State-of-the-art sustainable energy efficiency technologies roadmap for waterborne transport towards the fit-for-55 guidance compliance

Project 101192661— FLEETfor55

Deliverable D3.3 – Development of KPIs, assessment metrics and QFD method for evaluating use cases

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Acronyms and Abbreviations	Meaning
CAPEX	Capital Expenditure
CII	Carbon Intensity Indication
EEDI	Energy Efficiency Design Index
EET	Energy Efficiency Technologies
ER	Engineering requirements
EEXI	Energy Efficiency Existing Ship Index
ETS	Emissions Trading System
EU	European Union
GHG	Green House Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
HoQ	House of Quality
IMO	International Maritime Organization
IRR	Internal Rate of Return
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Lifecycle Assessment
MARPOL	International Convention for the Prevention of Pollution from Ships
MBTF	Mean Time Between Failures
MCDM	Multi-Criteria Decision-Making
NREL	National Renewable Energy Laboratory
NPV	Net Present Value
OPEX	Operational Expenditure
Particulate Matter	PM
QFD	Quality Function Deployment
TIN	Technologies Innovation Network
TRL	Technology Readiness Level
USLCI	U.S. Life Cycle Inventory

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Executive Summary

Deliverable D3.3 establishes an evaluation framework that supports the comparison of alternative Energy Efficiency Technologies (EETs) and vessel configurations within the FLEETfor55 project. The framework structures the assessment process around the evaluation principles that help quantify the contribution of different solutions to maritime decarbonization. It brings together a set of Key Performance Indicators (KPIs) spanning technical, environmental, economic, and socio-political aspects, each paired with measurable metrics. The KPI suite reflects current EU “Fit for 55” priorities and the International Maritime Organization’s (IMO) decarbonization agenda, ensuring that assessments capture factors such as emissions reduction potential, operational feasibility, technology maturity, scalability, and overall techno-economic performance.

The objectives and scope of deliverable D3.3 focus on creating an evaluation system that can be applied across diverse vessel types and operational contexts and integrating them into a Quality Function Deployment (QFD)-based methodology. The QFD approach links stakeholder requirements to engineering attributes through weighted scoring and sensitivity analysis, ensuring traceability between strategic priorities and technical solutions.

A comprehensive KPI and assessment metric framework has been developed to capture performance across four domains: technical readiness and integration complexity, environmental impact and lifecycle emissions, economic viability including Capital and Operational Expenditures (CAPEX/OPEX) and payback period, and socio-political factors such as crew training and regulatory alignment. Each KPI is supported by normalization formulas, qualitative scales, and data validation processes, enabling consistent and comparable evaluations.

The methodology for KPI development and evaluation combines multi-criteria decision-making (MCDM) principles with ISO-aligned QFD practices. It includes procedures for data collection, normalization, and quality assurance, ensuring transparency and reproducibility. The framework also incorporates stakeholder calibration to reflect real-world priorities and reduce bias in scoring.

KPIs are grouped into categories that reflect key evaluation goals: decarbonization potential, operational suitability, market uptake and transition speed, standardization and scalability, and techno-economic viability. This categorization ensures that assessments are balanced and aligned with both regulatory requirements and industry needs.

The resulting evaluation tool will be made publicly available after the project via the FLEETfor55 digital platform, accompanied by user guidelines.

1 Introduction

1.1 Background

The maritime sector faces increasing pressure to decarbonize in line with the EU “Fit for 55” package and IMO targets. While numerous EETs are emerging, their adoption is hindered by fragmented evaluation practices and the absence of standardized, transparent decision-support tools. Improving energy efficiency helps shipping companies comply with these regulations, avoiding penalties and preparing for future requirements. (Vittoria Battaglia, 2024) highlights emerging trends in maritime energy efficiency and the role of IMO-standard KPIs in guiding compliance strategies and promoting sustainability.

A critical gap identified during the preparatory phase of FLEETfor55 is the lack of open-access QF applications tailored to maritime needs. QFD is a proven methodology for translating stakeholder requirements into technical specifications and prioritizing solutions based on multiple criteria. However, its limited availability in an open, user-friendly format has slowed industry-wide adoption of structured evaluation methods. This deliverable, addresses that gap by developing a QFD-based framework integrated with a comprehensive KPI and metric system, ensuring that the methodology is not only robust but also openly accessible post-project to maximize impact and scalability.

1.2 Purpose of the Deliverable

The purpose of this deliverable (D3.3) is to establish a structured evaluation framework for assessing alternative EETs and vessel types within the FLEETfor55 project. This framework introduces a comprehensive set of KPIs, associated assessment metrics, and a QFD-based methodology to enable transparent, data-driven decision-making. By aligning with EU “Fit for 55” objectives and IMO regulatory requirements, the framework ensures that stakeholders can evaluate the technical, economic, environmental, and social feasibility of EET solutions in a consistent and systematic manner.

1.3 Context and Interdependencies

This deliverable builds upon the outputs of D2.3 (EETs preliminary economic feasibility analysis), D2.4 (Preliminary technical evaluation of EETs), D3.1 (Regulatory GAP Analysis) and D3.2 (Use Case Definition). D2.3 provides the preliminary economic feasibility assessment of available EETs, presenting the expected profitability and long-term sustainability of each solution. D2.4 complements this by evaluating the preliminary technical applicability and

feasibility of each EET in terms of integration potential and expected performance. Regulatory insights from D3.1 provide the compliance baseline for KPI formulation, ensuring that the evaluation framework reflects current and emerging legislative requirements. The eleven use cases defined in D3.2 establish the operational context for applying KPIs and assessment metrics across diverse vessel types and operational profiles. Similar stakeholder-driven KPI frameworks have been applied in EU projects, as shown by (Thalis P.V. Zis, 2023), who developed a multi-domain KPI system for autonomous shipping, emphasizing economic, environmental, and social dimensions.

1.4 Key Findings and Methodological Highlights

The methodology integrates multi-criteria decision-making (MCDM) with QFD principles to translate stakeholder requirements into measurable KPIs. These KPIs are grouped into five main categories:

- Decarbonization potential
- Operational suitability
- Market uptake
- Standardization and scalability
- Techno-economic viability

Each KPI is linked to quantifiable metrics, enabling consistent evaluation across different vessel types and EET configurations. The QFD-based approach ensures traceability between stakeholder priorities and technical solutions, while sensitivity analysis and expert validation enhance robustness. The resulting framework not only supports internal project assessments but will also be made publicly available post-project, ensuring broader adoption and long-term impact across the maritime sector.

2 Overview of Key Performance Indicators (KPIs)

Definition and Role of KPIs in Decision-making for EETs

In Task 3.3, KPIs translate stakeholder priorities into measurable criteria that allow consistent and transparent comparison of EETs across vessel types and use cases. They support decisions aligned with decarbonization targets, safety, operability, cost-effectiveness, and market readiness, and they provide traceability when combined with a QFD-based methodology. The House of Quality (HoQ) structure maps these KPIs to stakeholder requirements and technical attributes, enabling clear line-of-sight from regulatory and business goals to design trade-offs. This QFD practice links project requirements to engineering requirements through weighted relationship matrices.

2.1 KPI Domain Overview

All technologies are classified into four overarching domains: technological, socio-political, environmental, and economic. This classification ensures that the assessment captures not only technical feasibility and performance but also broader implications for stakeholders, regulatory compliance, sustainability, and market viability (Vittoria Battaglia, 2024).

The selected classification of the KPIs supports the development of a multi-criteria evaluation framework, enabling stakeholders to:

- Compare technologies across different vessel types and operational contexts.
- Identify trade-offs between performance, cost, sustainability, and feasibility
- Align technology selection with strategic decarbonization goals.

By structuring the assessment around these four domains, a balanced and transparent decision-making process is ensured that reflects the complexity of maritime energy transitions. It enables stakeholders to identify solutions that are environmentally impactful, operationally feasible, financially sound, scalable, and socially responsible, criteria that are essential for achieving long-term sustainability and competitiveness in the maritime industry.

2.1.1 Technical Domain

The technical evaluation of maritime technologies focuses on their maturity, integration feasibility, and operational impact. This domain provides insight into how readily a solution can be implemented within existing vessel infrastructures and how it affects performance and reliability. The following criteria serve as key indicators of a technology's readiness and practicality for fleet-wide deployment:

- Technology Readiness Level (TRL) is a scale used to assess the maturity of a technology, ranging from basic research (TRL 1) to operational application (TRL 9). As a KPI, TRL helps determine how close a technology is to being viable for real-world maritime applications allowing engineers to have a consistent datum of reference for understanding technology evolution, regardless of their technical background. A higher TRL indicates lower implementation risk and faster adoption potential.
- Compatibility with Existing Vessel Systems evaluates how well a new technology integrates with current onboard systems such as propulsion, power management, and navigation. High compatibility minimizes the need for extensive modifications, reduces costs, and ensures smoother operation and crew adaptation.
- Ease of Retrofitting or Integration measures how easily the technology can be installed or integrated into existing vessels without major structural changes.
- Impact on Vessel Performance and Reliability assesses how the technology affects operational parameters such as speed, fuel consumption, maintenance needs, and overall reliability. It ensures that energy savings do not compromise vessel performance or increase operational risks. A positive impact supports long-term sustainability and cost-effectiveness.

2.1.2 Socio-Political Domain

Socio-political factors play a vital role in the successful integration of new maritime technologies. This domain addresses the human, regulatory, and societal dimensions that influence technology acceptance, compliance, and operational impact. The following criteria help evaluate how well a solution aligns with industry standards, stakeholder expectations, and crew capabilities:

- Crew training and safety requirements assesses the level of training required for crew members to operate and maintain the new technology safely.
- Regulatory alignment (IMO, EU Fit for 55, etc.) evaluates how well the technology complies with current and upcoming maritime regulations, such as IMO decarbonization targets and the EU's Fit for 55 packages.
- Public and stakeholder acceptance measures the level of support or resistance from stakeholders including shipowners, charterers, regulators, and the public.
- Impact on operational procedures and crew workload assesses how the technology affects day-to-day vessel operations and crew responsibilities. A low-impact solution that simplifies or maintains current workflows may reduce disruption and operational risk.

