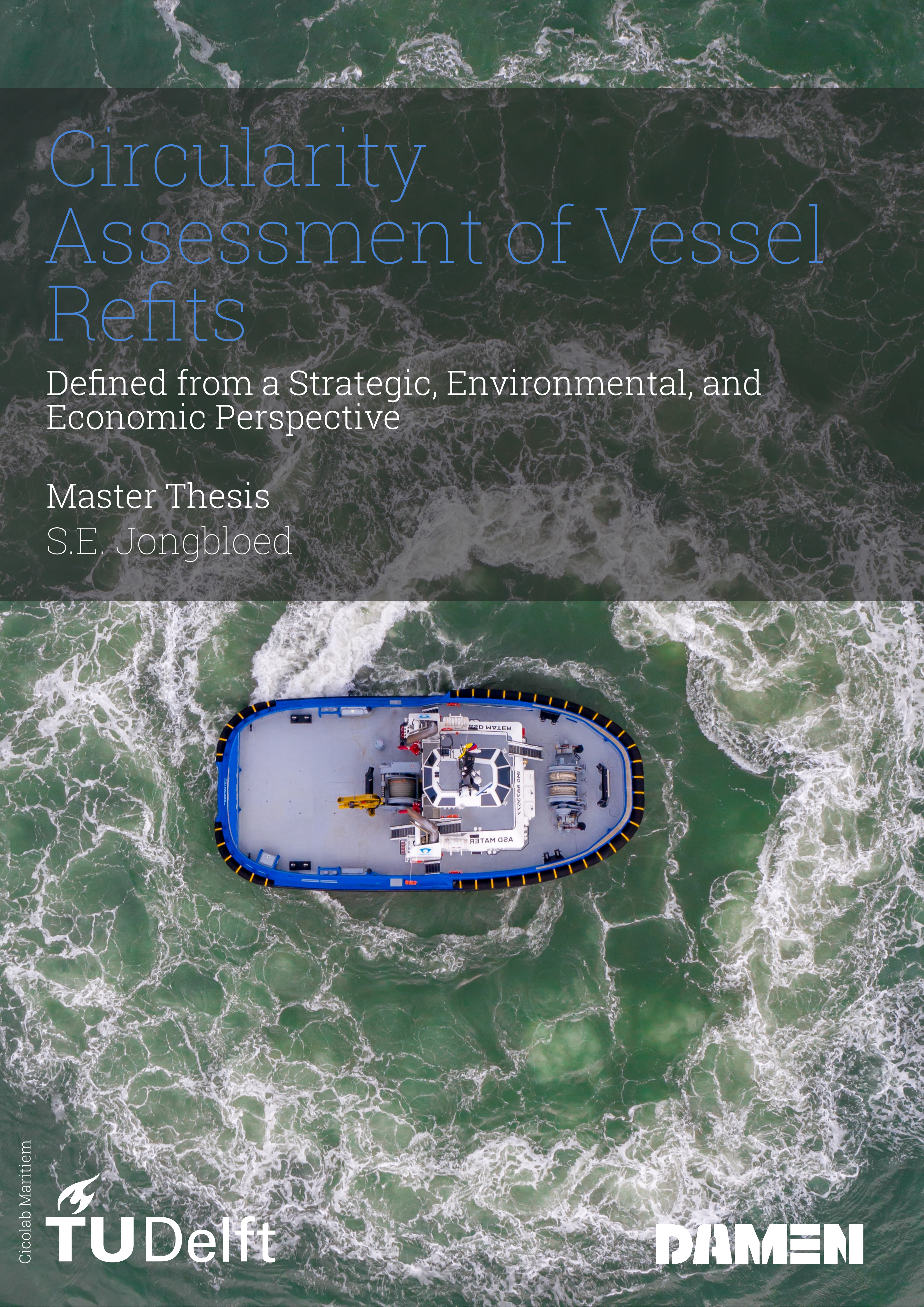

Circularity Assessment of Vessel Refits

Defined from a Strategic, Environmental, and Economic Perspective

Master Thesis

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Graduation thesis for the degree of MSc in Marine Technology in the specialisation of Maritime Operations and Management

Circularity Assessment of Vessel Refits

Defined from a Strategic, Environmental, and Economic Perspective

by

S.E. Jongbloed

performed at

Damen Shipyards

Delft University of Technology - Faculty of Mechanical Engineering

This graduation thesis (MT.25/26.016.M) is classified as confidential in accordance with the general conditions for projects performed by Delft University of Technology.

Wednesday 4th March, 2026

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Cover: ASD Tug 2813 ’ASD Mater’ in Ecuador (Damen Global, 2022)

Preface

This report is the graduation thesis for a master's degree in Marine Technology at Delft University of Technology and delves into circularity and emissions in the shipbuilding industry, with a focus on strategic, environmental, and economic aspects of refits.

The thesis began with a literature review carried out from mid-April to mid-July 2025, after which a more practice-oriented research phase followed, including data collection for a case study. In this case study, various refit strategies were examined with regard to their strategic, environmental, and economic advantages and disadvantages.

The topic of circularity was briefly introduced in the current educational programme of Marine Technology, but it was not covered in depth. Therefore, I had limited to no knowledge of the concept in relation to the Maritime Industry before conducting the literature study. This study has shown me that there are many opportunities when different parties within the sector collaborate. However, the availability of the right data (forms) and the options enabled by legislation still require improvement in order to create a more stimulating environment.

I would like to thank Jeroen Pruyn for his guidance on behalf of Delft University of Technology, as well as Dewi Wesselman, Martin Verboom, and Robert Oostergetel for their support and feedback on behalf of Damen Shipyards throughout my graduation internship. I also sincerely thank Mira de Voogd from Hogeschool Rotterdam for her valuable insights into maritime circularity and for helping to shape the direction of my research. Lastly, I would like to thank my mum, Ivette, for her help in proofreading, correcting both minor and major mistakes, and being a sparring partner throughout my thesis.

S.E. Jongbloed
Delft, March 2026

Summary

This thesis introduces a method for defining and evaluating circular economy strategies for vessel refits in the maritime sector. This work responds to tightening IMO/EU decarbonisation targets, and the approaching fleet-renewal wave. Although refits offer significant potential to extend the useful life of vessels, reduce upfront (embodied and yard) emissions, and improve economic efficiency, there is currently no structured framework to assess their circular value. Existing circular economy tools and performance indicators are either too generic or designed for newbuild vessel applications. Moreover, decision-makers lack quantitative methods to compare refit strategies (e.g. repair, refurbish, and remanufacture) at the vessel and component levels. A key finding of this study is that no single refit strategy dominates across strategic, environmental and economic impact areas, optimality is context-dependent and emerges from the trade-offs between cost, emissions, and strategic considerations. The framework's main contribution lies in making these trade-offs explicit through a structured set of 32 Key Performance Indicators (KPIs), allowing previously qualitative decisions to be evaluated in a transparent and reproducible way.

To address the measurement gap at the vessel- and component-level, the study presents a two-step evaluation methodology based on the 10R hierarchy and systems perspective (nano to macro levels):

1. Identification of possible circular strategies (repair, refurbish, remanufacture) based on vessel-specific and component-specific criteria;
2. Evaluation of the strategy's circular performance using a set of KPIs drawn from academic literature, regulatory frameworks (EU Taxonomy, IMO), and industry practice. These indicators are organised into three impact areas: strategic, environmental, and economic.

From the literature, 19 Key Performance Indicators were extracted, and the list was extended with 13 indicators. This created a final set of 32 KPIs used for the evaluation of Step 2. The assessment uses cradle-to-gate boundaries for capital emissions and tank-to-wake boundaries for operational emissions, which is essential for interpreting the results of hybrid and especially electric vessels.

The framework is demonstrated through a case study of a 20-year-old Damen ASD 3110 tug undergoing a refit. This refit is compared against equivalent newbuild vessels equipped with conventional, hybrid, and fully electric propulsion systems. In terms of environmental impact, the refurbish strategy performs worse than constructing a new vessel. For both remanufacture strategies (hybrid and electric), the remanufactured vessel achieves lower Total Emissions of Ownership than its newbuild counterpart. With respect to Total Cost of Ownership, all refit strategies outperform their equivalent newbuild vessels, since Operational Expenditures are comparable in each case, leaving the higher initial Capital Expenditure as a lasting disadvantage over the vessel's lifetime. Strategically, refits also reduce vessel lead time substantially (10-14 months versus 24 months for newbuilds), though intervention depth increases project complexity.

When the three refit strategies are compared with each other, the results indicate that the refurbish strategy produces the highest Capital Emissions but has the lowest Capital Expenditure. Converting the vessel to a hybrid configuration substantially cuts operational emissions (up to 40% compared with the refurbish strategy), though it requires a larger upfront investment while maintaining a comparable Total Cost of Ownership over the vessel's lifetime. Converting to a fully electric configuration offers the strongest environmental performance, achieving zero tank-to-wake operational emissions, but it also entails the highest Capital and Operational Expenditures, leading to the greatest Total Cost of Ownership. The sensitivity analysis shows that these relative results remain robust, but that hybrid and electric performance is sensitive to fuel and electricity prices, regulatory developments, and assumed vessel lifetime. The study concludes that the optimal strategy depends on factors including stakeholder priorities, the vessel's operational profile, its remaining service life, and the current regulatory context. This finding challenges the assumption that lower R-strategies (e.g., repair, refurbish) are always more circular. For long-lived, regulation-sensitive vessels, deeper interventions such as remanufacture may deliver higher lifecycle circularity.

The outcome is a transparent and repeatable decision-support framework that enables shipyards and shipowners to make data-driven choices about refit strategies across strategic, environmental, and economic impact areas. The framework supports early-stage project assessment within the defined system boundaries (cradle-to-gate Capital Emissions and tank-to-wake Operational Emissions), enabling comparison of refit options against newbuild alternatives. However, several data limitations, such as incomplete Bill of Materials for hybrid and electric systems, uncertain reuse percentages, and coarse yard-emission allocation, highlight the need for improved component-level documentation and future digital product passports. Additionally, the late decision to install an SCR system on the case vessel was not incorporated into the analysis and should be evaluated in future work. The framework aligns with EU Taxonomy principles, positioning it as a practical tool for sustainable financing assessments.

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List of Abbreviations

Abbreviation	Written out
ASD	Azimuth Stern Drive
BoM	Bill of Materials
CAPEM	Capital Emissions
CAPEX	Capital Expenditure
CE	Circular Economy
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalent
CPRM	Circular Product Readiness Method
DFS	DFS Maritime Solutions
DSR	Design Science Research
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ships Index
ECF	Embodied Carbon Factor
EMF	Ellen MacArthur Foundation
EoL	End-of-Life
EU	European Union
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, Air Conditioning
IMO	International Maritime Organisation
ISO	International Organisation for Standardisation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCI	Material Circularity Indicator
MGO	Marine Gas Oil
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OPEM	Operational Emissions
OPEX	Operational Expenditure
PTI/PTO	Power Take-in/Power Take-off
RSD	Reverse Stern Drive
SDG	Sustainable Development Goals
SFI	Ship Function Index
SO_2	Sulphur Dioxide
TCO	Total Cost of Ownership
TEO	Total Emissions of Ownership
UN	United Nations

1

Introduction

The maritime sector faces increasing regulatory and societal pressure to reduce its environmental footprint (Gallo et al., 2020). Global maritime trade is expected to grow rapidly in the coming decades (Okumus, Gunbeyaz, et al., 2024), raising the sector's potential contribution to global Greenhouse Gas (GHG) emissions from 2.7% in 2017 to possibly 19% in future scenarios (Gallo et al., 2020). This meeting point of environmental urgency and economic growth necessitates a fundamental transformation in how maritime stakeholders approach sustainability and operations.

To provide context for this transformation and establish the foundation of this research, the remainder of this introduction is structured as follows. Section 1.1 examines the current market trends and the regulatory framework established by governing bodies to address environmental concerns. Section 1.2 identifies the knowledge gap. Section 1.3 provides industry context for the research questions formulated in Section 1.4. Finally, Section 1.5 outlines the methodological approach used to address these questions. An AI statement is given in Section 1.6.

1.1. Worldwide Maritime Context

The maritime shipping sector is responsible for approximately 2.7%–3% of worldwide emissions (Fadaie et al., 2025), making it a major source of global Carbon Dioxide (CO_2) emissions. To reduce these emissions, the International Maritime Organisation (IMO) launched the first GHG strategy in 2018, which was revised in 2023. This strategy targets a 20% reduction in GHG emissions for international shipping by 2030 compared to 2008 and aims to achieve net zero emissions by 2050 (DNV, 2023; International Maritime Organisation (IMO), 2025).

In the Netherlands, these stricter IMO regulations are accompanied by European and national legislation and emission targets to reduce CO_2 emissions and material use. In 2014, the European Commission formalised a vision to move toward a zero-waste policy by keeping resources in the economy as long as possible and minimising waste generation (European Commisison, 2014). In 2020, the European Commission renewed its plan in 'A new Circular Economy Action Plan' (European Commission, 2020), which also promotes the development of a circular economy monitoring framework. In response to the European Union (EU), the Dutch government launched its own circular economy programme in 2016, collaborating with stakeholders across industries. The Netherlands set an intermediate goal of a 50% reduction in primary raw materials use by 2030 compared to 2016, working towards a fully circular economy by 2050 (Government of the Netherlands, 2016).

At the same time, the current fleet expansion is expected to continue, with a projected growth of 4% in 2026 (Gordon, 2025). In addition to expanding the fleet, renewing it will also be crucial over the next 10 years. Figure 1.1 shows the world shipbuilding deliveries between 1963 and 2007. The figure shows an increase in vessel deliveries in the early 2000s, with a peak production in 2007 (Hossain, 2018). Historically, the average scrapping age is between 25 and 30 years (Stopford, 2009). This implies that a large share of the existing fleet will reach the scrapping age and require replacement between 2030 and 2040 (Gordon, 2025). This is precisely the period when many emission regulations demand substantial commitments. As a result, limited shipyard capacity for constructing new vessels could become a problem.

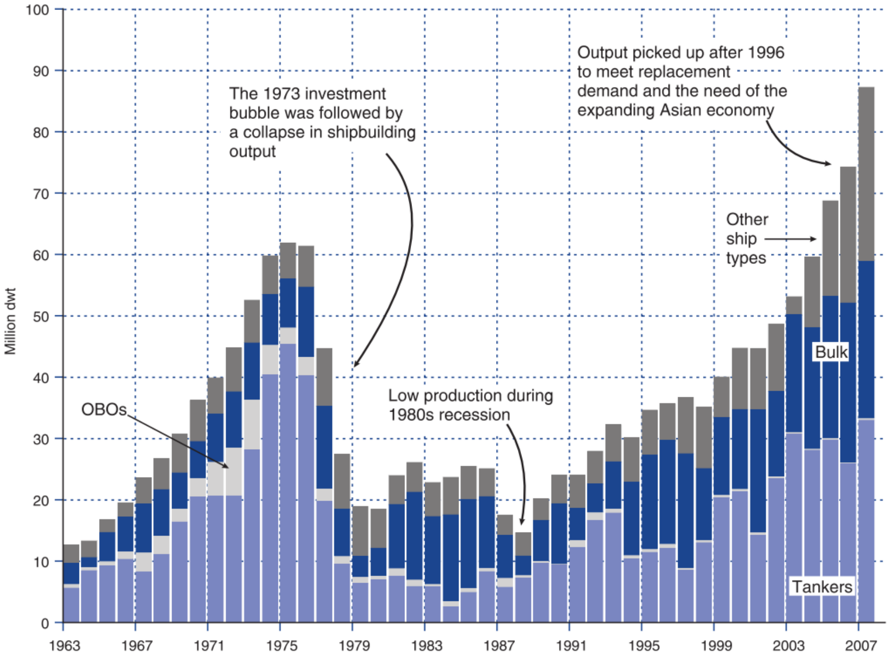


Figure 1.1: World Shipbuilding Deliveries by Type 1963-2007 (Stopford, 2009)

Shipyards play a crucial role in the effort to achieve national and international emission-reduction ambitions and to accommodate the expansion of the fleet. As a supplier to the international shipping sector, shipyards are responsible for constructing cleaner vessels. In this process, they are also expected to make their building processes more circular and reduce waste. Innovation in new build vessels, such as alternative fuels and propulsion systems, plays a central role in complying with future IMO regulations.

