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D1.1.

Design specification

Deliverable

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List of Abbreviations

ABBREVIATION	DESCRIPTION
ADP	Abiotic Depletion
AFIR	Alternative Fuel Infrastructure Regulation
AP	Acidification Potential
ALARP	As low as reasonably practicable
AMB	Active magnetic bearings
CFD	Computational Fluid Dynamics
CH4	Methane
CII	Carbon Intensity Indicator

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CO2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
COGES	Combined Gas Electric and Steam
DCS	Data Collection System
DWT	Dead Weight
ECR	Engine Control Room
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EMC	Electromagnetic Compatibility
EP	Eutrophication Potential
ESD	Emergency Shut-Down
ESR	Effort Sharing Regulation
ETS	Emission Trading System
FAETP	Freshwater Aquatic Ecotoxicity Potential
FAT	Factory Acceptance Test
FEA	Finite Element Analysis
FMEA	Failure Mode and Effect Analysis
GFS	Global Fuel Standard
GHG	Green House Gas
GT	Gross Tonnage
GT	Gas Turbine
GWP	Global Warming Potential
HP	High pressure
HTP	Human Toxicity Potential
HVAC	Heating, Ventilation and Air Conditioning

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IMO	International Maritime Organization
IT	Information Technology
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LNG	Liquid Natural Gas
LPC	Low pressure Compressor
MAETP	Marine Aquatic Ecotoxicity Potential
MBC	Magnetic Bearing Controller
MBM	Market Based Measures
MECS	MARPOWER Energy Conversion System
MEPC	Marine Environment Protection Committee
MJ	Megajoule
MGO	Marine Gas Oil
MRV	Measurement, Reporting and Verification
NO2	Nitrogen Oxide
NOx	Nitrogen Oxides
ODP	Ozone Layer Depletion Potential
OPEX	Operational Expenditure
PDA	Prototype Design Assessment
PDCA	Plan-Do-Check-Act
P&ID	Piping and Instrumentation Diagram
POCP	Photochemical Ozone Creation Potential
RCO	Risk Control Option
ROI	Return of Investment
SCR	Selective Catalytic Reduction
SEEMP	Ship Energy Efficiency Management Plan

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SMS	Safety Management System
SO2	Sulfur Dioxide
SRTP	Safe Return to Port
TETP	Terrestric Ecotoxicity Potential
TNS	IEC terminology for earthing arrangements (IEC 60364)
TQP	Technology Qualification Process
TQ	Technology Qualification
WHRS	Waste Heat Recovery System
WtW	Well to Wake

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1. Introduction

This document defines the design guidelines, considerations, constraints, and requirements for the system developed under the MARPOWER project.

It provides a comprehensive framework for the design process, starting with the general machinery and product requirements outlined in Chapter 2, Technical requirements.

Chapter 3, Policy framework, covers relevant marine legislation and regulatory requirements, ensuring compliance with industry standards.

Integration with the ship's systems and operational requirements is addressed in Chapter 4, Ship integration. This chapter details key factors such as the ambient conditions of the machinery room, interface requirements, and specifications for auxiliary systems like pressurized air and cooling water.

Chapter 5, Life Cycle requirements, outlines the life cycle analysis process, which will be conducted in Task 4.3. This section specifies the associated requirements, ensuring the system's sustainability and long-term performance.

The design of the gas turbine and waste heat recovery system is driven by cycle calculations, which serve as the foundation for component design. These calculations are iterative, with ongoing adjustments to align the system's performance with design goals. Chapter 6, MECS cycle and component design specifications, and specifically Subchapter 6.2, Component design & specification, provide detailed insights into the design considerations for each key component.

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2. Technical requirements

The objective is to design and develop a gas turbine system with an electrical output of 5400 kW, along with a waste heat recovery system capable of producing 400 kW of electrical power. The primary goal is to achieve the highest possible electrical efficiency. As specified in the Grant Agreement, the gas turbine is expected to meet a target electrical efficiency of 50%, while the total system efficiency should reach 54%.

The system design will prioritize minimizing the manufacturing costs of the final product. However, the scope of this project is limited to the development of key components (listed below) and does not cover the complete product design. These components will be prototyped and tested in WP2. Detailed design and drawings are required to enable the manufacturing of these prototype components:

- HP shaft arrangement with active magnet bearings (AMB) on a moving platform
- Recuperator
- Hydrogen combustor

The machinery design must comply with the following EU directives:

- Machinery directive (MD) 2006/42/EC and Machinery regulation 2023/1230
- EMC directive 2014/30/EU
- Low voltage directive (LVD) 2014/35/EC
- Pressure Equipment Directive (PED) 2014/68/EU
- ATEX 2014/34/EU

For marine applications, additional requirements are outlined in Chapters 3 (Policy Framework) and 4 (Ship Integration). These requirements must be followed if they are more stringent than the EU directives and regulations.

Detailed design considerations for each component and system are provided in Chapter 6 MECS cycle and component design specifications, and with a particular focus on component design in subchapter 6.2. Component design & specification.

The machinery is intended for installation in various environments and must operate reliably under the following conditions:

- Temperature range: -40°C to +55°C
- Relative humidity: less than 95%

Performance may be derated depending on temperature and installation altitude.

The gas turbine is designed for continuous 24/7 operation with an average of one start-stop cycle per 24-hour period. However, depending on application needs, the turbine may experience additional start-stop cycles within a 24-hour period. This may impact component lifespan and maintenance schedules, which will be monitored via automation software. The target gas turbine availability is 97%.

For structural integrity, the safety factor for Finite Element Analysis (FEA) simulations must conform to the applicable standards.

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3. Policy framework

3.1. Regulations for decarbonisation

At the MEPC 72, the Committee adopted the “Initial IMO Strategy on Reduction of GHG Emissions from Ships”. This strategy set ambitious targets, aiming to reduce carbon intensity per ship by 70% by 2050 compared to 2008 levels and to cut total greenhouse gas emissions from international shipping by at least 50% by the same year. At the MEPC 80 in July 2023, more stringent targets were adopted to reduce 20% - 30% of the total annual GHG emissions from international shipping by 2030 and to reduce 70% - 80% by 2040, compared to 2008. The IMO reached the consensus that there is a need for the adoption of additional GHG reduction measures by 2025 to reach the targets of the 2023 Revised GHG Reduction Strategy. These measures are intended to provide economic incentives for reducing emissions and improving energy efficiency in the maritime sector.

Discussions on combining technical and market-based measures are ongoing within the IMO. These combined measures include technical requirements to promote energy transition, thereby regulating greenhouse gas emissions throughout the entire fuel lifecycle. The Global Fuel Standard (GFS), discussed at the MEPC 80, limits the carbon intensity of different fuels. This system aims to progressively reduce greenhouse gas emissions by establishing consensus on the characteristics of various fuels. At the MEPC 80, the 2023 IMO GHG Strategy states that the selection of candidate mid-term GHG reduction measures should consider the well-to-wake GHG emissions of marine fuels, as outlined in the “Guidelines on life cycle GHG intensity of marine fuels”.

At the MEPC 81, the draft “IMO NET ZERO Framework” was agreed upon, with a target for final adoption in 2025 and enforcement starting in 2027. Further developing the Life Cycle Analysis (LCA) Guidelines adopted by resolution MEPC.376(80), the MEPC endorsed the 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels (2024 LCA Guidelines) annexed in the RESOLUTION MEPC.391(81). The Committee also decided that the regulatory application and implications of the 2024 LCA guidelines are to be established during the development of regulatory provisions. It calls upon Member Governments to circulate the annexed Guidelines to the participants of the marine sector, including shipowners, operators, shipbuilders, designers, energy companies, fuel producers, bunkering companies, engine manufacturers, and other relevant stakeholders. The experience gained from their application will be used for the 2024 LCA Guidelines reassessment by the Committee.

On the other hand, the European Union is one of the most ambitious regulators and strives towards the transition to low and zero-carbon fuels in shipping. In 2019 a roadmap was developed, The European Green Deal, with the aim for Europe to become the first climate-neutral continent by 2050. Along these lines, in the summer of 2021, the ‘Fit for 55’ legislative package and Fuel EU Maritime regulation were proposed. The former aims towards the inclusion of the sector in the EU Emissions Trading System (EU ETS), however focuses only on tank-to-wake emissions and neglects the emissions from production. On the other hand, FuelEU Maritime aims to increase the use of sustainable fuels through an increasingly stringent lifecycle GHG intensity requirement. This regulation, set to begin in 2025, requires the calculation of emissions intensity. Ships exceeding the annual GHG intensity of energy limit will incur penalties, incentivizing the adoption of cleaner fuels and technologies.

3.1.1. International Maritime Organization (IMO)

The International Maritime Organization (IMO) is a specialized agency of the United Nations, based in London, whose purpose is to establish intergovernmental regulations concerning maritime trade, safe shipping, and access to the seas. IMO also sets regulations for preventing ocean pollution of the marine environment. In addition to regulations to reduce GHG emissions from ships, IMO is continuously encouraging its 176 member states to develop and update National Action Plans consistent with IMO policies with 50 international conventions and protocols up to date.

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Figure 1. IMO logo

IMO started considering in the early 2000s technical and operational measures to improve the energy efficiency of ships, aimed at reducing the impact of international shipping on climate change, under the framework of the MARPOL, the International Convention for the Prevention of Pollution from Ships. More specifically, MARPOL Annex VI is mandating technical and operational energy efficiency measures to reduce the amount of CO_2 emissions from international shipping. IMO Member States have progressively adopted energy efficiency measures and targets to reduce the carbon intensity of international shipping.

Under the authority of IMO, the Maritime Environment Protection Committee (MEPC) handles environmental concerns. This involves the management and prevention of ship-source pollution, which is governed by the MARPOL Treaty. Examples of such pollution include oil, chemicals transported in bulk, sewage, rubbish, and emissions from ships, such as greenhouse gases and air pollutants. Ballast water management, anti-fouling systems, ship recycling, readiness for and reaction to pollution, identification of special regions, and particularly sensitive marine areas are some of the other topics discussed.

The initial IMO GHG Strategy was further revised in 2023, adopted by MEPC 80, setting out new ambitious goals for Member States. The levels of ambition to reduce GHG emissions and guiding principles include candidate mid- and long-term measures. The Strategy outlines the international shipping sector's ambitious goals and sets regular benchmarks to present updated emissions estimates, explore potential emissions reduction methods for global shipping, review Intergovernmental Panel on Climate Change (IPCC) reports, and evaluate any forthcoming IMO GHG studies to track progress.

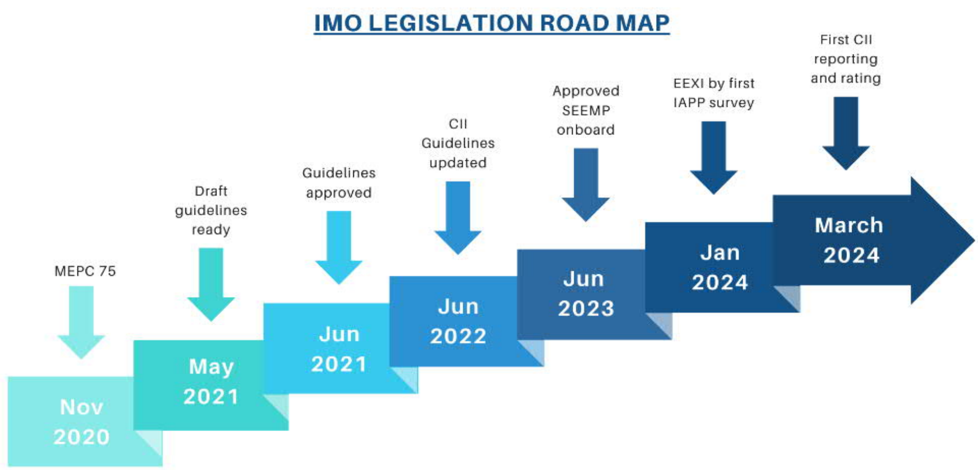

Figure 2. IMO legislation road map

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3.1.1.1. Short-terms measures

The MEPC, responsible for the safety and security of navigation about the prevention of marine and air pollution from ships, held its 80th session from 3 to 7 July 2023. At MEPC 80 agreements were reached on several issues, the most important of which is the adoption of a revised GHG Strategy to address emissions from ships. The following are summarized decisions taken and the timing proposed by the Committee. While the carbon intensity reduction target remains unchanged at 40% by 2030 compared to 2008, other aspects of the initial GHG strategy have been significantly strengthened by updating or introducing elements such as:

- Reduce greenhouse gas emissions on a WtW basis, as required by the LCA guidelines.
- Fuels and/or energy sources with low and zero carbon emissions represent at least 5% (con the goal of reaching 10%) of the energy used by international shipping.
- Achieve peak GHG emissions from international shipping as soon as possible and achieve net zero greenhouse gas emissions by or around 2050, i.e. close to 2050.
- Reduction of annual GHG emissions from international shipping by at least 20% (aiming for 30%) by 2030 compared to 2008; and at least 70% (aspiring to 80%) by 2040 compared to 2008.
- Recognition of the need for a comprehensive approach to regulating the safety of the use of technologies, fuels, and/or energy sources with zero or near-zero greenhouse gas emissions, including by addressing the human element, to ensure safe implementation of the strategy.

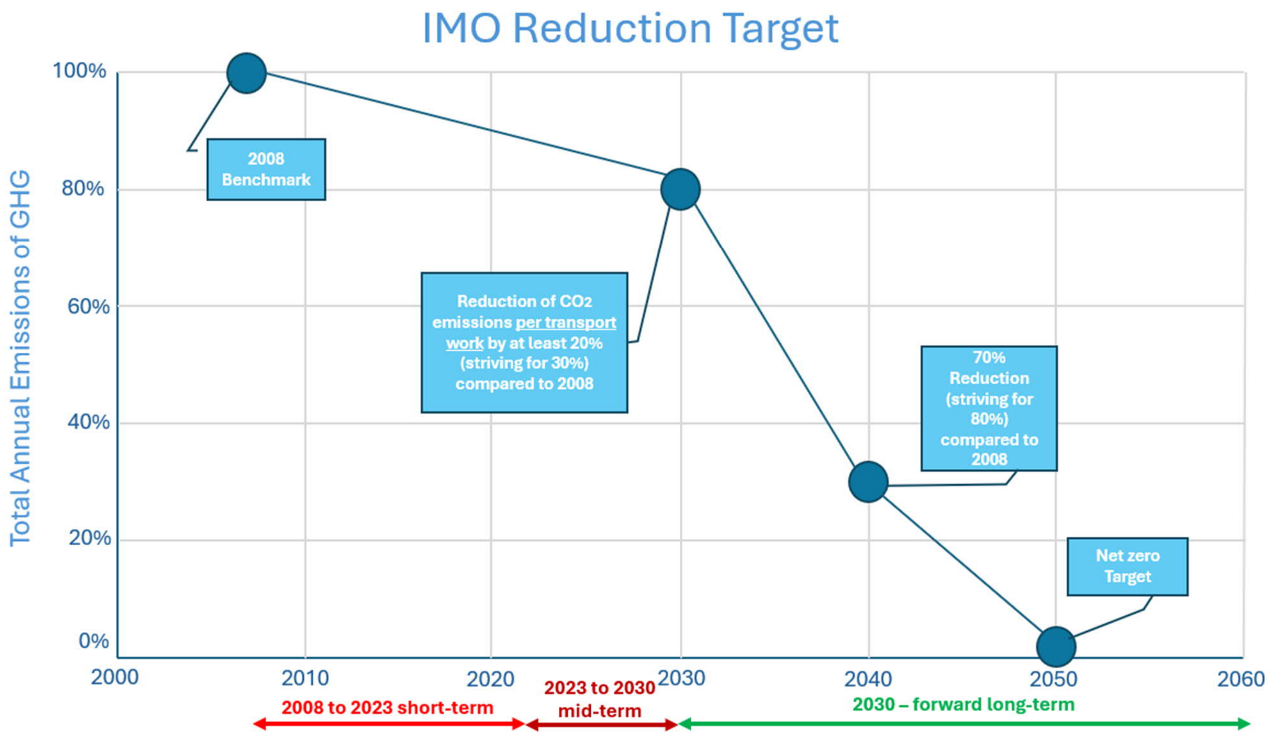

Figure 3. IMO reduction target

The levels of ambition and indicative checkpoints should be based on the Guidelines on Life cycle GHG intensity of marine fuels (LCA guidelines) developed by the IMO, preventing a shift of emissions to other sectors. The GESAMP Working Group on Life Cycle GHG Intensity of Marine Fuels will address LCA-related issues such as certification and accounting of captured CO_2.

