonized European standards for the Machinery Directive are categorized as type-A, type-B and type-C standards. The type-A standard is EN ISO 12100. It is directly applicable to all machines and also sets out a strategy for developers of more specific type-B and type-C machinery safety standards.

For most variable speed drives, the complex electronics and software that provide their functionality will not have been designed, developed, integrated and validated in accordance with an appropriate functional safety standard, such as EN 61800-5-2. Such drives are therefore unsuitable, by themselves, for fully implementing the safety functions of machinery.

For example, if a drive output is configured to control an electromechanical brake that constrains a mechanical load, but the parts of the drive that control this output have insufficient integrity for the specific application, then it will be necessary to provide supplementary interlocking measures for brake control. Although non-safety-related drives are able to perform many motion control functions, such as holding a motor at rest or limiting its position, speed or torque, the lack of verified integrity for such motion control functions implies that the drives cannot be regarded as safety-related. When integrating such a drive into a machine, it is therefore necessary to implement any safety functions independently of it, or across a combination of the drive and a supplementary safety-related control system. The concepts are synthetically expressed in **Error! Reference source not found.**. A safety function that is implemented independently of a drive will generally monitor some variable, and then initiate an appropriate reaction if this exceeds a set limit. For example, the position, speed or acceleration of a moving part of the machine, or the status of an emergency-stop actuator, could be monitored by a suitable controller, which initiates a response when the monitored variable violates a set limit, or if the emergency-stop actuator is pressed.

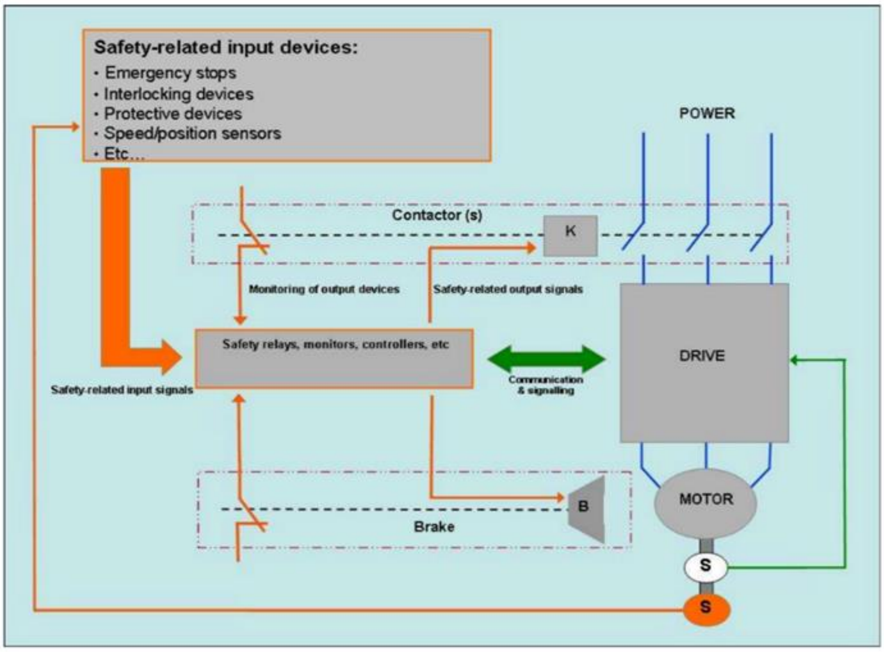

Figure 17: Example of non-safety-related drive supplemented by safety-related control measures [53].

5.5 Weather Routing

One of the most popular operational measures to reduce GHG emissions is ship weather routing optimisation. Optimizing a ship voyage, considering the prevailing weather conditions, can result in less fuel oil consumption and consequently less CO_2 emissions, about 3% to 10%. Moreover, operational costs are reduced not only due to less fuel oil consumption but also due to safer voyages avoiding severe weather conditions that can put in danger the crew, the cargo and the vessel itself. In addition, route planning and speed management can also minimize delays in ports and thus incorporate the just-in-time concept and lead to a better bunkering schedule.

A weather routing tool delivering all the above assets is developed at the NTUA and is described briefly in the following. The tool is developed in the MATLAB environment, employing functions and toolboxes, such as the mapping toolbox which provides functions for analysing geographic data and creating map displays. A key element of the tool is that it considers detailed design characteristics of the examined ship [54].