2.1.3 Environmental Domain

Environmental considerations are central to evaluating the sustainability and regulatory alignment of maritime technologies. This domain focuses on the ecological impact of a solution throughout its lifecycle, emphasizing its contribution to emissions reduction, resource efficiency, and circular economy principles. The following criteria provide a structured approach to assessing the environmental performance of a technology taking into consideration the circularity of an EET as well:

- Greenhouse Gas (GHG) Reduction Potential measures the extent to which a technology can reduce emissions of greenhouse gases such as CO_2, CH_4, and N_2O in CO_2 equivalent units.
- Lifecycle Emissions evaluates the total environmental impact of a technology throughout its entire lifecycle, from raw material extraction and manufacturing to operation and disposal.
- Pollutant reduction measures the reduction of pollutants other than GHG that an EET can lead to, such as NO_x, SO_x and Particulate matter (PM).
- Recycle Ratio measures the percentage of the mass for the recyclable materials found in an EET.
- Criticality Ratio measures the percentage of the number of critical materials, meaning those with heightened supply-chain vulnerability or essential functional importance, compared to the total number of materials of which an EET is consisted of.
- Critical Mass measures the percentage of mass of the critical materials compared to the total mass of an EET.

2.1.4 Economic Domain

The economic evaluation of maritime technologies is critical to determining their viability and potential for widespread adoption. This domain encompasses key financial and market-related criteria that influence investment decisions, operational planning, and strategic implementation. The following factors provide a structured framework for assessing the economic impact and feasibility of a given technology:

- CAPEX/OPEX capture the upfront investment costs and recurring operational and maintenance costs over the technology's lifecycle, respectively.
- Return on Investment (ROI) and Payback Period measures the financial return generated by the technology relative to its cost, and how quickly the investment is recovered.

- Scalability assesses the ability of the technology to be deployed across different vessel types and sizes.
- Market Readiness and Adoption Forecasts evaluates how prepared the technology is for commercial deployment and its projected adoption rate within the maritime sector. On a chart with MRL and TRL along the x and y axis, the closer the position is to the upper right corner of the resulting plot, the closer the product is to commercialization.

In the context of the present report, scalability and market readiness are grouped under the economic domain since they directly influence cost efficiency, investment risk, and commercial viability. While these factors have organizational aspects, their impact on CAPEX/OPEX, payback period, and fleet-wide deployment economics makes them integral to techno-economic evaluation rather than purely technical or socio-political considerations.

Figure 1 KPI to Industry Priorities Diagram

2.2 Methodology for translating KPIs into measurable indicators

Having defined the KPI domains, the following section outlines how these indicators are operationalized through measurable metrics. Each KPI is mapped to quantitative or qualitative metrics with defined units and data sources. The methodology ensures alignment with international standards, economic modelling practices, and structured scoring systems (see QFD-Based Evaluation Method in 4.6).

This section outlines the methodology for defining, sourcing, and validating the qualitative and quantitative metrics used to evaluate KPIs within the FLEETfor55 framework. These metrics serve as the foundation for transparent, evidence-based decision-making and are tailored to reflect the technical, economic, environmental, and social dimensions of EETs.

Qualitative Metrics

These are non-numerical indicators that capture subjective, experiential, or categorical aspects of performance. They are often based on:

- Structured expert judgment, such as technical panels or operational reviews.
- Categorical ratings, which simplify complex assessments into levels (e.g., low/medium/high).
- Survey-based scores, derived from stakeholder feedback or crew evaluations.

Examples include:

- Crew acceptance: Reflects how well a new system or procedure is received by onboard personnel, often gauged through interviews or surveys.
- Integration complexity: Assesses the difficulty of incorporating a new technology into existing systems, typically rated by technical teams.
- Safety risk levels: Evaluated through risk assessments and scenario analysis, often categorized to indicate severity or likelihood.

Qualitative metrics are particularly valuable when human factors, operational feasibility, or safety considerations play a central role, and when quantitative data is limited or unavailable.

Quantitative Metrics

These are numerically expressed indicators that allow for objective measurement, comparison, and trend analysis. They are typically derived from:

- Empirical data collected through sensors, logs, or operational records.
- Simulation outputs from digital models that replicate real-world conditions.
- Financial models that project costs, returns, or economic feasibility.

Examples include:

- Fuel consumption: Measures the rate at which fuel is used, critical for assessing energy efficiency.
- GHG emissions: Quantifies greenhouse gas emissions per tonne-nautical mile, useful for environmental impact assessments.
- CAPEX: Represents the upfront investment required for a solution or upgrade.

- Payback period: Indicates how long it takes for the investment to be recovered through savings or revenue.

These metrics are essential for cost-benefit analysis, benchmarking, and regulatory compliance.

2.3 KPIs list & formulas

Based on the analysis in the previous sections, the identified KPIs per domain can be found in Table 1, Table 2, Table 3, and Table 4. For quantitative KPIs, their respective formulas are also provided below. For qualitative KPIs the scale to be used is selected in the range of 1 to 9 in order to allow for a seamless incorporation into the QFD matrix scoring. In the below scoring assessment, the scale uses the odd values (1, 3, 5, 7, 9) as defined reference points. Even values (2, 4, 6, 8) should be used for intermediate cases that fall between the described levels.

2.3.1 Technical Domain KPIs

Table 1 Technical Domain KPIs

Technical Domain KPIs		
Sub-category	**KPI**	**Value/Unit**
TRL	TRL score	Scale (1–9)
Integration Complexity	Retrofitting Score	Score (1–9)
Compatibility with Existing Systems	Compatibility Index	Score (1–9)
Retrofit Time	Installation Duration	Days/vessel
Impact on Vessel Consumption	Δ Fuel Consumption on an equivalent basis	%
Propulsion efficiency	Shaft Power Savings	%
Auxiliary Power Demand	Effect on Auxiliary Load	%
Steam demand	Effect on Boiler Load	%
Maintenance Requirements	Maintenance Hours per Year	Hours/year
Maintenance Complexity	Skill level required	Score (1-9)

In the above table the terms used as follows:

- Retrofit Time = Total Installation Hours / 24, where
    - Total Installation Hours = Sum of all labour hours required to install the EET (including preparation, actual installation, and commissioning).
- Impact on Vessel Consumption = $\frac{Fuel_{baseline} - Fuel_{EET}}{Fuel_{baseline}} \cdot 100$, where

- $Fuel_{baseline}$ = Fuel consumption of the vessel before installing the EET (reference condition).
- $Fuel_{EET}$ = Fuel consumption after installing the EET under equivalent operating conditions.

- Propulsion Efficiency = $\frac{Power_{baseline} - Power_{EET}}{Power_{baseline}} \cdot 100$
  - $Power_{baseline}$ = Shaft power required for propulsion before EET installation under specified conditions (ship's speed, mean draught and weather conditions encountered).
  - $Power_{EET}$ = Shaft power required after EET installation under same conditions.
- Auxiliary Power Demand = $\frac{Aux_Load_{baseline} - Aux_Load_{EET}}{Aux_Load_{baseline}} \cdot 100$
  - $Aux_Load_{baseline}$ = Auxiliary engines' electrical load before EET installation.
  - Aux_Load_{EET} = Auxiliary engines' electrical load after EET installation.
- Steam Demand = $\frac{Boiler_Load_{baseline} - Boiler_Load_{EET}}{Boiler_Load_{baseline}} \cdot 100$
  - $Boiler_Load_{baseline}$ = Steam or boiler load before EET installation.
  - $Boiler_Load_{EET}$ = Steam or boiler load after EET installation.
- Maintenance Requirements = Σ (Scheduled Tasks + Unscheduled Repairs), where
  - Scheduled Tasks = Hours of planned maintenance activities (e.g., inspections, servicing).
  - Unscheduled Repairs = Hours of corrective maintenance due to failures or unexpected issues.

For the qualitative KPIs, below is a proposed methodology when evaluating them:

- TRL
  - 1 = Define basic properties
  - 3 = Proof of concept
  - 5 = Pre-prototype tested in lab
  - 7 = Approved prototype
  - 9 = Product on market

- Integration Complexity
  - 1 = Plug-and-play installation; no structural changes
  - 3 = Minor adjustments (e.g. downtime <3 days)
  - 5 = Moderate integration (e.g. downtime 1–2 weeks)
  - 7 = Significant structural changes (e.g. downtime >3 weeks)
  - 9 = Major structural modifications; complex commissioning
- Compatibility with Existing Systems
  - 1 = Incompatible without major redesign
  - 3 = Multiple system redesigns
  - 5 = Requires subsystem upgrades
  - 7 = Minor interface adjustments
  - 9 = Fully compatible; no interface changes
- Maintenance Complexity
  - 1 = Routine tasks; standard crew skills
  - 3 = Occasional specialized checks
  - 5 = Requires advanced technical skills
  - 7 = Frequent specialized interventions
  - 9 = OEM-dependent; high skill and tooling demand

2.3.2 Socio-Political Domain KPIs

Table 2 Socio-Political Domain KPIs

Socio-Political Domain KPIs		
Sub-category	**KPI**	**Value/Unit**
Crew Training Requirements	Training Hours	Hours/person
Impact on Crew Workload	Δ Workload Index	Score (1-9)
Safety Impact	Safety Risk Index	Score (1-9)
Regulatory landscape	Regulatory background in place	Score (1-9)
Impact on regulations	Number of regulations impacted from the EET	Score (1-9)

In the above table the terms used as follows:

- Crew Training Requirements = $\frac{\text{Total Training Hours Required}}{\text{Number of crew members to be trained}}$, where
    - Total Training Hours Required = The sum of all hours needed to deliver the training program for the EET. This includes classroom sessions, simulator time, onboard familiarization, and any certification modules.
    - Number of crew members to be trained = The count of individuals who must complete the training for the EET to be operated and maintained safely and effectively. This typically includes engineers, deck officers, and sometimes ratings, depending on the technology.