Beyond constructing new vessels, there is also potential for the current fleet to enhance circularity and minimise waste by extending the operational life of a vessel. This allows ship owners to modify existing vessels in response to rapid market changes, increasing their ability to meet emerging environmental demands (Wahab et al., 2018). This practice, known as refitting, lowers material use, mitigating the impact of material scarcity and reducing CO_2 emissions, and thus supports Circular Economy (CE) objectives (Gilbert et al., 2017).

1.2. Research Motivation

Vessel refits provide a strategic response to external regulatory pressure and internal operational needs. Refits offer advantages by reducing the dependency on long international supply chains. For shipbuilders and operators, applying CE principles in the form of life extending strategies allow vessels to be modernised without full replacement, supporting shorter lead times and compliance with environmental regulations (Alfnes et al., 2025; Okumus et al., 2023).

While environmental and regulatory considerations increasingly support vessel refits, economic viability remains a decisive factor. Carbon pricing mechanisms, such as the inclusion of maritime transport in the European Emissions Trading System or raw material resource tax (Milios, 2021), will increase costs for less efficient vessels. As shown in the 2021 Organisation for Economic Cooperation and Development (OECD) study on the cost of decarbonising shipping (OECD, 2021), compliance with these mechanisms will be a key economic driver for investing in cleaner or circular technologies. The EU Taxonomy for Sustainable Activities (Commission, 2021) exemplifies this trend. This framework, used by financial institutions to assess the environmental sustainability of projects and products, includes criteria such as thresholds for fuel efficiency improvements, waste management standards, and regulatory compliance.

Banks, insurers, and export credit agencies are increasingly applying these guidelines to validate financing decisions and prevent green washing.

Despite the potential of refits, several barriers continue to limit adoption. Two of these barriers are the lack of standardised measurement tools and limited data transparency (Alfnes et al., 2025; Okumus, Andrews, & Gunbeyaz, 2024). Beyond regulatory compliance, refit viability depends on financial attractiveness, not only in terms of upfront investment, but also lifecycle value and operational efficiency (Stopford, 2009). These barriers highlight the need for a structured, multi-criteria evaluation approach.

With major regulatory frameworks like the EU Taxonomy, Circular Economy Action Plan, and IMO emission regulations taking effect and a significant portion of the global fleet approaching end-of-life between 2030 and 2040, the window for developing standardised refit assessment methods is narrowing. Maritime stakeholders need actionable tools now to handle these overlapping pressures effectively.

Vessels are complex assets shaped by intersecting technical, regulatory and economic domains. Ongoing regulatory changes create strategic opportunities for maritime stakeholders, but evaluating these opportunities remains challenging. Despite growing academic interest in maritime circularity (Okumus, Andrews, & Gunbeyaz, 2024), existing methods lack standardisation and fail to integrate the multiple performance dimensions needed to compare different circular strategies effectively.

To address this gap, this research draws on CE principles, which aim to eliminate waste and preserve material value through closed-loop product lifecycles (Sassanelli et al., 2019). Circularity Indicators provide a quantitative basis for measuring such performance across different scales and strategies (Khadim et al., 2022). The developed method evaluates vessel refits through three perspectives: *strategic* alignment with regulatory requirements and market positioning, *environmental* performance measured through avoided emissions and material use, and *economic* viability assessed via lifecycle costs. It compares different circular strategies (repair, refurbish, remanufacture) and their impacts on vessel refits.

While this research focuses on strategic, environmental, and economic impact areas, it acknowledges that successful refit implementation also depends on organisational factors and stakeholder coordination, which are beyond the scope of this study but discussed as recommendations for future research.

To develop and validate this method in industrial practice, this research collaborates with Damen Shipyards. The following section outlines the company's specific context and challenges that motivate this collaboration.

1.3. Industry Context: Damen Shipyards

Damen Shipyards is a Dutch shipbuilding company that acknowledges that growing environmental demands, stricter regulations, and sector-wide sustainability goals are driving greater interest in vessel refits and extending the operational life of existing assets. One of Damen's companies, DFS Maritime Solutions, already performs refits regularly, but the related decisions are largely driven by intuition or specific client requests, rather than being used as a deliberate business opportunity. The company now aims to bring more structure to the process of acquiring and refitting second-hand vessels, in order to systematically assess the potential of various opportunities.

One of their current challenges is to quantify the environmental impact of their vessel refits. This is required to meet EU Taxonomy criteria for qualifying for Atradius export credit insurance. The challenge stems from the absence of a standardised assessment method, which this research aims to develop.

1.4. Research Questions

This thesis aims to answer the following question. Answering this main research question will provide maritime stakeholders with a standardised assessment method that enables evidence-based comparison of refit strategies, supports regulatory compliance, and facilitates access to sustainable financing mechanisms.

> **How can the optimal circular strategy for a vessel refit be chosen and evaluated from a strategic, environmental, and economic perspective?**

To answer this question systematically, the following sub-questions are created and grouped by theme. These questions are used as a guide throughout the thesis. Each category builds towards answering the main research question. The sub-questions need to be answered before answering the main question.

Chapter 2 answers the following questions and describes the current status of circularity within the maritime sector. This chapter also addresses the research gap and outlines a solution.

- How is circularity currently addressed in the maritime sector?
- Which Circular Economy frameworks and strategies are relevant to vessel refits?
- What gaps remain in the way existing studies evaluate circular strategies in vessel refits?

Chapter 3 answers questions regarding Key Performance Indicators (KPIs) in the context of refits.

- What performance indicators are used in the maritime sector?
- How could strategic, environmental, and economic performance indicators be adapted to compare different refit strategies (e.g. repair, refurbish, remanufacture)?
- What data is needed to apply the selected indicators to a vessel refit, and how can this data be obtained?

The calculation of the KPIs will answer the following questions in Chapters 5 & 6.

- How do the different refit strategies perform compared to each other, and how do they perform compared to newbuild reference vessels?
- What methodological challenges arise in quantifying and comparing circularity performance across different refit strategies?
- How can the KPI results be used to identify the optimal circular strategy for vessel refits?

The main research question is answered in Chapter 8.

1.5. Thesis Approach

This study uses the Design Science Research (DSR) method, inspired by Boorsma et al. (2022), who used this method to develop the Circular Product Readiness Method (CPRM). DSR is particularly suited for this research because it explicitly bridges academic rigour with practical utility, enabling the development of artefacts (in this case, an assessment method) that address real-world problems while contributing to scientific knowledge (Boorsma et al., 2022). Although CPRM focuses on remanufacturing and excludes refurbish or repair, its underlying framework can be adapted for broader strategy evaluation.

The DSR approach, as shown in Figure 1.2, follows six iterative steps:

1. **Identify problem and motivate:** Problem background and relevance (Chapter 1).
2. **Define objectives of a solution:** Building blocks and boundaries of the solution based on literature (Chapter 2).
3. **Design and development:** Selection, refinement, and explanation of KPIs (Chapter 3).
4. **Demonstration:** Describe the case study and results (Chapters 4, 5 & 6).
5. **Evaluation:** Conclusion based on the case study, discussion and advice to refine the approach (Chapter 7).
6. **Communication:** Share the outcomes through visualisation and reporting (this report and final presentations).

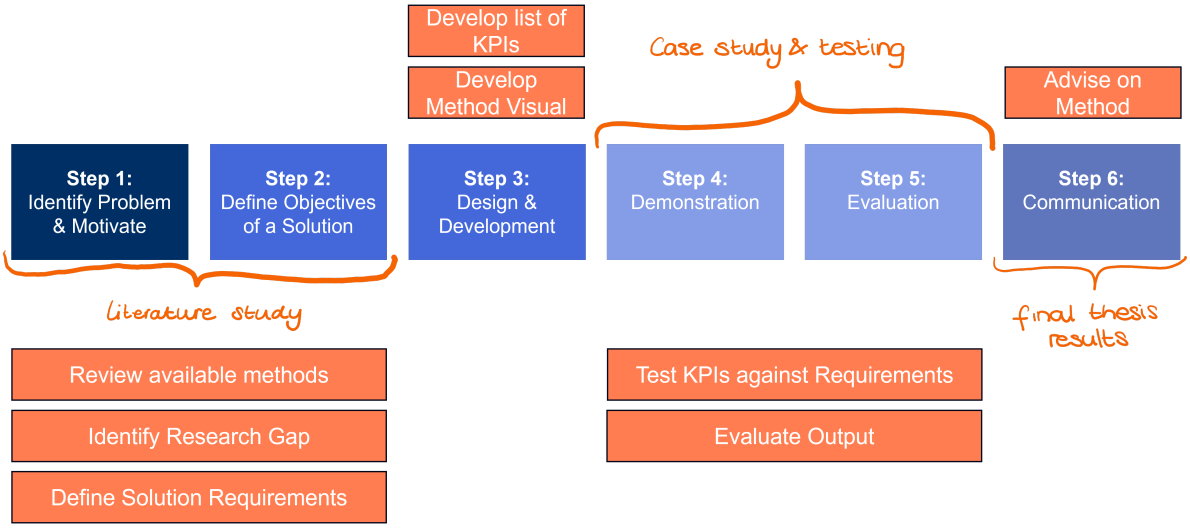


Figure 1.2: Design Science Research (DSR) Method based on Boorsma et al. (2022)

Adapting the DSR method to maritime refits helps stakeholders identify the most appropriate circular strategy for a vessel. It encourages an assessment of product conditions and lifecycle goals and supports visualisation to communicate eligibility for different refit strategies (e.g., repair, refurbish, remanufacture).

1.6. AI Statement

I acknowledge the use of Writefull, Grammarly, Chat GPT, Copilot, Claude and Consensus to support the development of this thesis by:

- Refining language (Writefull, Grammarly, Copilot, Claude);
- Acting as a brainstorming partner (Chat GPT, Copilot, Claude);
- Providing feedback (Chat GPT, Claude);
- Create tables (Chat GPT, Claude).

2

Literature Review

This chapter addresses the following research sub-questions from Chapter 1: How is circularity currently addressed in the maritime sector? Which Circular Economy frameworks and strategies are relevant to vessel refits? And critically, what gaps remain in the way existing studies evaluate circular strategies in vessel refits?

These questions are addressed through a literature review following the research methodology presented in Section 2.1. An overview of the theoretical foundations important to vessel refits is presented in Section 2.2. This section synthesises existing literature on CE, circularity frameworks, circular strategies, and maritime stakeholders, and examines how these concepts have been applied within the maritime sector, and identifies the limitations that currently hinder their practical implementation in refit decision-making. These findings provide the basis for the measurement gap defined in Section 2.3. Section 2.4 presents the system boundaries for the solution outline that bridges the measurement gap in Section 2.5. Finally, Section 2.6 concludes the literature review.

2.1. Research Methodology

The literature study identifies, compares, and evaluates CE frameworks and strategies applicable to vessel refits, with the aim of developing a practical assessment method for circular performance measurement. To gather academic literature, Scopus, Web of Science, Science Direct and the TU Delft Repository were used. Boolean search operators were used to combine relevant keywords. The most frequently used search terms combined 'Circular Economy' with 'Maritime Industry', 'Strategy', and '9R', and combined 'Maritime' with 'Refit'. Search terms were iteratively refined as the study progressed, and synonyms were used to broaden the scope where needed.

Table 2.1: Search Terms Literature Study

Search Terms	Amount of Results
Circular AND Economy AND Maritime OR (Maritime AND Industry)	42
Circular AND Economy AND Strategy OR Strategies AND Maritime	33
Circular AND Economy AND 9R AND Strategy	33
Refit OR Retrofit AND Maritime AND Industry	49

To ensure relevance to current practices and policies, literature published between 2015 and 2025 was considered. Exceptions were made when articles were widely cited or deemed foundational. During the analysis process, titles and abstracts were scanned to ensure focus on CE frameworks, performance indicators, or strategies relevant to the maritime or heavy industrial sectors. In addition, publications that provide information on KPIs related to strategic, environmental, or economic performance were included. The criteria mentioned in Table 2.2 are used to justify the exclusion of articles. In the final criterion, consumer goods were excluded because their economic, technical, and organisational contexts differ fundamentally from those of industrial maritime assets.

Table 2.2: Exclusion Criteria

Exclusion Criteria
Other languages than Dutch or English
Only abstract available
No clear methodological basis or anecdotal evidence only
Articles focusing purely on consumer goods without industrial relevance

The academic literature found by these methods is extended with grey literature, such as EU publications, IMO documents and local government legislation. In addition to structured database searches, backward and forward snowballing were applied to identify relevant publications from the reference lists or citations of key articles. Additional sources identified through backward/forward citation snowballing include Okumus, Gunbeyaz, et al. (2024), Stopford (2009), and Kristensen and Mosgaard (2020).

When more information was needed on a specific topic, the Consensus AI tool was used. This tool extracts answers from academic papers. The articles suggested were evaluated based on the predefined inclusion and exclusion criteria, and those that met the criteria were added to the database.

2.2. State of the Art

This Section establishes the conceptual foundations for circular vessel refits. It defines CE principles, explores their alignment with United Nations Sustainable Development Goals, compares existing circular frameworks, defines applicable strategies, and examines stakeholder roles in refit decision-making. Together, these elements provide the theoretical basis for identifying the measurement gap addressed in Section 2.3.

2.2.1. Circular Economy

In the context of maritime sustainability, circularity offers a promising way to achieve improvements across design, construction, operation, and End-of-Life (EoL) phases. Realising these improvements, however, requires a shared understanding of what circularity entails in the maritime sector.

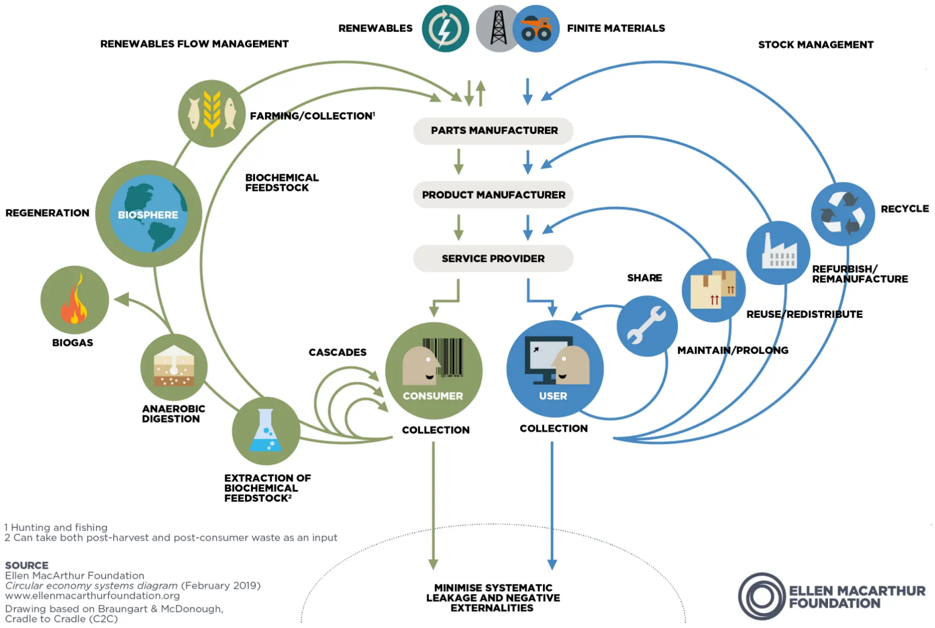
The traditional economic model is linear and based on a take-make-consume-throw away pattern. The European Parliament defines CE as 'a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible' (European Parliament, 2023). This approach seeks to reduce waste generation and material use by extending product lifecycles. A visual representation of CE by the European Parliament Research Service is given in Figure 2.1.