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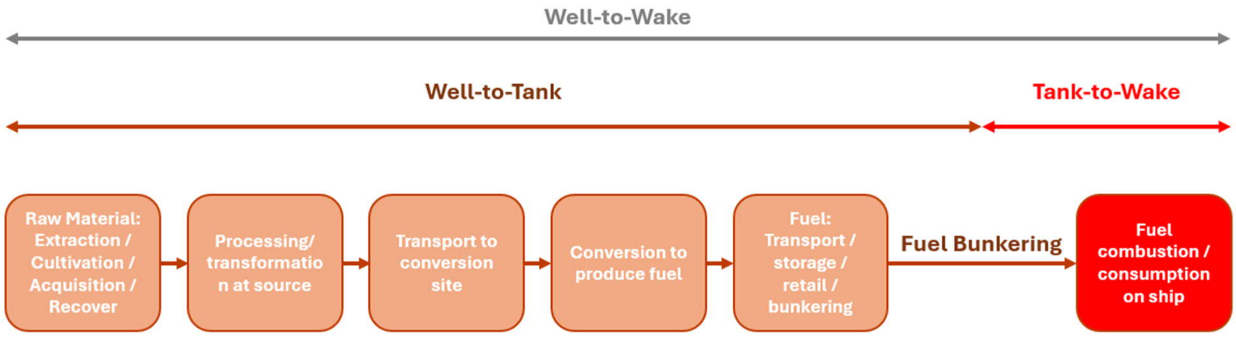

Figure 4. Well-to-Wake

To ensure that shipping reaches the revised ambitions, the IMO has decided to implement a basket of measures consisting of two elements:

- A technical element which will be a goal-based marine fuel standard regulating the phased reduction of marine fuel GHG intensity.
- An economic element, based on a GHG emissions pricing mechanism to effectively promote the energy transition and provide the world fleet a needed incentive while contributing to a level playing field and a just and equitable transition.

The IMO is refining its regulatory framework to meet strategy targets and has introduced these measures under the MARPOL Convention, affecting both new and existing ships:

- *Energy Efficiency Design Index* (EEDI): New ships must be built and designed to be more energy efficient.
- *Ship Energy Efficiency Management Plan* (SEEMP): A practical tool for helping ship owners manage their environmental performance and improve operational efficiency.
- *Energy Efficiency Existing Ship Index* (EEXI): EEXI applies many of the same design requirements as the EEDI, with some adaptations regarding limited access to design data of existing ships.
- *The Fuel Oil Consumption Data Collection System* (DCS): Mandates annual reporting of CO_2 emissions and other activity data and ship particulars for all ships above 5,000 GT.
- *Carbon Intensity Indicator* (CII): a rating scheme (A-E) to measure the annual performance of all ships above 5,000 GT in terms of CO_2 per DWT and distance covered.

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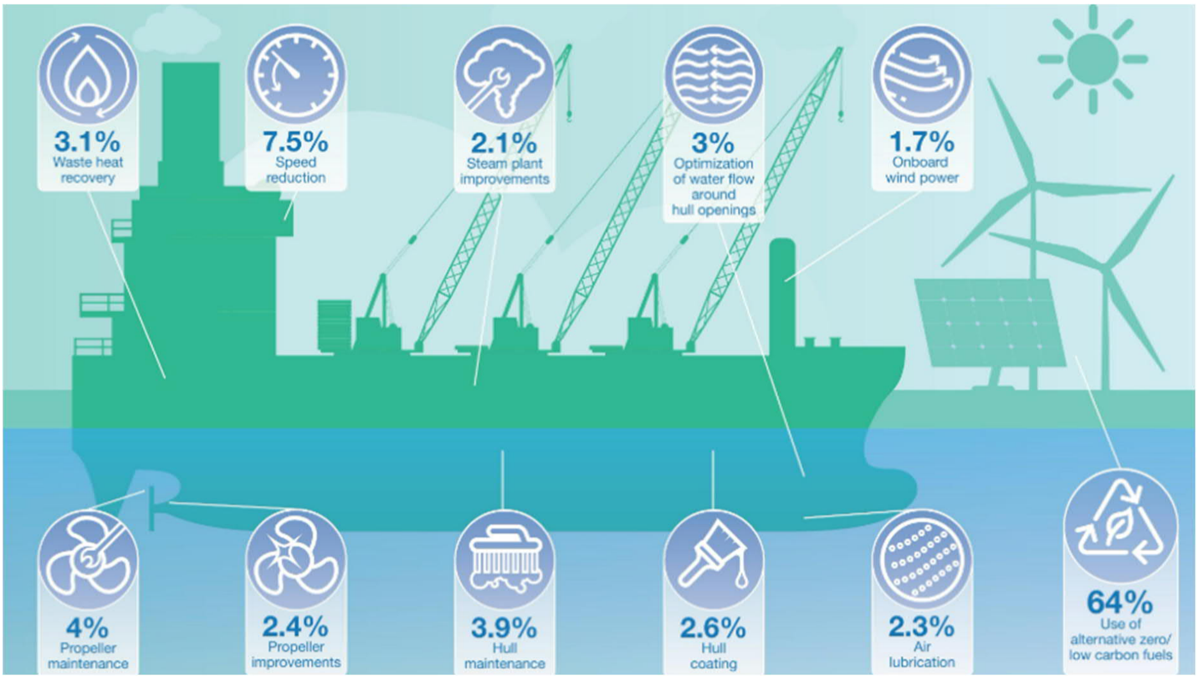

Figure 5. Estimated contribution of selected technologies in the total amount of CO2 reduction in shipping

The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), which entered into force on 1 Jan.2013, represent measures which are part of goal-based and technology-neutral IMO regulations. The amount of carbon dioxide a ship emits in proportion to its speed and transport capacity is measured by the EEDI index. The IMO created the index in 2011 as a component of technological steps to lower GHG emissions from the marine industry. The goal is to boost the creation of innovative technologies and increase the energy efficiency of new building ships, used during the design or construction stages of the vessel.

The EEDI sets a minimum energy efficiency level for new ships and is based on the amount of carbon dioxide emitted per ton-mile, which is the unit of work done by a ship, of cargo carried. The mathematical equation for calculating the EEDI considers variables, including the ship's displacement, load capacity, speed, and fuel consumption, as well as the carbon dioxide emissions of the fuel used. The EEDI is expressed in grams of carbon dioxide per ton-mile, and the lower the EEDI value, the more energy-efficient the ship is.

The IMO has set minimum EEDI values for distinct types of ships – containers, cargo, tankers, cruises, etc., and new ships must meet these standards to be built. This international regulatory regime addresses 85% of the CO_2 emissions from international shipping.

As said before the new ship design needs to meet the reference level of the EEDI for each specific ship type. Such level is to be tightened incrementally every five years to keep pace with technological developments until 2025 and onwards when a 30% reduction is mandated for the applicable ship types, to stimulate continued innovation and technical development in ship design, for the first phase was set to 10% compared to a reference line calculated from the average efficiency for ships built between 2000 and 2010. IMO developed guidelines on the EEDI (regulation 22 of MARPOL Annex VI – Chapter IV) and survey and certification (regulation 5), available at IMO under the "Guidelines and Circulars related to MARPOL Annex VI".

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As shown in Figure 6 the ships need to be more efficient as desired by the IMO, and to do so, need to be assessed two values for the EEDI:

- The Required EEDI, which is the maximum value of EEDI required for the ship
- And the Attained EEDI, which is the actual value of EEDI attained for the ship

The formula for the Required EEDI is provided in the MARPOL Annex VI, Chapter 4, Regulation 21. The formula itself has two key terms, the *reference line value* and the *reduction factor*. Obtaining the value for the reference line is complex and it can be found in *Resolution MEPC. 231(65): 2013 Guidelines for Calculation of Reference Lines for use with the Energy Efficiency Design Index,* but briefly the line value is in function of both the Dead Weight (DWT) of the ship and the ship's type. As per the reduction factor, this was introduced so that the ship gets more efficient through time, for this the reduction factor for the calculation of the Required EEDI was divided into distinct phases:

We are currently in Phase 2 and the Required EEDI value will have to be 20% less than the reference line which is the Required EEDI value in Phase 0. The cutoff levels, shown in Figure 6, which is the size limit the EEDI is mandatory, are dependent on the type of ship. For example, the limit for gas carriers is 2'000 DWT and for bulk carriers is 10'000 DWT. Whereas the Attained EEDI is the actual EEDI Value of the ship that can be calculated through the formula present in Resolution MEPC.245(66) IMO Guidelines on the Calculation of Attained EEDI.

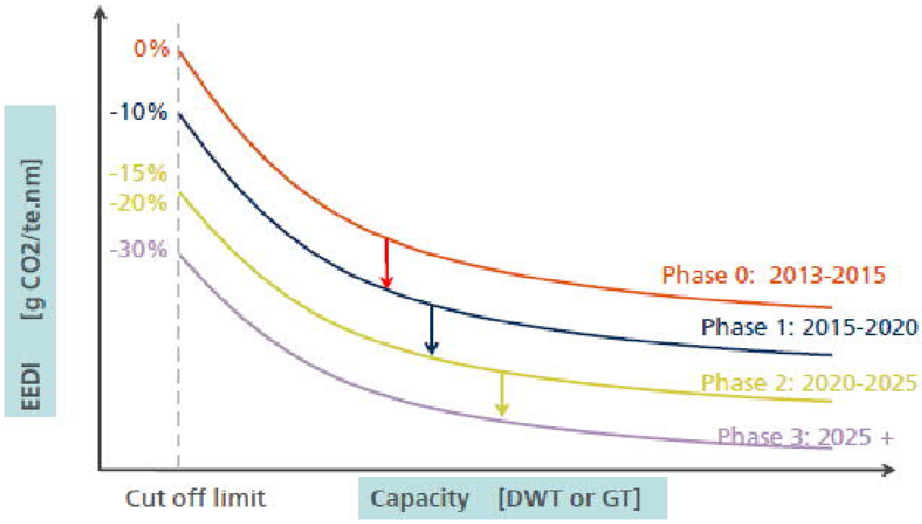

Figure 6. EEDI phases

The EEDI is non-prescriptive on the technologies and performance-based, which leaves the choice of technologies to be used in a specific ship design to the industry. If the required EEDI level is attained, ship designers and builders can use the most cost-efficient solutions.

3.1.1.2. Ship Energy Efficiency Management Plan

The Ship Energy Efficiency Management Plan (SEEMP) is an operational mechanism to improve cost-effectively the energy efficiency of a ship, this might form part of the ship's Safety Management System (SMS). It shall be developed using Guidelines adopted by the IMO during MEPC Resolution 280(70).

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This states that each ship which is involved in international shipping with a gross tonnage (GT) of more than 400 must have SEEMP on board, as per MARPOL Annex IV, Regulation 22.

The goal of the SEEMP is to create a system for a company and/or a ship to increase the ship's energy efficiency while in operation. The ship-specific SEEMP should ideally be connected to the company's overall corporate energy management system. The ship-specific SEEMP is required since no two shipping companies or shipowners are the same, and ships operate under a variety of situations, including geographical and commercial. The SEEMP is a management tool that helps companies manage the environmental performance of their vessels. It recommends that companies develop procedures for applying the SEEMP, limiting on-board administrative activities by using recognized monitoring tools.

IMO issued the 2022 guidelines for the development of the SEEMP, which defines best practices for fuel efficient ship operation and templates for the development of SEEMPs, subdivided into three Parts:

- Part I: Ship management plan to improve energy efficiency
- Part II: Ship fuel oil consumption data collection plan
- Part III: Ship operational carbon intensity plan

The SEEMP should be planned as a ship-specific strategy by the ship owner, operator, or other relevant parties, such as charter companies. The SEEMP aims to increase a ship's energy efficiency in four steps:

- Planning
- Implementation
- Monitoring and
- Self-assessment and improvement

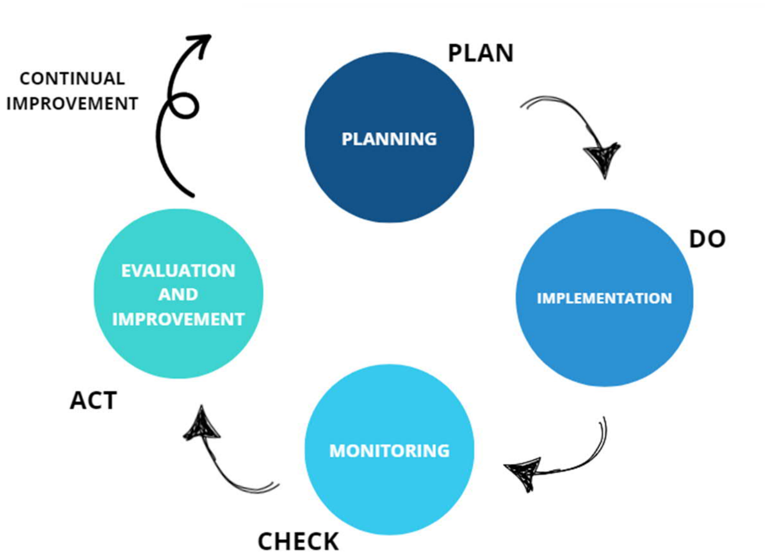

Figure 7. Four steps in SEEMP

Figure 7 depicts the steps of SEEMP, which are comparable to the Plan Do Check Act (PDCA) stages of any other management system or perpetual improvement cycle.

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3.1.1.3. Data Collection System

In October 2016 IMO adopted, by resolution MEPC.278(70), mandatory MARPOL Annex VI requirements for ships to record and report their fuel oil consumption, to get the necessary data to make decisions on further measures to improve the energy efficiency of ships.

The steps to use and implement the IMO DCS are the following:

- Data Collection: Ships are required to collect data on their fuel consumption, distance travelled, and hours underway. This data is collected for each voyage and aggregated on an annual basis.
- Data Submission: At the end of each calendar year, the ship must submit a report to its flag state, containing the aggregated data on fuel consumption, distance travelled, and hours underway. The flag state then submits this data to the IMO.
- Data Verification: The data submitted by the ship is subject to verification by the flag state or a recognized organization acting on its behalf. The verification process ensures that the data is accurate and complete.
- Data Analysis: The IMO uses the data collected through the DCS to analyse trends in fuel consumption and carbon emissions from ships. This information is used to inform the development of future regulations and policies aimed at reducing greenhouse gas emissions from shipping.

3.1.1.4. Energy Efficiency Existing Ship Index and Carbon Intensity Indicator

3.1.1.4.1. Short-term GHG Reduction Measures

In 2021, IMO adopted by resolution MEPC.328(76) new measures: the Energy Efficiency Existing Ship Index (EEXI – a technical requirement) and the Carbon Intensity Indicator (CII – an operational requirement) which entered into force on 1 January 2023.