For the qualitative KPIs, below is a proposed methodology when evaluating them:

- Impact on Crew Workload
    - 1 = No added workload; automation handles tasks
    - 3 = Minor monitoring tasks
    - 5 = Moderate manual intervention
    - 7 = Frequent manual adjustments
    - 9 = Continuous monitoring; high operational burden
- Safety Impact
    - 1 = Negligible hazards; no new procedures
    - 3 = Minor procedural updates
    - 5 = Moderate risk; new safety checks
    - 7 = High-risk failure modes; multiple mitigations
    - 9 = Severe hazards; redesign of safety systems
- Regulatory Landscape
    - 1 = No framework; high compliance uncertainty
    - 3 = Significant regulatory gaps
    - 5 = Requires new interpretations
    - 7 = Minor clarifications needed
    - 9 = Fully aligned; existing rules cover technology

- Impact on Regulations
    - 1 = Minimum regulations compliance relevance
    - 3 = Addresses few key regulation
    - 5 = Supports compliance with multiple regulations
    - 7 = Strong multi-regulation compliance enabler
    - 9 = Broad compliance enabler across the majority of relevant regulations

2.3.3 Environmental Domain KPIs

Table 3 Environmental Domain KPIs

Environmental Domain KPIs		
Sub-category	**KPI**	**Value/Unit**
GHG Reduction Potential	gCO_2e saved per specific duration of time	%
Lifecycle Emissions	Total gCO_2e per lifecycle	gCO_2e
Pollutant Reduction	$g(NO_x/SO_x/PM)$ per specific duration of time	%
Recycle Ratio	Percentage of recyclable materials	%
Criticality Ratio	Percentage of number of critical materials	%
Critical Mass	Percentage of mass of critical material	%

In the above table the terms used as follows:

- GHG Reduction Potential = $\frac{\text{Emissions}_{\text{baseline}} - \text{Emissions}_{\text{EET}}}{\text{Emissions}_{\text{baseline}}} \cdot 100$ where:
    - $\text{Emissions}_{\text{baseline}}$ = Total greenhouse gas emissions (gCO_2e) for the vessel before installing the EET, under reference operating conditions.
    - $\text{Emissions}_{\text{EET}}$ = Total greenhouse gas emissions (gCO_2e) after installing the EET, under equivalent conditions.
- Lifecycle Emissions = $\text{Emissions}_{\text{manufacturing}} + \text{Emissions}_{\text{operation}} + \text{Emissions}_{\text{disposal}}$, where:

- $Emissions_{manufacturing}$ = Total emissions during production of the EET (including raw material extraction and fabrication).
- $Emissions_{operation}$ = Emissions during the operational life of the EET (including fuel savings or penalties).
- $Emissions_{disposal}$ = Emissions from end-of-life processes (e.g., recycling, scrapping, waste treatment).

- Pollutant Reduction = $\frac{Pollutant_{baseline} - Pollutant_{EET}}{Pollutant_{baseline}} \cdot 100$, where:
  - $Pollutant_{baseline}$ = Emissions of NO_x, SO_x, or PM before EET installation.
  - $Pollutant_{EET}$ = Emissions of NO_x, SO_x, or PM after EET installation.
- Recycle Ratio = $\frac{\text{Mass of Recyclable materials}}{\text{Mass of total materials}} \cdot 100$, where:
  - Mass of Recyclable Materials = Total weight of components that can be recycled using current technologies and infrastructure.
  - Mass of Total Materials = Total weight of all materials in the EET.
- Criticality Ratio = $\frac{\text{Number of critical materials}}{\text{Total number of materials}} \cdot 100$, where:
  - Number of Critical Materials = Count of materials classified as critical (high supply risk or strategic importance)[1].
  - Total Number of Materials = Count of all distinct materials used in the EET.
- Critical Mass = $\frac{\text{Mass of critical materials}}{\text{Total Mass of Materials}} \cdot 100$, where:
  - Mass of Critical Materials = Combined weight of all critical materials in the EET.
  - Total Mass of Materials = Total weight of all materials in the EET.

[1] Critical materials are those that present high supply risk, such as limited global availability, dependence on geopolitically sensitive regions, or lack of viable substitutes, or those with high strategic importance to system performance, safety, or compliance. Materials meeting either of these conditions are classified as critical for the purposes of calculating the Criticality Ratio

2.3.4 Economic Domain KPIs

Table 4 Economic Domain KPIs

Economic Domain KPIs		
Sub-category	**KPI**	**Value/Unit**
Scalability Potential	Deployment Feasibility Score	Score (1–9)
Market Readiness	Commercial Deployment Index	Score (1–9)
Infrastructure Dependency	Reliance on port or shore-side infrastructure	Score (1–9)
CAPEX	EET cost in EUR	€
OPEX	(Δ) EUR per year	%
Payback Period	Years to ROI	Years
Net Present Value (NPV)	EUR over lifecycle	€
Internal Rate of Return (IRR)	%	%
Cargo carrying capacity	Effect on cargo carrying capacity	Score (1–9)
Cost per Transport Work	EUR per t·nm	€/t·nm

In the above table the terms used as follows:

- OPEX = $\frac{OPEX_{baseline} - OPEX_{EET}}{OPEX_{baseline}} \cdot 100$, where:
  - $OPEX_{baseline}$ = Annual operating expenses before EET installation, under specified conditions (ship's speed, mean draught and weather conditions encountered, fuel costs).
  - $OPEX_{EET}$ = Annual operating expenses after EET installation for the same conditions.
- Payback Period = $\frac{CAPEX}{OPEX_{baseline_annual} - OPEX_{EET_annual}}$, where
  - CAPEX = Initial investment cost for the EET.
  - $OPEX_{baseline\ annual}$ = Annual operating cost before EET.
  - $OPEX_{EET\ annual}$ = Annual operating cost after EET.
- NPV = $\sum[\frac{\text{Cash Flow}_t}{(1+r)^t}] - CAPEX$, where:
  - Cash Flow_t = Net savings or earnings in year t.
  - r = Discount rate.

- t = Year index.
- CAPEX = Initial investment cost

- IRR = $\sum[\frac{\text{Cash Flow}_t}{(1+r)^t}] - CAPEX$, where:
  - Same as NPV, but IRR is the discount rate r that makes NPV = 0.
- Cost per Transport Work = $\frac{OPEX}{Total\ transport\ work}$, where:
  - OPEX = Operating expenses (annual or voyage-based).
  - Total Transport Work = Cargo moved × distance (tonne-nautical miles).

For the qualitative KPIs, below is a proposed methodology when evaluating them:

- Scalability Potential
  - 1 = Not scalable beyond pilot cases
  - 3 = Limited scalability; major redesign needed
  - 5 = Scalable for selected vessel classes
  - 7 = Scalable with minor adjustments
  - 9 = Easily scalable across all vessel types
- Market Readiness[2]
  - 1 = Concept only; no real-world validation
  - 3 = Lab-scale; major development needed
  - 5 = Prototype stage; limited pilots
  - 7 = Near-commercial; minor validation pending
  - 9 = Fully commercial; proven deployments

[2] While the TRL scale evaluates the technical maturity of a technology, from basic principles to a market-ready product, Market Readiness assesses the commercial maturity of the solution, reflecting how prepared it is for real-world deployment, adoption, and scaling. In other words, TRL measures whether the technology works, whereas Market Readiness measures whether it is viable and established in the market

- Infrastructure Dependency
    - 1 = No shore-side dependency
    - 3 = Minor port adjustments
    - 5 = Requires dedicated infrastructure at major ports
    - 7 = Requires extensive infrastructure upgrades
    - 9 = Cannot operate without global infrastructure overhaul
- Cargo Carrying Capacity Impact
    - 1 = No impact on cargo space
    - 3 = Negligible (<1% reduction)
    - 5 = Moderate (1–3% reduction)
    - 7 = Significant (3–5% reduction)
    - 9 = Severe (>5% reduction)

2.4 Practical Application of KPIs and Metrics

The KPIs and associated metrics developed in this task are designed to support both structured, QFD-based evaluations and broader, standalone assessments of EETs. While the QFD methodology provides a framework for multi-criteria decision-making, the KPI system is also intended to be usable independently, offering flexibility for diverse stakeholder needs and varying levels of analytical maturity.

2.4.1 Use of KPIs Without the QFD Matrix

In cases where the full QFD matrix is not applied, such as during early-stage technology screening, policy analysis, or investment scoping, the KPI framework can still provide valuable insights. Stakeholders may apply the KPIs as follows:

- Scorecard-Based Evaluation: The KPI tables as shown in section 2.3 can be used to create structured scorecards for comparing EETs across technical, environmental, economic, and socio-political dimensions. This enables criteria-based assessments even in the absence of formal weighting or stakeholder calibration.
- Domain-Specific Prioritization: Depending on the strategic focus (e.g. decarbonization, cost-efficiency, retrofit feasibility), users may emphasize specific KPI domains and apply simplified weighting schemes to reflect their priorities.

- Scenario Filtering: The KPI metrics can be used to filter technologies based on predefined thresholds (e.g. minimum GHG reduction potential, maximum CAPEX), supporting rapid screening aligned with operational or regulatory constraints.
- Benchmarking and Gap Analysis: Normalized metrics allow for benchmarking against regulatory targets (e.g. Fit for 55, IMO 2050), industry best practices, or peer technologies, helping identify performance gaps and innovation needs.

The KPI framework also supports broader strategic planning and policy development by:

- Informing R&D and innovation roadmaps: Highlighting areas where technologies underperform in terms of readiness, integration complexity, or market uptake.
- Supporting funding and investment decisions: Providing structured, evidence-based justifications aligned with EU climate and innovation objectives.
- Facilitating stakeholder dialogue: Offering a common reference framework for discussing trade-offs between environmental, economic, and operational priorities.

2.4.2 Preparing for QFD Integration

For stakeholders intending to adopt the full QFD methodology, the KPI framework serves as a foundational layer. The metrics, scoring scales, and data sources defined in this deliverable are directly compatible with the HoQ structure, ensuring consistency and traceability. Early use of the KPIs also helps build familiarity with the evaluation logic, facilitating smoother integration into structured decision-support tools.