Source: European Parliament Research Service

Figure 2.1: The Circular Economy (CE) Model (European Parliament, 2023)

The figure shows the process raw materials undergo during their lifetime. It starts with the inflow of raw materials, which are designed, manufactured and distributed as products. Subsequently, the visual shows the use, reuse and repair of products, after which products are collected and as much of the product's materials are recycled during waste management. However, this visual is not fully circular as it shows an outflow of residual waste.

The Ellen MacArthur Foundation (EMF) goes further in their definition of CE and state that it is a system where materials never become waste and nature is regenerated (Ellen MacArthur Foundation (EMF), 2020). CE is called a 'systems solution framework that tackles global challenges like climate change, biodiversity loss, waste and pollution'. According to EMF, CE is based on three principles which are driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature. Keeping materials or products in their highest value implies that the original form, function and energy invested in their production is preserved as much as possible. CE is visualised in a butterfly diagram, illustrating the continuous flow of materials. This diagram, shown in Figure 2.2, makes a distinction between a biological cycle, consisting of renewable materials and products (green), and the technical cycle, consisting of finite materials (blue). In the technical cycle value retention is achieved through processes like repair, refurbish, and remanufacture.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 2.2: Butterfly Diagram (Ellen MacArthur Foundation (EMF), 2021)

Despite growing interest in the concept of CE, there is no universal definition of CE. Nobre and Tavares (2021) tried to change this in their study by researching scientific articles on circular economy and asking for expert opinions. They came up with a framework that allows identification and separation of the definition itself (the what) from its surrounding principles, concepts and enablers (the how), where it is applicable (the where) and the sustainability 'nested concept' (the why)(Nobre & Tavares, 2021).

'Circular Economy is an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, in case of a treated organic residual, safely back to the environment as in a natural regenerating cycle. It operates creating value at the macro, meso and micro levels and exploits to the fullest the sustainability nested concept. Used energy sources are clean and renewable. Resources use and consumption are efficient. Government agencies and responsible consumers play an active role ensuring correct system long-term operation.' (Nobre & Tavares, 2021)

Based on the preceding discussion of multiple CE definitions, this study adopts a maritime-specific definition that emphasises lifecycle extension strategies:

> CE in the maritime sector refers to an industrial model that eliminates waste, retains material and functional value, and extends the useful life of vessels and components. It involves strategies such as reuse, repair, refurbish, and remanufacture throughout the lifecycle of the vessel, supporting sustainability objectives and strengthening resilience to supply chain and regulatory pressures.

Refits offer the opportunity to apply CE strategies that extend the lifetime of vessels. Lifetime extending strategies are already applied to vessel refits in various degrees in the form of replacing a bearing or bolts as part of general maintenance (repair), overhauling engines (refurbish), and modernising bridge systems or returning thrusters to as-new condition (remanufacture).

However, successful implementation depends on alignment of incentives among all stakeholders, technical feasibility, regulatory acceptance, and component availability (Alfnes et al., 2025; Okumus, Andrews, & Gunbeyaz, 2024; Senavirathna et al., 2022).

The circular economy is therefore not just a design or environmental concept, it provides a systemic approach to addressing global sustainability challenges. Having established a working definition of CE for maritime refits, it is important to situate these practices within the broader global sustainability agenda.

2.2.2. Sustainable Development Goals

The United Nations (UN) Sustainable Development Goals (SDGs), adopted in 2015, offer a global framework to achieve a more sustainable, equitable, and resilient future by 2030 (United Nations, 2024a). The SDGs shown in Figure 2.3 provide a policy framework that both motivates and validates circular strategies in the maritime sector. The objective of each SDG is explained in Appendix A. Although initially developed for national policymaking, the SDGs are increasingly used by industries to align strategies and demonstrate environmental and social responsibility.

The CE principles outlined in Section 2.2.1 support SDGs by reducing waste, extending asset lifetimes, and promoting cleaner industrial processes (Ortiz-de-Montellano et al., 2023; Schroeder et al., 2019). For the maritime sector, an industry with high emissions, resource intensity, and global visibility, SDGs 9, 12, 13 and 14 are specifically relevant to shipbuilding.

Figure 2.3: United Nations Sustainable Development Goals (United Nations, 2024b)

- **SDG 9 - Industry, Innovation and Infrastructure**: Modernising infrastructure and encouraging sustainable innovation, including upgrading retrofit industries and the adoption of clean and environmentally sound industrial processes. (Target 9.4 (United Nations, 2024a))
- **SDG 12 - Responsible Consumption and Production**: Encourage sustainable practices such as resource efficiency and waste reduction through circular strategies (Targets 12.2, 12.5 & 12.6 (European Commission, 2020; United Nations, 2024a)).
- **SDG 13 - Climate Action**: Integration of climate change measures into policies and strategies, such as reducing greenhouse gas emissions from vessels and improving energy efficiency (Target 13.2 (International Maritime Organisation (IMO), 2025; United Nations, 2024a)).
- **SDG 14 - Life Below Water**: Limiting marine pollution, including emissions, discharges, and noise (Target 14.1 (United Nations, 2024a)).

Therefore, this industry is closely related to several SDGs. Contributing to these goals is important not only from a sustainability perspective but also from a business and policy perspective. Companies in the maritime sector are increasingly expected to demonstrate alignment with the SDGs in sustainability reports, such as described in the Corporate Sustainability Reporting Directive (CSRD) (Commission, 2025), and innovation programmes (Ministerie van Infrastructuur en Waterstaat, 2023; European Parliament, 2023). This motivates the need for concrete strategies to reduce waste and emissions during the design, construction, operation and EoL phases of a vessel's lifecycle.

Circular shipbuilding applies CE principles such as repair, refurbish, and remanufacture, and has the potential to significantly advance progress on the mentioned SDGs (Alfnes et al., 2025; Milios et al., 2019; Okumus, Gunbeyaz, et al., 2024). Beyond environmental gains, CE strategies can transform business models and improve financial sustainability in the maritime sector (Okumus, Andrews, & Gunbeyaz, 2024).

Having positioned refits within the broader sustainability agenda through the SDGs, the following subsections examine the specific frameworks and strategies available for implementing circularity in practice. Section 2.2.3 compares existing circular frameworks for their applicability to maritime refits.

2.2.3. Circular Frameworks

Circular frameworks are used to structure the view on circularity, guide decision-making, and assess the impact of interventions on circularity. Existing frameworks originate from diverse sectors, each with its own terminology, system boundaries, and priorities. Most circular frameworks are designed for generic products or industrial systems rather than vessels, which operate under strict safety, regulatory, and classification requirements. As a result, it is not always clear which frameworks are suitable for refits, which strategies they encompass, or how they can be applied in practice to maritime components or systems.

For the maritime industry, circular frameworks are particularly relevant as shipowners, shipyards, and Original Equipment Manufacturers (OEMs) increasingly seek ways to extend vessel lifetimes and reduce material footprints. Each framework offers valuable tools for assessing and guiding circularity in the maritime sector. However, overlapping definitions, scales of application, and varying assumptions result in a fragmented landscape that complicates the standardisation of circular practices (Nobre & Tavares, 2021). Despite their potential, few existing circularity frameworks were specifically developed with the maritime sector in mind (Nobre & Tavares, 2021), which leads to difficulty in selecting the most appropriate tools for evaluating circular value in vessel refits. While most frameworks rely on R-strategies (e.g. reuse, repair, refurbish, remanufacture, recycle) as core elements, the way they prioritise or quantify these strategies differs. Given the diversity of frameworks and the lack of maritime-specific guidance, Table 2.3 provides a comparison to clarify which frameworks are most relevant for vessel refits.

Table 2.3: Comparison of Circularity Frameworks for Maritime Refits. Refit relevance: High = directly applicable with minimal adaptation; Medium = Applicable with moderate adaptation; Low = Limited direct applicability, useful for context only.

Framework	**Lifecycle Phases Covered**	**System Level (Khadim et al.)**	**Refit Relevance**	**Explanation**
Waste Hierarchy (Gallo et al., 2020; Scipioni et al., 2023; Senavirathna et al., 2022)	EoL, Operation	Micro, Macro	Low: Relevant for ship waste management, onboard systems	A prioritisation framework that guides decision-making at the port and onboard levels. It is oriented toward EoL waste management, offering limited input during the design phase and lacking detailed granularity for component-level assessment.
10R Framework (Hoffmann & Pruyn, 2024; Kirchherr et al., 2017; Muñoz et al., 2024)	All phases (Design to EoL)	Nano, Micro	High: applied to ship refits and redesigns	A detailed hierarchy of CE strategies, helping to structure decision-making by clarifying the order of preferred actions. While it offers clear guidance on circular options, it is not inherently quantitative and can lead to ambiguity when multiple R-strategies apply to the same system or component.
Systems Perspective (Khadim et al., 2022; Moraga et al., 2019)	All	Nano, Micro, Meso, Macro	Medium: aligns with how ship components and systems are organised	A scalable structure for assessing circularity, making it suitable for aligning strategies across both policy and product levels. Paired with other frameworks to enable practical application and measurement.
Cradle-to-Cradle (C2C) (Gallo et al., 2020; Hoffmann & Pruyn, 2024; Koilo, 2025)	Design, Operation, EoL	Micro, Meso	Medium: design-focused; used in product–service strategies	Focus on aspects as material health, modularity, and digital traceability, which can enable service-oriented models and closed-loop material cycles. Implementation is complex and data-intensive, thus less practical for refits compared to newbuild vessels, where full design control is possible.
Life Cycle Frameworks (Favi et al., 2017; Nagel et al., 2015; Pero et al., 2024)	All (but often missing EoL)	Nano, Micro, Meso	High: already used to assess emissions and costs in refits	Trade-offs between environmental impact and economic cost and benefits are quantified. They are standardised and allow analysis of refit options. The application is data-intensive, and maritime-specific guidelines are limited.

Overall, the assessment in Table 2.3 shows that no single framework fully meets maritime refit needs. This research integrates elements from three frameworks: the 10R framework provides the strategy hierarchy (repair → refurbish → remanufacture), the systems perspective enables multi-level analysis (component → vessel → company), and lifecycle frameworks (Life Cycle Assessment (LCA)/Life Cycle Costing(LCC)) provide quantification methods. Section 2.5 details how these are combined into a coherent assessment method.

In Section 2.2.4, the core strategies that underlie these frameworks, reuse (R3) to remanufacture (R6) and recycle (R8), are described in more detail.

2.2.4. Circular Strategies in Refits

Circular strategies define the types of interventions available during a vessel refit and the extent to which value, materials, and functionality can be preserved. In the maritime context, where equipment is expensive, heavily regulated and has long lifetimes, selecting the right strategy is essential for extending vessel lifetime while managing costs and resource use.

The key circular strategies to vessel refits focus on life extension. Table 2.4 explains reuse, repair, refurbish, remanufacture, and recycle. Refit implies at least certain repair works need to be done while the vessel maintains its function, therefore reuse and recycle function as boundary cases. All 5 strategies vary in intervention depth, output quality, and degree of value recovery. The choice between them depends not only on technical feasibility but also on strategic, environmental and economic considerations.

Table 2.4: Distinction Between Reuse, Repair, Refurbish, Remanufacture, and Recycle based on Hoffmann and Pruyn (2024), Kirchherr et al. (2017), and Muñoz et al. (2024)

Strategy	Process Depth	Output Quality	Typical Maritime Examples
Reuse	**Low:** inspection, non-destructive testing, and certification	**High:** if traceability and compliance are ensured	Propeller shafts, pumps, turbochargers, rudder stocks
Repair	**Low to moderate:** fixing broken or malfunctioning parts	**Moderate:** restored to operational status	Pipe welds, sensor replacements, pump seal repairs
Refurbish	**Moderate:** cleaning, upgrading, or replacing minor parts	**High;** restored to functional or updated (as-new) state	Bridge equipment updates, valve recoating and reassembly
Remanufacture	**High:** full teardown, part testing, and rebuild to OEM specifications	**Very high:** better-than-new or certified performance	Engine type change, thruster remanufacturing, Z-drive units
Recycle	**High:** destructive disassembly and material reprocessing	**Low to medium:** raw material value retained, product function lost	Hull steel, structural metals, non-functional EoL components

Each strategy offers a different balance between cost, resource efficiency, and performance restoration. Refurbish represents a useful middle ground when repair is insufficient, yet full remanufacture is unnecessary. Many vessel subsystems, such as HVAC units, control systems, and accommodation interiors, can be efficiently refurbished to extend operational life or comply with updated standards. Reuse retains the highest product value and requires the least intervention, though it is often limited by logistic and regulatory constraints. Recycling provides material recovery when no higher value strategy is feasible.

The suitability of a component or subsystem for a given strategy is influenced by factors such as its physical state, degree of modularity, ease of disassembly, certification requirements, and innovation potential. Design attributes, particularly those enabling easy access and reassembly, significantly influence the feasibility of future repair, refurbish or remanufacture activities.

A key challenge in refit decision-making is determining which strategy to apply in which situation, particularly when choosing between refurbished, remanufactured, or new equipment. The absence of standardised assessment criteria complicates decision-making, hindering industry-wide adoption of circular practices (Alfnes et al., 2025; Okumus, Andrews, & Gunbeyaz, 2024; Wahab et al., 2018), and likely leading to inconsistent refit strategies across the industry. This challenge is compounded by the need to coordinate across a diverse network of maritime stakeholders, including shipowners/operators, shipyards, OEMs, and classification societies. The successful adoption of circular strategies depends not only on technical feasibility, but also on the willingness and ability of these actors to align incentives, share data, and support new ways of designing and executing refits.

The following subsection examines the specific stakeholder roles that shape refit decision-making and implementation.

2.2.5. Stakeholder Roles in Refits

Vessel refits involve coordination across multiple stakeholders, each with distinct responsibilities and decision-making power across design, operation, refit, and EoL stages. As outlined by Okumus, Andrews, and Gunbeyaz (2024), circular performance in the maritime sector spans the activities of the following stakeholders.

- **Ship Owners / Operators**, who manage vessel lifecycle and usage, and benefit from increased asset longevity and reduced operational impact;
- **Ship Designers**, who influence vessel lifecycle through modularity, durability, and design-for-disassembly;

- **Building Shipyards**, who can adopt CE practices by incorporating recycled materials and modular construction methods;
- **Repair Yards**, who benefit from measurement frameworks to assess reuse, reverse logistics, and component recovery;
- **OEMs**, whose technical expertise is critical for enabling reuse or remanufacture of high-value components (e.g. engines or propulsion systems) (Alfnes et al., 2025);
- **Classification Societies**, who act as technical gatekeepers, providing certification and influencing the extent to which CE solutions are considered compliant and insurable (Okumus, Gunbeyaz, et al., 2024; Stopford, 2009).

For this research, the assessment method focuses primarily on the perspectives of ship owners/operators and shipyards (particularly repair yards), as these stakeholders drive refit decision-making and directly benefit from KPIs that evaluate strategic, environmental, and economic performance. While OEMs, classification societies, and designers play essential enabling roles, their specific perspectives are not explicitly modelled in the KPI framework developed in Chapter 3.

Because each stakeholder has different incentives and responsibilities, the success of refits depends on transparent information exchange and collaboration throughout the value chain. While this research develops a method assessed primarily from ship owner and shipyard perspectives, the broader adoption of such frameworks requires buy-in from OEMs (for component certification), classification societies (for regulatory approval), and designers (for lifecycle-oriented design). Developing a circular strategy assessment method is not only a technical task, but also a means of supporting shared decision-making within this network.

The preceding sections established the conceptual foundations of CE in maritime contexts: definitions, strategic alignment with SDGs, relevant frameworks, and the specific strategies applicable to refits. However, understanding what these strategies are does not automatically provide the means to measure their effectiveness. Section 2.3 examines this measurement challenge in detail.

2.3. Measurement Gap

Having established the theoretical foundations of CE in maritime contexts, this section examines why current measurement approaches fall short for vessel refits. It identifies a critical gap at the vessel and component levels, precisely where refit decisions are made, and explains why existing methods like LCA and LCC are often impractical. This gap analysis motivates the methodological solution outlined in Section 2.5.