The core of the algorithm lies in the calculation of the required fuel oil consumption between any two spatial points. To achieve that, it is necessary to estimate the weather conditions and the total resistance for each one of them. Information that concerns weather conditions is derived from open-source weather forecast providers, such as the Copernicus database. Moreover, a ship model is constructed, based on the unique characteristics of the ship. These characteristics are the propeller open water diagrams and the main engine loading manual, while the ship model entails the required resistance calculations. Regarding the calm water resistance, information is fed to the model either from available towing tank tests or from any other method at our disposal (CFD calculations, empirical methods, etc.). In an analogous way, added wave resistance is precalculated for a range of speeds, headings, wave heights and wave peak periods, constructing suitable response surfaces that will be used in the model, while weather conditions are considered. The last resistance component considered is the wind resistance (again based on available prevailing wind conditions). Finally, the ocean current effect also takes part in the process, by correcting the calm water resistance calculations, in which the speed through water is utilized [54].

Since the total resistance is known, the required power and speed from the main engine are determined, as long as the Specific Fuel Oil Consumption. Using this data, FOCi (Fuel Oil Consumption between point i and point i+1)) is calculated, resulting in the total FOC.

For the optimization process, a genetic algorithm is employed to identify the best possible path in terms of fuel oil minimization. Constraints can also be introduced to the process with respect to shipping and/or cargo and/ or crew safety (slamming, parametric rolling, seasickness, etc.). When any of the given constraints are violated, the respective route is notated as unfeasible, and the algorithm rejects it from the optimization procedure [54].

5.5.1 Operational principles

Random routes can be generated by giving one starting and one ending point (port of departure and port of arrival respectively), as well as the desired number of the n-waypoints. Each one of these (n+1) created legs is broken down into equidistance points depending on the user's desired spatial resolution. Between every two of these points ship speed and weather conditions are assumed constant and using the ship model, the required FOCi is calculated. Summing up all the FOCi elements, the total FOC along the candidate route is estimated. Since for the examined ship, the ship model described previously has been developed and verified as can be seen in **Error! Reference source not found.**, the next steps shall be taken by the user of the tool in practical application.

Firstly, setting the chosen ports and the n-waypoints, as already mentioned, is considered. Next, the user can determine the "no go zones" such as ECAs, piracy zones or even low depth zones. Moreover, criteria concerning safety aspects can be introduced like unacceptable accelerations on the bridge or at the bow, etc. Time limitations can also be implemented by setting a maximum/minimum voyage duration criterion and by adding to the process speed optimization. Between every two legs speed can be assumed constant or be part of the optimization procedure as an optimized variable. Alternatively, the main engine RPM can be assumed constant depending on the needs of each optimization or the users' demands. The optimization is carried out on the voyage start but can be also performed during the transit considering updated weather forecasts.

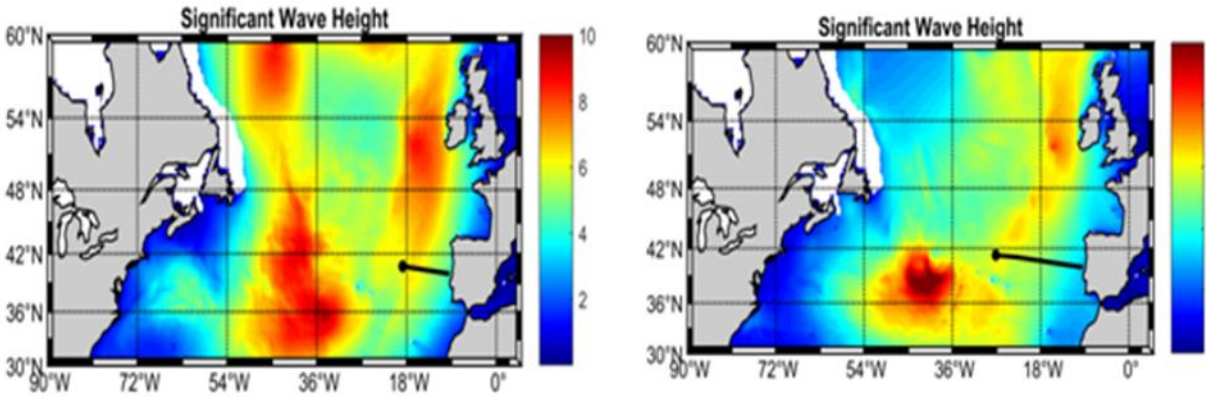

Figure 18: The weather routing tool [54].