Each metric, whether quantitative or qualitative, is normalized and validated in accordance with the procedures outlined in this chapter before being mapped into the HoQ matrix. This ensures that stakeholder requirements are linked to KPIs through consistent, traceable data. Qualitative scores (e.g., Integration Complexity, Safety Risk) use the anchored scales defined in Section 2.3, while quantitative metrics (e.g., GHG reduction, CAPEX) are normalized to common baselines (e.g., per t·nm, lifecycle cost) for comparability across vessel types and operational scenarios.

3 Data Register and Quality Assurance

3.1 Data Collection and Validation

The process of KPIs data collection is governed by a structured workflow designed to ensure traceability, reproducibility, and data integrity. This workflow supports the consistent generation of performance metrics and facilitates transparent reporting across different systems and operational contexts. The key steps involved are shown below.

3.1.1 Define Metric Scope and Units

Each metric is first contextualized by mapping it to the relevant Key Performance Indicator (KPI). This includes:

- Clarifying the intended purpose of the metric (e.g., environmental impact, economic feasibility, operational efficiency).
- Specifying the units of measurement (e.g., $gCO_2e/t{\cdot}nm$, EUR/year, qualitative rating, %).
- Establishing the temporal and spatial boundaries of the data (e.g., per voyage, per annum, per vessel class).

This step ensures that metrics are aligned with evaluation objectives and are interpretable within the broader assessment framework.

3.1.2 Identify Relevant Data Sources and Extract Values

Once the metric scope is defined, appropriate data sources are identified based on availability, relevance, and credibility. This includes:

- Extracting values from empirical datasets, technical documentation, financial reports, or regulatory texts.
- Ensuring that data is current, context-specific, and sourced from authoritative entities.

This step is critical for maintaining data representativeness and minimizing reliance on assumptions.

3.1.3 Normalize and Preprocess Data

Normalization is a critical step in the metric development process, particularly for environmental and economic indicators, as it enables fair comparisons across different vessel classes, operational profiles, and technology configurations. By adjusting raw data to common reference units or baselines, normalization ensures that performance metrics are both

scalable and comparable, regardless of vessel size, route characteristics, or deployment context.

Table 5 Normalization Decision Table

Evaluation Context	Recommended Normalization	Rationale
Design comparison (technology concept stage, lifecycle sustainability	Absolute lifecycle metrics (e.g., total gCO_2e per EET unit, total € CAPEX/OPEX over lifecycle)	Captures full environmental and economic impact of the technology across its life cycle.
Operational comparison across vessels/routes (fleet deployment, voyage	Intensity metrics (e.g., $gCO_2e/t{\cdot}nm$, €/t·nm, %)	Enables comparison across different vessel sizes, cargo capacities, and route profiles.
Scenario-based QFD evaluation (mixed fleet, multi-criteria ranking	Use intensity metrics for environmental/economic KPIs; qualitative scales for technical/socio KPIs	Ensures consistency in weighted scoring and comparability across diverse use cases.

This normalization allows stakeholders to assess the economic viability of technologies or operational strategies in a manner that is scalable, context-sensitive, and aligned with fleet-level decision-making.

3.1.4 Document Assumptions and Calculation Rules

All assumptions made during data processing are explicitly documented, including:

- Estimation techniques, such as interpolation or extrapolation.
- Modelling assumptions, such as fuel mix ratios or operational profiles.
- Calculation rules, including formulas and parameter selections.

This documentation supports transparency, facilitates peer review, and enables future updates or recalibrations.

3.1.5 Validate Data

The final step involves validation to ensure accuracy and credibility. This may include:

- Peer review by subject matter experts.
- Stakeholder consultation, particularly for metrics involving operational or social dimensions.

- Benchmarking against reference cases, industry standards, or historical data.

Validation enhances confidence in the results and ensures that metrics are suitable for decision-making and reporting.

3.2 Typical Data Sources

In order to populate the KPI database with the proper metric information, a variety of data sources should be utilized, spanning from environmental, technical, financial, regulatory, to operational domains. The most referenced sources are shown below.

3.2.1 Environmental & Life Cycle Assessment (LCA) Databases

These databases provide standardized environmental impact data across fuel production, distribution, and usage pathways. They are essential for calculating metrics such as GHG emissions, energy intensity, and resource depletion. Commonly used LCA databases include:

- Ecoinvent[3]: Offers detailed inventories for energy systems, materials, and transport.
- GaBi[4]: Widely used in industrial applications for modelling product life cycles.
- GREET[5] (Greenhouse gases, Regulated Emissions, and Energy use in Technologies): Developed by Argonne National Laboratory, focused on transportation fuels and vehicle technologies.
- U.S. Life Cycle Inventory (USLCI)[6] Database: developed by the National Renewable Energy Laboratory (NREL), can be used to assess the environmental impacts of materials, components, and assemblies manufactured in the USA.

3.2.2 Technical Data

Technical data is usually sourced from:

[3] Database - ecoinvent
[4] GaBi Databases | GHG Protocol
[5] GREET | Department of Energy
[6] U.S. Life Cycle Inventory Database | Energy Systems Analysis | NLR

- Manufacturer datasheets, which provide performance characteristics, dimensions, and operational limits of equipment.
- Classification society reports, offering compliance data, certification status, and safety evaluations.
- Onboard measurements, including sensor data and operational logs, which reflect real-world performance under specific conditions.

3.2.3 Economic Data

Economic metrics are derived from:

- CAPEX/OPEX estimates provided by shipyards, technology vendors, and operators.
- Feasibility studies and cost models developed during project planning or retrofit evaluations.

These sources inform indicators such as payback period, total cost of ownership, and economic viability, supporting investment decisions and financial planning.

3.2.4 Regulatory Documents

Compliance-related metrics are based on:

- IMO guidelines, including MARPOL Annexes, EEDI/EEXI frameworks, and GHG reduction strategies.
- EU Fit for 55 documentation[7], which outlines decarbonization targets and funding mechanisms.
- National maritime regulations, which may impose additional requirements or incentives.

These documents ensure that metrics reflect current and emerging regulatory landscapes, enabling alignment with policy objectives.

3.2.5 Expert Surveys

Social and operational metrics are often derived from:

- Structured questionnaires targeting crew members, operators, and technical experts.

[7] Fit for 55 - Consilium

- Workshops and interviews, which provide qualitative insights into usability, safety, and acceptance.

These sources are particularly valuable for assessing human factors, operational complexity, and technology readiness, where empirical data may be limited.

3.3 Data Quality Considerations

Ensuring high data quality is essential for credible KPI evaluation and decision-making. Three core principles guide this process:

3.3.1 Transparency

Every metric must include clear documentation of its source, calculation method, and assumptions.

Formulas and normalization rules should be traceable to enable independent verification and stakeholder confidence.

3.3.2 Representativeness

Data must reflect the operational context of the evaluated technology, including vessel type, route profile, and environmental conditions.

Using context-specific datasets prevents misleading comparisons and supports scenario-based assessments.

3.3.3 Uncertainty Management

To ensure transparency in uncertainty quantification, variability should be addressed by reporting confidence intervals or sensitivity ranges.

When expert or forecast based estimates are used, qualitative annotations should additionally document the assumptions, rationale, and potential sources of bias underlying the judgment. This is because several KPIs may rely partly on expert input, requiring a structured approach to capturing uncertainty and, where applicable, metrics that indicate the degree of consensus among experts (e.g., dispersion of estimates or agreement scores).

Applying these principles ensures that KPI scoring remains robust, comparable across use cases, and aligned with regulatory and industry standards.

3.4 KPI gathering – Data register

The KPI Data Register serves as the central repository for all KPIs defined within the FLEETfor55 evaluation framework. Its purpose is to ensure traceability, consistency, and transparency in

the assessment of EETs across diverse vessel types and operational contexts. By consolidating KPIs, normalized metrics, units, and primary data sources into a structured format, the register provides a practical foundation for both standalone evaluations and integration into the QFD-based methodology. This register is designed to be modular and adaptable, supporting scenario-specific assessments without imposing rigid operational constraints.

The data register does not prescribe fixed responsibilities, measurement intervals, or detailed data collection protocols. These elements are highly context-dependent and vary, according to the specific operational environment, stakeholder roles, and technology deployment scenarios. Defining them at this stage would risk imposing rigid structures, such as fixed reporting hierarchies, mandatory sampling frequencies, or uniform data-handling procedures, that may not align with diverse user needs. Instead, the framework is designed to remain flexible, allowing each stakeholder to tailor these aspects to their organizational processes, resource availability, and compliance requirements. This approach ensures adaptability and practical relevance across different vessel types, routes, and operational strategies

Table 6 KPIs Data Register

#	Category	Sub-category	Domain	KPI	Type	Target	Value/Unit	Source
Market Status		TRL	Technical	TRL score	Qualitative	Max	Scale (1–9)	Expert panels, classification society reports
		Scalability Potential	Economic	Deployment Feasibility Score	Qualitative	Max	Score (1–9)	Feasibility studies, pilot projects, expert evaluations
		Market Readiness	Economic	Commercial Deployment Index	Qualitative	Max	Score (1–9)	Market analysis studies
		Infrastructure Dependency	Economic	Reliance on port or shore-side infrastructure	Qualitative	Min	Score (1–9)	Port data, vendor specs, policy docs, expert input
Retrofit Impact		Integration Complexity	Technical	Retrofitting Score	Qualitative	Min	Score (1–9)	Technical datasheets, shipyard evaluations
		Compatibility with Existing Systems	Technical	Compatibility Index	Qualitative	Max	Score (1–9)	Onboard system audits, manufacturer specs
		Retrofit Time	Technical	Installation Duration	Quantitative	Min	Days/vessel	Shipyard installation records, project documentation
Energy Efficiency		Impact on Vessel Consumption	Technical	Δ Fuel Consumption on an equivalent basis	Quantitative	Max	% or kg/ t·nm or MJ per t·nm	Onboard measurements, simulation outputs
		Propulsion efficiency	Technical	Shaft Power Savings	Quantitative	Max	% or kW	Onboard measurements, simulation outputs
		Auxiliary Power Demand	Technical	Reduction in Auxiliary Load	Quantitative	Max	% or kW	Onboard measurements, simulation outputs
		Steam demand	Technical	Reduction in Boiler Load	Quantitative	Max	% or kW	Boiler system logs, manufacturer datasheets
Crew Impact		Maintenance Requirements	Technical	Maintenance Hours per Year	Quantitative	Min	Hours/year	Maintenance logs, PMS, technical service reports