Circularity in the maritime sector can be assessed at several levels, as outlined in the Systems Perspective summarised in Table 2.3. Khadim et al. (2022) distinguishes four levels:

- Nano: focusing on materials;
- Micro: focusing on components or individual companies;
- Meso: covering industrial networks and supply chains;
- Macro: referring to regional or national policy context.

Vessel refits operate across these levels simultaneously. At the nano level, refits involve the inspection, replacement or upgrading of materials and subcomponents. At the micro level, the vessel can be treated as the product being restored, repaired or modernised, consistent with the shipowner or operator's perspective. However, a refit is rarely executed by one organisation alone. OEMs or local service suppliers of OEMs, shipyards, and specialised subcontractors work together to deliver the refit, forming an industrial network characteristic of the meso level.

Circular strategies relevant to refits, repair, refurbish and remanufacture are primarily at the micro level, but require meso-level coordination to implement effectively. This dual perspective complicates assessment as no single level captures the full circular impact of a refit. This study, therefore, examines circularity in refits across four interconnected levels: company, vessel, component, and material. These levels are visualised in Figure 2.4, which adapts the hierarchical structure of Muñoz et al. (2024).[1]

The multi-level nature of vessel refits creates a measurement challenge. While circular strategies are often applied at the component level (micro), their success depends on network-level enablers (meso), such as reverse logistics capacity and OEM certification. Existing literature provides indicators at the material level (nano) and company level (micro) (Okumus, Andrews, & Gunbeyaz, 2024), but substantial gaps remain at the vessel and component levels. Although lifecycle methods like LCA and LCC could theoretically provide insights, they are often impractical for refits due to the inclusion of the complete supply chain, leading to missing documentation, incomplete baseline data and limited information on partial reuse scenarios.

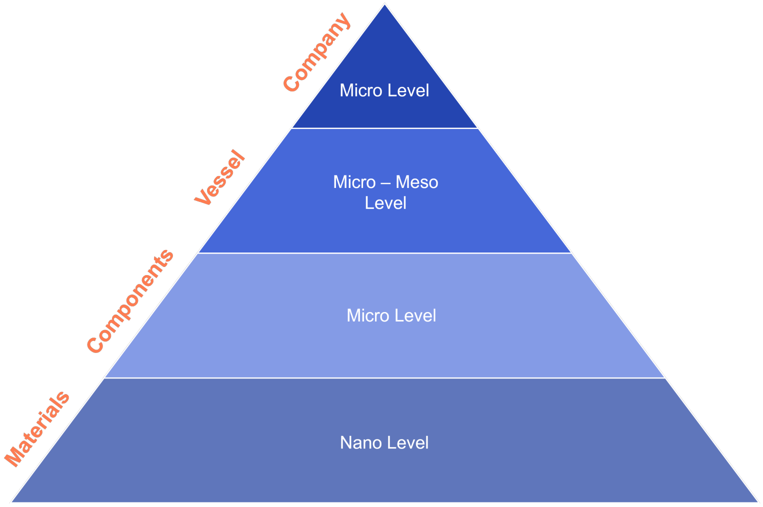


Figure 2.4: Visualisation of Maritime Systems Perspective Levels

From a strategic perspective, company-level circular ambitions influence decisions at the vessel and component levels, for example, prioritising remanufacture over replacement or selecting suppliers that support modularity and reverse logistics. Yet without performance indicators at these levels, it becomes difficult to verify whether such decisions actually contribute to the intended circular outcomes.

In practice, assessment should function as a feedback loop: KPIs measure the results of circular strategies and inform whether strategic objectives are being achieved, enabling companies to adjust decisions where necessary. The absence of suitable indicators at vessel and component level therefore limits transparency, weakens decision-making, and disrupts the link between high level ambitions and operational choices.

This study addresses this measurement gap by developing a framework and a shortlist of KPIs that enable shipyards, designers, and operators to evaluate refit strategies on the component and vessel levels in terms of their strategic, environmental, and economic performance.

2.4. System Boundaries

Before proposing a solution to the measurement gap, it is necessary to define what is included and excluded from the analysis. This section establishes system boundaries across strategic, environmental, and economic impact areas, ensuring that the proposed assessment method remains transparent, repeatable, and feasible given typical data constraints in refit projects.

2.4.1. Data Availability Constraints

Data availability is a primary constraint in selecting KPIs for refit assessment. Unlike newbuild vessels with increasingly comprehensive digital documentation, older vessels often lack detailed material inventories, component specifications, or operational history. Therefore, selected KPIs must be calculable using commonly available data sources such as engine data, operational profiles and prices.

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[1] The original 9R circularity bottom-up approach is depicted in Appendix B.

2.4.2. Strategic System Boundaries

From a strategic perspective, the system boundary is limited to aspects that directly influence the feasibility and comparability of refit strategies. The analysis focuses on vessel- and component-level decisions, rather than company-wide or fleet-level optimisation.

The assessment considers only the technical systems and activities that are directly affected by the refit, such as propulsion systems, energy systems, and major machinery. For example, replacing a main engine would be included, while updating crew quarters or galley equipment would be excluded unless these changes significantly impact operational costs or regulatory compliance. Minor auxiliary systems are excluded unless they have a significant impact on emissions, cost, or vessel performance.

Long-term uncertainties, such as regulatory changes, price volatility, or technological progression, are excluded.

2.4.3. Environmental System Boundaries

Capital Emissions (embodied emissions and yard emissions) generated over the vessel life cycle are assessed using a cradle-to-gate boundary visualised in Figure 2.5. This means emissions due to maintenance and repair over the vessel's lifetime are excluded. Figure 2.5 includes an indication of the type of emissions generated in each lifecycle stage. In this study, embodied carbon is considered based on the types of materials used, upfront carbon is addressed through yard emissions associated with the vessel construction process, operational carbon is accounted for via Tank-to-Wake fuel-related emissions, and beyond-lifecycle carbon represents the emissions saved or prevented through refits.

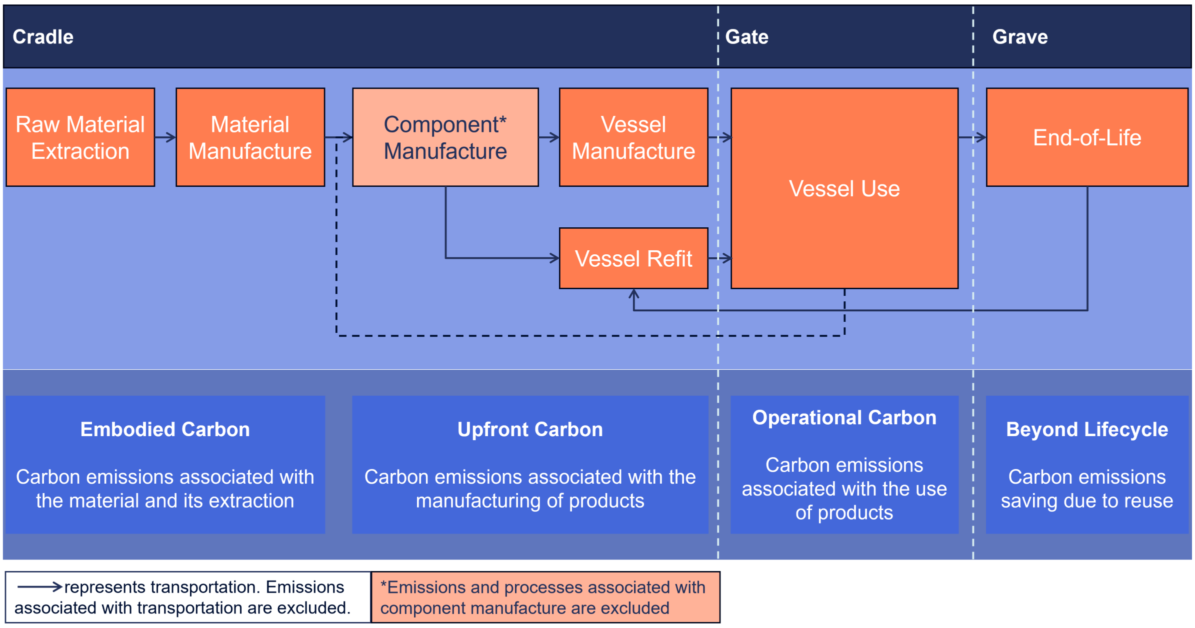


Figure 2.5: Life Cycle of a Vessel including Carbon Emissions based on Delzenne (2022) and Construction Industry Development Board (CIDB) Malaysia (2022)

It should be noted that major equipment, such as the systems described in Subsection 2.4.2, can themselves be repaired, refurbished, or remanufactured. Although such practices remain limited and often lack transparency for clients, the dotted line in Figure 2.5 indicates the potential for such component-level R-strategies.

Upfront carbon associated with component manufacture is excluded due to an expected lack of data from OEM's about their production processes and footprint. The same exclusion reason applies to transportation of materials, components and vessels. An additional reason for exclusion is because emissions vary significantly based on vessel location, component sourcing, and shipyard proximity. For instance, transporting a remanufactured engine from Rotterdam to Vietnam would add substantial emissions, but these are unrelated to the circular strategy itself (the same engine shipped new would have comparable transport emissions).

Indirect operational emissions, such as those arising from the extraction and production of fuel, are excluded in accordance with the Tank-to-Wake principle. This is because it is not feasible to determine which fuel extraction methods will be used for all fuel consumed over the vessel's lifetime. Likewise, emissions linked to maintenance activities, spare parts, and auxiliary services are omitted, since maintenance-related emissions cannot be reliably projected across the entire service life of the vessel. These factors are external to the refit strategy itself and are difficult to standardise across cases.

Finally, EoL treatment, including recycling or disposal, is not considered, because there is uncertainty regarding both the types of materials that will be removed from the vessels to be refitted and the recycling practices available at the shipyard where this will take place.

This boundary is selected to balance data availability and comparability. These exclusions limit uncertainty, reduce data requirements, and ensure that the proposed method remains transparent, repeatable, and suitable for comparative assessment of refit strategies.

2.4.4. Economic System Boundaries

The economic boundary includes costs that are directly affected by refit decisions and can be consistently compared across strategies. The analysis considers Operational Expenditure associated with fuel use, maintenance, crew, and insurance.

Costs related to financing structures, taxation, subsidies, or residual value at end-of-life are excluded. This ensures that the economic assessment remains comparable across vessels and refit strategies, and aligned with the early-stage decision-making focus of the study.

2.5. Solution Outline

Building on the identified measurement gap (Section 2.3) and working within the defined system boundaries (Section 2.4), this section introduces a two-step methodological framework for assessing circular performance in vessel refits. This framework builds on and integrates findings from existing literature. Step 1 identifies the possible circular strategies for the refit, step 2 evaluates the performance of these strategies using vessel- and component-level KPIs.

- **Step 1: Identify Possible Circular Strategies -** Identify the possible circular strategies for the refit (repair, refurbish, remanufacture) by evaluating the vessel and its systems or components against a set of predefined criteria.
- **Step 2: Impact Evaluation -** Quantify the expected circular impact of the selected strategy using a set of KPIs representing strategic, environmental, and economic impact.

Structuring the method in two steps ensures that the selected circular strategy is clearly defined before its implications are measured. This integration creates a coherent framework for evaluating refits at both the vessel and component level and supports consistent decision-making across projects. Each step is elaborated in the following sections.

2.5.1. Step 1: Identify Possible Circular Strategies

Step 1 determines what circular strategy or strategies, repair, refurbish, or remanufacture, are possible for the vessel refit. This step builds on the multi-level perspective introduced in Section 2.3, where vessels are viewed as assemblies of components and systems with varying conditions, functions, and operational requirements. Because refits operate at these micro- and meso levels, a structured classification is needed before any meaningful performance assessment can take place.

Selecting an appropriate strategy is essential, as it influences downtime, costs, certification requirements, and environmental outcomes. As shown by Senavirathna et al. (2022), different strategies applied to the same component or material can lead to substantially different results, underscoring the need for a consistent and transparent decision-making process.

A key challenge is determining when remanufactured or refurbished components can replace new ones without compromising compliance, performance or reliability (Alfnes et al., 2025). Therefore, the refitted vessels are compared to equivalent newbuilds using the KPIs of step 2. Refit strategy decisions depend on factors such as the physical condition of the product, its modularity and accessibility, and the operational requirements of the vessel (Boorsma et al., 2022; Joensuu et al., 2023).

In practice, the strategy of a refit is determined by stakeholders, such as the shipbuilder, shipowner or maybe sometimes an OEM, while complying with classification society regulations. These stakeholders have varying criteria, shown in Table 2.5. These criteria can determine whether the desired refit strategy aligns most with repair, refurbish, or remanufacture. In cases where no substantial intervention is needed (direct reuse), or where the vessel condition prevents meaningful lifetime extension (recycle), the vessel falls outside the scope of value-retaining strategies and instead aligns with reuse or recycle. These boundary strategies are acknowledged, but not analysed further in this study.

Table 2.5: Potential Stakeholder Criteria for Circular Strategy Classification Split into Strategic, Environmental, and Economic Impact Areas

Strategic	Environmental	Economic
Vessel Sailing Area Degree of Structural Changes Vessel Availability	Expected Emission Regulations Lifecycle Extension Potential Operational Profile Vessel Emission Reduction Ambitions	Low Initial Investment Low Operational Cost Viability vs Newbuild

The outcome of Step 1 is one or multiple strategies that can be evaluated through Step 2 before a final decision on the strategy is made. Step 2 evaluates the strategic, environmental, and economic impact areas of the selected strategy or strategies using dedicated performance indicators. How Step 1 and Step 2 affect each other is visualised in Section 2.6.

2.5.2. Step 2: Impact Evaluation

After identifying the possible refit strategy or strategies, the second step assesses their expected performance across the strategic, environmental, and economic domains. This evaluation uses KPIs at vessel and component levels, two scales within the micro-meso perspective where standardised indicators remain limited (Kristensen & Mosgaard, 2020; Okumus, Andrews, & Gunbeyaz, 2024).

The goal of this step is to improve the transparency, comparability, and strategic relevance of refit decision-making. The selected KPIs must therefore be evidence-based and practical. Their selection draws from established frameworks and regulations, including the EU taxonomy (Commission, 2021), the Circular Economy Action Plan (European Commission, 2020), classification society requirements, and the UN SDGs (United Nations, 2024a). While SDG indicators such as GHG emissions per unit of value added (SDG 9.4) or recycling rates (SDG 12.5) are defined at higher system levels, they offer direction when translating sustainability ambitions to the vessel or component scale.

Existing CE measurement approaches vary widely in scope and orientation. UN frameworks are goal-driven, while maritime circularity indicators (Okumus, Andrews, & Gunbeyaz, 2024) target specific stakeholders such as designers, OEMs, or shipyards. However, these perspectives do not always translate to the product-level system view required for evaluating the impact of vessel refits. Therefore, a filtering process, described in Section 3.1, is used to determine which indicators meaningfully apply at the vessel/component level and if there is a difference between the three refit strategies

To be suitable for refit assessment, KPIs must meet several criteria: they must be calculable with data typically available during early-stage refit planning, applicable across different vessel types and sizes, detailed enough to distinguish between circular strategies, and aligned with regulatory frameworks (Commission, 2021; DNV, 2023) that influence financing and compliance. The following seven themes, derived from CE literature (Alfnes et al., 2025; Favi et al., 2017; Joensuu et al., 2023; Okumus, Andrews, & Gunbeyaz, 2024), operationalise these requirements.