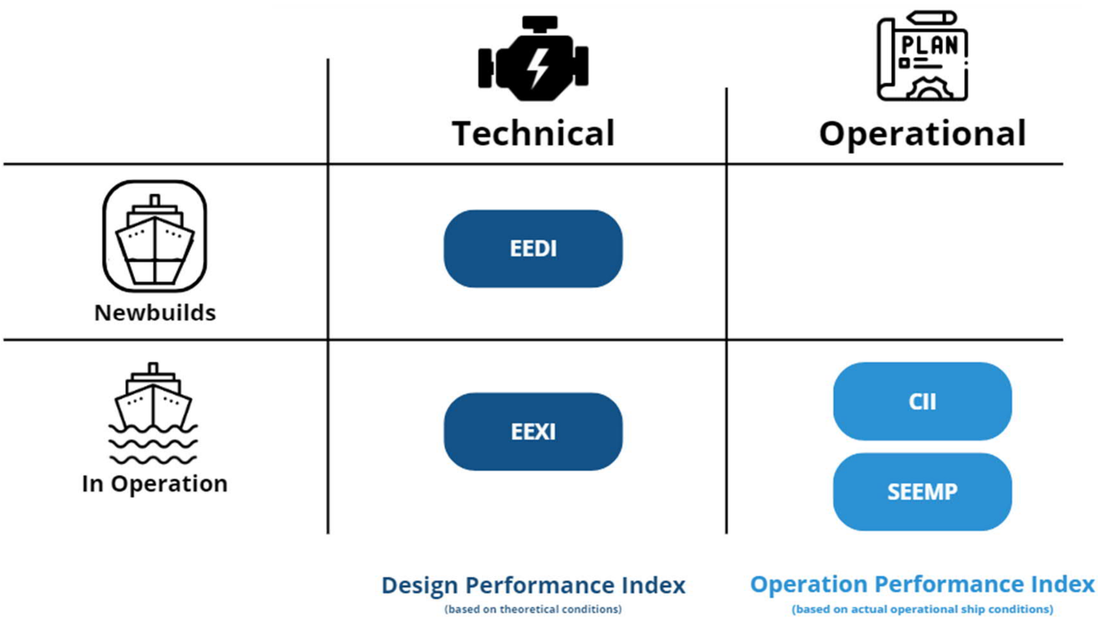

Figure 8. Performance indexes by IMO

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3.1.1.4.2. Energy Efficiency Existing Ship Indicator

In 2020, the EEXI was granted approval as a short-term approach to raise the energy efficiency of current ships. It seeks to promote the use of energy-saving technology and bring older vessels up to speed with the newest ships. The EEXI is determined by dividing a ship's real carbon dioxide emissions by the amount of labour it does during transit, which is determined by the ship's installed power, deadweight, and speed. The fuel consumption data of a ship over a representative period is used to verify the EEXI, and a certificate is produced to verify compliance. On November 1, 2022, the EEXI came into effect and is applicable from the first annual, intermediate, or renewal IAPP survey after the 1st of January 2023 at the latest.

Under the EEXI framework, all existing ships of 400 GT and above are required to calculate their attained Energy Efficiency Existing Ship Index (EEXI), which reflects the "technical" or "design" efficiency of the ship, in accordance with different values set for different ship types and size categories. Ships then must reach a "required EEXI", equivalent to Required EEDI levels for 2022, aimed at creating a level-playing field among the fleet. The EEXI of 400GT ships and above should be equal to or lower than the Required EEXI, calculated based on a reference line and specific reduction factors for each ship type

The EEXI framework is technology neutral, and the shipowner or charterer can choose the most appropriate means and technologies to achieve the goals set by IMO (engine/shaft power limitation, heat/energy recovery, wind-assisted propulsion, etc.).

Similarly to the EEDI the EEXI has two values the Required EEXI and the Attained EEXI. The required value is determined by ship type, capacity of the ship, and principle of propulsion and is the maximum acceptable attained value for the EEDI, whereas the attained value shall be calculated for each individual ship that has to follow the IMO regulations.

The main difference between the EEXI and the EEDI is that the second is based on real ship emissions, whilst the first is based on theoretical emissions. A ship's operational and real performance are reflected in the EEXI, whilst its design and prospective performance are reflected in the EEDI. While the EEXI is confirmed after a ship has been in operation for some time, the EEDI is validated prior to a ship's launch. Due to differences in calculating techniques, characteristics, and correction factors, the EEDI and EEXI may yield different results for the same ship.

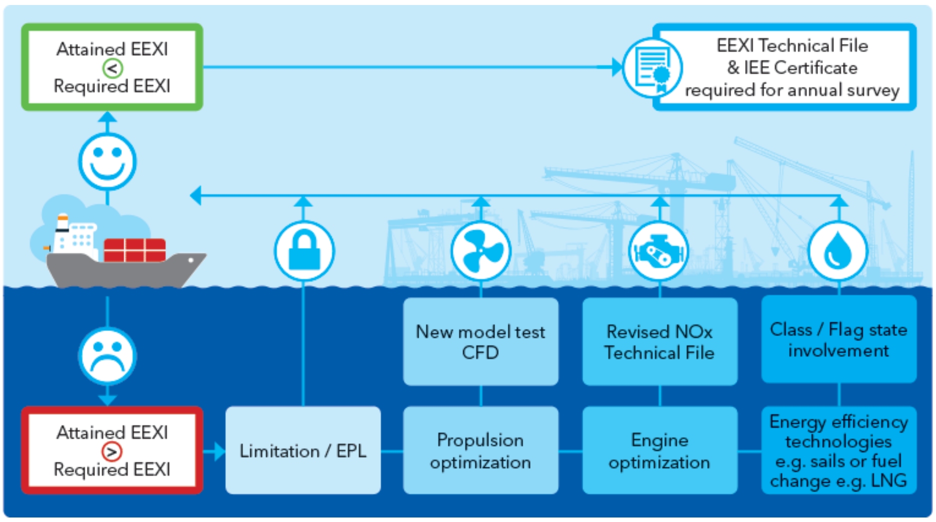

Figure 9. EEXI process

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3.1.1.4.3. Carbon Intensity Indicator

The Carbon Intensity Indicator (CII) rating reflects the operational energy efficiency of ships, based on fuel oil consumption from the IMO DCS and the SEEMP as a management tool. Under the MARPOL amendments, cargo, ro-pax, and cruise ships equivalent and above 5'000GT shall need every year from 2030 to calculate the CII and their rating from a score of As to E.

The quantity of GHG emissions per unit of energy generated or consumed is measured by the carbon intensity index (CII). For every megajoule (MJ) of energy, it is commonly stated as grams of Carbon Dioxide Equivalent (CO_2e). The environmental effects of various energy sources, such as nuclear power, renewable energy, and fossil fuels, may be compared using CII.

As said before, the total mass of CO_2 is the sum of CO_2 emissions in grams from all the fuel oil consumed onboard a ship.

For ships subject to the new SEEMP requirements:

- Starting from 2023, at the end of each calendar year, the attained annual operational CII is calculated over 12 months and electronically communicated to the Flag Administration /RO by the following March.
- The required annual operational CII is reduced by the same percentage each year for all ship types (5% for 2023; 7% for 2024; 9% for 2025; and 11% for 2026, with percentages yet to be decided for 2027- 2030).

Similarly to the EEDI, the CII has Calculation Guidelines from which the Attained CII is calculated; this can be achieved by dividing the ship's total mass of carbon dioxide emitted (M) by the total transport work (W) undertaken in a given calendar year as follows:

$$Attained\ CII = M/W$$

The CII is aimed at determining the operational carbon intensity rating of the ship. The resulting value is then compared to a set of established benchmarks given on a scale - operational carbon intensity rating A, B, C, D, or E as shown in Figure 10 shows which is namely superior boundary, lower boundary, upper boundary, and inferior boundary. Thus, a rating can be assigned by comparing the attained annual operational CII of a ship with the boundary values. The boundaries are set based on the distribution of CIIs of individual ships in the year 2019. The appropriate rating boundaries are expected to generate the following results: the middle 30% of individual ships across the fleet segment, in terms of the attained annual operational CIIs, are to be assigned rating C, while the upper 20% and further upper 15% of individuals are to be assigned rating D and E respectively, the lower 20% and further lower 15% of the individuals are to be assigned rating B and A respectively.

The Flag Administration / Recognized Organization (e.g. Classification Society) is to verify the attained annual operational CII against the required annual operational CII to determine the energy efficiency of class A, B, C, D, or E. The required annual operational CII is the midpoint of the range corresponding to the C-rating level. A ship rated D for 3 consecutive years or rated as E for just one year, must develop a "Plan of corrective actions". This plan must be included in the SEEMP and submitted to the Flag Administration /RO for verification.

The CII framework also provides tools for Administrations, ports, and other stakeholders, including the financial sector, to incentivize the most energy-efficient ships.

The CII is verified through a two-step process. First, the ship's carbon dioxide emissions are reported to the IMO's Fuel Oil Data Collection System (DCS). The data is then verified by an independent third party, such as a recognized organization or a flag state, to ensure its accuracy. Once the values have been verified, the ship's CII rating is calculated and assigned.

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It's worth noting that the CII has been heavily criticized for its inability to accurately describe a ship's efficiency. As a simple metric with few elements, it fails to accurately describe a ship's efficiency in the case of:

- Anchored ships
- Ships in port (e.g. heavily impacting cruise ships)
- Ships under repair
- Ships manoeuvring
- Ballast voyages compared to laden voyages
- Actual cargo carried

By January 1, 2023, the ship types mentioned above, along with conventional propulsion cruise ships with a gross tonnage of 5,000 GT or more engaged in international voyages, must include in the SEEMP:

- The methodology used to calculate the ship's attained annual operational index CII and reporting this value to the Flag Administration.
- An implementation plan to meet the required annual operational index CII for the following three years.
- A self-assessment and improvement procedure.

Confirmation of compliance is to be provided by the Flag Administration or its Recognized Organization (RO) before January 1, 2023, and kept on board. The SEEMP will be subject to verification during Company audits.

Given these shortcomings, the revision of the CII within the context of short-term measures planned by 2026 will be of great importance. It will be an opportunity to study and propose modifications and improvements to the CII, also in collaboration with European Member States.

This should consider challenges such as strikes, port congestion, and technical stops, and include increased data granularity resulting from the revision of data submission to the DCS.

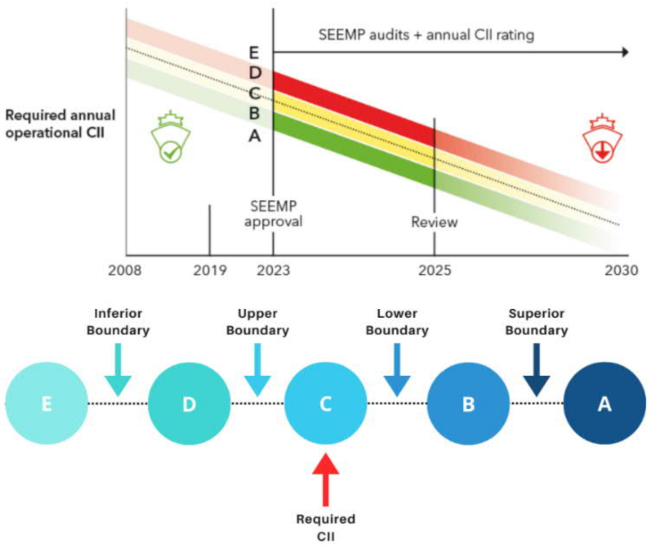

Figure 10. CII boundaries

The development of the measures will continue at the IMO and will, according to the agreed timeline, be adopted in 2025 and enter into force around mid-2027.

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Regarding mid and long-term measures to achieve the 2050 target defined in the 2023 IMO GHG Strategy, these will include a combination of technical measures (goal-based marine fuel standards) and economic measures (MBMs - market-based measures).

For economic measures, it may be desirable to impose a direct tax on fossil fuels to reduce the "green premium", aimed at promoting the adoption of sustainable fuels, as discussed, and proposed during IMO MEPC 80.

Funds collected could be used, for example, to incentivize first movers, promote R&D projects, and finance alternative fuel infrastructure.

3.1.2. European Union

The European Commission (EC) adopted the European Climate Law on July 9, 2021, setting two ambitious goals for the EU:

- Reduce GHG emissions by at least 55% compared to 1990 levels by 2030.
- Achieve climate neutrality, meaning a 90% reduction in greenhouse gas emissions from the transport sector by 2050.

The EU requirements have been incorporated into the so-called Fit55 which stands for "Fit for 55%" which reflects the EU's goal of cutting its net emissions by more than half in the next decade. The fit55 initiative consists of 12 legislative proposals that cover various sectors and policy areas, such as energy, transport, industry, taxation, and trade.

The following five proposals affect the marine transport sector:

- Alternative fuel infrastructure regulation (AFIR)
- Energy Taxation Directive
- Renewable Energy Directive
- EU ETS Directive
- Fuel EU Maritime

In addition to the five proposals affecting marine transport mentioned above, Figure 12 also includes the Effort Sharing Regulation (ESR). This regulation established national targets for reducing GHG emissions by 2030 across multiple sectors, including domestic transport, buildings, agriculture, and waste. With the updated rules, the EU aims to cut GHG emissions in ESR sectors by 40% by 2030, compared to 2005 levels. This target is set because these sectors are not covered by the existing EU ETS, which applies to large installations, power plants, and commercial aviation.

Some of the key measures when it comes to legislative instruments for shipping are:

- The revision of Directive 2003/87/EC, establishing a system for greenhouse gas emission allowance trading (ETS Directive).
- The new FuelEU Maritime Regulation, aimed at incentivizing the use of low or zero-carbon emissions alternative fuels.

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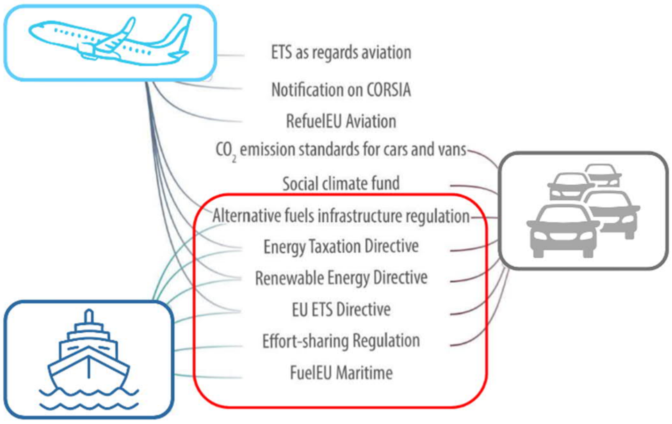

Figure 11. Key measures for shipping

3.1.2.1. Directive (EU) 2023/959 – ETS

Directive (EU) 2023/959, amending the ETS Directive, will be implemented by European Member States and by Iceland and Norway, which are part of the European Economic Area (EEA), and will apply from January 1, 2024, to emissions from ships, regardless of their flag, exceeding 5,000 GT. From January 1, 2027, it will also apply to offshore units exceeding 5,000 GT. The regulation covers:

- 100% of GHG emissions in European/EEA ports and for voyages between European/EEA ports.
- 50% of GHG emissions for voyages arriving in European/EEA ports from non-European ports or vice-versa.

Where GHG emissions include CO_2 emissions from January 1, 2024, and CO2, methane (CH4), and nitrous oxide (N2O) emissions from January 1, 2026.

According to the Directive, from 2025 onwards, every shipping company operating in Europe must:

- Report aggregated and verified emission data for the previous year (by March 31 of each year).
- Surrender the following allowances (by September 30 of each year):
- 40% of the reported aggregated verified emissions for 2024.
- 70% of the reported aggregated verified emissions for 2025.
- 100% of the reported aggregated verified emissions for 2026 and each subsequent year.
- Pay a penalty of EUR 100 for each ton of emissions for which allowances have not been surrendered.

Payment of the penalties does not exempt the Company from surrendering the allowances. If a Company fails to comply with the ETS Directive for two consecutive years, its ships may be denied entry to European ports until the Company fulfills its obligations.

The Directive also provides the following exemptions until December 31, 2030:

- Ships with ice class (IA or IA Super or equivalent) may surrender 5% less allowances than the required amount for their reported aggregated verified emissions.
- GHG emissions do not need to be counted in the following cases:
  - Voyages made by passenger ships (other than cruise ships) or passenger ro-ro ships to/from
  - European islands with a population of fewer than 200,000 permanent residents.

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- Voyages made by passenger ships or passenger ro-ro ships as part of a transnational public service contract
- Voyages between a port located in the remote regions of a European state and a port in the same state

It is essential to note that these exemptions are not automatic, and it is the responsibility of the Member State to communicate any exemption to the Commission.

Considering the emissions data from the publicly available MRV database, it is worth noting that the types of ships used in Motorways of the Sea services will be most affected by the ETS system, as:

- At the European level, ro/pax and ro/ro ships represent approximately 20% of the ETS emissions quota.
- At the national level (Italy), ro/pax and ro/ro ships represent approximately 60% of the ETS emissions quota.