#	Category	Sub-category	Domain	KPI	Type	Target	Value/Unit	Source
		Maintenance Complexity	Technical	Skill level required	Qualitative	Min	Score (1-9)	Training manuals, OEM documentation
		Crew Training Requirements	Socio-Political	Training Hours	Quantitative	Min	Hours/person	Training manuals, Manufacturer's recommendations
		Impact on Crew Workload	Socio-Political	Δ Workload Index	Qualitative	Min	Score (1-9)	PMS, crew interviews
		Safety Impact	Socio-Political	Safety Risk Index	Qualitative	Min	Score (1-9)	Risk assessments, incident reports
Regulations		Regulatory landscape	Socio-Political	Regulatory background in place	Qualitative	Max	Score (1-9)	IMO and EU regulatory databases, Classification Societies documentation, International and domestic regulations
		Impact on regulations	Socio-Political	Number of regulations impacted from the EET	Qualitative	Max	Score (1-9)	Regulatory impact assessments
Emissions Impact		GHG Reduction Potential	Environmental	gCO_2e saved per t·nm	Quantitative	Max	gCO_2e/t·nm or %	Modelling and simulations tools, onboard measurements, manufacturer's data
		Lifecycle Emissions	Environmental	Total gCO_2e per lifecycle	Quantitative	Min	gCO_2e/t·nm or %	Modelling and simulations tools, lifecycle analysis tools, sustainability reports
		Pollutant Reduction	Environmental	g(NO_x/SO_x/PM) per t·nm	Quantitative	Max	g/t·nm or %	Modelling and simulations tools, emission monitoring systems, simulation outputs
Economic Viability		CAPEX	Economic	EET cost in EUR	Quantitative	Min	€	Vendor quotes, project budgets

#	Category	Sub-category	Domain	KPI	Type	Target	Value/Unit	Source
		OPEX	Economic	(Δ) EUR per year	Quantitative	Max	(Δ) €/year or %	Modelling and simulations tools, PMS, operational cost reports, fleet management systems
		Payback Period	Economic	Years to ROI	Quantitative	Min	Years	Simulations tools, financial models, ROI calculators
		NPV	Economic	EUR over lifecycle	Quantitative	Max	€	Lifecycle cost analysis, investment feasibility studies
		IRR	Economic	%	Quantitative	Max	%	Financial modelling tools, investment analysis reports
		Cargo carrying capacity	Economic	Effect on cargo carrying capacity	Qualitative	Min	Score (1–9)	Weight increase analysis, updated inclination tests
		Cost per Transport Work	Economic	EUR per t·nm	Quantitative	Min	€/t·nm or %	Voyage data, economic performance models
	Circularity	Recycle Ratio	Environmental	Percentage of recyclable materials	Quantitative	Max	%	Bill of Materials (BoM), Material passports, EPDs
		Criticality Ratio	Environmental	Percentage of critical materials	Quantitative	Min	%	BoM, critical material lists, supplier declarations
		Critical Mass	Environmental	Percentage of mass of critical material	Quantitative	Min	%	BoM, supplier material breakdowns

4 QFD Methodology

This chapter outlines the design and implementation of the QFD matrix, the scoring logic and weighting mechanisms applied, and the validation process involving industry stakeholders.

4.1 Adaptation of QFD to the maritime context

To address the complexity of evaluating decarbonization technologies in maritime transport, the FLEETfor55 project applies the QFD methodology. The proposed QFD framework was designed to meet project objectives and ISO-aligned principles. During development, ISO 16355-1:2021 was accommodated for its guidance on structuring information sets, prioritization, and deployment matrices. Additionally, recent academic contributions such as (Ya-Juan Han, 2025) and (Okan Duru, 2012) were consulted to understand emerging practices in consensus modelling and KPI weighting in maritime contexts.

At the heart of QFD lies the HoQ, a matrix-based tool that enables transparent mapping between what stakeholders value and how technologies perform. Stakeholder expectations (e.g., alignment with IMO and EU Fit for 55 targets, ease of retrofitting, crew safety, and training requirements) are positioned on one axis, while technical attributes of EETs (e.g., emissions reduction potential, lifecycle cost, integration complexity) are placed on the other. The relationships between these elements are scored using weighted scales, allowing for a structured comparison of how well each technology meets the defined priorities.

This adaptation supports scenario-based assessments across vessel types and operational profiles, helping stakeholders visualize trade-offs and make informed, context-sensitive decisions.

The following sections detail the structure of the QFD matrix, the scoring logic, and the stakeholder calibration process that underpin this adaptation.

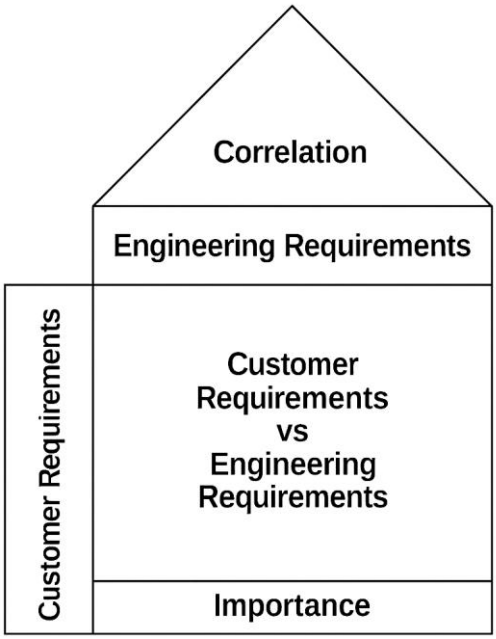

Figure 2 Simplified QFD matrix template

4.2 Converting KPIs to QFD Scoring

To integrate the KPI framework into the QFD methodology, all KPIs, both qualitative and quantitative, must be expressed on a common scoring scale from 1 to 9. While qualitative KPIs already use anchored scales, quantitative KPIs require normalization to ensure comparability.

4.2.1 Performance Ranges

For each quantitative KPI, establish realistic minimum and maximum values based on industry benchmarks, regulatory targets, or project-specific data.

Example:

- GHG Reduction Potential: 0 → 50 $gCO_2e/t{\cdot}nm$
- CAPEX: €0 → €5,000,000

4.2.2 Normalization Formula

For KPIs where higher is better (e.g., GHG reduction, propulsion efficiency):

- $Score = 1 + \frac{(X-Xmin)\cdot(9-1)}{Xmax-Xmin}$

For KPIs where lower is better (e.g., CAPEX, retrofit time):

- $Score = 9 - \frac{(X-Xmin)\cdot(9-1)}{Xmax-Xmin}$

Where:

- X = actual KPI value
- X_{min}, X_{max}= defined range

For handling purposes of the produced values, the above scoring will be rounded to the closest integer.

4.2.3 Scoring ranges and Document Assumptions

Values outside the range are capped at 1 or 9. All assumptions, ranges, and formulas must be documented for transparency.

This approach ensures that quantitative KPIs can be integrated seamlessly into the House of Quality, enabling weighted scoring and stakeholder-driven prioritization.

Table 7 Example template for converting quantitative KPIs for QFD method

Sub-category	Unit	Range (Min–Max)	Direction	Score 1	Score 5	Score 9
GHG Reduction Potential	%	0 – 100	Higher better	0	50	100
CAPEX	€	0 – 25,000,000	Lower better	25,000,000	12,500,000	0
Payback Period	Years	0 – 10	Lower better	10	5	0
Propulsion Efficiency	%	0 – 15	Higher better	0	7.5	15

In summary, the KPI framework developed in this task is designed to be both modular and scalable, supporting a wide range of evaluation needs, from rapid screening to in-depth, stakeholder-calibrated assessments. This flexibility ensures its relevance across different stages of technology development and across the diverse stakeholder landscape of the maritime sector.

4.3 Engineering requirements

The grouping of the engineering requirements (ERs) is done into the eight categories from 3.4. This approach provides a structure that mirrors the main dimensions of technology evaluation: market feasibility, retrofit practicality, operational performance, crew considerations, regulatory compliance, environmental impact, economic viability, and circularity. This

classification simplifies analysis, supports traceability, and ensures that all relevant aspects of technology adoption are captured in the QFD process.

4.3.1 Engineering Requirements (ER) correlation (roof) matrix

The ER correlation matrix, also referred to as the roof matrix in the QFD methodology, is a critical tool for identifying interdependencies among technical requirements. It highlights how improvements in one KPI may influence others, positively or negatively, thus revealing potential synergies and trade-offs during technology selection and design optimization.

The matrix ensures that decision-makers understand the systemic impact of changes across multiple domains (technical, economic, environmental, socio-political). By mapping correlations, it prevents isolated decisions that could inadvertently compromise overall performance or compliance objectives.

The table below summarizes the correlation values among the 31 KPIs, including technical, operational, economic, environmental, and circularity indicators. Negative values (−1, −2) represent potential conflicts, while positive values (+1, +2) indicate synergies.

The matrix uses a standardized scale to express the strength and direction of relationships:

- +2 = Strong Positive Correlation: Improvement in one KPI strongly supports improvement in the other.
- +1 = Positive Correlation: Improvement in one KPI moderately supports improvement in the other.
- 0 = Neutral: No significant interaction between the two KPIs.
- −1 = Negative Correlation: Improvement in one KPI slightly hinders the other.
- −2 = Strong Negative Correlation: Improvement in one KPI strongly hinders the other.

In terms of interpretation the following apply:

- Positive correlations indicate areas of synergy where improvements can deliver multiple benefits (e.g., propulsion efficiency and OPEX reduction).
- Negative correlations highlight trade-offs that require careful management (e.g., reducing retrofit time may increase integration complexity).
- Neutral entries suggest independence, allowing decisions without major cross-effects.