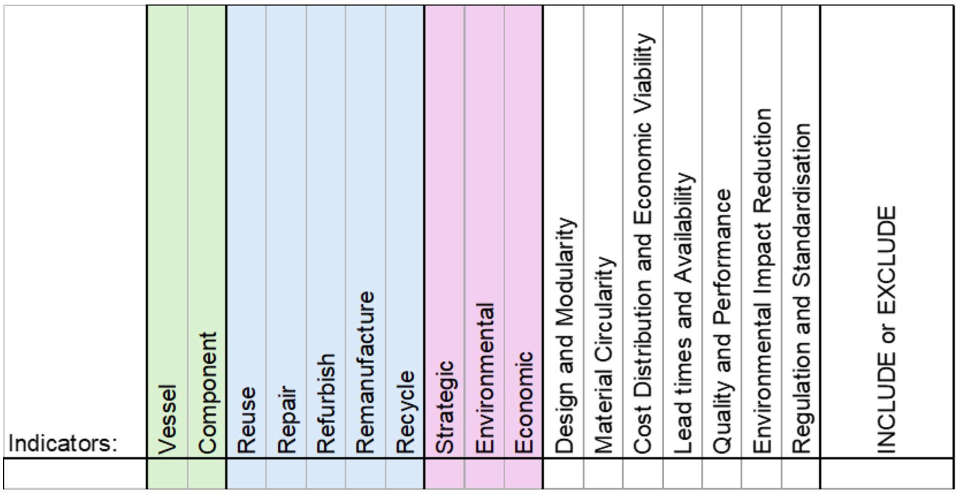
1. Design and Modularity: The extent to which systems enable disassembly, upgrading, and remanufacturing.
2. Material Circularity: Degree of recycled, reused, or virgin material content.
3. Cost Distribution and Economic Viability: Cost shares of reused, repaired, remanufactured, and new components.

4. Lead Times and Availability: Responsiveness of supply chains and availability of circular alternatives.
5. Quality and Performance: Compliance of reused or remanufactured parts with performance and safety requirements.
6. Environmental Impact Reduction: Indicators related to GHG emissions, waste, and resource use, aligned with SDG and EU ambitions.
7. Regulation and Standardisation: Presence of enabling policies, class rules, and certifications that support circular uptake.

These seven themes are not equally weighted in all refit contexts. Environmental impact reduction aligns with regulatory drivers (Commission, 2021), while cost distribution and lead times often dominate operational decision-making. Chapter 3 presents what KPIs can be used to assess each theme. The results of the case study will reveal which themes prove most influential in practice and whether conflicts arise between environmental ambitions and economic constraints.

These themes capture recurring operational challenges in the maritime sector, such as limited component data, complex reverse logistics, and extended product life spans. Based on these themes, a set of candidate KPIs, extracted from literature (including Okumus, Andrews, and Gunbeyaz (2024) and United Nations (2024a)), is assessed for applicability to the vessel/component scope and the different circular strategies. This ensures that the resulting KPIs are both theoretically grounded and practically usable, as demonstrated in the case study application (Chapter 5).

The assessment is performed using the matrix in Figure 2.6, which maps each potential indicator against levels, strategies, and domains. Indicators meeting the criteria are shortlisted for testing in the case study. Finally the method distinguishes between quick-assessment KPIs requiring minimal data, and in-depth KPIs, which provide richer analytical insights but require more detailed information.



Indicators:	Vessel	Component	Reuse	Repair	Refurbish	Remanufacture	Recycle	Strategic	Environmental	Economic	Design and Modularity	Material Circularity	Cost Distribution and Economic Viability	Lead times and Availability	Quality and Performance	Environmental Impact Reduction	Regulation and Standardisation	INCLUDE or EXCLUDE

Figure 2.6: Matrix to evaluate KPIs based on level, strategy and domain criteria

2.6. Conclusion Literature Review

This chapter reviewed the theoretical foundations for assessing circularity in vessel refits, drawing on CE frameworks, value-retention strategies, system level perspectives, and existing measurement approaches. The literature shows that while frameworks such as 9R hierarchy, LCA/LCC, and systems perspective provide conceptual structure, most were not developed for maritime applications, leaving uncertainty about how to assess circular value at the vessel and component levels.

The review also showed that circular strategies, repair, refurbish, and remanufacture, offer different value-retention potentials but require criteria-based evaluation to determine which is technically and operationally suitable for a given refit. At the same time, existing circularity indicators tend to focus on company-wide or sector-level performance, rather than product-level interventions, making them difficult to apply to refit decisions.

To address these gaps, the chapter introduced a two-step methodological outline: first, identifying the possible strategy or strategies for a refit based on vessel and system characteristics; second, evaluating its performance through KPIs across strategic, environmental, and economic impact areas. This provides a structured foundation for translating circular principles into practical refit decisions. The method is visualised in Figure 2.7. Figure 2.8 illustrates how the two steps affect one another and shape the decision-making process.

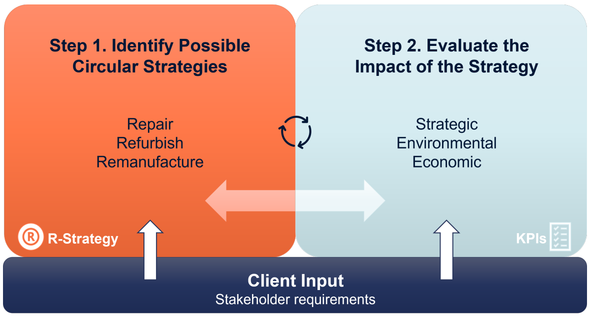


Figure 2.7: Visualisation Two-Step Methodology for the Evaluation of Refit Strategies

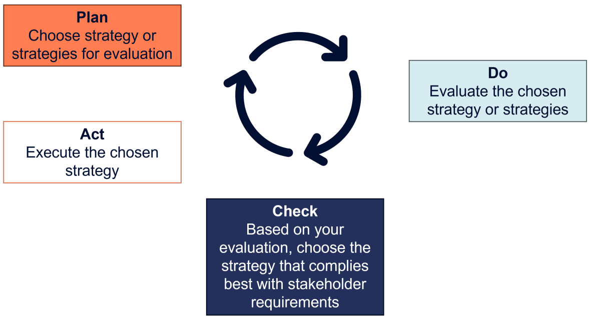


Figure 2.8: Plan–Do–Check–Act Cycle Embedded in the Two-Step Methodology

Chapter 3 extends this foundation by identifying, filtering, and refining candidate indicators across strategic, environmental, and economic dimensions. The seven themes introduced in Section 2.5.2 are operationalised, translating the conceptual framework into measurable KPIs ready for application in the case study (Chapters 4 and 5).

3

Selection, Refinement, and Explanation of KPIs

Chapter 2 identified a measurement gap at the vessel and component levels and proposed a two-step approach: first, identifying possible circular strategies for the refit, second, evaluating their performance using KPIs across strategic, environmental, and economic impact areas. This chapter addresses the second step by systematically filtering candidate indicators from literature, regulatory frameworks, and industry practices to a final set of KPIs applicable at vessel and component levels.

The selected KPIs are organised across three impact areas: strategic feasibility, environmental impact, and economic viability, and provide balanced coverage of the seven themes introduced in Section 2.5.2. For each KPI, this chapter provides: literature-grounded justification, calculation methodology, data source identification, and explicit assumptions.

Section 3.1 establishes the selection criteria and details the three-step filtering process to set the final set of KPIs. Sections 3.2, 3.3, and 3.4 present the selected KPIs for the three impact areas, each beginning with a literature review followed by calculation methods. Section 3.5 synthesises the complete framework, and bridges to the case study application. Section 3.6 presents the conclusion of the KPI selection. A complete database of all reviewed indicators, including those excluded during the refinement process, is provided in Appendix C.

3.1. Systematic KPI Identification and Refinement

This section outlines the refinement process used to reduce the full set of indicators into a list of practical and applicable KPIs.

3.1.1. Initial KPI Database Construction

The construction of the initial KPI database followed a systematic approach aligned with the literature review methodology described in Chapter 2. All sources consulted during the literature review were examined for performance indicators, circularity metrics, and sustainability measures applicable to maritime operations.

The database draws from three primary categories of sources.

1. **Academic Literature**: Key sources included Okumus, Andrews, and Gunbeyaz (2024), who reviewed over 400 circularity indicators across industries and developed 57 metrics tailored to maritime applications, and Favi et al. (2017), who provided a comprehensive review of lifecycle costing methods in manufacturing. Additional indicators were extracted from LCA studies (Pero et al., 2024), CE frameworks (Kirchherr et al., 2017; Moraga et al., 2019), and maritime sustainability assessments (Kristensen & Mosgaard, 2020).
2. **Regulatory and Policy Frameworks:** The UN SDGs provided sector-level indicators for indus-

trial innovation (SDG9), responsible production (SDG12), and climate action (SDG13), (United Nations, 2024a). The EU Taxonomy (Commission, 2021) and CEAP (European Commission, 2020) contributed environmental performance thresholds. IMO regulations, particularly MARPOL Annex VI, provided operational efficiency indicators such as Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ships Index (EEXI).

3. **Industry Practice and Grey Literature:** Classification society guidelines, shipyards performance reports, and maritime consultancy studies were reviewed to identify indicators used in practice but not yet documented in academic literature.

All indicators from these sources were catalogued with their source, resulting in an initial database of 87 indicators, provided in Appendix C.

Database Limitations

Two limitations of the initial database should be noted. First, non-English or -Dutch sources were excluded due to language constraints, potentially missing relevant indicators from other maritime industries. Second, proprietary indicators used by classification societies or shipyards but not publicly documented could not be included.

The following section describes the three-stage filtering process used to refine this database into a practical KPI framework.

3.1.2. Three Step Filtering Process

The process consists of three filtering stages that ensure each indicator is relevant, non-redundant, and suitable for assessing the performance of the refit strategy at vessel and component levels.

Step 1 - Applicability filtering

The 87 indicators were filtered to retain only those applicable at the vessel or component level, relevant to refit strategies, and linked to one of the three impact areas: strategic, environmental, and economic. This eliminated company-level, material-level, design-only, and social indicators.

Examples of excluded indicators:

- Having standards or regulations regarding remanufactured marine equipment (industry-level)
- Having standards or regulations regarding refurbished electronics on board (industry-level)
- Reuse or recycle rate of packaging (CO-CM1) (micro-level, no vessel impact)
- Ratio of customers offered designs with circular products on board (company-level)
- Volume of returns (OEMs)
- Circular Freight Ratio (Operator)

The results of the first step of the filtering process are presented in Table 3.1.

Step 2 - Redundancy Elimination

The second step in the filtering process is the merging of duplicates. Indicators with overlapping definitions, or which represented the same concept under different names, were merged into a single KPI. This step reduced redundancy and eliminated inconsistent terminology across sources.

The examples of indicators that were merged:

- The Recycled-reused material proportion by mass (SD-CM3), Advanced recycled content ratio (reused or remanufactured parts ratio by weight in products) (OEM-CM1), Recycled-reused material proportion by mass in ship construction (BS-CM2)
- Cost distribution of new, remanufactured, and reused onboard components (SD-CM4, BS-CM3)

Step 3 - Impact Area Classification

The remaining indicators were assigned to one of the three impact areas (strategic, environmental, and economic). The filtering steps reduced the initial list of 87 indicators to a final set of 19 KPIs: 2 strategic, 11 environmental, and 6 economic. Table 3.1 summarises the reduction in indicator count through each step of the filtering process.

Table 3.1: Quantitative Results of Three-Stage Filtering Process

Stage	Indicators In	Indicators Out	Indicators Remaining
Initial Database	—	—	87
Stage 1: Applicability	87	47	40
Stage 2: Redundancy	40	21	19
Stage 3: Classification	19	0	19

This set lacks strategic KPIs. Therefore, four strategic KPIs were added, adapted from the literature. Time in Dock was added to account for downtime during the refit. If a client wants to refit their own vessel, they will incur downtime that needs to be taken into consideration. It is also used as part of the calculation of the Vessel Lead Time. Adapted from Okumus, Andrews, and Gunbeyaz (2024) OEM-CM3 this study uses Complexity of Work as another point of view for modularity by determining the effort it takes to remove or repair certain systems. Okumus, Andrews, and Gunbeyaz (2024) defined many legislative metrics, but nothing specifically targeting the requirement for reclassification and the extra time this takes. Therefore, it was decided to add two KPIs: Reclassification Required and Reclassification Duration. This brings the total amount of strategic KPIs to 6.

To capture a vessel's lifetime emissions in a manner analogous to how Total Cost of Ownership (TCO) is assessed, an additional KPI was introduced: Total Emissions of Ownership (TEO). This KPI makes use of Capital Emissions (CAPEM) and Operational Emissions (OPEM). To fully capture the CAPEM, besides the existing KPI Embodied CO_2, Yard Emissions is added as a KPI to account for the emissions generated during the building process. This adds two environmental KPIs to bring the total of environmental KPIs to 13.

To provide a transparent calculation of the TCO, CAPEX and OPEX are clearly defined. This case study looks at CAPEX from two perspectives, the shipbuilder and shipowner/operator. CAPEX for the shipbuilder consists of the Acquisition Cost of the to-be-refitted vessel and the refit costs. These are combined in the Total Refit Cost. The refit costs are distributed over different systems, using Ship Function Incex system coding to identify what systems are most cost-intensive.

From the shipowners' perspective, CAPEX is the price paid for the refitted vessel. To account for this in the TCO calculation, the Market Value or Expected Sales Price is added as a KPI. OPEX consists of Crew Costs, Energy Costs, Maintenance Costs, and Insurance Costs. These are separately described to provide transparency and build towards the calculation of OPEX. These additions bring the total number of economic KPIs from 6 to 13.

The total number of KPIs used in this study is 32: 6 strategic, 13 environmental, and 13 economic.

3.1.3. Seven-Theme Coverage

To ensure the final KPI set addressed all dimensions of circular performance identified in the literature review (Section 2.5.2), each indicator was mapped to one or more of the seven evaluation criteria. Table 3.2 presents this mapping. All KPIs mentioned will be explained in Sections 3.2, 3.3, and 3.4.

Note: Some KPIs address multiple themes. For example, ”Embodied Emissions” relates to both material circularity (theme 2) and environmental impact reduction (theme 6). The count column shows unique KPIs associated with each theme.

This verification confirms that the final KPI set provides comprehensive coverage across all seven themes, with each theme addressed by at least three indicators. Themes 3 (Cost Distribution and Economic Viability), and 6 (Environmental Impact Reduction) receive the most coverage (12 and 7 KPIs), reflecting their central importance in regulatory frameworks (EU Taxonomy, IMO regulations) and companies to define business opportunities.

Table 3.2: Mapping of Final KPIs to Seven Evaluation Themes

Theme	**KPIs Addressing Theme**	**Count**
1. Design and Modularity	Complexity of Work, Component Cost Share, Reclassification Required & Duration	4
2. Material Circularity	Embodied Emissions, % Reused Components, Resource Depletion, Solid Waste Reduction, Value retention	5
3. Cost Distribution and Economic Viability	Acquisition Cost, Refit Cost per SFI, Total Refit Cost, Market Value, Component Cost Share, Value Added, TCO, OPEX per Year (Crew Costs, Energy Costs, Maintenance Costs, and Insurance Costs)	12
4. Lead Times and Availability	Component Lead Time, Vessel Lead Time, Time in Dock	3
5. Quality and Performance	Reclassification Required & Duration, EEXI, Fuel Consumption, TEO	5
6. Environmental Impact Reduction	Embodied Emissions, Prevented CO_{2e}, OPEM per Year, Particulate Matter, EEDI/EEXI, Vessel Life Extension, Yard Emissions	7
7. Regulation and Standardisation	Reclassification Required, EEDI/EEXI, CO_{2e}/Value Added	3
Total		39

3.2. Strategic KPIs

3.2.1. Literature Review: Strategic Performance in Refits

Strategic performance indicators in the maritime context capture operational and competitive factors that influence the feasibility and attractiveness of circular strategies. Unlike environmental or economic KPIs, which have established frameworks (LCA, LCC), strategic indicators are more context-dependent and reflect sector-specific constraints such as vessel downtime, regulatory approval processes, and supply chain coordination.

Lead Time as a Competitive Advantage

Lead time, the duration from project initiation to vessel delivery, is a critical differentiator between refits and newbuilds (Okumus, Andrews, & Gunbeyaz, 2024). Stopford (2009) notes that vessel acquisition timelines directly affect shipping companies' ability to respond to market opportunities, particularly in volatile freight markets. A refit that can deliver a vessel in 6-10 months competes favourably against newbuild timelines of 18-24 months.