5.5.2 Safety Hazards and Mitigation Principles

It shall be mentioned that such tools have a supportive role in route planning. Many uncertainties are introduced during the whole process, and for this reason, the final decision shall be also based on the captain's experience. Reliable forecast data and on-the-go re-optimization can minimize some of the uncertainties and make more appealing these supportive tools to the captains. Also, a detailed construction of the ship model would also result in uncertainty mitigation. Such improvements could be the consideration of the status of the hull and the propeller (e.g. the fouling level), limitations on sharp turnings between two waypoints and the examination of the ship's capability to follow the recommended course. Finally, avoidance of other ships and generally the detailed route shall be planned according to the authorized maps and ship procedures.

5.6 Digital Twin

A digital twin for maritime, often referred to as a "Maritime Digital Twin" or "Ship Digital Twin," is a virtual representation of a ship or a maritime asset, such as a vessel, offshore platform, port, or even an entire fleet. The concept of a maritime digital twin is becoming increasingly important in the maritime industry for various purposes, including ship design, operation, maintenance, and safety.

In the maritime sector, IMO has also been working on the adoption of digital technologies and the digitalization of shipping through various initiatives.

The implementation of a maritime digital twin relies on a combination of technologies, including Internet of Things (IoT) sensors, data analytics, cloud computing, and advanced simulation software. These technologies enable the creation of an accurate and dynamic representation of a ship and its operations, helping to enhance safety, efficiency, and environmental sustainability in the maritime industry.

In the ship model (digital twin) all relevant systems of the ship are represented by numerical models describing their behaviour depending on operational conditions. Whilst these numerical models are stand-alone descriptions of the individual systems, the ship model computes the aggregate of their influence on the system “ship” as well as their interaction. Digital twins can be used for the following scenarios:

- **During the design and construction phase of ships**. They allow naval architects and engineers to create a virtual representation of a ship to analyse its performance, stability, and various other design parameters before the physical ship is built. This helps in optimizing the design and avoiding costly mistakes.
- **Real-time Monitoring and Operation.** Once a ship is in operation, digital twins can provide real-time data from various sensors on the ship, such as engine performance, fuel consumption, weather conditions, and cargo status. This data can be used to optimize the ship operation, improve fuel efficiency, and ensure the safety of crew and cargo.
- **Predictive Maintenance.** By continuously monitoring the ship components and systems, digital twins can predict maintenance needs. Maintenance schedules can be optimized to reduce downtime and maintenance costs.
- **Voyage Optimization.** Digital twins can analyse real-time data to suggest optimal routes and speeds, taking into account factors like weather, sea conditions, and fuel consumption. This helps reduce voyage times and fuel consumption.
- **Safety and Emergency Preparedness.** Maritime digital twins can be used for safety drills and emergency preparedness. Simulations of various scenarios, such as fire, collision, or grounding, can be conducted to train crew and ensure readiness for emergency situations.
- **Environmental Impact Assessment.** Digital twins can assess the environmental impact of a ship's operations, including its emissions and interactions with marine ecosystems. These data can help in making the shipping industry more sustainable.
- **Fleet Management.** For companies with multiple ships in their fleet, a digital twin can provide centralized monitoring and control of the entire fleet, allowing for better coordination and decision-making.
- **Cargo and Port Operations.** Digital twins can be used to optimize cargo loading and unloading operations, as well as the efficiency of port facilities.

The ship model is generated based on the process integration and design optimisation (PIDO) platform CAESES as developed by Friendship Systems AG.

For a given set of outer operational conditions (e.g. ship speed, wind, …) and retrofitting options the balances of forces/moments and energy, flows are solved in an inner optimisation loop by adjusting the operational settings of the systems (e.g. engine rpm, wing-sail trim, …). This is done with a focus on minimising the consumption of non-renewable energy respectively noxious emissions.

In **Error! Reference source not found.** in the outer loop, the setup of the retrofit options can be seen to be optimised for minimal consumption of non-renewable energy, respectively noxious emissions. This is built on all the computational models and the equilibrium state.