Table 8 KPIs correlation (roof) matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1- TRL		1	2	0	0	0	1	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2- Scalability Potential	1		2	1	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
3- Market Readiness	2	2		2	1	1	0	1	1	1	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
4- Infrastructure Dependency	0	1	2		0	0	1	1	1	1	0	1	0	1	-1	0	0	-1	0	1	-1	0	0	0	0	-1	-1	-1	-1	0	0
5- Integration Complexity	0	0	1	0		-1	1	0	0	1	0	1	1	1	1	0	0	1	-1	1	-1	1	0	0	0	1	0	-1	1	0	0
6- Compatibility with Existing Systems	0	0	1	0	-1		1	2	0	0	1	1	0	1	0	0	1	0	1	-1	1	0	0	0	0	1	-1	-1	0	0	1
7- Retrofit Time	1	0	0	1	1	1		1	1	0	0	0	0	1	0	0	0	0	1	-1	-1	0	0	0	0	-1	1	1	-1	0	1
8- Impact on Vessel Consumption	0	0	1	1	0	2	1		2	1	1	1	0	0	0	0	0	0	-1	0	-1	0	0	0	-1	0	0	0	1	0	1
9- Propulsion efficiency	1	1	1	1	0	0	1	2		0	0	0	1	0	0	0	1	0	-1	-1	-1	0	0	0	1	-2	0	1	-1	0	-2
10- Auxiliary Power Demand	1	1	1	1	1	0	0	1	0		1	1	1	1	1	0	0	0	-1	-1	0	0	0	0	-1	0	0	1	0	1	-1
11- Steam demand	0	0	1	0	0	1	0	1	0	0		1	1	1	0	0	0	1	0	0	1	0	0	0	-1	-1	-1	1	0	0	-1
12- Maintenance Requirements	0	0	0	1	1	1	0	1	0	1	1		2	2	1	0	0	0	1	0	1	1	0	0	1	-1	1	0	-1	0	0
13- Maintenance Complexity	0	1	0	0	1	0	0	0	1	1	1	2		2	1	0	0	1	0	0	1	0	0	0	0	-1	1	1	1	0	1
14- Crew Training Requirements	1	0	0	1	1	1	1	0	0	1	1	2	2		1	0	0	1	0	0	0	0	0	0	-1	1	0	-1	1	-1	-1
15- Impact on Crew Workload	0	0	1	-1	1	0	0	0	0	1	0	1	1	1		0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	-1	0
16- Safety Impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	1	0	1	0	0	0	0	0	0	0	0	0	1	0
17- Regulatory landscape	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2		1	1	1	1	1	0	0	0	0	1	0	0	1	0
18- Impact on regulations	0	0	0	-1	1	0	0	0	0	0	1	0	1	1	0	1	1		1	1	0	0	0	0	0	0	0	1	0	0	0
19- GHG Reduction Potential	0	0	0	0	-1	1	1	-1	-1	-1	0	1	0	0	0	0	1	1		-2	2	0	0	0	0	0	1	0	1	0	0
20- Lifecycle Emissions	0	0	0	1	1	-1	-1	0	-1	-1	0	0	0	0	0	1	1	1	-2		2	0	0	1	-1	1	1	1	1	0	1
21- Pollutant Reduction	0	1	0	-1	-1	1	-1	-1	-1	0	1	1	1	0	0	0	1	0	2	2		0	0	0	1	1	0	1	1	0	0
22 - Recycle Ratio	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0		-1	-1	0	0	0	0	0	0	0
23 - Criticality Ratio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1		1	1	1	1	-1	-1	0	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
24 - Critical Mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1	1		1	1	1	-1	-1	0	0
25- CAPEX	0	0	0	0	0	0	0	-1	1	-1	-1	1	0	-1	0	0	0	0	0	-1	1	0	1	1		1	2	-2	-2	1	1
26- OPEX	0	0	0	-1	1	1	-1	0	-2	0	-1	-1	-1	1	0	0	0	0	0	1	1	0	1	1	1		2	-2	-2	1	1
27- Payback Period	0	1	0	-1	0	-1	1	0	0	0	-1	1	1	0	-1	0	1	0	1	1	0	0	1	1	2	2		-2	-2	1	0
28- NPV	0	0	0	-1	-1	-1	1	0	1	1	1	0	1	-1	-1	0	0	1	0	1	1	0	-1	-1	-2	-2	-2		2	1	0
29- IRR	0	0	0	-1	1	0	-1	1	-1	0	0	-1	1	1	0	0	0	0	1	1	1	0	-1	-1	-2	-2	-2	2		1	0
30- Cargo carrying capacity	0	0	1	0	0	0	0	0	0	1	0	0	0	-1	-1	1	1	0	0	0	0	0	0	0	1	1	1	1	1		1
31- Cost per Transport Work	0	0	0	0	0	1	1	1	-2	-1	-1	0	1	-1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	1	

The correlation values in the roof matrix express how changes in one KPI tend to affect another, enabling users to foresee synergies and trade-offs. While the scale definitions (+2 strong positive; +1 positive; 0 neutral; −1 negative; −2 strong negative) are described earlier, below KPI-specific rationales are provided for common interactions (especially negative ones).

The reasoning for the values of +2 and -2 is shown in Annex A.

4.4 Customer requirements

The QFD approach begins by defining Customer (project) Requirements (CRs), the high-level objectives that reflect stakeholder priorities and goals. These requirements form the foundation of the HOQ and guide the evaluation of ERs. Each CR represents a critical dimension of technology selection, ensuring that decisions balance economic, operational, environmental, and safety considerations.

4.4.1 Analysis of Customer Requirements

4.4.1.1 Economic Viability

Economic Viability ensures that EETs deliver a strong business case. It encompasses lifecycle cost factors such as CAPEX, OPEX, payback period, and investment metrics like NPV and IRR. Technologies that minimize costs and maximize returns are prioritized because they enable compliance and sustainability without compromising profitability.

4.4.1.2 EET Readiness

EET Readiness, measures technology maturity and deployability. It considers TRL, market readiness, and scalability potential. High readiness reduces implementation risk and accelerates adoption, making this CR essential for meeting regulatory timelines and operational schedules.

4.4.1.3 Performance

Performance focuses on operational efficiency, including propulsion improvements, reduced fuel consumption, and optimized auxiliary loads. Strong performance translates into lower energy use and better voyage economics.

4.4.1.4 GHG Compliance with Regulations

Compliance with decarbonization mandates such as IMO Carbon Intensity Indicator (CII) and European Union Emissions Trading System (EU ETS) is supported by technologies that reduce greenhouse gas emissions and pollutants help operators avoid penalties and future-proof investments.

4.4.1.5 EET Complexity

Complexity captures integration challenges, compatibility with existing systems, and retrofit time. Lower complexity reduces installation costs, downtime, and training needs, making technologies more practical for fleet-wide deployment.

4.4.1.6 EET Safety & Risk

Safety and risk management are non-negotiable in maritime operations. This CR evaluates the impact of technology on onboard safety, including hazards during installation, operation, and maintenance. Technologies that maintain or enhance safety are prioritized.

4.4.2 Stakeholder calibration

As mentioned above, a central feature of the QFD methodology is its ability to link stakeholder requirements to technical performance attributes. In the context of the maritime sector, this mapping ensures that the evaluation of EETs reflects not only engineering feasibility but also the strategic priorities of shipowners, operators, regulators, and other industry stakeholders.

To ensure that the QFD evaluation framework reflects real-world priorities and expert consensus, a structured stakeholder calibration process is implemented. This process engages key actors across the maritime value chain, including shipowners, operators, technology providers, regulatory bodies, and classification societies, to align scoring practices and reduce bias.

Calibration activities include:

- Surveys and structured questionnaires to gather expert judgments on qualitative metrics and weighting preferences.
- Iterative feedback loops that allow stakeholders to refine inputs based on preliminary scoring outcomes.
- Scoring simulations to test consistency and usability across technologies and vessel types.
- Sensitivity analyses to evaluate how changes in assumptions or weightings affect KPI outcomes.
- Consensus-building sessions to resolve discrepancies and harmonize interpretations.

This integrated approach ensures that the QFD matrix remains adaptable to evolving stakeholder needs and regulatory landscapes.

4.4.3 Assigning Customer Requirements Weights and Policy-Based Presets

The QFD HoQ requires Customer Requirement (CR) weights that reflect the stakeholder's strategic priorities.

- Economic Viability
- EET Readiness
- Performance
- GHG Compliance
- EET Complexity
- EET Safety & Risk

Priority scale (for inexperienced users):

- Low priority → 1
- Medium priority → 3
- High priority → 5

Policy-based suggested presets (users may select one and adjust):

Table 9 QFD policy-based suggested presets

Criterion	Performance	Economic	Compliance	Rapid-transition	Balanced (default)
Economic Viability	3	5	2	3	3
EET Readiness	2	2	2	4	2
Performance	5	4	1	3	3
GHG Compliance	3	2	5	2	3
EET Complexity	2	2	2	2	3
EET Safety & Risk	1	1	4	2	2

Normalized weights are used (sum = 100%) across the six CR categories.

4.5 QFD – relationship matrix

The QFD relationship matrix defines how Customer Requirements (CRs) relate to Engineering Requirements (ERs), providing a methodology to evaluate the contribution of each technical parameter toward the strategic objectives. This matrix is a core element of the HOQ and ensures that technology selection aligns with customer priorities such as economic viability, readiness, performance, compliance, complexity, and safety.

The strength of each relationship is expressed using a discrete scale of 0, 1, 3, and 9, where:

- 0 = No relationship
- 1 = Weak influence
- 3 = Moderate influence
- 9 = Strong influence

These values are assigned based on a structured evaluation of how strongly each ER influences a given CR. This evaluation combines expert engineering judgment, regulatory expectations, and an understanding of operational consequences, ensuring that assessors consider both direct technical dependencies and practical, real-world effects. For example, a strong link (9) is given where an ER directly drives a CR, such as CAPEX and OPEX influencing Economic Viability. Moderate values (3) indicate partial influence, while weak values (1) reflect minor or indirect effects. This structured scoring ensures consistency and transparency in prioritization.