3.1.2.2. Fuel EU Maritime Regulation

The FuelEU Maritime Regulation (EU 2023/1805) was adopted in July 2023 as part of the Commission's Fit for 55 legislative package to reduce EU greenhouse gas emissions by at least 55% by 2030.

The FuelEU Maritime Regulation promotes the use of renewable, low-carbon fuels and clean energy technologies for ships, to support maritime transport decarbonization.

The FuelEU Maritime Regulation is likely to be implemented by the Member States of the whole European Economic Area (EEA) (i.e., including Norway, Iceland, and Liechtenstein) and applies to ships with a gross tonnage (GT) of 5,000 or more that transport passengers or goods for commercial purposes, regardless of their Flag. The regulation covers the following:

- 100% of the energy used in European/EEA ports and for voyages between European/EEA ports.
- 50% of the energy used for voyages arriving in European/EEA ports from non-European ports or vice versa, and for voyages to and from remote regions of the EU

Targets will ensure that the GHG intensity of fuels used in the sector will gradually decrease over time.

3.1.2.3. Requirements

Starting from 2025, an annual average greenhouse gas (GHG) intensity index must be calculated for each ship, which must not exceed a target value that will decrease significantly over the years (from 2% in 2025 to 80% in 2050). The calculation of the GHG intensity index requires dividing the total emissions of CO_2, CH4, and N2O by the energy used by the ship during the reference year. If the GHG intensity index exceeds the target, the company must pay a penalty proportional to the cost of renewable and low-carbon emission fuels that the ship should have used to comply with the regulation. However, the regulation allows for the borrowing or baking of a ship's compliance surplus between two reference periods and for the pooling of two or more ships, even from different Companies. Compliant ships (i.e., with a GHG intensity index below the target or with paid penalties) must have a FuelEU Document of Compliance on board.

It is important to note that the possibility of forming ship "pools" promotes the use of alternative fuels, particularly biomethane or other biofuels that, when used on a limited number of ships, can still meet the standard, or mitigate the impact on the entire fleet.

Starting from 2030, container ships and passenger ships berthed in EU/EEA ports subject to the "Alternative Fuels Infrastructure Regulation" (under development) must connect to onshore power supply (OPS) systems and use them to meet all energy needs while at berth unless:

- They stay at the quay for less than two hours
- They use zero-emission technology (definition still subject to working groups)

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- They cannot connect due to compatibility/unavailability of connection points
- They need to carry out maintenance/functional tests
- There are safety/emergency reasons

If this requirement is not met, the company is required to pay a penalty calculated based on the hours spent in port and the total electricity demand of the ship while berthed.

EU/EEA Member States may exempt:

- Ice-class ships (IA or IA Super or equivalent) until December 2034.
- Passenger ships (other than cruise ships) when traveling between ports of the same EU/EEA State
- to/from islands with a population of fewer than 200,000 permanent residents, until December 2029.
- Specific routes between ports located in remote regions, until December 2029.
- Voyages (and related stay in port) undertaken by passenger ships as part of transnational public service obligations, until December 2029.
- Until December 2029, specific routes between EU continental ports and ports on an island of the same
- Member State operated by passenger ships providing maritime transport services under a public service obligation/contract and operating before the Regulation comes into force.

The FuelEU Maritime is based upon a lifecycle, goal-based, and technology-neutral approach, offering operators the freedom to decide which fuels to use based on ship-specific / operation-specific profiles, introducing some flexibility to find suitable compliance strategies and rewarding early investment in energy transition.

The FuelEU Maritime will enter into force from 1 January 2025 except for Articles 8 and 9 on Monitoring plans which shall apply from 31 August 2024.

3.1.3. Considerations on the regulatory framework

The decarbonization measures of the IMO and the EU are independent of each other and are based on two different approaches: while the IMO currently requires ships to comply with the mandatory requirements of the MARPOL Annex VI Convention (otherwise, the ships will not be allowed to operate), the EU imposes payment for equivalent CO_2 emissions and penalties for non-compliance on the principle of "polluter pays."

This difference in approach makes it extremely difficult for both shipbuilders and shipowners to identify a ship platform that can meet the needs of both regulations. It is urgently necessary to harmonize both regulations to have a single global objective that makes the performance index on which the ship platform should be developed unequivocal. The current dichotomy makes the decarbonization process difficult and significantly slows it down due to the high level of uncertainty it generates, limiting the propensity to invest in innovative technologies. Both IMO and EU regulations should achieve the same objectives and use the same tools. This harmonization is necessary to avoid the risk of having different rules and regulations regarding the same "tools" used and recognized for the calculation and measurement of:

- LCA (Life-Cycle Assessment)
- GHG saving calculation
- Sustainability criteria
- Certification systems

Moreover, European measures are regional and only affect traffic to/from and within Europe. In this sense, these measures may create market distortions and a loss of competitiveness for the European

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maritime sector and related industries. For this reason, it is of utmost importance that if an international agreement (at the IMO level) is reached on issues already regulated at the EU regional level, European rules should be revised to align with it. This is in line with what has already been clarified by European institutions and would prevent duplication of obligations and administrative burdens for ships operating in Europe.

It is further emphasized that the application of regional (EU) rules imposes a managerial burden on shipping companies and, more importantly, market distortion.

In both regulations (IMO and EU), there are many implementation aspects still unclear, or leaving room for interpretation, preventing a clear understanding by shipbuilders and operators. It is also crucial to develop and prepare rules for the training and education of crews who will operate on ships powered by alternative fuels. Almost all alternative fuels, to be managed safely, require a much higher level of preparation and competence than current fuels. The risk is to have technologies and alternative fuels available but not enough maritime personnel trained to handle them safely.

Therefore, all aspects must be considered as soon as possible so that all stakeholders (shipowners, operators, fuel producers, ports, Recognized Organizations, verifiers, and Flag Administrations) have a clear understanding of how to comply with their obligations.

Another critical aspect of international regulations is to adopt a uniform approach, agreed upon at the IMO level, to avoid each Administration making different decisions, introducing disparities in treatment for ships flying different flags, such as calculating CII values differently, making them incomparable.

In this regard, it would be advisable for unified interpretations and circulars approved by the MEPC to be consistently applied internationally by IMO Member States.

Several documents submitted to the MEPC highlighted that any technical and/or economic measure alone or as part of a basket of measures is ineffective in achieving decarbonization goals unless the availability of future fuels, innovative technologies, engines at affordable prices, and onboard personnel trained for their safe use are guaranteed.

Finally, both at regional and international levels, funds collected through economic measures can be used, for example, to incentivize first movers, promote R&D projects, and finance infrastructure for alternative fuels. It should be emphasized that in the drafts of the delegated acts, the European Commission has provided that a portion of the Innovation Fund funded by the proceeds from the EU ETS be allocated to support the decarbonization of the maritime sector.

3.1.4. Regulatory mapping of alternative fuels

The Maritime Safety Committee, at its 107th session, agreed to include in its biennial agenda, a new output for the development of a safety regulatory framework for the reduction of Greenhouse Gas (GHG) emissions from ships using new technologies and alternative fuels (under the coordination of the US). The key terms of reference are (MSC108/5, 2024):

- to conduct an assessment for each identified fuel and new technologies (e.g. the state of knowledge of risks and the technical considerations of solutions, hazards and risks, and risk control measures) concerning persons, ships (newly built and converted), and applicable operations for these, from e.g. projects applying alternative design and approval process where permitted, and
- to develop a record for safety obstacles and gaps in the current IMO instruments that may impede the use of alternative fuel or new technology.

This Group developed a summary list of alternative fuels and provided comprehensive references, background, and detail to support the assessments for any of the fuels or technologies being considered. Those references have been compiled and saved on IMO Space for further ongoing

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consideration. Document (MSC108/5, 2024) offers views and comments on the risks posed by several alternative fuels and new technologies under consideration by the maritime industry. Information in this reference has been used to initially populate "description" and "risks/hazards" fields in the annex for those fuels and technologies that are discussed in the document. Moreover, a coding system has been used for the regulatory mapping, whereby:

- Low (red colour coded): Indicates the absence of related marine standards, regulations and/or interim/final guidelines with required work yet to start.
- Medium (orange colour coded): Indicates the availability of work in progress or approved (waiting for adoption) related marine standards, regulations, and/or approved interim/final guidelines.
- High (green colour coded): Indicates the availability of related marine standards, adopted regulations, and/or adopted interim/final guidelines.

It is evident that the progress of this IMO Group (participated by RINA) in conducting an assessment for each identified fuel and new technology and developing a record for safety obstacles and gaps, may introduce revised criteria to be progressively adopted for regulatory compliance of newbuilds and retrofits. Such activities will be constantly monitored, and RINA will keep the MARPOWER Consortium updated on the progress and any possible consequences for the project. The regulatory mapping of alternative fuels can be found in Table 2.

Table 1. Fuel regulatory mapping 1

FUELS	EXTERNAL STANDARDS	IMO SAFETY- SOLAS	IMO ENVIRONMENT-MARPOL
Methyl Alcohol (Methanol)	***Marine standards in progress*** Marine standards in progress ISO/AWI 6583 "Specification of methanol as a fuel for marine applications" is under development. Currently, IMPCA Methanol reference specification and ASTM D1152 standard are used when specifying methanol quality.	***High regulatory readiness level*** SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively SOLAS Ch II-1 Part F (Alternative design and arrangement) – MSC.1/Circ.1212/Rev.1 and MSC.1/Circ.1455 The IGF Code does not cover methanol as fuel but MSC.1/Circ.1621 Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel have been developed.	***Low regulatory readiness level*** Methanol is assigned category Y as per the IBC Code, meaning it presents a hazard to either marine resources or human health. MARPOL Annex II requirements do not apply for spill and discharges of methanol as fuel. ***High regulatory readiness level*** MARPOL Annex VI regulates emissions of CO_2 and NOx

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Table 2. Fuel regulatory mapping 2

FUELS	EXTERNAL STANDARDS	IMO SAFETY- SOLAS	IMO ENVIRONMENT- MARPOL
Methane	***Marine standards available*** ISO 23306:2020 "Specification of liquefied natural gas as a fuel for marine applications"	***High regulatory readiness level*** SOLAS Chapter II regulates methane (LNG) as fuel through SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and the IGF Code.	***High regulatory readiness level*** MARPOL Annex VI regulates emissions of CO2 and NOx ***Low regulatory readiness level*** Fugitive emissions of methane are not currently regulated under MARPOL Annex VI.
Ammonia	***No marine standards available*** No marine standards available	Medium regulatory readiness level SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively SOLAS Ch II-1 Part F (Alternative design and arrangement) – MSC.1/Circ.1212/Rev.1 and MSC.1/Circ.1455 IGC Code identifies ammonia as a toxic product and prohibits toxic cargo from being used as fuel. The IGF Code does not cover ammonia as fuel. Draft interim guidelines for the safety of ships using ammonia as fuel are currently under development.	***Low regulatory readiness level*** "Ammonia aqueous" is assigned category Y as per the IBC Code, meaning it presents a hazard to either marine resources or human health. MARPOL Annex II requirements do not apply for spills and discharges of ammonia as fuel. ***High regulatory readiness level*** MARPOL Annex VI regulates emissions of NOx ***Low regulatory readiness level*** Other combustion products e.g., N2O are not currently regulated under MARPOL Annex VI.

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Table 3. Fuel regulatory mapping 3

FUELS	EXTERNAL STANDARDS	IMO SAFETY- SOLAS	IMO ENVIRONMENT-MARPOL
Hydrogen	***No marine standards available*** ISO 14687:2019 "Hydrogen fuel quality – Product specification"	***Medium regulatory readiness level*** SOLAS Chapter II regulates low-flashpoint fuels (< 60°C) through SOLAS Ch II-1 Part G (low-flashpoint liquid fuel or gas) and IGF Code; alternatively SOLAS Ch II-1 Part F (Alternative design and arrangement) – MSC.1/Circ.1212/Rev.1 and MSC.1/Circ.1455 The IGF Code does not cover hydrogen as fuel. Resolution MSC.420(97) provides interim recommendations for the carriage of liquid hydrogen in bulk. Draft interim guidelines for the safety of ships using hydrogen as a fuel are currently under development.	***High regulatory readiness level*** MARPOL Annex VI regulates emissions of NOx

3.2. Classification Society Rules and Guidelines

MARPOWER Project aims to develop and validate a highly efficient two-shaft gas turbine - based energy conversion system designed to operate on sustainable fuels in maritime transport. Therefore, the two main technologies that will be developed are the gas turbine and steam turbine.

The general requirements for design and construction, arrangement installation as well as material tests, workshop inspection, testing, and certification for gas and steam turbines can be found in RINA REP3 Part C Chapter 1 Section 5 and RINA REP3 Part C Chapter 1 Section 4, respectively.

3.2.1. Steam Turbines

When it comes to Steam Turbines the Section to be addressed is Sec.4 of the RINA Rules, applying to all the propulsion turbines and those intended for auxiliary services, also for the auxiliary turbines driving electric generators are to comply with the requirements in Chapter 2 as well.

All the information regarding the design and materials to be used is to be verified by the Classification Society as well as submitting documentation on the turbine. The documentation that is to be presented to RINA to recognize as safe to be installed on board is reported in the table seen in Figure 12 below.

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No.	A/I (1)	ITEM
1	I	Sectional assembly
2	A	Rotors and discs, revolving and stationary blades for each turbine
3	A	Fastening details of revolving and stationary blades
4	A	Casings
5	A	Schematic diagram of control and safety devices
6	I	General specification of the turbine, including an operation and instruction manual
7	I	Maximum power and corresponding maximum rotational speed, and the values of pressure and temperature at each stage
8	A	Material specifications of the major parts, including their physical, chemical and mechanical properties, the data relevant to rupture and creep at elevated temperatures, when the service temperature exceeds 400°C, the fatigue strength, the corrosion resistance and the heat treatments
9	I	Distribution box
10	A	Strength calculations of rotors, discs and blades and blade vibration calculations
11	A	Where the rotors, stators or other components of turbines are of welded construction, all particulars on the design of welded joints, welding conditions, heat treatments and non-destructive examinations after welding
(1) A = to be submitted for approval in four copies I = to be submitted for information in duplicate		

Figure 12. List of documentation

3.2.2. Certification Schemes

Where certification of a generic product is concerned, Chapter 2 of the RINA Rules for Testing and Certification of Marine Materials and Equipment, NC/C.23 specifies the procedures to be applied in each possible phase (e.g., document reviews, inspections, onboard tests, etc.), even though a specific product may not deal with all the phases reported in general. Specifications for reviews and inspections include the following aspects:

Approval of technical documentation: the Manufacturer needs to prepare the technical documentation according to applicable Class Rules and submit it to RINA. Understanding of design, manufacturing, and operation processes is required to be guaranteed by the submitted documentation, to assess compliance with Rules and applicable standards. Among all the technical documents possibly required, the most common consist of:

1. general description of the product
2. the conceptual design, the component schemes, the manufacturing drawings as well as standards
3. explanatory notes and descriptions referring to the drawings, schemes, and operation of the product
4. computations and assumptions underlying the design procedure
5. manuals addressing installation, usage, and maintenance
6. control and test procedures applied to the product

Eventually, attestations and certificates related to components and manufacturing/inspecting/monitoring methods shall be included in the design documentation.

- Type tests: they consist of more extensive tests compared with standard production tests and aim at validating prototype design. They can be applied to purpose-built prototypes or products randomly sampled within the production line. Tests can be carried out at either the Manufacturer’s facility, RINA laboratory, or independent laboratory. In case tests are performed at an independent laboratory, a witness from a RINA Surveyor is required, unless stated otherwise, with complete reporting to be submitted to RINA for approval or information.