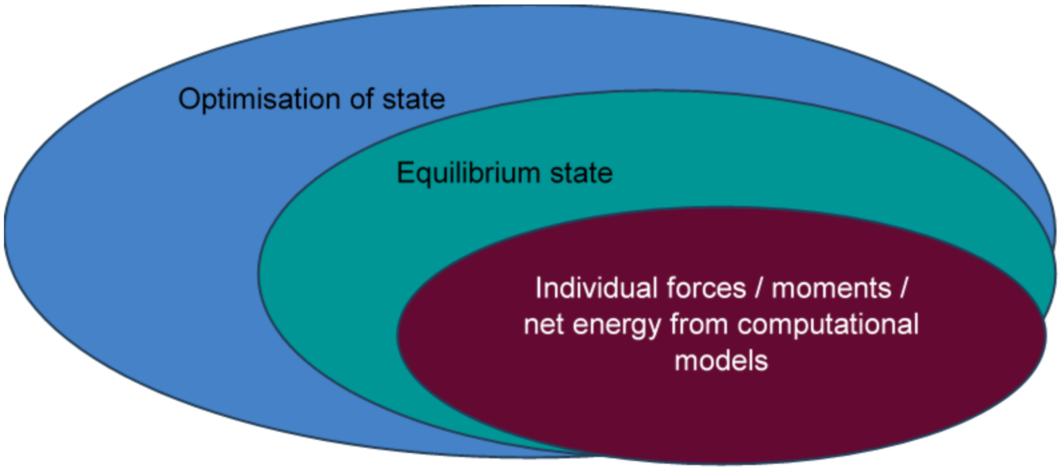

Figure 19: Digital Twin loops.

While the digital twin describes discrete states of the retrofitted vessel, this is not a viable representation of actual savings in operation. Particularly the environmental conditions, as well as loading conditions, vary significantly over the duration of operation of the vessel. By applying a representative distribution to the discrete states, a weighted average is computed to give an indication of possible long-term savings. This distribution of operating conditions can either be generalised or be based on historical voyage data on loading, operating and weather conditions.

The ship model and long-term retrofitting synthesis as implemented in CAESES are fed by and serve as backbone to the catalogue of retrofitting solutions and web interface, as displayed in **Error! Reference source not found.**. In the web interface, the user enters the ship and operational data and selects viable retrofitting options from the catalogue. Further, the level of analytical detail must be selected, ranging from generic representations of ships and system properties to actual numerical analyses, based on the ship and system geometries. This is calculated from the produced digital twin.

As a result of the long-term synthesis the expected fuel savings/emission reductions as well as mass and spatial requirements and installation costs are provided by the system.

Within the constraints of allowable mass/space requirements and costs, the selection and sizing of the retrofitting measures are then optimised for maximum fuel savings/emission reductions achievable under the given operating conditions.

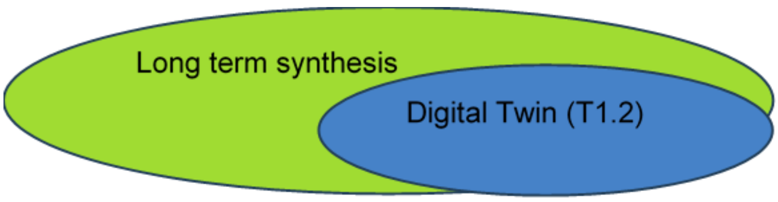

Figure 20: Long-term synthesis and digital twin.

6 Conclusion

In conclusion, this deliverable has addressed the critical need for a clear and concise roadmap guiding maritime stakeholders through the complex transition towards a more sustainable future. Recognizing the urgency of environmental change within the shipping industry, this work has provided valuable resources to empower informed decision-making and facilitate the adoption of greener practices.

Part of this deliverable is the introduction of the LCA model. This tool serves as a powerful asset for stakeholders, enabling them to meticulously evaluate and compare various retrofit options. Moving beyond a simplistic focus on operational emissions, the LCA model delves deeper, providing a comprehensive picture of environmental impact. By encompassing emissions generated during the crucial installation phase, stakeholders gain a holistic understanding of the environmental footprint associated with each retrofit option. Furthermore, the model enables users to validate the generated data, fostering trust and confidence in the decision-making process.

This comprehensive understanding is further enriched by the exploration of prominent technologies aligned with the RETROFIT55 call to action. By elucidating the operational principles and potential safety hazards associated with these innovative technologies, such as air lubrication systems and wind-assisted propulsion, stakeholders can gain valuable insights to guide their technology selection and implementation strategies.

Ultimately, this deliverable serves as a valuable compass, equipping maritime stakeholders with the knowledge and tools necessary to navigate the complexities of the industry's transition towards a greener future. By embracing sustainable practices and leveraging the resources provided within this framework, stakeholders can play a pivotal role in shaping a more environmentally responsible and sustainable maritime industry.

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