The main criteria used to assign these values include:

- Direct impact on CR objectives (e.g., cost KPIs strongly affect Economic Viability).
- Regulatory and compliance relevance (e.g., GHG Reduction Potential strongly supports GHG compliance).
- Operational performance contribution (e.g., propulsion efficiency strongly influences Performance).
- Lifecycle and sustainability considerations (e.g., Circularity KPIs affect Economic Viability and Complexity).

These values are adjustable and can be refined as more data becomes available or stakeholder priorities change, making the matrix a dynamic decision-support tool.

Economic Viability shows strong relationships (value 9) with CAPEX, OPEX, Payback Period, and NPV, reflecting their direct effect on cost efficiency and return on investment. EET Readiness is strongly linked to TRL and Market Readiness, as technology maturity drives deployment feasibility. Performance is primarily associated with energy efficiency KPIs such

as propulsion efficiency and vessel consumption, while GHG compliance correlates strongly with emissions-related KPIs and regulatory landscape. Circularity indicators, Recycle Ratio, Criticality Ratio, and Critical Mass, are integrated with strong ties to Economic Viability and moderate links to complexity and safety, highlighting their growing importance in lifecycle sustainability.

By quantifying these relationships, the QFD matrix feeds into the HOQ calculator, which aggregates weighted scores to rank technologies against customer-driven objectives. This approach ensures balanced trade-offs between cost, performance, compliance, and sustainability, supporting informed and transparent technology selection.

Table 10 QFD relationship matrix

CR \ ER	Market Status				Retrofit Impact			Energy Efficiency				Crew Impact				
CR \ ER	TRL	Scalability Potential	Market Readiness	Infrastructure Dependency	Integration Complexity	Compatibility with Existing Systems	Retrofit Time	Impact on Vessel Consumption	Propulsion efficiency	Auxiliary Power Demand	Steam demand	Maintenance Requirements	Maintenance Complexity	Crew Training Requirements	Impact on Crew Workload	Safety Impact
Economic Viability	1	3	3	3	3	9	3	9	9	3	3	3	3	1	1	3
EET Readiness	9	3	9	3	3	3	1	1	0	0	0	1	1	3	1	1
Performance	0	0	0	0	0	0	0	9	9	3	3	1	1	0	1	0
GHG compliance with regulations	0	0	0	0	0	0	0	3	3	1	1	0	0	1	1	3
EET Complexity	1	1	1	9	9	9	9	0	0	0	0	3	9	9	9	3
EET Safety & Risk	3	1	3	3	3	1	1	0	0	0	0	3	9	3	3	9

CR \ ER	Regulations		Emissions Impact			Economic Viability							Circularity		
CR \ ER	Regulatory landscape	Impact on regulations	GHG Reduction Potential	Lifecycle Emissions	Pollutant Reduction	CAPEX	OPEX	Payback Period	NPV	IRR	Cargo carrying capacity	Cost per Transport Work	Recycle Ratio	Criticality Ratio	Critical Mass
Economic Viability	3	3	9	3	3	9	9	9	9	9	9	9	1	9	9
EET Readiness	3	1	0	1	1	0	0	0	0	0	0	0	1	3	3
Performance	0	9	9	3	9	0	3	9	9	9	1	3	0	0	0
GHG compliance with regulations	9	9	9	3	9	0	0	3	3	3	1	0	1	0	0
EET Complexity	1	1	0	0	0	3	1	1	1	1	3	0	3	3	3
EET Safety & Risk	3	1	0	0	0	3	1	0	0	0	3	0	1	3	3

4.6 QFD based evaluation method working principle

4.6.1 Purpose and rationale

As seen in the present chapter, the developed QFD methodology provides an ISO-aligned way to translate stakeholder priorities into measurable, comparable scores for EETs. It uses the HoQ to link CRs, reflecting requirements such as economic viability, readiness, performance, compliance, complexity, and safety, to ERs, operationalized as KPIs across technical, environmental, socio-political, and economic domains. The result is a traceable ranking that shows which requirements each EET satisfies most and how different criteria contribute to the final outcome. The QFD evaluation method is a dynamic process in order to rank the EETS basis the CRs. Different CRs will result to different ranking results.

A worked example of the usage of the QFD methodology is available for the reader in Annex B – Example QFD Calculation for Two EETs

4.6.2 Structure of the QFD model

In the context of the present analysis, the adapted QFD framework consists of three main elements:

- CRs: These represent stakeholder priorities, such as cost-effectiveness, readiness for deployment, energy efficiency, compliance with decarbonization targets, and safety. Each CR is assigned a weight to indicate its relative importance.
- ERs: These are technical and operational parameters that describe how a technology performs. ERs are expressed through Key Performance Indicators (KPIs) covering technical, environmental, economic, and socio-political dimensions.
- Relationship Matrix (HoQ): This matrix links CRs to ERs using a structured scoring scale (e.g., 0, 1, 3, 9), indicating the strength of influence. This ensures that technologies are evaluated based on how well they satisfy stakeholder priorities.

4.6.3 Converting metrics to QFD scores (normalization)

To make heterogeneous metrics comparable, all KPI inputs are expressed on a 1–9 score:

- Benefit-type KPIs (higher is better)
- Cost-type KPIs (lower is better)

The analysis and normalization of the above KPIs is already developed in 4.2.2.

4.6.4 Deriving KPI importance from stakeholder priorities

The translation of the CR weights into KPI importance is done through the relationship matrix with the below formula:

- $\text{Importance}_j = \sum_{i=1}^{n}(r_i \cdot S_{i,j})$, where:
  - r_i =normalized weight of CR_i as shown in 4.4.3
  - $S_{i,j}$ = relationship score between CR_i and KPI_j as shown in Table 10.
  - n is the total number of ERs

As a next step, the normalized KPI weights are computed:

- $Weight_j = \frac{Importance_j}{\sum_{j=1}^{n} Importance_j}$

Finally the EETs' scores are computed via the following formula:

- $Total\ Score = \sum_{j=1}^{n}(Weight_j \cdot Score_j)$, where
  - $Score_j$ is the score of the EET across the ERs

4.6.5 EETs Domain-Level Calculation

As seen in 3.4, KPIs can be grouped into domains (e.g., Market Status, Retrofit Impact, Energy Efficiency, Crew Impact, Regulations, Emissions Impact, Economic Viability, Circularity). Each category score is calculated as:

- $Category\ Score_d = \sum_{j=1}^{d}(Weight_j \cdot Score_j)$, where:
  - $d = category\ group\ index$ as shown in 3.4

Ranking is done based on the total score of each EET on a descending order.

The QFD approach developed in this deliverable is flexible and can be applied to both individual technologies and combined solutions. Its structure, based on mapping customer requirements to engineering attributes, allows the integration of multiple performance indicators without altering the core logic of the HoQ. When technologies are combined, the methodology simply aggregates or recalculates KPI values according to predefined normalization rules, ensuring that the evaluation remains consistent and transparent.

5 Conclusions

This deliverable has established an evaluation framework for EETs within the FLEETfor55 project, addressing the need for structured, transparent, and multi-dimensional decision-making tools. The framework integrates KPIs across technical, environmental, economic, and socio-political domains, supported by measurable assessment metrics and normalization procedures. These KPIs reflect industry priorities such as decarbonization potential, operational suitability, market readiness, scalability, and techno-economic viability.

A key outcome of this work is the adaptation of the QFD methodology to the maritime context, enabling systematic mapping of stakeholder requirements to engineering attributes. The developed HoQ structure ensures traceability between objectives and technical solutions, while the inclusion of correlation matrices and weighting mechanisms supports robust trade-off analysis. The methodology is designed to be flexible, allowing application to individual technologies as well as combined solutions, and scalable for diverse vessel types and operational scenarios.

The QFD framework will be made publicly available after the project, ensuring long-term usability for industry stakeholders and supporting informed investment, regulatory compliance, and innovation planning. Future work will focus on validating the methodology through real-world use cases and refining stakeholder calibration to enhance practical relevance.

Table 11 Deliverable description

Deliverable D3.3 Development of KPIs, assessment metrics and QFD method for evaluating the use cases
This deliverable establishes a structured evaluation framework for assessing EETs and vessel types within the FLEETfor55 project. It defines techno-, socio-, environmental, and economic KPIs aligned with decarbonization, scalability, and market readiness objectives. The report introduces measurable assessment metrics, a comprehensive KPI data register, and an ISO-aligned QFD methodology adapted to the maritime context. The QFD approach links stakeholder requirements to engineering attributes through weighted scoring and normalization, enabling transparent, multi-criteria decision-making. The framework is designed to be flexible, supporting both individual and combined EET evaluations across diverse vessel types and operational scenarios.

Table 12 Task description

T3.3 - Development of KPIs, assessment metrics and QFD method for evaluating the use cases
This task develops techno-, socio-, environmental, and economic KPIs, corresponding assessment metrics, and a QFD-based method for evaluating alternative combinations of EETs and vessel types. KPIs include indicators on decarbonization, suitability for a broad range of vessels, potential for commercial uptake and rapid transition, standardization and scaling, and techno-economic viability. A data register and assessment metrics will be established, and the QFD-based method will be made available post-project for industry stakeholders.

Table 13 Task elements

FLEETfor55 GA Element Title	FLEETfor55 GA Element Outline	Respective Document Chapter (s) and Description
ST3.3.1 – KPI Development	Define techno-, socio-, environmental, and economic KPIs aligned with decarbonization, scalability, and market readiness objectives.	Chapter 2 - Overview of KPIs: Introduces KPI domains, definitions, and detailed KPI lists with formulas and normalization rules.
ST3.3.2 – Assessment Metrics & Data Register	Establish measurable metrics for each KPI and create a structured	Chapter 3 - Data Register and Quality Assurance: Describes data collection,

FLEETfor55 GA Element Title	FLEETfor55 GA Element Outline	Respective Document Chapter (s) and Description
	data register for traceability and transparency.	normalization, validation, and presents the KPI Data Register
ST3.3.3 – QFD Methodology Development	Adapt QFD principles to maritime context, linking stakeholder requirements to engineering attributes through HoQ.	Chapter 4 - QFD Methodology: Explains QFD adaptation, scoring logic, normalization, CR/ER mapping, and includes worked examples (Annex B).
ST3.3.4 – Integration for Use Case Evaluation	Ensure methodology supports evaluation of individual and combined EETs across diverse vessel types and operational scenarios.	Chapter 4.6 - Adaptability to Combinations of EETs: Discusses flexibility of QFD for combined solutions

Annex A - QFD Engineering Requirements correlation matrix scoring reasoning

This appendix explains the reasoning behind each the +2 and -2 entries in the QFD Engineering Requirements correlation matrix. To avoid redundancy, each KPI pair is documented once

Scale: +2 strong positive, −2 strong negative.