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- Design approval: the Manufacturer shall prepare technical documentation in accordance with applicable Rules and Standards. Generally, the design documentation is to include:
    1. general description of the product
    2. conceptual design, schemes of components as well as sub-assemblies, and the Standards adopted for manufacturing. Additional descriptions and explanations of drawings and schemes may be required to improve understanding.
    3. description of the operation and limitations of the product
    4. analyses, computations, and examinations related to the design process
    5. control and test procedures
    6. manuals addressing installation, use, and maintenance
- Manufacturer and manufacturing process approval: details on the requirements related to the approval of Manufacturers and manufacturing processes are available in the RINA “Rules for the approval of Manufacturers of materials”.
- Material testing: material testing shall be carried out according to applicable Rules and Standards. Surveyors need to attend material testing if required by the Rules and shall be allowed to access a certificate of material testing. The raw material supplier must provide the chemical composition of the materials, and the corresponding analyses shall be carried out in adequately equipped laboratories by qualified personnel. All the testing and measuring equipment shall be kept in good condition as well as properly calibrated.
- Attendance and final inspection and testing at the workshop: free access of Surveyors to all the production phases, collection of test samples and internal control shall be guaranteed. Final inspection of products encompasses document review, visual examination, dimensional check, and non-destructive examination, as far as applicable. Instead, equipment and materials to be installed onboard are to be tested through a procedure similar to tests at workshops, integrated with all the products or materials they are part of. In particular, testing may include, depending on the complexity of the product as well as on application standards:
    1. final tests of the completed product (e.g., hydrostatic tests for pressure vessels)
    2. performance tests (e.g., running tests for reduction gears)
    3. collection of data (e.g., performance data for energy systems)

Three main certification schemes are identified by the Rules:

1. individual or traditional inspection scheme: it is applicable if inspection and testing are carried out as prescribed in the Rules and are witnessed by a RINA Surveyor.
2. alternative inspection scheme: it involves a properly qualified Manufacturer in the inspection, testing and certification processes. The type of product, its mass production, and the quality control plans of the Manufacturer are considered in setting up the alternative inspection scheme. Qualification of Manufacturers must be periodically checked.
3. type approval scheme: it is applicable either when product certification is required by the Rules or in case no specific requirements exist, i.e. certification is requested by the Manufacturer on a voluntary basis. In the latter case, particular standards and/or specifications agreed with the Manufacturer are adopted by the Class Society for product approval. Type Approval certificate can be optionally combined with a Production Control Certificate, which in turn is divided into two schemes:
    a. Product verification
    b. Production quality assurance, for Manufacturers having a certified Quality Assurance System

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Generally, the type approval certificate remains valid for five years, despite variations that can arise depending on specific requirements of the reference Standards the certification is based on.

- MED Type Approval scheme: it concerns products listed in the implementing Regulation of the European Directive 2014/90/EU and, simultaneously, intended to be installed on vessels flying European Community flags. These products need to be certified in accordance with the requirements of the RINA "Rules for the certification of marine equipment in accordance with European Directive 2014/90/EU and subsequent amendments". Alternatively, they can be certified using equivalent Rules developed by other Class Societies.

In the following, deep insight into the two main certificates possibly issued by RINA for either equipment or software products is provided, focusing on the steps and requirements the certification process relies on. Thus, attention is paid to:

- Type Approval Certificate (TA)
- Prototype Design Assessment Certificate (PDA)

Both certification schemes can be applied either when product certification is required by the Class Rules or in case no specific requirements exist, i.e. certification is requested by the Manufacturer on a voluntary basis. In the latter case, industrial standards and/or specifications agreed with the Manufacturer are adopted for approval.

3.2.3. Type Approval Certification

Type Approval certificate is compulsory for products covering essential services to be fitted on board ships and consists of the approval of the product design, including drawing appraisal, and prototype test performance. Nevertheless, Type Approval can also be requested on a voluntary basis by the Manufacturer. The Type Approval for a specific product is assessed once since the certificate successively remains valid for all the subsequent products dealing with identical design and manufacturing processes. For this reason, Type Approval is a commercially valuable option for Manufacturers who intend to broaden their selling activities. In detail, since it gives evidence of compliance with performance as well as safety requirements, Type Approval can be useful to facilitate product acceptance by potential buyers.

The type approval certification procedure consists of the following operational steps:

- the Manufacturer forwards an application to RINA for requesting Type Approval
- technical documentation requested by applicable Rules is thoroughly examined
- technical drawings are preliminarily approved if required by the Rules
- test campaign for prototypes or sample products is defined according to the Rules or industrial standards
- the laboratory where to conduct tests is identified (Manufacturer's facility, RINA laboratory or independent laboratory). In particular, an initial audit and evaluation of the Manufacturer's production facility is first carried out as a starting point
- the type tests are conducted in the laboratory and reports containing the required information are generated
- the technical reports related to the testing activity are reviewed in detail
- the Type Approval certificate is issued, in case results obtained from the tests met industrial standards/specifications as well as rules

Successively, the Production Quality Assurance Certificate is issued. It remains valid for 5 years, subject to the positive outcome of periodical audits according to the following surveillance cycles:

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- An intermediate audit at the Manufacturer's facility is required in case of products for which testing shall be carried out by the Surveyor for each unit or batch
- At least an annual audit of the Manufacturer's production site is required in case of products for which testing of each unit or batch is not required to be attended by the Surveyor (e.g., sensors).

In the case of certification of software, the TA certificate is issued upon satisfactory outcome of design approval and prototype tests only. The initial audit of the software house and the issuance of a Production Quality Assurance Certificate are not required.

3.2.4. Prototype Design Assessment

This certification applies to products for which there are no specific requirements in the Class Rules. For this reason, Prototype Design Assessment Certification cannot be applied to products which are required to be Type Approved and can be requested on a voluntary basis by Manufacturers.

The approval process is established against standards/specifications agreed with the Manufacturer and shipowner installing prototypes onboard, according to a case-by-case approach.

The Prototype Design Assessment Certification consists of the two following steps:

- Design approval and prototype tests, intended to verify compliance of the product with the Manufacturer's specification and/or the applicable standards
- Issuance of the Prototype Design Assessment Certificate.

The procedure aims to verify that the performance of the product guarantees the service for which the shipowner intends to install and operate it onboard (fit for service). Furthermore, it must be ensured that the installation of the product on board does not have negative consequences due to the marine environment rather than land-based (marinization).

In general, the validity of Prototype Design Assessment Certificates lasts for 5 years, subject to possible changes in the reference Standards in terms of product requirements/specifications.

3.2.5. Certification Technical Documentation and Inspection Procedures

The Manufacturer needs to forward an application to the Classification Society and submit technical documentation for approval. Specifically, the technical documentation should allow a clear as well as precise understanding of the design, manufacturing, installation, and operation of the product.

Furthermore, compliance of the technical documentation with the Rules and the applicable Standards should be easily investigated.

In general, all information relevant to verify compliance with Rules and Standards is to be included in documentation and encompasses, as far as applicable:

1. General description of the product
2. Description of both the location and layout of the product onboard
3. The conceptual design, the building standard, the manufacturing and construction drawings as well as the schemes of components, sub-assemblies, etc.
4. All the specifications, descriptions, and explanations necessary for the understanding of drawings, schemes, and operation of the product
5. The results obtained by computations and examinations carried out during the design process
6. Preliminary test reports, if present

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7. Manuals for product installation, usage, and maintenance
8. Control and test procedures

No	Document
1	Technical specification of the system, including technical data as power output parameters including min./max. design voltage and current, information about min./max. temperature/pressure/rate of process air/cooling water/ventilation, etc.
2	List of mechanical and electrical components which are part of the system with specification of the pumps, compressors and fans.
3	P&I diagrams of systems conveying fluids, exhaust air/gas, cooling media, process air, technical water, ventilation and of other systems
4	Description of thermal insulation (if any), electrical heat tracing
5	System module / casing construction details with max. design pressure
6	Construction drawings of all components of the equipment considered as pressure vessel e.g., heat exchangers
7	Functional description of the system including at least its design, safety principles, auxiliary systems arrangement (e.g. cooling medium, process air, ventilation, venting, process water, as applicable)
8	Block diagram of the safety, alarm, control and monitoring system
9	Wiring diagrams of power supply and automation system
10	List of controlled and monitored parameters and cause and effect matrix with normal/emergency shutdown functions.
11	Electrical protection and hazardous zones categorization study with calculation according to IEC 60079-10 (using CFD simulations or empirical formula) and list of EX equipment with relevant EX certificates, as applicable.
12	Functional profile description of the system, highlighting if the power generation is used for essential or non-essential ship services according to IACS Unified Interpretation (UI) SC134
13	A FMEA according to the RINA (GUI23) "*Guide for Failure mode and Effect Analysis*" or other equivalent methods for the system installations
14	Type test reports including information about overview, adopted standards, test laboratory, test rig description, witnessing persons and final results.
15	Lifecycle operational, maintenance and inspection manual of the system

Figure 13. List of documentation

Additional documents to be possibly submitted are:

1. certificates related to components
2. certificates related to the product manufacturing/inspection/monitoring methods
3. any other document possibly required by the Classification Society to facilitate the assessment of compliance with Rules and Standards

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3.2.6. Type tests

Type tests aim at validating the design of the prototype. Generally, they are more extensive than tests required during normal production processes and may include destructive testing.

Type tests can be performed at either the Manufacturer's facility, independent laboratory, or Class Society laboratory (if available). In case tests are performed at an independent laboratory, they need approval from the Class Society and a witness from a surveyor is required, unless stated otherwise in the applicable Rules. Tests are to be witnessed by a Class Society Surveyor also when the campaign is carried out in the Manufacturer's facility unless otherwise stated.

Test reporting must contain the following basic information:

1. description and identification of the product
2. identification of the testing specifications
3. description of testing setup and measuring instruments (where the instruments are concerned, the identification number and the last calibration date shall be reported)
4. environmental conditions being present during the test campaign
5. test results, including any negative results.

3.2.7. Issuance of Certificate

Once the technical documentation has been approved and the prototype has been validated by type tests, the Class Society can issue a Prototype Design Assessment Certificate. It must be reminded here that a certificate can be issued when compliance with reference specifications and/or Standards previously accepted by the Manufacturer, Class Society, and shipowner is clearly proved.

However, further supplementary verifications can be required, if appropriate, within a twofold aim:

1. ensuring that the product performances guarantee its fit for service onboard
2. verifying that negative consequences on performances are avoided when the product is installed onboard (marinization and integration), hence complying with RINA rules.

Detailed information on the requirements for inspection and testing of products at the workshop before their delivery to the shipyard is contained in the RINA Rules for Testing and Certification of Marine Materials and Equipment, NC/C.23, Ch. 6.

3.2.8. Approval in Principle

In this section Approval in Principle (AIP) of novel technologies is presented in detail.

Novel technology coincides with technology that is not proven, i.e. documented track record for its defined application does not exist. According to this definition, the concept of novel technology encompasses the application of both proven technology in a new environment and unproven technology in a known environment.

The AIP procedure applies to components, equipment, and systems, which can be defined as novel technology. Since novel technologies are generally not adequately covered by established codes and procedures, a twofold verification is requested:

- the concept underlying novel technology needs to be feasible and realistic
- the intent of the applicable rules and regulations is to be met

Since AIP is a systematic process of verification that includes examination of the design procedure and engineering analyses, it depends on the engineering phase of the novel technology, potentially ranging

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from conceptual design to complete design. Complete design possibly includes tests on prototypes whereas detailed testing programs on full-scale products are typically not encompassed in an AIP procedure, hence they are carried out in successive engineering phases.

The AIP verification program needs to be focused on novel elements or novel applications of known elements, hence identifying where the novelty is located constitutes the preliminary step of AIP.

The systematic application of the AIP procedure traditionally consists of the following steps:

1. Description of the technology to be qualified
2. Detailed assessment of the operational conditions and corresponding constraints related to the novel technology
3. Definition of the functional requirements the novel technology deals with
4. Risk and safety assessment aimed at identifying, ranking, and controlling hazards or failures which affect the novel technology
5. Engineering analyses and, possibly, tests on prototypes as supporting evidence to demonstrate that the design of the novel technology fulfils the requirements for its intended service. In detail, the novel technology must be shown fit-for-service, i.e. it fulfils functionality, safety, reliability, availability, and maintainability requirements which were defined in the qualification process.

Official statement of fitness-for-service can be obtained by the Technology Qualification Process (TQP), in the form of a certificate, class notation, or other equivalent documents (see the section below for more details on TQP). In the event engineering analyses and prototype tests are not available, the feasibility of novel technology may be demonstrated using alternative methods and providing proper justifications.

The typical documentation to be produced during an AIP process consists of, as far as applicable:

- Design criteria of the novel technology
- Applicable rules and regulatory framework
- Detail drawings and schemes
- Technical specifications ensuring fitness-for-service
- Engineering analyses performed during the design procedure
- Reports on risk and safety assessment

Finally, following the evaluation of all the documents reported above, the AIP certificate can be issued, thus confirming that the novel technology meets the general requirements for its intended service.

Details on the systematic approach underlying the Approval in Principle of new technologies which are not adequately covered by established codes and procedures can be found in the RINA Guidelines GUI19 “Guide for Approval in Principle of Novel Technologies” or equivalent. In addition, details on the systematic approach to the qualification of novel technology, to ensure that it is fit for its intended Service can be found in the RINA Guidelines GUI16 “Guide for Technology Qualification Processes” or equivalent. On the other hand, risk assessment involved in the AIP procedure is to be conducted according to the methods described in the RINA GUI015 “Guide for Risk Analysis” and GUI23 “Guide for Failure Mode and Effect Analysis (FMEA)” or equivalent.

Systems to be installed on board for demonstration purposes (e.g., demo prototypes) require at least an Approval in Principle. Therefore, the required documents outlined above need to be submitted for consideration and approval to a Class Society, which in turn may witness compliance with the applicable rules and regulations as well as applicable Standards.

Successively to the AIP procedure, the assessment of the integration of the novel technology onboard the ship takes place.

As said above, novel technologies are not adequately covered by established codes and procedures. Therefore, they need to be qualified through a specific procedure called the Technology Qualification

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Process (TQP), to prove that novel technologies meet all the requirements for their intended use (fitness-for-service concept).

It must be reminded here that novel technology has no documented track record for a defined application. Thus, both new technologies applied in a known environment and known technologies applied in a new environment are included within the novel technology concept.

Novel technologies are considered fit for service when supporting evidence demonstrates that they fulfill all the requirements of functionality, safety, reliability, availability, and maintainability defined in the Technology Qualification (TQ) basis, i.e. specified criteria, boundary conditions, and interface requirements.

The systematic and documented process of qualification encompasses an examination of the design, engineering analyses, and testing programs.

Preliminary steps for the evaluation of the novel technology are reported below:

- the novel technology is subdivided into subsystems and components by means of system schematics and P&ID. Particularly, attention is focused on manufacturing, installation, and operation processes concerning subsystems and components.
- the possible novelty of each subsystem and component is investigated
- the main challenges and uncertainties faced by the novel technology are identified

The main steps the TQP is based on are listed in the following:

- risk and safety assessment aimed at identifying, ranking, and controlling failure modes which possibly compromise the fitness for service of the novel technology
- engineering analyses are carried out to demonstrate that all specific requirements for intended service are met by the design of the novel technology
- measurements and tests are needed to support evidence that the novel technology fulfills the specified requirements for its intended service
- functionality assessment aimed at ensuring that the functional requirements as well as the safety, reliability, availability, and maintainability criteria are fulfilled

Where the first step is concerned, the risk and safety aspects of the novel technology are to be assessed by applying well-established techniques to investigate compliance with regulations. Attention is here focused on the events possibly affecting the fitness for service of the novel technology as well as its interfaces with ship systems based on already proven technologies.

The risk assessment is typically carried out as follows:

- hazards are identified
- risks are assessed against the defined acceptance criteria and interfaces with other ship systems
- risk control options (RCO) are defined. In detail, strategies of prevention, mitigation, or a possible combination of them are built up in case the risk is to be reduced according to the ALARP principle to settle on acceptable levels
- the overall study is documented

Examples of potential hazards to be accounted for within the risk assessment are:

- extreme weather, influencing maximum ship motions, accelerations, inclinations, temperatures
- mechanical damage, possibly leading to liquid/gas release or progressive ship flooding
- fire and/or explosion
- release of flammable or toxic gases
- release of cryogenic liquids or gases
- loss of electrical power supply with a negative impact on ship essential services

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- failures related to single or possibly multiple systems onboard

Technical outcomes provided by the systematic application of TQP include:

- Description of the technology to be qualified together with its boundaries
- Detailed information on the operational conditions and corresponding constraints related to the novel technology
- Definition of the functional requirements the novel technology deals with
- Formulation of the safety, reliability, availability, and maintainability criteria to be adopted for the novel technology

Information reported above is successively used as input to define specifications concerning the design, manufacturing, and installation of the novel technology. Analogously, the maintenance schedule is defined from a lifecycle perspective.