Lead time analysis in shipbuilding typically distinguishes three components: **1)** design and engineering time **2)** procurement and component availability, and **3)** yard production and commissioning. For refits, design and engineering time is significantly reduced (existing vessel design is preserved), while procurement and component availability become critical, particularly when circular strategies rely on remanufactured or refurbished components with uncertain availability.

To determine what systems are critical in the procurement phase, the lead times of components can be estimated per system. Ship Function Index (SFI) provides codes per ship system, organising multiple components into system groups. The allocation of components or systems to certain system groups can differ per vessel type or company. Damen uses the SFI codings depicted in Table 3.3.

Table 3.3: Damen System Codes (SFI)

Damen System Code (SFI)	Systems
100	Tanks, Hull, Superstructure, Deck, Mast
200	Engines, Gearbox, Generators, Steering Gear, Bow Thrusters, Shafts
300	Primary Ship Systems
400	Electric Equipment
500	Deck Equipment
600	Auxiliary Systems
700	Accommodation
800	Navigational Equipment
000/900	General

Downtime and Operational Continuity

Time in Dock measures the period during which a vessel is unavailable for revenue-generating operations. Alfnes et al. (2025) found that shorter delivery times are one of the main drivers for suppliers and shipyards to choose R-strategies. This creates a strong incentive for strategies that minimise intervention depth, favouring repair over remanufacture when performance gains are marginal.

The strategic value of minimising downtime varies by vessel type and operational context. For vessels on long-term charter contracts, downtime may be scheduled during off-hire periods with minimal revenue impact. For vessels operating in spot markets, any downtime represents a direct opportunity cost.

Complexity of Work and Project Risk

Complexity of Work is a qualitative indicator capturing the technical and organisational difficulty of the refit scope. Senavirathna et al. (2022) identified complexity as a key driver of cost overruns and schedule delays in refit projects. Factors contributing to complexity include:

- Interdependencies between various components (or ship systems) (e.g., propulsion changes affecting electrical distribution)
- Tight spatial constraints within existing vessel design
- Uncertainty in 'as-built' conditions (particularly for older vessels lacking complete documentation)
- Coordination requirements across multiple suppliers and subcontractors

Higher complexity increases project risk from both schedule and cost perspectives, making simpler strategies (repair, or like-for-like refurbishment) strategically preferable when performance benefits of more complex interventions are uncertain.

Regulatory Complexity and Reclassification

Classification society requirements significantly influence refit strategy selection. When refits involve "substantial modifications", defined variably across classification societies but typically including propulsion changes, structural alterations, or mission profile shifts, reclassification is required. This process involves:

- Technical documentation review and approval
- On-site inspections during and after refit
- Sea trials and performance verification
- Issuance of updated class certificates

Okumus, Gunbeyaz, et al. (2024) emphasise that classification societies act as 'technical gatekeepers', and their approval timelines can add to the project duration depending on scope and society workload. The strategic indicators Reclassification Requirement and Reclassification Duration capture this regulatory domain.

Avoiding reclassification, by keeping modifications within ”like-for-like” replacement boundaries, reduces both project risk and timeline uncertainty, making repair and refurbish strategies strategically attractive even when remanufacture offers better environmental performance.

Supply Chain Resilience and Component Availability

The COVID-19 pandemic and recent geopolitical disruptions highlighted supply chain fragility in maritime industries (Joensuu et al., 2023). Component lead times, particularly for specialised equipment like thrusters, generators, and propulsion systems, extended from typical 6-9 months to 12-18 months in some cases.

Circular strategies can improve supply chain resilience by reducing dependency on new component manufacturing. However, Wahab et al. (2018) note that remanufactured component availability is currently limited in maritime applications compared to automotive or aerospace sectors, where remanufacturing infrastructure is more developed. This creates a strategic trade-off: refits relying on circular strategies face lead time risk if remanufactured components are unavailable, potentially negating the time advantage over newbuilds.

Research Gap and Contribution

Strategic assessment tools developed focus on timeline and resource allocation for individual projects (Stopford, 2009), but do not systematically integrate regulatory complexity, component availability, or certification requirements into comparative assessment across refit strategies. While Alfnes et al. (2025) identified supply chain coordination and OEM involvement as critical success factors for maritime remanufacturing, no standardised set of indicators exists to quantify their impact on project timelines or market responsiveness.

This research contributes by:

1. Developing time-based KPIs (dock time, component lead time, vessel lead time) that quantify the strategic advantage of refits in fleet availability and market responsiveness
2. Introducing complexity assessment as a qualitative indicator when detailed planning data are unavailable
3. Integrating reclassification requirement and duration as an explicit KPI, making regulatory processes visible in strategic comparison.

3.2.2. Selected Strategic KPIs and Calculation Methods

Lead Time and Scheduling

Vessel Lead Time

The vessel lead time captures the total time from the start of the project (contract signing or acquisition) to vessel delivery. It includes both planning and execution phases, reflecting the strategic advantage of refits. A shorter vessel delivery time of a refit strengthens competitive positioning over newbuild alternatives.

$$\text{Vessel Lead Time (months)} = \text{Time in Dock} + \text{Component Lead Time} \tag{3.1}$$

Equation 3.1 provides a calculation method for the Vessel Lead Time that can be used before the refit takes place during the decision-making process. The variables in this equation are estimates based on historical project data or expert experience. After the refit is finished, the actual vessel lead time can be calculated using Equation 3.2.

$$\text{Actual Vessel Lead Time (months)} = \text{Delivery Date} - \text{Project Start Date} \tag{3.2}$$

This helps refine estimates in the future, making predictions more robust. The data required for this Equation 3.2 is the contract signing/acquisition date and the delivery/commissioning date. This data is likely to be found in project management files, Gantt charts, or operations department project tracking.

To simplify the calculation and the amount of data required, administrative processes (e.g. tendering, financing) are excluded. Furthermore, the vessel delivery date marks full operational readiness.

Component Lead Time

The component lead time measures the time required to procure or refurbish each main component category. It provides insight into supply chain responsiveness and the logistical bottlenecks of circular strategies. Lower and more predictable lead times reduce logistical risk and make life-extending strategies more attractive to clients with strict operational schedules.

Similar to the vessel lead time, the component lead time can be estimated using historical project data or expert experience. After the procurement phase of the refit project is finished, the actual component lead times can be calculated using Equation 3.3.

$$\text{Component Lead Time (months)} = \text{Delivery Date} - \text{Order Date} \tag{3.3}$$

For this calculation, the order and delivery dates per component are required. To identify which system is the most critical, the longest component lead time per SFI system is used for this KPI. Data sources are the Damen procurement database (purchase orders), supplier delivery schedules or OEM communication and the logistics department. For components that are reused from the vessel, the lead time is assumed to be negligible, unless refurbishment is required.

Time in Dock

Time in Dock represents the total duration a vessel remains unavailable due to refit activities. It directly influences operational downtime and, therefore, the strategic and financial viability of a refit. A shorter docking period improves fleet availability and strengthens the operator's market competitiveness.

Beforehand, Time in Dock can be estimated using historical project planning data and expert experience based on the assessed work that needs to be done. When the project is further along, Time in Dock can be calculated using Equation 3.4, that uses the start and end dates of the docking period from the project or yard planning.

$$\text{Time in Dock (months)} = \text{Dock-Out Date} - \text{Dock-In Date} \tag{3.4}$$

Depending on how far along a refit project is, this data can be acquired from Damen Operations projects database (such as planning logs), yard progress reports or dry-docking schedules and interviews with project managers or superintendents.

In order to provide a clear calculation method, some assumptions are made. The first assumption is that dock-in and dock-out represent the full unavailability period. Next to that, external delays (like component logistics or class inspections) are ultimately included in total dock time.

Project Complexity

Complexity of Work (per SFI)

The Complexity of Work reflects the relative technical and organisational complexity of the refit scope across different system groups. It provides a qualitative measure of labour intensity, risk, and coordination effort. These are key drivers of both project duration and cost. Lower complexity reduces project risk and likely investment costs, increasing confidence for both shipowners and shipyards when considering a refit strategy.

This indicator is assessed qualitatively on a low-medium-high scale per SFI category, to be able to identify critical systems. **Low** entails a simple replacement or inspection (e.g. repainting or lighting). **Medium** consists of minor modification or component upgrade. **High** is a full system overhaul or re-engineering.

To provide an accurate scaling, the scope of work per SFI category (e.g. work orders, engineering estimates) is needed. At the beginning of a project, this can be based on expert judgement from project engineers and supervisors.

The sources of this data can vary between technical work packages or specification documents, to interviews with Damen engineers or repair yard leads.

This KPI assumes comparable vessel sizes and refit contexts. If labour hours or man-days are available, these can be used as a proxy.

Reclassification Required and Duration

Reclassification ensures that the refitted vessel continues to comply with class and statutory regulations. This KPI assesses whether reclassification is required after the refit, and, if applicable, how long the process takes. It reflects both strategic feasibility and regulatory constraints. Avoided reclassification improves regulatory feasibility and reduces perceived project risk, supporting decision-making in favour of some refit strategies.

Whether the vessel needs reclassification is depicted using a binary variable: ***yes or no***. Before the refit, the duration of the reclassification is estimated based on historical project data or expert experience. After the refit, the duration of the reclassification can be calculated using Equation 3.5 to refine future estimates.

$$\text{Duration Reclassification (days)} = \text{Date Class Approval} - \text{Date Class Submission} \tag{3.5}$$

The data required to calculate Equation 3.5 consist of the class status before and after the refit, the data of submission and approval of class documentation and the scope of modifications affecting classification. Data sources providing this data are project documentation, class survey reports, and classification society correspondence.

It is assumed that reclassification is only required when major systems are replaced or upgraded (e.g. propulsion or structure). Any additional reclassification costs are included in the Total Refit Cost KPI of Section 3.4.

3.2.3. Summary and Data Requirements

Table 3.4 provides a comprehensive overview of the 6 strategic KPIs, including calculation units, data sources, assumptions, explanatory notes, and literature sources.

Table 3.4: Complete Overview of Strategic KPIs

KPI	Unit	Data Source	Assumption	Note	Source
Vessel Lead Time	Days	Project Management	Historic averages used when data missing	Total lead time for vessel readiness	(Okumus, Andrews, & Gunbeyaz, 2024)
Component Lead Time	Days	Procurement	If data missing, OEM delivery times or experience based estimates used	Time required to source and deliver components	(Okumus, Andrews, & Gunbeyaz, 2024)
Time in Dock	Days	Project Planning / Operations	Includes delays; yard estimates used when data missing	Duration of vessel downtime during refit	(Alfnes et al., 2025; Stopford, 2009)
Complexity of Work	Qualitative (Low/Med/ High)	Engineering / Operations	Relies on expert assessment; comparable vessel sizes assumed	Degree of technical difficulty in refit tasks	adapted from (Okumus, Andrews, & Gunbeyaz, 2024)
Reclassification Required	Binary (Yes/No)	Class Societies, Project Documentation, Class Survey Reports	Only required for major system changes	Requirement for class society reclassification	adapted from (Okumus, Gunbeyaz, et al., 2024)
Reclassification Duration	Days	Class Societies	Experience based duration used if not recorded	Time required for reclassification process	adapted from (Okumus, Gunbeyaz, et al., 2024)

3.3. Environmental KPIs

Environmental KPIs capture the environmental impact of a vessel over its lifetime. They address differences in building emissions (embodied emissions, yard emissions), operational emissions, resource efficiency, and waste reduction. For each KPI, the following section provides: purpose and relevance, calculation method, required data sources, and underlying assumptions.

3.3.1. Literature Review: Environmental Assessment in Maritime Context

Environmental performance assessment in maritime applications has evolved significantly over the past two decades, driven by tightening regulations (IMO GHG Strategy) and growing stakeholder pressure for decarbonisation (International Maritime Organisation (IMO), 2025). This subsection reviews the literature on environmental indicators for vessel lifecycle assessment, with particular focus on challenges and adaptations required for refit evaluation.

Lifecycle Carbon Emissions in Shipbuilding

Pero et al. (2024) provide a comprehensive review of LCA applications in shipbuilding, identifying two distinct carbon footprints: **embodied carbon**, emissions associated with material production and vessel construction, and **operational carbon**, emissions from fuel consumption during vessel operation.

For most vessel types, operational carbon due to combustion engines dominates the lifecycle emissions (Pero et al., 2024). The ratio between upfront (Capital Emissions (CAPEM)) and OPEM shifts for vessels with shorter operational profiles (e.g., standby vessels) or when comparing refits to newbuilds: refits inherit the embodied carbon of the existing vessel, making incremental embodied carbon from refit modifications relatively small.

Although upstream processes like material extraction and component manufacturing also contribute to emissions, they are often excluded from assessments due to their comparatively smaller share (Okumus, Gunbeyaz, et al., 2024).

All projects or products described in the EU Taxonomy (Commission, 2021) come with a set of technical screening criteria. In the maritime context, these consist of climate change mitigation requirements and ”Do No Significant Harm” (DNSH) requirements that projects must meet in order to qualify as Taxonomy-aligned. These include minimum thresholds for the reduction of fuel consumption, the exclusion of vessels dedicated to the transport of fossil fuels, proper waste and material handling, and compliance with environmental and emission regulations. By meeting the criteria outlined in the EU Taxonomy, refit projects demonstrate environmental responsibility and gain access to sustainable financing mechanisms.

Challenges in Applying LCA to Vessel Refits

Standard LCA methodologies (ISO 14040, ISO 14044) assume complete lifecycle data availability and clearly defined system boundaries (Favi et al., 2017). Vessel refits present several methodological challenges:

1. Incomplete historical data: Older vessels often lack detailed material inventories or component specifications. Nagel et al. (2015) note that ”as-built” documentation may differ significantly from original design, particularly for vessels that have undergone previous modifications.

2. Allocation of shared impacts: When components are remanufactured for use across multiple vessels, allocating embodied carbon to individual refits becomes ambiguous. Pero et al. (2024) suggest mass-based or economic allocation, but acknowledge this introduces uncertainty.

3. System boundary selection: Full cradle-to-grave LCA includes material extraction, transportation, use phase, and EoL disposal. However, Scipioni et al. (2023) note that transportation emissions (of materials, components, and vessels) vary dramatically based on shipyard location and sourcing decisions, making cross-project comparison difficult.

These challenges motivate the system boundary choices in Section 2.4: this study uses cradle-to-gate for embodied carbon (excluding transportation) and direct tank-to-wake operational emissions (excluding maintenance-related impacts), prioritising consistency and data feasibility over completeness.

IMO Regulatory Indicators: EEDI and EEXI

The IMOs EEDI and EEXI represent the primary regulatory framework for vessel carbon performance (DNV, 2023). Both indicators express CO_2 emissions per transport work unit, enabling comparison across vessel types and sizes.

EEDI applies to newbuild vessels and sets progressively stricter baseline requirements (Phase 3: 30% reduction from reference line). EEXI, introduced in 2023, extends similar requirements to existing vessels, creating regulatory pressure for efficiency improvements through refits.

Koilo (2025) analysed EEXI compliance strategies for the global fleet and found that approximately 20% of existing vessels required technical modifications (e.g., engine power limitation, propulsion system upgrades) to meet Phase 1 EEXI requirements. This creates both a regulatory driver for refits and a measurable target: refits improving EEXI scores demonstrate compliance and enhance vessel marketability.

However, EEDI/EEXI have limitations as circularity indicators. They measure operational efficiency but do not account for embodied carbon, material circularity, or component reuse. A refit achieving EEXI compliance through remanufactured propulsion equipment and a refit achieving it through new equipment are scored identically, despite different circular performance.

Circular Economy-Specific Indicators

Beyond lifecycle carbon, CE frameworks emphasise material flow indicators such as:

- **Material Circularity Index (MCI):** Quantifies the proportion of recycled/reused material inputs and the recyclability of outputs (Ellen MacArthur Foundation (EMF), 2020).
- **Percentage of Reused Components:** Simple count-based metric tracking the share of reused vs. new components. Okumus, Andrews, and Gunbeyaz (2024) identified this as a key indicator for shipyards (SD-CM3) and OEMs (OEM-CM1).
- **Vessel Life Extension:** Measures the additional operational years gained through refit. Alfnes et al. (2025) argue this is the most direct indicator of circular value, as extending vessel life avoids the substantial embodied carbon of newbuild construction.