- TRL – Market Readiness: Mature tech reduces adoption risk; market pull accelerates maturation.
- Market Readiness – Scalability Potential: Proven market fit enables scaling; scaling further validates readiness.
- Infrastructure Dependency – Market Readiness: Available infrastructure unlocks adoption; adoption pressure accelerates infra roll-out.
- Compatibility with Existing Systems – Impact on Vessel Consumption: Good fit enables optimal operation/controls that translate to lower consumption.
- Impact on Vessel Consumption – Propulsion efficiency: Efficiency gains directly reduce consumption; consumption reflects propulsion performance.
- Maintenance Requirements – Maintenance Complexity: More tasks/procedures raise complexity; complex systems demand more maintenance.
- Maintenance Complexity – Crew Training Requirements: Complex equipment/processes need more specialized training; trained crew sustain complex operations.
- Maintenance Requirements – Crew Training Requirements: Heavier maintenance programs require broader crew skills/certifications.
- Safety Impact – Regulatory landscape: Safety outcomes drive regulatory action; stricter regulation elevates safety practices.
- GHG Reduction Potential – Recycle: Ambitious decarbonization pushes circular design and higher recyclability.
- Lifecycle Emissions – Pollutant Reduction: Cleaner processes cut both lifecycle GHG and regulated pollutants.
- CAPEX – Payback Period: Bigger upfront spend lengthens payback; long payback often implies high capital intensity.

- OPEX – Payback Period: Higher running costs delay breakeven; quick payback typically reflects low OPEX.
- NPV – IRR: Stronger project economics raise both NPV and IRR together.

Negative Correlations (-2)

- Propulsion efficiency – Cost per Transport Work: Better efficiency lowers fuel per tonne-nm, strongly cutting unit transport cost.
- OPEX – Propulsion: Efficiency improvements reduce operating/fuel costs; high OPEX signals poorer efficiency.
- CAPEX – NPV: Larger upfront outflows depress NPV unless benefits scale disproportionately.
- CAPEX – IRR: Higher capital burden lowers return rates without commensurate gains.
- NPV – OPEX: Costly operations erode cash flows/NPV; strong NPV reflects leaner OPEX.
- IRR – OPEX: Heavy operating costs drag IRR down; high IRR implies lower OPEX.
- Payback Period – IRR: Faster payback corresponds to higher IRR; long payback implies low IRR.
- Payback Period – NPV: Longer payback heavily discounts benefits, reducing NPV; high NPV often accompanies quick payback.
- GHG Reduction Potential – Lifecycle Emissions: Rising lifecycle emissions reduce achievable GHG reduction.

Annex B – Example QFD Calculation for Two EETs

This annex demonstrates the QFD-based scoring and ranking workflow using two example technologies (“EET 1” and “EET 2”). It applies the methodology described in Chapter 4.

Input assumptions

CRs and relative weights are (as per default option as shown in 4.4.3):

- Economic Viability: 3
- Performance: 2

- GHG Compliance: 3
- EET Readiness: 3
- EET Complexity: 3
- Safety & Risk: 2

Relationship scores (0, 1, 3, 9) between CRs and ERs/KPIs are considered fixed and not altered as shown in 4.5.

The two EET KPIs scoring is considered as per below table.

Table 14 EETs KPIs - scoring example

Sub-category	EET 1	EET 2
TRL	1	3
Scalability Potential	7	8
Market Readiness	8	4
Infrastructure Dependency	1	8
Integration Complexity	4	7
Compatibility with Existing Systems	8	1
Retrofit Time	8	1
Impact on Vessel Consumption	5	4
Propulsion efficiency	3	3
Auxiliary Power Demand	1	4
Steam demand	9	5
Maintenance Requirements	8	9
Maintenance Complexity	6	6
Crew Training Requirements	2	4
Impact on Crew Workload	1	1
Safety Impact	6	9
Regulatory landscape	1	8
Impact on regulations	7	7
GHG Reduction Potential	3	8
Lifecycle Emissions	6	2
Pollutant Reduction	7	6
CAPEX	7	9
OPEX	5	3
Payback Period	5	9
NPV	8	7

Sub-category	EET 1	EET 2
IRR	3	5
Cargo carrying capacity	9	9
Cost per Transport Work	9	9
Recycle Ratio	8	8
Criticality Ratio	8	8
Critical Mass	8	8

KPI weights are derived from CR→ER relationships (the HoQ), using the "Normalized Weight" vector.

All equations used for KPI importance, Technology total score, Domain score and Grouped view have been presented in 4.6.

KPI-level calculation and ranking

For each EET, the Total Score is the sum of all contributions. For each EET the top 10 KPI contributions are shown in the below two tables.

Table 15 Top 10 KPI contributions - EET 1

Sub-category	Score	Contribution	Normalized Weight
NPV	8	36.3	4.5
Compatibility with Existing Systems	8	34.1	4.2
Impact on regulations	7	33.7	4.8
Pollutant Reduction	7	31.3	4.5
Cargo carrying capacity	9	29.7	3.3
Critical Mass	8	26.4	3.3
Criticality Ratio	8	26.4	3.3
Maintenance Complexity	6	24.3	4.1
Payback Period	5	22.7	4.5

Sub-category	Score	Contribution	Normalized Weight
Impact on Vessel Consumption	5	22.3	4.5

Table 16 Top 10 KPI contributions - EET 2

Sub-category	Score	Contribution	Normalized Weight
GHG Reduction Potential	8	44.5	5.6
Payback Period	9	40.8	4.5
Impact on regulations	7	33.7	4.8
NPV	7	31.8	4.5
Cargo carrying capacity	9	29.7	3.3
Safety Impact	9	29.1	3.2
Regulatory landscape	8	28.1	3.5
Pollutant Reduction	6	26.8	4.5
Criticality Ratio	8	26.4	3.3
Critical Mass	8	26.4	3.3

The results per category group level for each EET are shown in the below table.

Table 17 Category level - example scoring

Domain	EET 1	EET 2
Market Status	17	23
Retrofit Impact	20	9
Energy Efficiency	18	16

Domain	EET 1	EET 2
Crew Impact	23	29
Regulations	8	15
Emissions Impact	16	16
Economic Viability	46	51
Circularity	24	24
Total QFD Score (KPI view)	542	596

In this example, EET 2's advantage is concentrated in Market Status, Crew Impact, Regulations, Economic Viability, while EET 1 is stronger in Retrofit Impact and Energy Efficiency. Emissions impact and circularity are comparable.

The performance gap between the two technologies is explained by the distribution of weighted contributions across individual KPIs. EET 2's advantage is primarily driven by strong results in high-weight indicators, including GHG Reduction Potential (+27.8 points), Regulatory Landscape (+24.5), Infrastructure Dependency (+23.1), Payback Period (+18.2), Integration Complexity (+9.9), and Safety Impact (+9.7). These areas correspond to priorities such as compliance with decarbonization targets, operational feasibility, and financial attractiveness.

When all KPI contributions are aggregated using their respective QFD-derived weights, EET 1 achieves a total of 542 points, while EET 2 reaches 596 points. This outcome reflects the influence of high-priority criteria such as emissions reduction potential and economic performance.

Annex C – QFD method empty tables

In this section, the empty tables of the QFD are presented:

Table 18 TRL correlation (roof) matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1- TRL																															
2- Scalability Potential																															
3- Market Readiness																															
4- Infrastructure Dependency																															
5- Integration Complexity																															
6- Compatibility with Existing Systems																															
7- Retrofit Time																															
8- Impact on Vessel Consumption																															
9- Propulsion efficiency																															
10- Auxiliary Power Demand																															
11- Steam demand																															
12- Maintenance Requirements																															
13- Maintenance Complexity																															
14- Crew Training Requirements																															
15- Impact on Crew Workload																															
16- Safety Impact																															
17- Regulatory landscape																															
18- Impact on regulations																															

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
19- GHG Reduction Potential																															
20- Lifecycle Emissions																															
21- Pollutant Reduction																															
22 - Recycle Ratio																															
23 - Criticality Ratio																															
24 - Critical Mass																															
25- CAPEX																															
26- OPEX																															
27- Payback Period																															
28- NPV																															
29- IRR																															
30- Cargo carrying capacity																															
31- Cost per Transport Work																															

Table 19 QFD relationship matrix

CR \ ER	Market Status				Retrofit Impact			Energy Efficiency				Crew Impact				
	TRL	Scalability Potential	Market Readiness	Infrastructure Dependency	Integration Complexity	Compatibility with Existing Systems	Retrofit Time	Impact on Vessel Consumption	Propulsion efficiency	Auxiliary Power Demand	Steam demand	Maintenance Requirements	Maintenance Complexity	Crew Training Requirements	Impact on Crew Workload	Safety Impact
Economic Viability																
EET Readiness																
Performance																
GHG compliance with regulations																
EET Complexity																
EET Safety & Risk																

CR \ ER	Regulations		Emissions Impact			Economic Viability							Circularity		
	Regulatory landscape	Impact on regulations	GHG Reduction Potential	Lifecycle Emissions	Pollutant Reduction	CAPEX	OPEX	Payback Period	NPV	IRR	Cargo carrying capacity	Cost per Transport Work	Recycle Ratio	Criticality Ratio	Critical Mass
Economic Viability															
EET Readiness															
Performance															
GHG compliance with regulations															
EET Complexity															

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