An official statement declaring that novel technology is fit for service on the TQ basis is finally issued as a positive outcome of the TQP, in the form of a certificate, class notation, or equivalent document. Appropriate documentation reported below must be included to support evidence of the fitness-for-service concept:

- system specifications, drawings, technical reports, design calculations
- applicable rules, regulations, and standards
- survey requirements for construction/installation/commissioning
- operational instructions in normal and in emergencies
- maintenance requirements

Additionally, requirements in terms of crew training and/or personnel certification are to be possibly inserted in the TQP documentation.

Detailed insight into the application of the Technology Qualification Process can be found in the RINA guidelines (GUI16) “Guide for Technology Qualification Processes” and both the IMO MSC/Circ. 1002 “Guidelines for alternative design and arrangements for fire safety” and the IMO MSC.1/Circ.1212 “Guidelines on Alternative Design and Arrangements for SOLAS Ch II-1 and III” shall be taken into account.

3.2.9. Marinization

The purpose of marinization is to ensure that the installation of novel technology onboard does not have negative consequences on its operation and safety, due to the marine environment compared to land-based applications. Therefore, where marinization is concerned, the design, installation, and operation of the novel technology needs to comply with Class Rules (i.e., RINA Rules Part C Section 1 Part 2), which focus on three main aspects:

- Marine ambient conditions: the marine environment is typically characterized by salt-bearing, wet and possibly very hot ambient conditions. Thus, all the types of machinery and systems installed onboard are required to be designed to operate properly under the ambient conditions reported in Figure 14. This is valid for all the machinery and systems covered by the Rules unless otherwise specified.

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AIR TEMPERATURE	
Location, arrangement	Temperature range (°C)
In enclosed spaces	between 0 and +45 **(2)**
On machinery components, boilers In spaces subject to higher or lower temperatures	According to specific local conditions
On exposed decks	between -25 and +45 **(1)**

WATER TEMPERATURE	
Coolant	Temperature (°C)
Sea water or, if applicable, sea water at charge air coolant inlet	up to +32
(1) Electronic appliances are to be designed for an air temperature up to 55°C (for electronic appliances see also Chapter 2). **(2)** Different temperatures may be accepted by the Society in the case of ships intended for restricted service.	

Figure 14. Ambient conditions

- Operation in inclined positions: the rolling and pitching motions of the vessel must not negatively influence the operation and safety of all the systems installed onboard and covered by the Rules. Specifically, main and auxiliary pieces of machinery providing essential services onboard the vessel (i.e., propulsion and safety services) shall be designed to operate when the ship is upright and when inclined at any angle of the list either way and trimmed by bow or stern. Details on the heeling angles and trim, either positive or negative, to be considered during the design are reported in Figure 15. Machinery with a horizontal rotation axis is generally to be fitted on board with such axis arranged along ships. If this is not possible, the Manufacturer is to be informed at the time the machinery is ordered.

Installations, components	Angle of inclination (degrees) **(1)**			
	Athwartship		Fore and aft	
	static	dynamic	static	dynamic
Main and auxiliary machinery	15	22,5	5 **(4)**	7,5
Safety equipment, e.g. emergency power installations, emergency fire pumps and their devices Switch gear, electrical and electronic appliances **(3)** and remote control systems	22,5 **(2)**	22,5 **(2)**	10	10

(1) Athwartship and fore-and-aft inclinations may occur simultaneously.
(2) In ships for the carriage of liquefied gases and of chemicals the emergency power supply must also remain operable with the ship flooded to a final athwartship inclination up to a maximum of 30°.
(3) No undesired switching operations or operational changes are to occur.
(4) Where the length of the ship exceeds 100m, the fore-and-aft static angle of inclination may be taken as 500/L degrees, where L is the length of ship, in metres, as defined in Pt B, Ch 1, Sec 2, [3.1.1].

Figure 15. Inclination of ship

- Vibrations: Special consideration is to be given to the design, construction, and installation of propulsion machinery systems and auxiliary machinery so that any mode of

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their vibrations shall not cause undue stresses in this machinery in the normal operating ranges.

All the requirements reported above assume that the novel technology is installed on commercial vessels.

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4. Ship integration

4.1. Introduction for ship integration

The goal of the MARPOWER project is to develop and validate a highly efficient two-shaft gas turbine-based energy conversion system. This power generation system is designed to produce 5.8 MW of electrical power with an overall efficiency of 54%. The specific application within the MARPOWER project focuses on integrating this system on board a cruise ship. This deliverable outlines the constraints, both regulatory and technical, that must be considered for successful integration onboard a cruise ship.

This deliverable includes:

- Key parameters for the system design and integration
- Elements regarding the main interfaces available on-board the reference ship
- Elements regarding the reference ship electrical network
- Elements regarding the reference ship automation system.

It should be noted that in this report, the term "gas turbine system" refers to the complete COGES installation, which includes both the gas turbine and the associated steam turbine. A reference ship has been defined by the shipyard for the MARPOWER project, and this report is based on the characteristics of this specific vessel.

4.2. Key parameters

4.2.1. Electrical efficiency

To be competitive with engines, the turbine system efficiency should be at least equivalent to engine ones at high load. Ideally, the turbine system (gas turbine and steam turbine) electrical net efficiency is:

- $\eta \geq 54\%$ at peak efficiency load

Heat recovery is also expected on gas turbine exhausts for energy efficiency optimization.

4.2.2. Multi-fuel requirement

4.2.2.1. Dual-fuel requirement

The SRTP is a requirement under SOLAS regulations for ships with a length of 120 meters or more. The objective is to ensure that passengers can be safely transported to the nearest port in the event of severe damage, such as a fire or flooding of a watertight compartment. According to SOLAS, all essential onboard equipment must remain operational even if a critical compartment (including a machinery room) is affected by severe damage. The SRTP scenario, including power requirements and the distance to the nearest port, is defined in collaboration with the ship owner.

For SRTP purposes, marine gas oil (MGO) is typically chosen as the fuel, as it has fewer storage constraints compared to other fuel types.

Once a certain nominal power threshold is reached, the gas turbine is considered essential equipment onboard. In this context, a dual-fuel capability for the MARPOWER turbine would be advantageous, as many existing maritime gas turbines are dual-fuel. In emergencies (such as an Emergency Shutdown

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or gas process malfunction), MGO would serve as the backup fuel, allowing for an immediate switch from the primary fuel to MGO.

4.2.3. Class society approval

Class society approval is required for the integration of the system onboard a ship. The choice of class society is determined by the ship owner and may include organizations such as RINA, DNV-GL, Bureau Veritas, Lloyd's Register, and others. Since RINA is a project partner, all the rules outlined below will follow RINA's rules.

The gas turbine system supplier must obtain class approval for the system itself before it is delivered to the shipyard.

4.2.4. Compacity (kW/m3)

The design of the gas turbine system should be optimized for high compacity (kW/m3), as a more compact system facilitates easier integration and aligns with the cruise ship industry's demand for maximizing available space, such as passenger cabins and public areas.

Compacity is defined as the power produced by a system, relative to its total volume, including auxiliaries, air supply casing, maintenance spaces, and other components. Optimising compacity involves:

- Direct optimisation: Reducing the volume of power production equipment to make the system more compact.
- Indirect optimisation: Reducing air supply requirements, which can decrease the diameter of air supply piping, or minimizing the volume of auxiliary systems.

4.3. Regulation, rules, and applicable documents

4.3.1. Class rules

RINA rules are considered in the MARPOWER project.

Main rules defined for a RINA-classified ship:

- Rules for the classification of ships: pt C, Ch1, Sec 1 – General requirements
- Rules for the classification of ships: pt C, Ch 1, Sec 5 – gas Turbines
- Rules for the classification of ships: pt C, Ch2, Sec 2 – General design requirements

The main IMO rules are listed below. The main IMO rules ship and turbine system should comply with:

- MSC/Res.97(73) - Adoption of the international code of safety for high-speed craft, 2000 (2000 HSC code)- Chap 9 – Machinery.
- MSC/Res.391(95) – International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code)

4.4. Certificate, technical documents, and sea trials

A system could be integrated on board a ship only if the system itself and its integration strategy are approved by the ship Class society. The main steps of this process are listed below.

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- System approval obtained by the system supplier

All systems integrated on-board should have the ship class society approval. This approval is obtained after a detailed analysis of the system design (sub-elements, materials, etc.), gas safety concept, and fire safety concept.

The system approval is obtained by the system supplier before the delivery to the yard.

- Factory acceptance test (F.A.T)

Factory Acceptance Test of the complete turbine system should be organized by the gas turbine supplier, before delivery to the shipyard. The F.A.T. detailed test procedures are defined by the system supplier, in collaboration with the ship class society and the yard.

- Commissioning, Tests, and sea trials

Commissioning, harbour tests, and sea trials are then organized by the yard in the presence of the gas turbine system supplier. Those tests aim to validate the performances of the system within the ship environment, and its compliance with Class rules and class requirements.

Final ship-owner and Class society approval of the equipment are given before the ship delivery.

4.5. Machinery room constraints

4.5.1. Machinery room arrangement and characteristics

4.5.1.1. Characteristics and location

General description:
On passenger ships, there are usually two engine rooms. The ship is designed for an autonomy of a few weeks with its main fuel.

Engine rooms are connected to casings, which is an internal duct for the technical pipes (machinery room inputs and outputs): exhausts, air supply, etc.

Ambient air in the machinery room:
The air is supplied to the lower deck machinery rooms is usually used for engine air supply and the machinery room ventilation.

Electrical equipment associated to the gas turbine system:
Ideally, the turbine electrical conversion system and automation system should be able to work in the usual machinery room without air-conditioning.

4.5.2. Vibrations and inclination

4.5.2.1. Vibrations

The vibration levels of systems installed in machinery rooms should comply with the following rules and guidelines:

ISO rules:

- ISO 20816-1/2016 “Mechanical vibration – Measurement and evaluation of machine vibration”: Part 1 (2016) “General guidelines”.

RINA rules:

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Location	Frequency range Hz	Displacement amplitude mm	Acceleration amplitude g
Machinery spaces, command and control stations, accommodation spaces, exposed decks, cargo spaces	from 2,0 to 13,2 from 13,2 to 100	1,0 -	- 0,7
On air compressors, on diesel engines and similar	from 2,0 to 25,0 from 25,0 to 100	1,6 -	- 4,0
Masts	from 2,0 to 13,2 from 13,2 to 50	3,0 -	- 2,1

Figure 16. Vibration levels[1]

4.5.2.2. Inclinations

Regarding ship movements (list, rolling, trim, and pitch), all systems, equipment, and components must be designed in accordance with the following guidelines.

RINA rules:

Type of machinery, equipment or component	Angles of inclination, in degrees (1)			
	Athwartship		Fore-and-aft	
	static	dynamic (4)	static	dynamic (5)
Machinery and equipment relative to main electrical power installation	15	22,5	5	7,5
Machinery and equipment relative to the emergency power installation and crew and passenger safety systems of the ship (e.g. emergency source of power, emergency fire pumps, etc.)	22,5 (2)	22,5 (2)	10	10
Switchgear and associated electrical and electronic components and remote control systems (3)	22,5	22,5	10	10

(1) Athwartship and fore-and-aft angles may occur simultaneously in their most unfavourable combination.
(2) In the case of gas carriers or chemical tankers, the emergency power supply must also remain operable with the ship flooded to a final athwartship inclination up to a maximum of 30°.
(3) No undesired switching operations or functional changes are to occur.
(4) The period of dynamic inclination may be assumed equal to 10 s.
(5) The period of dynamic inclination may be assumed equal to 5 s.

Figure 17. Inclination of ship[2]

4.5.3. Exhaust and vents

Exhausts:
In normal operation, the gas turbine system exhausts are not considered flammable. If in case of dysfunction, the exhausts may contain flammable gases, pipes are routed accordingly by the yard.

Vents:
Potential flammable gas released through venting lines will be routed properly by the yard to a safe area.

[1] Source: RINA rules
[2] Source: RINA rules

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The temperature of the vent flow should be as low as possible, whatever the function mode of the turbine (maintenance, ESD, emergency ESD, etc.).

4.5.4. Safety concept and integration on board

4.5.4.1. Definitions as per the IGF code

Table 4. Definitions

Area	Definition
Hazardous area	*Hazardous area* means an area in which an explosive gas atmosphere is or may be expected to be present, in quantities such as to require special precautions for the construction, installation, and use of equipment.
Non-Hazardous area	Non-hazardous area means an area in which an explosive gas atmosphere is not expected to be present in quantities such as to require special precautions for the construction, installation, and use of equipment.
Gas safe machinery	Gas-safe machinery spaces: Arrangements in machinery spaces are such that the spaces are considered gas-safe under all conditions, normal as well as abnormal conditions, i.e. inherently gas safe. In a gas-safe machinery space, a single failure cannot lead to a release of fuel gas into the machinery space.
Machinery room	Room on-board, in the machinery area, where are located the internal combustion engines (engine machinery rooms) or other machinery equipment.
Turbine room	Machinery room on-board, where is located the gas turbine system.

4.5.5. Gas turbine room

The gas turbine will be integrated into a standard machinery space, referred to as the gas turbine room. The safety concept for the gas turbine room will be developed in collaboration with the classification society.

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4.5.6. Maintenance

Maintenance on cruise ships is divided into two main categories: regular/preventive maintenance performed at sea during cruises and dry dock maintenance, which occurs every five years for more extensive operations.

Maintenance at sea must be carried out while other ship systems are operational and in safe conditions for maintenance personnel.

Dry dock maintenance typically lasts two weeks and is reserved for exceptional tasks, such as the servicing of heavy or large components.

4.6. Electrical network constraints

4.6.1. Rules and regulation regarding the electrical network

General specifications:
In general terms, the electric networks and electrical equipment should comply with:

- RINA rules: pt C, Ch2, Sec 2 – "General design requirements"

Explosive atmosphere:
Explosive areas are defined according to the Class society/IMO rules and, when the possibility is given in the rules, by the IEC 60079 standard. In all those areas, the equipment should be chosen in accordance with the classification and the gas mixture characteristics. ATEX certificates, corresponding to the directive 2014/34/UE shall be provided for the concerned equipment.

4.6.2. Gas turbine system auxiliaries

Gas turbine system auxiliaries (in supplier scope):
The gas turbine system should be independent, meaning that the auxiliaries of the system are powered internally. The power delivered to the ship in normal function is AC power.

4.6.3. Electrical room characteristics

The electrical electronic appliances and instrumentation equipment rules are designed to comply with the following guidelines:

- Rina Rules pt C, Ch2, Sec 2 – "General design requirement"

All the electrical equipment should be certified for marine application by class societies.

All equipment shall have a protection class IP44 so that it is possible to install them in electrical rooms or directly in the turbine room.

4.7. Automation and Control

Main interactions between the turbine system controller and the ship:

- Gas turbine system => Ship
    - o Turbine system main parameters for ship information: status, power delivered, potential failure identified, etc.

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    - Data acquisition (sensors, status, etc.) for data analysis and performance optimization.
- Ship => Gas turbine system
    - Ship basic monitoring of the gas turbine system, at least: starting order, emergency shut-down, shut-down sequence, operating modes selection
    - Power/load request.

4.8. Interfaces

The paragraph below lists the main interfaces with the ship:

4.8.1. Natural gas

Liquefied naturel gas composition is subjected to an LNG source and the bunkering place. There is no standard defining precisely the LNG composition.

4.8.2. Process air / ventilation air

The table below gathers the ventilation air characteristics for machinery rooms.