Avoided Emissions and Baseline Comparison

Prevented CO_2 or avoided emissions quantify the environmental benefit of circular strategies by comparing refit emissions to newbuild counterfactual emissions. Okumus, Andrews, and Gunbeyaz (2024) defines emission reduction in percentages of GHG emissions prevented.

EU Taxonomy and "Do No Significant Harm"

The EU Taxonomy for Sustainable Activities (Commission, 2021) establishes technical screening criteria for maritime activities to qualify as environmentally sustainable investments. For shipbuilding and refits, key requirements include:

- Operational Emissions reduction below sector-specific thresholds
- No dedicated use for fossil fuel transport
- Compliance with pollution prevention regulations (MARPOL, ballast water management)
- Circular economy principles in design and material selection

Meeting EU Taxonomy criteria unlocks access to 'green' finance instruments and demonstrates leadership. Several KPIs in this study align with EU Taxonomy requirements:

- CO_{2e}/Value Added aligns with SDG 9.4 (reduce CO_{2e} per unit of value added)
- EEDI/EEXI demonstrate operational efficiency
- % Reused Components and Waste Reduction demonstrate circular design

Research Gap and Contribution

Existing maritime LCA studies focus predominantly on newbuild vessels or single-vessel case studies (Pero et al., 2024). Comparative assessment of circular strategies (repair vs. refurbish vs. remanufacture) within a consistent methodological framework remains rare. While Okumus, Andrews, and Gunbeyaz (2024) developed 57 maritime circularity indicators, they were validated at company level, not vessel or component level, limiting their applicability to refit decision-making.

This research contributes by:

1. Adapting established LCA methods (embodied carbon, operational emissions) to refit-specific constraints (limited historical data, partial system interventions)
2. Integrating regulatory indicators (EEDI/EEXI) with circular performance metrics (reused components, prevented emissions)
3. Providing practical calculation methods using commonly available data sources (material lists, operational profiles, class documentation)

3.3.2. Selected Environmental KPIs and Calculation Methods

Total Emissions of Ownership (TEO)

Total Emissions of Ownership (TEO) represents the comprehensive lifecycle carbon footprint of a vessel, integrating both capital emissions (embodied carbon from materials and yard processes) and operational emissions over the vessel's service life. This indicator is introduced in this study to reduce data requirements of LCA approaches, but capture the CAPEM as well as the OPEM. TEO mirrors the TCO concept in the economic assessment, providing a holistic view of environmental impact comparable across refit and newbuild alternatives.

TEO is particularly valuable for evaluating circular strategies because it reveals trade-offs between upfront embodied carbon and long-term operational efficiency. For example, a refit with higher embodied emissions (due to new hybrid propulsion system) may deliver lower TEO if operational emissions decrease sufficiently over the extended vessel life.

TEO is calculated using Equation 3.6, where capital emissions include embodied CO_2 and yard production emissions, and operational emissions are summed over the vessel's expected remaining service life *n*.

$$\text{TEO} = \text{Capital Emissions} + \sum_{t=1}^{n} \text{Operational Emissions} \tag{3.6}$$

To calculate TEO, the data used to calculate the capital emissions and the operational emissions are used. Data sources include engineering Bill of Materials (BoM), shipyard environmental reports, and operational profile of the vessel.

The TEO calculation assumes that the operational profile and fuel emission factors remain constant over the service life. There is no discounting of future emissions, meaning that all tonnes of CO_2 are weighted equally regardless of timing. The expected service life is based on the vessel life extension KPI discussed later in this section.

Capital Emissions (CAPEM)

Capital emissions account for the emissions released during the production and installation of materials involved in a refit. Transportation emissions and component manufacturing emissions are excluded due to data collection constraints.

Embodied Emissions

The embodied emissions in material represent the total CO_{2e} associated with the production of the materials used in the vessel. Lower embodied emissions demonstrate a resource-efficient vessel and support environmental sustainability claims toward regulators and clients. This is calculated using Equation 3.7, where m_i is the mass of material *i*, and ECF_i is the Embodied Carbon Factor of material *i*.

$$\text{Embodied Emissions [t CO}_{2e}\text{]} = \sum_i (m_i \cdot ECF_i) \tag{3.7}$$

To calculate the embodied CO_{2e}, a material list is needed as well as material-specific emission factors. The material list can be obtained from the engineering or RD&I department of Damen. The emission factors are extracted from the Ecoinvent Database (Circular Economy, 2024).

It is assumed that embodied carbon factors are representative of European production averages if this is not specifically mentioned in the database. Additionally, minor materials are excluded if they consist of less than 1% of the total mass.

Yard Emissions
The yard emissions per vessel can be calculated by normalising the emissions from the building of the vessel by vessel size, enabling cross-vessel and cross-shipyard comparison. This indicator reflects the relative newbuild/refit impact per Gross Tonnage (GT) of the vessel capacity of a shipyard. This indicator shows how environmentally responsible the yard is compared to industry benchmarks, influencing customer selection.

$$\text{Yard Emissions } [\text{t CO}_2] = \frac{\text{Vessel GT}}{\text{Total Shipyard GT's built}} \cdot \text{Total Production CO}_2 \tag{3.8}$$

For the calculation of the CO_2 emissions per CGT from Equation 3.8, the vessel GT is needed as well as the total amount of vessels and their corresponding GT's built by the shipyard. If such data are unavailable, it is possible to rely on assumptions based on the proportion of the total number of vessels constructed and on a conservative estimate of the annual share of time that a vessel spends in the yard. On the other hand, the total CO_2 emissions from all yard processes are needed.

Prevented Emissions
The Prevented Emissions [CO_{2e}] indicator quantifies the avoided emissions by reusing or remanufacturing components instead of manufacturing new ones. It demonstrates the climate benefits of the refit strategies, strengthening their justification. Prevented CO_2 emissions are calculated using Equation 3.9, where m_i is the mass of material *i*, and ECF$_i$ is the Embodied Carbon Factor of material *i*.

$$\begin{aligned}\text{Prevented Emissions [t CO}_{2e}\text{]} &= \sum_i (m_i \cdot (ECF_{new,i} - ECF_{refit,i}) \\ &= \text{Embodied Emissions}_{\text{newbuild}} - \text{Embodied Emissions}_{\text{refit}}\end{aligned} \tag{3.9}$$

The data required for this calculation consists of a component list with a reuse, repair or new indication. It is assumed that reuse prevents 100% of new manufacturing emissions and repair prevents 90% of new manufacturing emissions.

CO_2 Emissions per Unit of Value Added
This KPI aligns with UN SDG 9.4 (United Nations, 2024a), expressing the carbon intensity of capital investment. It reflects the efficiency of economic value creation to environmental impact. A lower carbon intensity per euro invested signals that the refit delivers sustainability gains, improving the vessel's environmental profile.

$$\frac{\text{CAPEM [t CO}_{2e}\text{]}}{\text{Value Added [€]}} = \frac{\text{Embodied Emissions + Yard Emissions}}{\text{Value Added by newbuild or refit}} \tag{3.10}$$

To calculate Equation 3.10, the estimated total CO_2 emissions from refit or newbuild activities is needed. This data is split up into embedded emissions in materials (Equation 3.7) and emissions during yard processes (Equation 3.8).

Furthermore, an increase in projected vessel market value is needed. This data can be found in the Damen operations database and procurement files.

Operational Emissions

The operational emissions reflect the CO_2 released during daily vessel operation and are influenced by the propulsion type, efficiency, and operational profile.

Fuel Consumption

The estimate for the annual fuel use is based on the fuel type, the operational profile and its corresponding engine powers and running hours. Reduced fuel demand improves the vessel's operational sustainability performance in the eyes of clients and charterers. The fuel consumption is calculated using Equation 3.11, where H_i is the total running hours per year.

$$\text{Fuel Consumption [t Fuel/year]} = \frac{\text{Fuel Consumption}}{\text{Hour}} \cdot H_i \tag{3.11}$$

The data required to calculate the fuel use consists of the operational profile of the vessel, which includes operating hours, and engine data, which provides the specific fuel consumption. For hybrid vessels, it is assumed that the hybrid fuel split (MDO/electric) is the same as the free sailing/bollard pull split. Furthermore, it is assumed that the engine shows no degradation in efficiency over its service life.

Operational Emissions (per year)

The OPEM per year give an indication of the environmental impact related to the operation of the vessel. Lower annual emissions make the vessel compliant with tightening regulations and more attractive for environmentally conscious clients. To calculate the total operational CO_2 emissions, the fuel consumption per year (Equation 3.11) is multiplied by the CO_2 Emissions per Unit of Fuel, depicted as the emission factor of the fuel (EF_{fuel}) (Equation 3.12). Emission factors per fuel type can be obtained from the EU ETS or the IMO.

$$\text{Operational Emissions [t CO}_2\text{/year]} = \text{Fuel Consumption} \cdot EF_{fuel} \tag{3.12}$$

Particulate Matter

Sulphur Dioxide (SO_2) is one of the contributors to the formation of particulate matter. SO_2 emissions are derived from the sulphur content of the fuel. The calculation assumes that a fixed percentage of the sulphur present in the fuel is converted to SO_2 during combustion. Equation 3.13 expresses this conversion using the molar mass ratio between sulphur and SO_2, combined with the assumed conversion efficiency.

$$\begin{aligned} SO_2 \text{ emissions [t SO}_2\text{/year]} &= \text{mass of fuel } \cdot \frac{\text{molar mass of SO}_2}{\text{molar mass of sulphur}} \cdot \% \text{ sulphur converted to SO}_2 \\ &= \text{mass of fuel } \cdot (\frac{64.066}{32.065}) \cdot 97.753\% \end{aligned} \tag{3.13}$$

EEDI and EEXI

The Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) are IMO indicators expressing CO_2 emissions emitted per transport work unit. Better efficiency scores increase compliance confidence and improve the marketability of the vessel. The EEDI and EEXI are calculated using Equation 3.14, where EF_{fuel} is the fuel Emission Factor, and V_{ref} is the reference speed.

$$\text{EEDI or EEXI} = \frac{\frac{\text{Fuel Consumption}}{\text{Hour}} \cdot EF_{fuel}}{Capacity \cdot V_{ref}} = \frac{\frac{\text{CO}_2 \text{ emissions}}{\text{Hour}}}{\text{Transport Work } (tonne \cdot nm)} \tag{3.14}$$

Resource Efficiency

Percentage of Reused Components

This indicator gives an idea of the amount of reused parts compared to the total amount of parts. Higher reuse rates demonstrate circular performance, offering a strong sustainability communication value. The percentage of reused parts can be calculated using Equation 3.15.

$$\%\text{Reused Parts} = \frac{\text{Number of reused or remanufactured components}}{\text{Total components}} \cdot 100\% \tag{3.15}$$

The data required for this KPI is a component list, including condition reports and classification of whether components can be reused or need to be changed. For simplification, repair of a component counts as reuse.

Vessel Life Extension

Vessel Life Extension reflects the years the vessel can continue sailing after the refit. It is similar to the vessel design life, but specifically targets the estimated vessel life after the refit. Extending the lifetime reduces the need for newbuilds, highlighting a significant reduction in environmental footprint. Because the framework enables comparison with newbuild vessels, this KPI is defined as the remaining service life of the vessel. Before the refit, this KPI is estimated based on historical project data and expert experience. After the refit, the vessel can be monitored to ultimately define the actual remaining service life of the vessel.

For this KPI, the required data consists of the original design life, which should be available at the Damen Engineering department, and the remaining service life post-refit, which can be obtained from the DFS Operations department because they oversee the refit. This lifetime extension is verified by engineering judgment if it cannot be verified by class approval.

Resource Depletion

Resource depletion quantifies material consumption. This KPI can be split up by system type, showing which systems dominate new material use. Resource depletion identifies material-intensive systems and supports transparent resource management, improving credibility toward stakeholders. This KPI is calculated using Equation 3.16, where m_i is the mass of virgin material.

$$\text{Resource Depletion}(kg) = \sum_i m_i \tag{3.16}$$

For the calculation of the resource depletion, the material mass per system is needed. When data is missing, mass data can be estimated using equipment specifications or steel weight ratios.

Waste Reduction

Solid Waste Reduction

Solid Waste Reduction shows the percentage of the amount of waste that is avoided due to reuse compared to newbuild. Lower waste generation improves client perception of the yards environmental performance and circularity. Solid Waste Reduction can be calculated using Equation 3.17.

$$\text{Solid Waste Reduction}(\%) = \frac{\text{Waste Avoided by Reuse}}{\text{Total Waste (newbuild baseline)}} \cdot 100\% \tag{3.17}$$

The data required to calculate the waste reduction consists of EoL treatment reports, recycling volumes and waste certificates. It is assumed that the disposal waste is derived from the difference in the mass of reused material.

3.3.3. Summary and Data Requirements

Table 3.5 provides a comprehensive overview of the 13 environmental KPIs, including calculation units, data sources, assumptions, explanatory notes, and literature sources.

Table 3.5: Complete Overview of Environmental KPIs

KPI	Unit	Data Source	Assumption	Note	Source
Total Emissions of Ownership (TEO)	t CO_2	BOM + Yard + Operational Profile	Constant operational profile; no emission discounting	Lifecycle carbon (CAPEM+ OPEM)	Developed in this study
Capital Emissions					
Embodied Emissions	t CO_{2e}	BOM + Ecoinvent	Materials <1% weight excluded	Emissions from material production	(Circular Economy, 2024; Khadim et al., 2022)
Yard Emissions	kg CO_2	Yard data	Normalized for vessel size	Yard-level environmental performance	(Okumus, Andrews, & Gunbeyaz, 2024)
Prevented CO_2 Emissions	t CO_2	Component list	Reuse prevents 100%, repair 90%	Avoided emissions through CE	(Okumus, Andrews, & Gunbeyaz, 2024)
CO_2/Unit Value Added	kg CO_2/€	LCA + Financial	Cradle-to-Gate boundary	Embodied carbon per economic output (SDG 9.4)	(United Nations, 2024a)
Operational Emissions					
Fuel Consumption	t fuel/year	Operational Profile + Specs	No engine degradation assumed	Fuel use during operations	(Commission, 2021)
OPEM per year	t CO_2/year	Operational Profile + Emission Factor	Constant operational profile	Annual emissions from fuel use	(United Nations, 2024a)
Particulate Matter	t SO_2/year	Operational Profile	Constant operational profile	Annual emissions of SO_2 from fuel use	(Pero et al., 2024)
EEDI/EEXI	g CO_2/t·nm	IMO calculator	Newbuild / All vessels	Compliance required for vessels >400 GT	(DNV, 2023)
Resource Efficiency					
% of Reused Components	%	Maintenance Log	Repair counts as reuse	Share of reused parts	(Okumus, Andrews, & Gunbeyaz, 2024)
Vessel Life Extension	%	Class / Engineering	Based on design life and service years	Extension achieved through refit	(Alfnes et al., 2025; Okumus, Andrews, & Gunbeyaz, 2024)
Resource Depletion	kg material	SFI mass data	Representative materials only	Virgin material consumption	(Pero et al., 2024)
Waste Reduction					
Solid Waste Reduction	%	EoL data	Benchmark to typical EoL	Reduction in solid waste	(Okumus, Andrews, & Gunbeyaz, 2024)

3.4. Economic KPIs

3.4.1. Literature Review: Economic Evaluation of Refits

Lifecycle Costing and CAPEX-OPEX Trade-offs

Economic assessment of vessel refits requires consideration of both upfront capital requirements and long-term operational costs. According to Senavirathna et al. (2022), marine assets approaching the end of their design life present opportunities to reduce lifecycle costs by applying circular strategies such as repair or remanufacture. In particular, remanufacture can significantly extend the useful life of high-value components and reduce CAPEX compared to full replacement, especially in vessel systems with high durability, such as propulsion units, auxiliary engines, or hull structures (Alfnes et al., 2025; Joensuu et al., 2023; Okumus et al., 2023).