Table 5. Machinery room characteristics

Characteristic	Value
Machinery room temperature	• 0…+50 °C in engine rooms and casing
Ambient air relative humidity	1. Up to 95 %

4.8.3. Other utilities available on-board

Other utilities are available on-board the ship, a non-exhaustive list is available below:

- Compressed air
- Heat recovery networks
- Water cooling
- Nitrogen

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5. Life Cycle requirements

Considering the life cycle impacts related to traditional and alternative fuels in the maritime sector, as described in Chapter 3 Policy framework, in Task 4.3 of MARPOWER Project a comprehensive Life Cycle Assessment (LCA) and Life Cycle Costing will be developed, including not only the whole life cycle of the fuel, but focusing also on MECS system.

This section briefly describes the methodologies that will be applied to conduct LCAs and LCCs in Task 4.3, also specifying the objective and scope of the analysis and system boundaries. In addition, the main data to be collected (among the project partners and from literature) with the KPIs that will be calculated to evaluate the MECS from a sustainability (both environmental and economic) point of view are listed in the following paragraphs.

5.1. LCA and LCC methodology

Life Cycle Assessment (LCA) is a structured, comprehensive, and internationally recognised technique for assessing the environmental aspects of a product (i.e., good or service) and the potential environmental impacts throughout the product's life cycle. A product life cycle includes all stages of a product system, from raw material acquisition to the end of life, including extracting and processing of raw materials, manufacturing, distribution, use, and final disposal (i.e., 'cradle-to-grave' approach).

Figure 18: LCA and its stages[3]

Through the LCA study, it becomes possible to evaluate all production processes, with the results proving especially valuable for:

[3] https://green-business.ec.europa.eu/environmental-footprint-methods/life-cycle-assessment-ef-methods_en

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- describing the overall environmental impact of the production process.
- comparing the environmental impacts of different products with the same production process.
- identifying the life cycle steps having higher environmental impacts.
- supporting the design of new products or services.
- developing strategies for enhancing environmental performance.

The LCA methodology is regulated by the following standards and guidelines:

- ISO 14040: 2006 - Environmental management − Life Cycle Assessment − Principles and framework4;
- ISO 14044: 2006 - Environmental management − Life Cycle Assessment − Requirements and guidelines[5];
- ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance6, published by Joint Research Centre (JRC) of the European Commission;
- PEF/OEF Recommendation 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations[7].

Life Cycle Costing (LCC) is a method that summarises all costs associated with the life cycle of a product (or service) that are directly covered by one, or more, of the actors involved in the product life cycle (e.g., supplier, producer, user/consumer, end-of-life actor).

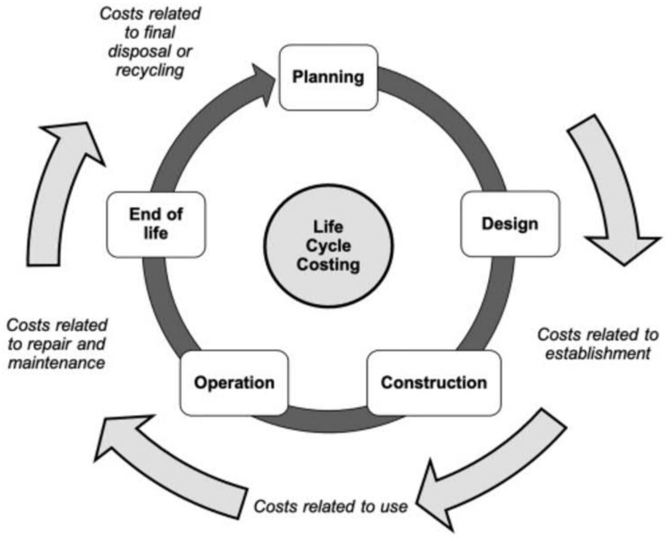

Figure 19: LCC and its stages[8]

[4] https://www.iso.org/standard/37456.html
[5] https://www.iso.org/standard/38498.html
[6] https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf
[7] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013H0179
[8] https://www.sciencedirect.com/topics/engineering/life-cycle-costing

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Life cycle costing can be used as a stand-alone tool or in the broader context of sustainable development of a product, together with environmental LCA and social LCA. Cost information for the entire life cycle is often useful in combination with LCA.

Basically, LCC analysis has a similar structure as an LCA in that it is conducted in parallel. Therefore, many aspects need to be defined and aligned with the decisions taken for the LCA to obtain an overall consistent analysis.

LCC can be used to understand the cost drivers of a product system, to identify improvement options as well as to validate pricing strategies.

The LCC methodology is regulated by the standards mentioned before (ISO 14040:2006 and ISO 14044:2006) and by the guidance "SETAC Guidelines: Environmental Life Cycle Costing: A code of Practice[9].

5.2. Goal and scope of the analysis and system boundaries

LCA and LCC and methodologies follow the Life Cycle Assessment framework defined in the ISO 14040 and ISO 14044 standards. The analysis consists of four steps: Goal and Scope Definition, Life Cycle Inventory, Impact Assessment and Interpretation, as shown in the Figure 20, taken from ILCD Handbook.

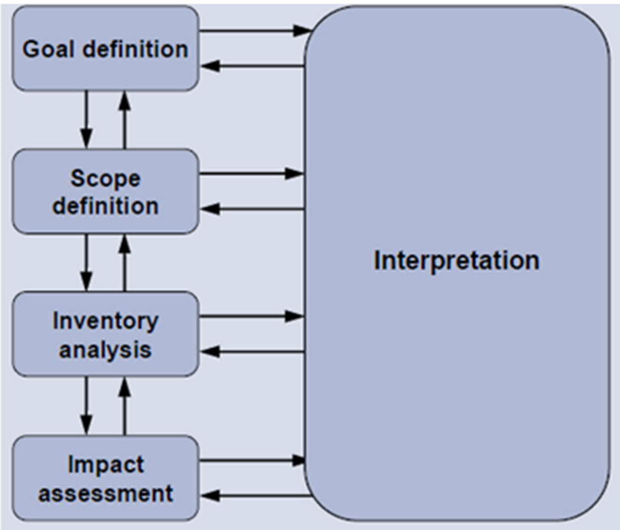

Figure 20: Framework for Life Cycle Assessment

Within the Goal and Scope definition stages of the LCA and LCC of MARPOWER Project, the study to be conducted in Task 4.3 will aim to evaluate the sustainability performances (both environmental and economic) of MECS system. In this project, a Cradle-to-Grave approach will be applied, which means that the entire production chain and utilization of MECS will be studied, until the end phase that consists of the disposal and potential recycling of the system. The lifetime of the system will be assumed to be equal to 30 years. In Figure 21 a first draft of the system boundaries diagram is

[9] https://link.springer.com/article/10.1007/s11367-011-0287-5

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reported highlighting all the main energy and mass flows as input and output of the different life cycle stages of MECS system. The main input/output of the system is listed in the following paragraphs.

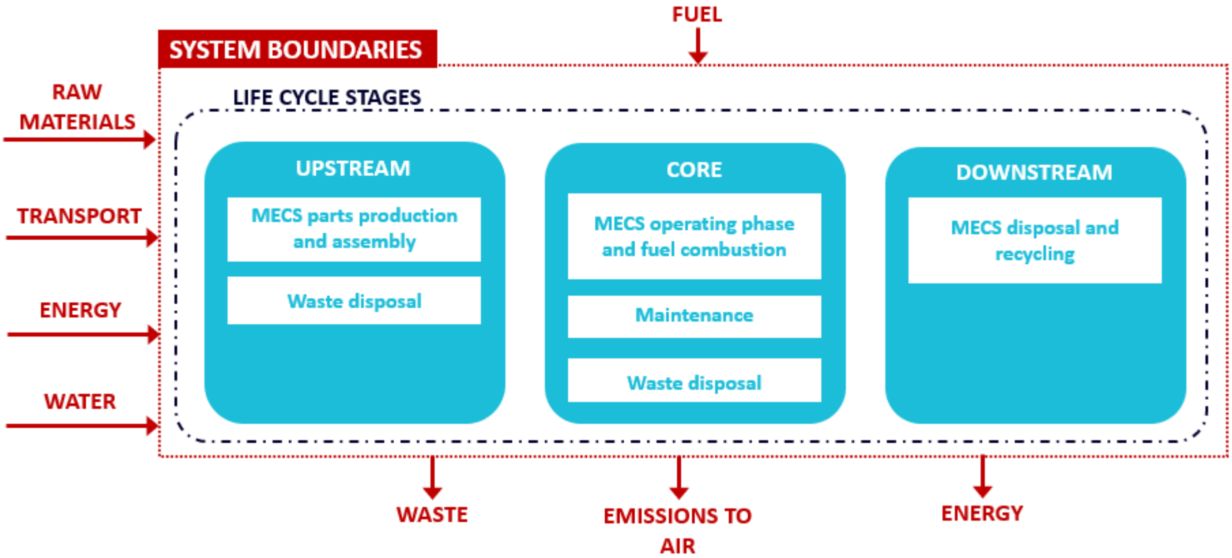

Figure 21: MECS system boundaries for LCA and LCC

In particular, the functionality of the MECS system for power supply in maritime transport will be assessed through two case studies:

1. vessel propulsion (electricity generation);
2. vessel electrical power and heating (cogeneration).

Based on the alternative fuels that will be tested (or simulated) during WP2 and WP3 activities, the environmental and economic impacts will be assessed for 1 kWh of energy produced (electricity alone or heat energy plus electricity together). The results of the analysis will be compared with each other and with those obtained using conventional fuels. It is specified that the functional unit of the analyses, as defined by the LCA framework, will be 1 kWh of energy produced by MECS.

5.3. Data requirements

During Task 1.1, a preliminary list of data required to perform LCA and LCC has been established, which is summarised in Table 6. Data that cannot be collected during Task 4.3, as primary data, from project activities or technology providers will be collected from internationally recognized databases or literature.

Table 6: Preliminary data to collect (for LCA and LCC)

Life Cycle Stage	Flows	Description
MECS production and installation phase	Raw materials consumption	Quantity of steel, copper, chemicals
	Energy consumption	Quantity of fossil fuels and electricity, specifying also the origin (e.g. renewable or not)

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Life Cycle Stage	Flows	Description
	Water consumption	Quantity of water and source specification (e.g. river, urban network, from osmosis plant)
	Raw materials and MECS transportation	Typology of transportation (e.g. truck, ship) and distance not only for raw material supply for the production process but also for MECS transportation to the installation place
MECS operating phase	O&M materials consumption	Quantity of material used during operation and maintenance phases for 30 years of lifetime (e.g. spare parts, oils, chemicals)
	Emission to air	Typology and quantity of emissions to air to produce 1 kWh of energy, based on different fuels that will be tested
	Fuel consumption	Quantity and typology of fuel to produce 1 kWh of energy from MECS. It is important also to specify the origin of the typology of the fuel and the source (e.g. e-fuel, fossil fuel)
MECS disposal and potential recycling	Material disposal or recycling	Quantity and typology of materials that will be recycled and/or disposed
	Waste transportation	Distance between the installation place and the recycling/disposal activity

5.4. KPIs definition

The simulation that will be carried out during Task 4.3, will identify a set of KPIs that will be used for the assessment of the MECS from the point of view of sustainability (environmental and economic aspects).

According to EU Commission indications[10] and the impact assessment method of CML 2001 (Aug 2016 version), the main KPIs and impact categories (related to 1 kWh of produced energy) to calculate through the LCA will be:

1. **Water use:** the abstraction of water from lakes, rivers or groundwater can contribute to the 'depletion' of available water. The impact category considers the availability or scarcity of water in the regions where the activity takes place if this information is known. The potential impact is expressed in cubic metres (m^3) of water use related to the local scarcity of water.
2. **Cumulative energy demand:** this information includes all renewable and non-renewable energy sources used (expressed in MJ), during the life cycle, for: production processes, production and transport of raw materials, and transport and disposal of waste. This includes in

[10] https://green-business.ec.europa.eu/environmental-footprint-methods/life-cycle-assessment-ef-methods_en

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addition to the energy consumed within the site, all energy sources consumed for the extraction, processing/production, and transportation of all materials and energy sources used.

3. **Abiotic Depletion (ADP elements):** this category corresponds to minerals and resources used and is, in this sense, mainly influenced by the rate of resources extracted. The effect of this consumption on their depletion is estimated according to their available stock at a global scale.
4. **Abiotic Depletion (ADP fossil):** this factor is derived for each extraction of fossil fuels. The resources in the impact category of fossil fuels are fuels like oil, natural gas, and coal, which are all energy carriers and assumed to be mutually substitutable. As a consequence, the stock of fossil fuels is formed by the total amount of fossil fuels, expressed in Megajoules (MJ).
5. **Acidification Potential (AP):** acidification estimates the potential of emissions to contribute to the development and deposit of acid rain on soil and water which can seriously affect plant and animal life and damage infrastructure. The acidification impacts are mainly primarily caused by fossil fuel combustion emissions, particularly Sulphur Dioxide (SO_2) and Nitrogen Oxides (NOx). Emissions from burning fossil fuel to generate grid electricity, are a significant contributor to acidification effects for the system. Also, emissions from the extraction and processing of natural gas impact the AP category.
6. **Eutrophication Potential (EP):** eutrophication occurs when excess nutrients (nitrates, phosphates) are introduced to surface water causing the rapid growth of aquatic plants. Excess releases of these substances may provide undesired effects on the waterways. The characterization factors for eutrophication are the product of a nutrient factor and a transport factor. The nutrient factor is based on the amount of plant growth caused by each pollutant, while the transport factor accounts for the probability that the pollutant will reach a body of water. Atmospheric emissions of nitrogen oxides (NOx), as well as waterborne emissions of nitrogen, phosphorus, ammonia, biochemical oxygen demand (BOD), and chemical oxygen demand (COD), are the main contributors to eutrophication impacts, converted in Kg Phosphate equivalent.
7. **Freshwater Aquatic Ecotoxicity Potential (FAETP inf.):** is the toxic effects of a chemical on an ecosystem, in this case in the freshwater, causing biodiversity loss and/or species extinction. The characterisation factors are expressed like ETP in kg. 1.4-dichlorobenzene equivalent.
8. **Global Warming Potential (GWP 100 years):** Greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space; different GHGs can have different effects on the Earth's warming. The Global Warming Potential (GWP) indicator was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time. The period mostly used for GWPs is 100 years, with the GWP 100 factors reported by IPCC 2021: fossil carbon dioxide 1 kgCO_2eq/kg, fossil methane 27.9 kgCO_2eq/kg, nitrous oxide 273 kgCO_2eq/kg, etc.
9. **Global Warming Potential (GWP 100 years), excl biogenic carbon:** the time horizon used is GWP 100 years, excl. biogenic carbon. It only includes fossil carbon dioxide and thereby excludes the uptake and emissions of biogenic carbon dioxide. Burning fossil fuels releases carbon that has been locked up in the ground for millions of years while burning biofuel emits carbon that is part of the biogenic carbon cycle. In other words, fossil fuel use increases the total amount of carbon in the biosphere-atmosphere system while bioenergy systems operate

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within this system; biomass combustion simply returns to the atmosphere the carbon that was absorbed as the plants grew[11].

10. **Human Toxicity Potential (HTP inf.):** considers the toxic effects of chemicals on humans. It reflects the potential impact of a unit of chemicals released into the environment that is mainly caused by electricity production from fossil sources. HTP is measured in kg. 1.4-dichlorobenzene equivalent.
11. **Marine Aquatic Ecotoxicity Pot. (MAETP inf.):** is the toxic effects of chemicals on an ecosystem, in this case in the marine ecosystems, causing biodiversity loss and/or species extinction. The characterisation factors are expressed in kg. 1.4-dichlorobenzene equivalent.
12. **Ozone Layer Depletion Potential (ODP, steady state):** the reduction of protective ozone in the stratosphere caused by emissions of ozone-depleting substances (e.g. CFCs and halons) is known as Ozone Layer Depletion (ODP). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical's reactivity and lifetime. Effects related to ozone depletion can include skin cancer, cataracts, material damage, immune system suppression, crop damage, and other plant and animal effects.
13. **Photochemical Ozone Creation Potential (POCP):** the Photochemical Ozone Creation Potential (POCP) impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NOx and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth. Smog formation impacts are generally dominated by emissions associated with fuel combustion, so impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements.
14. **Terrestris Ecotoxicity Potential (TETP inf.):** is the toxic effects of chemicals on an ecosystem, in this case in the terrestrial ecosystems, causing biodiversity loss and/or species extinction. The characterisation factors are expressed in kg. 1.4-dichlorobenzene equivalent.

For the LCC, fixed and variable costs will be calculated: mainly related to long-term investments, operating and maintenance expenses, and disposal at the end of life, all expressed in €/kWh of energy produced.

[11] IPCC distinguishes between the slow domain of the carbon cycle, where turnover times exceed 10,000 years, and the fast domain (the atmosphere, ocean, vegetation and soil), vegetation and soil carbon have turnover times in the magnitude of 1– 100 and 10– 500 years, respectively. Fossil fuel transfers carbon from the slow domain to the fast domain, while bioenergy systems operate within the fast domain. (source: National Council for Air and Stream Improvement)

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6. MECS cycle and component design specifications

The development of the MARPOWER Energy Conversion System (MECS) requires a comprehensive and precise specification of system design requirements. A critical aspect of these requirements is the meticulous definition of component specifications, ensuring that each part of the system functions optimally and integrates cohesively. This precision is essential for the seamless and fail-safe integration of both the gas turbine (GT) and waste heat recovery system (WHRS) cycles.

This section outlines the specific design requirements for the GT and WHRS cycles, as well as the design and specification of various subsystems, including the combustion chamber, turbomachinery, generator, HP shaft prototype, bearing system, and recuperator.

Accurate component design specifications are fundamental to achieving the desired performance, efficiency, and reliability of the overall system. They provide a clear framework for the design, development, and validation processes, ensuring that each component adheres to stringent operational, safety, and regulatory standards. By precisely defining these requirements, we aim to enable the seamless integration and interoperability of all system components, ultimately ensuring the successful realization of the energy conversion technology.

The following subsections provide detailed specifications for each component, underscoring their roles and interactions within the broader system. These specifications are designed to guide the engineering, manufacturing, and testing processes, ensuring that the final system meets all performance criteria and complies with regulatory standards.

6.1. GT-cycle & WHRS

The initial gas turbine (GT) cycle shall be designed using Excel to determine initial cycle values for each point of the cycle. The nominal operating point shall be designed at ISO conditions at the gas turbine inlet:

- Inlet temperature: 15 °C
- Inlet pressure: 101.32 kPa
- Relative Humidity: 60%

The gas turbine shall operate between the following minimum and maximum temperatures, with potential derate of generated output power due to turbomachinery and/or component limitations:

- Minimum inlet temperature: -40 °C
- Maximum inlet temperature: +55 °C

The high-pressure gas turbine shall be cooled by air, with warmed air led back to the cycle at the most efficient point, as determined by initial cycle simulations. The target is to achieve the highest possible electrical efficiency for the GT cycle, with a turbine inlet temperature of 1250 °C.

The GT cycle shall consist of the following components:

- Radial low-pressure compressor
- 1st Intercooler
- 1st Radial high-pressure compressor
- 2nd Intercooler

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- 2nd Radial high-pressure compressor
- Recuperator
- Combustor
- Axial high-pressure turbine (cooled nozzles and blades)
- Axial low-pressure turbine

The WHRS cycle simulation shall commence once the GT cycle has initial values. Heat recovery boiler data shall be determined using specification tools and used in the WHRS cycle design. The WHRS cycle design shall be conducted in Excel.

Once the final cycle is specified and frozen, a simulation tool for cycle simulation shall be designed, which can also be used in the digital twin. The simulation tool shall be capable of simulating partial load points.

6.2. Component design & specification

6.2.1. Combustion chamber design

The combustor shall be developed to use 100% hydrogen and exhibit significant fuel flexibility, capable of operating with other neutral or green fuels such as green methane, green methanol, or ammonia. Fuel flexibility and necessary adjustments shall be researched during the design phase.

The gas turbine cycle and process values for the combustor shall be determined in chapter 6.1 GT-cycle & WHRS, including targeted pressure loss over the combustor.

Adjustments to pressure loss shall be communicated and updated as necessary to achieve optimal combustion. The combustor shall operate from ignition to nominal thermal power, with emissions determined at the nominal operating point. Surface temperature points shall be determined and measured during prototype testing.

The combustor shall withstand ambient conditions as specified in chapter 4.5 Machinery room constraints, and surface temperatures shall be provided for insulation design during prototype testing.

The igniter exciter shall be supplied with 24 VDC, with specifications included in the combustor design.

Safety aspects and necessary EU directives shall be considered in the machinery design.

6.2.2. Turbomachinery design

A turbomachinery setup for the gas turbine system fuelled by a hydrogen combustor shall be designed based on the GT cycle and calculations defined in Chapter 6.1 GT-cycle & WHRS. Iterations may be required due to generator, bearings, and rotor dynamics limitations.

The turbomachinery shall initially operate at a rotational speed of 15,000 RPM. Aerodynamic geometrical design/dimensions shall be shared to create 3D models of the HP turbine unit.

The gas turbine hot component lifetime shall be a minimum of 50,000 hours and 2,500 start-stop cycles, while compressor parts shall have a lifetime of at least 200 000 hours and 10 000 start-stop cycles. More demanding marine application requirements shall be applied if specified in Chapters 3 Policy framework or 4 Ship integration.

The mechanical design and lifetime shall be determined by FEA, with gas turbine cooling considered when analysing stresses in rotating and stationary components. Necessary CFD shall confirm cooling flow, pressure losses, and component temperatures.

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Fuel flexibility research shall investigate the impact of different fuels on turbine performance, efficiency, and operational limitations.

6.2.3. Generator design

The generator design shall commence once initial turbomachinery rotational speed and power are known. The generator shall be designed according to the permanent magnet generator design, with iterations continuing until all design aspects are satisfied.

The generator shall be designed from an electromagnetic perspective, sharing dimensional information with mechanical engineering. Mechanical design information required includes:

- Stator lamination (shape, dimensions, material, thickness)
- Length of stator stack (active length)
- Slot wedges and finger plate dimensions & specifications
- Dimensions of the end windings (radial and axial minimum dimensions)
- Insulation specification (cooling fluid and windings)
- Rotor active part axial length
    - Permanent magnet specification and dimensions

The PM shaft sleeve and PM cage shall be designed iteratively. Standard dimensions of carbon fibre tubes shall be checked before finalizing shaft dimensions.

The generator cooling system shall be specified and dimensioned, ensuring operation in ambient conditions of 55 °C and 95% relative humidity. The cooling system design and specification need to include the following minimum requirements:

- Generator losses in rotor and stator with details of loss location:
    - Losses are determined according to inverter supply to know realistic losses.
    - Losses are determined at the nominal operating point.
- Cooling fluid hoses/pipes inside the winding.
- Specification of the cooling fluid used for winding.
- Cooling fluid flow specification to identify pumps, heat exchangers, and other auxiliaries.
- Rotor cooling design, including fan dimensions at the rotor to ensure sufficient cooling flow:
    - Rotor cooling is checked and designed together with AMB cooling.
- Heat exchanger specifications for the cooling fluid circuit on the rotor:
    - Heat exchanger to transfer heat to ambient air.

Generator winding instructions and necessary tests during and after winding manufacturing shall be provided.

Generator lifetime shall be a minimum of 200 000 hours and 10 000 start-stop cycles. CFD simulations shall validate generator cooling system functionality and operation, including partial load conditions.

6.2.4. HP shaft prototype design

The HP shaft prototype shall be used on a moving platform to test the HP shaft with two compressor impellers and an axial gas turbine with AMB. Dummy impellers shall be designed according to the compressor impellers and turbine blades specified in Chapter 6.2.2 Turbomachinery design. **Error! Reference source not found.**. The prototype shall be safe for test engineers and allow easy access for balancing the shaft and dummy impellers.

Necessary manufacturing drawings, risk assessments, and other documents for the prototype design shall be created.

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6.2.5. Bearing system design

The AMB system shall be designed, analysing dynamic forces on a moving platform before design. AMB controllability and observability shall be checked in the pre-analysis phase.

The AMB design shall withstand normal operation through the speed range with necessary safety margins. Axial forces shall be calculated based on GT cycle information in in Chapter 6.1 GT-cycle & WHRS.

Initial AMB dimensions and design shall be based on turbomachinery and generator design. The shaft design shall be updated accordingly, with iterations between turbomachinery, generator, AMB, rotor dynamics, and FEA of the shaft.

AMB design documents and information provided shall include:

- Stator lamination (shape, dimensions, material, thickness)
- Rotor lamination (shape, dimensions, material, thickness)
- Length of stator stack
- Length of rotor stack
- Dimensions of the end windings (radial and axial minimum dimensions)
- Insulation specification of windings
- Campell diagram and other rotor dynamics-related information
- Safety bearing selection and specification
- Heat loss of the AMB stator winding

The AMB cooling system shall be designed to work with the generator shaft cooling system. Winding instructions and necessary tests during and after winding manufacturing shall be provided. The magnetic bearing controller (MBC) shall be specified and considered in the actuator design, targeting the use of market-available MBC.

6.2.6. Recuperator design

The recuperator design shall be based on the gas turbine cycle determined in Chapter 6.1 GT-cycle & WHRS, with a lifetime of a minimum of 180 000 hours and 10 000 start-stop cycles. The recuperator shall withstand partial load requirements and be insulated with a removable insulation system.

The design shall include start-up and shutdown times as listed in

Table 7, The design shall ensure safe operation during normal and emergency shutdowns, with specific purge conditions to prevent explosive gas mixtures.

In a normal shutdown, temperatures shall decrease slowly, and air shall be circulated in the process. The normal shutdown shall be done in steps to decrease temperature levels to a lower level before the shutdown of the combustor. Following the combustor shutdown, the compressor shall blow air through the turbine, pipes, and recuperator to ventilate and dissipate the heat out of the turbine. At a specific temperature, specified by the recuperator designer, the shafts shall be stopped by the automation system.

In an emergency shutdown, the shafts decrease the speed as fast as possible, and the dump valve is opened immediately after the emergency shutdown is activated. The dump valve is located between 2nd high-pressure compressor and the recuperator air inlet. In the emergency shutdown, there is no air circulation through the recuperator.

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Table 7. Start-up and shutdown times for recuperator

Sequence	Value
Start-up time from ambient to nominal temperature	300 sec
Hot start time: Recuperator inlet temperature increased from 300 C to nominal	120 sec
Normal shutdown time (temperature decreased slowly)	300 sec
Emergency shutdown	15 sec

Before each ignition of the flame in the combustor, the entire machine, including ductwork and the recuperator, shall be purged for safety reasons and to comply with regulations. The purge shall be performed at low speed, meaning low airflow and temperature. The mass flow shall be about 10% of the nominal air mass flow at the air side of the recuperator, with the temperature close to ambient or hotter. The design of the recuperator shall ensure that no flow zones contain or build up explosive gas mixtures. CFD for one load case ("purge") shall show this and specify the needed purge time at these purge conditions.

Before each ignition of the flame in the combustor, the entire system, including the machine, ductwork, and recuperator, must be purged for safety reasons and to comply with regulations. The purge will be performed at low speed, meaning with low airflow and temperature. The mass flow will be approximately 10% of the nominal air mass flow at the air side of the recuperator, with the temperature being close to ambient or slightly higher. The design of the recuperator must ensure that no flow zones can contain or accumulate explosive gas mixtures. Computational Fluid Dynamics (CFD) analysis for the purge load case must demonstrate this, specifying the required purge time under these conditions.

The recuperator design must provide surface temperatures and interface thermal expansions for each interface. The recuperator designer shall specify allowable torques and forces for the interfaces.

6.3. Component design approvals

To ensure that all components of the MARPOWER Energy Conversion System (MECS) meet the required technical standards and integrate seamlessly into the overall system, a formal process of design verification and approval is essential. Each component, from the gas turbine to the waste heat recovery system (WHRS), is subject to a rigorous check and approval process. This process ensures that all design criteria are met, including performance, safety, reliability, and compliance with relevant regulations.

All components are designed within the Aurelia Product Data Management (PDM) system, which centralizes design data and facilitates collaboration across multiple teams. Manufacturing drawings and design specifications are generated, reviewed, and approved according to the established Aurelia engineering workflow, which is aligned with industry best practices.

The approval process involves multiple stages of review by designated teams from various parties. These teams are responsible for confirming that the designs comply with technical requirements, safety standards, and project-specific objectives. The final approval is granted once the designs meet all necessary criteria and are verified for manufacturability, functionality, and integration compatibility.

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Table 8 outlines the specific components, the responsible parties for each design and design review, with Aurelia serving as the final approval party.

Table 8. Design and review responsibilities and approvals

Designed system	Designed by	Checked by	Approved by
GT Cycle	LUT	POLIMI	AURELIA
Combustor	DLR	LUT	
Turbomachinery	POLIMI	LUT	
Generator	LUT	UVIGO	
AMB	LUT	DTU	
Recuperator	ALFA LAVAL	LUT	
WHRS	LUT	POLIMI	

This structured approval system ensures that all components undergo thorough evaluation and validation by the relevant parties before being finalized for manufacturing. By adhering to this process, we can guarantee that the MECS will meet the required performance and safety standards while ensuring its smooth integration into the broader system design.

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7. Conclusion

This deliverable outlines the design specifications for the MARPOWER Energy Conversion System (MECS), incorporating key considerations from technical, policy, life cycle, and ship integration perspectives. The precise specification of system and component requirements is critical to ensuring that every element of the MECS operates optimally and in harmony. By carefully defining these parameters, we facilitate the efficient and reliable integration of both the gas turbine (GT) and waste heat recovery system (WHRS) cycles, ensuring their performance aligns with the project's objectives.

The document provides detailed specifications for the GT and WHRS cycles, alongside critical subsystems such as the combustion chamber, turbomachinery, generator, HP shaft prototype, bearing system, and recuperator. These components are designed to work together cohesively, supporting the overall system's efficiency, safety, and performance.

Beyond system-cycle and component-specific requirements, this deliverable also addresses broader technical, policy, life cycle, and ship integration aspects essential for the system's success. These frameworks are crucial for achieving the desired operational standards, regulatory compliance, and seamless integration with ship systems. They ensure that the energy conversion system not only meets technical performance goals but also adheres to rigorous safety, sustainability, and regulatory guidelines throughout its entire life cycle.

By following these requirements and specifications, the MARPOWER project will progress toward realising a fully integrated, high-performance energy conversion system. This holistic approach ensures that all components function as a unified system, effectively supporting the project’s goals and contributing to the successful development of cutting-edge maritime energy solutions in line with industry standards and policy frameworks.

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Annex: List of MARPOWER partners

Table 9. List of partners

1. LAPPEENRANNAN-LAHDEN TEKNILLINEN YLIOPISTO LUT, the Coordinator of MARPOWER, with legal address at Yliopistonkatu 34, 53850 Lappeenranta, Finland
2. POLITECNICO DI MILANO with legal address at Piazza Leonardo Da Vinci 32, 20133 Milano, Italy
3. DEUTSCHES ZENTRUM FÜR LUFT - UND RAUMFAHRT EV with legal address at Linder Höhe, 51147 Köln, Germany
4. DANMARKS TEKNISKE UNIVERSITET with legal address at Anker Engelunds Vej 101, 2800 Kongens Lyngby, Denmark
5. UNIVERSIDAD DE VIGO with legal address at Lg Campus Lagoas Marcosende, 36310 Vigo Pontevedra, Spain
6. AURELIA TURBINES OY with legal address at Höyläkatu 1, 53500 Lappeenranta, Finland
7. ALFA LAVAL AALBORG OY with legal address at Kaivopuistontie 33, 26100 Rauma, Finland
8. RINA SERVICES SPA with legal address at Via Corsica 12, 16128 Genova, Italy
9. RINA CONSULTING SPA with legal address at Via Cecchi 6, 16129 Genova, Italy
10. CHANTIERS DE L'ATLANTIQUE with legal address at Avenue Antoine Bourdelle, 44600 Saint Nazaire, France
11. ZABALA INNOVATION CONSULTING SA with legal address at Paseo Santxiki 3 bis, 31192 Mutilva Alta Navarra, Spain

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