To structure this economic analysis, a distinction can be made between CAPEX and OPEX. CAPEX refers to the upfront investment required to purchase or significantly upgrade assets. In vessel refits, this includes costs for replacement components, labour, and yard time. OPEX contains the costs of operating and maintaining the vessel, including fuel, crew, maintenance, and insurance.

Circular strategies can influence both. By avoiding the purchase of new components, CAPEX might be reduced. The OPEX could be reduced by modular design or upgrades that reduce fuel consumption and improve system reliability. As shown by Favi et al. (2017), analysing the CAPEX-OPEX ratio over a vessel's extended lifecycle can provide a more accurate view of economic viability, especially when vessel refits affect long-term efficiency or compliance.

Total Cost of Ownership Framework

TCO can be used to evaluate this CAPEX-OPEX relationship (Favi et al., 2017). TCO considers all direct and indirect costs over the asset's life. This helps shipowners and operators compare the financial impact of different circular strategies, especially under new regulatory or market conditions. Refits preserve existing capital assets, which reduces capital investment.

Value Retention and Market Valuation

Beyond cost analysis, refits affect vessel market value, a dimension often omitted in traditional engineering economics. Stopford (2009) distinguishes between ”book value” (accounting depreciation) and ”market value” (actual resale price).

Value retention depends on factors including:

- Remaining service life post-refit
- Market demand for vessel type and specifications
- Quality of refit execution and component selection
- Regulatory compliance (e.g., EEXI, emissions standards)
- Classification society approval and survey status

This study includes ”Value Retention” and ”Value Added” KPIs to capture these market effects, recognising that refit strategies affect not only costs but also asset value.

Research Gap and Contribution

Existing maritime economic studies analyse fleet-level investment strategies or sector-wide trends (Stopford, 2009), but lack granular frameworks for comparing circular strategies at the vessel and component levels. While lifecycle costing (LCC) is well-established in manufacturing (Favi et al., 2017), its application to maritime refits does not account for market value effects or circular strategy differentiation (repair vs. refurbish vs. remanufacture).

This research contributes by:

1. Developing vessel-level cost transparency through SFI-coded CAPEX breakdowns, enabling identification of which systems benefit most from circular strategies;
2. Integrating ”Value Retention” and ”Value Added” KPIs alongside traditional cost metrics, capturing market valuation effects often omitted in engineering economics;

3. Providing a simplified TCO calculation adapted to refit contexts with transparent assumptions for data-limited scenarios.

3.4.2. Selected Economic KPIs and Calculation Methods

Total Cost of Ownership (TCO)

TCO represents the full lifecycle cost, integrating both CAPEX and OPEX over the operational period. This KPI allows comparison of the long-term financial efficiency of refits versus newbuilds. The TCO is calculated using Equation 3.18.

$$\text{TCO} = \text{CAPEX} + \sum_{t=1}^{n} \text{OPEX} \tag{3.18}$$

In this equation, *n* represents the remaining service life after the refit. The data required for the calculation of this KPI consists of the initial CAPEX for the client (Market Value) and annual OPEX estimates.

Capital Expenditure (CAPEX)

CAPEX represents the upfront investment required to acquire a refitted vessel or to buy a newbuild vessel. This is based on acquisition costs and refit costs for the shipyard and expected market value for the shipowner/operator.

Acquisition Cost

This KPI measures the purchase price of the vessel before refit activities begin. It forms the baseline for assessing the total investment required. Lower acquisition cost improves the initial feasibility and strengthens the financial case versus newbuild investment. The acquisition costs consist of the vessel purchase price ($P_{purchase}$), the delivery or towing costs ($T_{transport}$), and the initial inspection/survey costs (F_{survey}), and can be calculated using Equation 3.19.

$$\text{Acquisition Cost (€)} = P_{purchase} + T_{transport} + F_{survey} \tag{3.19}$$

The data required for this calculation are the purchase contracts or broker quotations and transportation and logistics invoices. It is assumed that survey and towing costs are proportional to vessel length and distance. Next to that, refits done using owned fleet vessels may exclude acquisition costs.

Refit Cost per SFI

This KPI represents the capital investment in various ship systems, based on the SFI coding system. It provides transparency in how capital is distributed across functional areas. Transparent cost allocation helps identify where circular strategies reduce capital requirements, improving investment visibility. Refit costs per SFI group can be calculated by all capital costs for components per SFI group (e.g. hull, machinery, auxiliary systems), as depicted by Equation 3.20. In this equation *C* stands for the component costs, and *n* is the number of components in an SFI group.

$$\text{Cost}_{SFI} = \sum_{i=1}^{n} C_n \tag{3.20}$$

For this calculation, a cost breakdown per SFI category is needed. Administrative costs are grouped under 'General' (SFI900).

Total Refit Cost

The Total Refit Cost captures the total investment required for the refit project and reflects the CAPEX for the shipyard. The KPI sums the costs per SFI group with the acquisition costs, to get a total as depicted in Equation 3.21. In the equation, all refit costs from SFI systems 100-900 are summed.

$$\text{Total Refit Cost} = \text{Acquisition Cost} + \sum_{i=100}^{900} \text{Cost}_{SFI} \tag{3.21}$$

This KPI can also be used to compare refit cost to newbuild cost of a vessel with equivalent specifications and propulsion type.

Market Value or Expected Sales Value
The Market Value or Expected Sales Value is an estimate of the value of the refitted vessel. This helps companies evaluate the benefit of refitting a certain vessel. This KPI is estimated based on market data, historical project data, and expert experience.

Operational Expenditure (OPEX)

OPEX per year represents the recurring annual costs associated with operating and maintaining the vessel. It includes fuel and energy use, crew costs, maintenance, and insurance. Lower operational costs improve lifetime profitability and strengthen long-term return on investment.

$$\text{OPEX/year} = \text{Crew costs} + \text{Energy costs} + \text{Maintenance costs} + \text{Insurance costs} \tag{3.22}$$

Crew Costs
The crew costs represent the labour costs associated with the operation of the vessel. It is calculated using Equation 3.23, where *N* is the number of crew and *C* is the average salary costs per crew member.

$$\text{Crew Cost} = N_{crew} \cdot C_{salary} \cdot 12 \tag{3.23}$$

The required data for this calculation consists of the average monthly salary per crew member and the crew complement size. This can be determined based on the experience of Operations or derived from vessel specs.

It is assumed that there is no change in crew size between refit and newbuild, as the vessel remains the same. These assumptions lead to equal crew costs for all comparative vessels.

Energy (Fuel and Electricity) Costs
The energy costs give an estimation of the costs of the energy used during operation. This marks a large part of the operational expenditure. This KPI is calculated using Equation 3.24. In this equation, Q_i is the annual energy consumption per fuel type (derived from Equation 3.11), and P_i is the average market price per unit of energy. This means in €/kWh for electricity, and €/m^3 for Marine Gasoil (MGO).

$$\text{Energy Cost} = \sum_i (Q_i \cdot P_i) \tag{3.24}$$

Required data for this KPI is the operational profile to determine the energy consumption, and the corresponding energy prices. The assumption was made that hybrid vessels sailing in bollard pull sail on MGO, and when free sailing, they sail on electricity. The amount of time spent in each sailing mode is determined by the operational profile.

Maintenance Costs
The Maintenance Costs cover routine servicing, spare parts, and preventive maintenance, and are estimated by using historical project data or expert experience. If this information is not available, Maintenance Costs can be determined with a percentage (α)of the CAPEX as shown in Equation 3.25.

$$\text{Maintenance Cost} = \alpha \cdot CAPEX \tag{3.25}$$

The data required is maintenance logs from Operations for similar vessels. It is assumed that hybrid systems may reduce mechanical wear, but add electronic maintenance.

Insurance Costs
The insurance protects the owner of the vessel against physical loss or damage. These costs are estimated as 1 % of the vessel's insured value. For newbuild vessels, this means the sales price, for refitted vessels, this means the market price. This estimation is based on the rule of thumb used at Damen, and the calculation is depicted in Equation 3.26.

$$\text{Insurance Cost} = 0.01 \cdot V_{market} \tag{3.26}$$

The required data for this equation is the estimated post-refit market value and an indication of the newbuild sales price. Newbuild data can be retrieved from market trends and internal sales data, and refit data is obtained from market trends or expert experience of trading teams.

Value and Lifecycle-based Indicators

Value Added

The value added quantifies the financial enhancement gained through refit investment.

$$\text{Value Added} = V_{post-refit} - V_{pre-refit} \tag{3.27}$$

It is assumed that the increase in vessel value attributed solely to technical and operational improvements.

Value Retention

Value retention assesses how much of the vessel's original value is preserved after refit compared to a newbuild.

$$\text{Value Retention}(\%) = \frac{V_{post-refit}}{V_{newbuild}} \cdot 100 \tag{3.28}$$

For the calculation of this KPI, the post-refit market value and the equivalent newbuild sales value are required. This data is acquired internally.

Component Cost Share

The cost distribution of components shows which R-strategies dominate capital investment. This is useful for identifying cost reduction opportunities and determining circular business practices. This KPI is calculated using Equation 3.29.

$$\text{Component Cost Share}(\%) = \frac{C_{strategy}}{\text{Total Refit Cost}} \cdot 100 \tag{3.29}$$

In this equation, $C_{strategy}$ stands for the total costs of components following a certain strategy, for example, reuse or repair. The required data for this KPI is the total refit costs and the costs of all major equipment, including a strategy label.

3.4.3. Summary and Data Requirements

Table 3.6 provides a comprehensive overview of the 13 economic KPIs, including calculation units, data sources, assumptions, explanatory notes, and literature sources.

Table 3.6: Complete Overview of Economic KPIs

KPI	Unit	Data Source	Assumption	Note	Source
TCO	€	CAPEX + OPEX	Discounted future OPEX	Total Cost of Ownership	(Favi et al., 2017)
Capital Expenditure (CAPEX)					
Acquisition Cost	€	Purchase Contracts	Tow & survey costs estimated	Initial purchase cost	(Stopford, 2009)
Refit Cost/SFI	€	Yard expense data	Missing subsystems grouped under SFI 900	Capital per ship system	based on: (Okumus, Andrews, & Gunbeyaz, 2024)
Total Refit Cost	€	Contracts + Yard data	Acquisition + refit costs	Total capital expenditure	(Favi et al., 2017)
Market Value or Expected Sales Value	€	Market trends	Market Valuation or Total Cost	CAPEX for Shipowner	
Operational Expenditure (OPEX)					
OPEX per year	€/year	Sum of above	Crew + Energy + Maintenance + Insurance	Total operational expenditure	(Favi et al., 2017)
Crew Costs	€/year	Crew plan	Constant crew size	Annual crew-related costs	(Stopford, 2009)
Energy Costs	€/year	Operational Profile	Energy split over sailing modes	Annual fuel/ electricity costs	(Stopford, 2009)
Maintenance Costs	€/year	Operations data	Hybrid adds electronic maintenance	Annual service costs	(Favi et al., 2017)
Insurance	€/year	Vessel Value	1% of market value	Annual insurance premium	(Stopford, 2009)
Value and Lifecycle					
Value Added	€	Pre/post valuations	Refit-driven value gain	Financial enhancement	(United Nations, 2024a)
Value Retention	%	Market Value	Based on resale value	Retained value post-refit	(Okumus, Andrews, & Gunbeyaz, 2024)
Component Cost Share	%	Refit Cost per Strategy	Costs proportional to effort	Share per component group	(Okumus, Andrews, & Gunbeyaz, 2024)

3.5. KPI Integration and Framework Overview

This section synthesises the complete KPI framework. As demonstrated in Section 3.1.3, the 32 selected indicators provide comprehensive coverage across the seven evaluation themes. The framework is further organised by data intensity to support flexible application across different project stages.

3.5.1. Quick-Assessment vs. In-Depth KPIs

The final KPI set is balanced between quick-assessment indicators (requiring limited data and enabling rapid preliminary evaluation) and in-depth indicators (requiring detailed data but providing richer insights). Table 3.7 classifies KPIs by data intensity.

Table 3.7: Classification of KPIs by Data Intensity

Data Intensity	Strategic KPIs	Environmental KPIs	Economic KPIs
Low (Quick-assessment)	Time in Dock, Complexity of Work, Reclassification Required	% Reused Components, Vessel Life Extension	Acquisition Cost, Market Value (CAPEX client)
Medium	Component Lead Time, Vessel Lead Time, Reclassification Duration	Yard Emissions, Fuel Consumption, OPEM per year, Particulate Matter, EEDI/EEXI	Refit Cost per SFI, OPEX (Crew Costs, Energy Costs, Maintenance Costs, Insurance Cost), Value Added
High (In-depth)	—	TEO, Embodied Emissions, Prevented CO_{2e}, CO_{2e}/Value Added, Resource Depletion, Solid Waste Reduction	TCO, Total Refit Cost (CAPEX shipyard), Value Retention, Component Cost Share

This classification enables flexible application of the framework:

- **Stage 1 - Feasibility screening:** Use quick-assessment KPIs to rapidly compare refit options.
- **Stage 2 - Detailed evaluation:** Apply medium and high-intensity KPIs to shortlisted options.
- **Stage 3 - Post-implementation:** Validate predictions using actual project data, to improve future predictions.

3.5.2. Framework Limitations

Four limitations of the KPI framework should be acknowledged.

1. Data availability constraints: High-intensity KPIs assume access to detailed engineering data, operational logs, and market valuations. For older vessels or companies with limited data infrastructure, some KPIs may be impossible to calculate.

2. Validation scope: The KPIs are validated through a single case study (Chapter 5) focusing on tugboat refits. Applicability to other vessel types (e.g., cargo vessels, passenger ferries) requires further validation.

3. Temporal dynamics: The framework provides snapshot assessment at the time of refit decisions. It does not capture performance evolution over time (e.g., degradation of remanufactured components, market value changes).

4. Stakeholder-specific KPIs excluded: Following the scope definition in Chapter 2, the framework focuses on shipyard and ship owner perspectives. OEM-specific KPIs (e.g., remanufacturing capacity utilisation, return logistics efficiency) and designer-specific KPIs (e.g., modularity indices at design stage) are not included.

These limitations are deemed acceptable given the framework's intended use: supporting refit decision-making in the shipyard context with typical data availability.

3.5.3. Application Roadmap

The complete framework is applied to a real-world case study described in Chapters 4 and 5. The case study will:

1. Demonstrate calculation of all KPIs using actual vessel and refit data.
2. Identify which KPIs provide the most decision-relevant insights.
3. Reveal data collection challenges and propose practical workarounds.
4. Compare circular strategies (repair, refurbish, remanufacture) across all three impact areas (strategic, environmental, economic).

3.6. Conclusion KPIs

This chapter developed a comprehensive KPI framework for evaluating vessel refits from strategic, environmental, and economic perspectives. The literature review identified 87 indicators used in the maritime sector. Through a systematic three-stage refinement process, this initial database of performance indicators was filtered to a set of 19 KPIs suitable for vessel- and component-level assessment. Some existing KPIs were adapted to fit the evaluation requirements, and Time in Dock, Complexity of Work, Reclassification Required and Duration, TEO, Yard Emissions, Acquisition Costs, Total Refit Cost, Market Value, Crew Cost, Energy Cost, Maintenance Costs, and Insurance Cost were added to reach a total set of 32 KPIs.

The final framework comprises 6 strategic KPIs, 13 environmental KPIs, and 13 economic KPIs. Each KPI is supported by:

- Literature-grounded justification demonstrating relevance to maritime circular economy.
- Detailed calculation method with transparent equations.
- Practical data source identification for shipyard application.
- Explicit assumptions when data are unavailable or uncertain.

The strategic KPIs capture operational feasibility factors (lead times, downtime, regulatory complexity) that differentiate refits from newbuilds. The environmental KPIs integrate lifecycle carbon assessment (embodied and operational emissions) with circular material flow indicators (% reused components, vessel life extension) and regulatory compliance metrics (EEDI/EEXI). The economic KPIs provide comprehensive lifecycle costing (CAPEX, OPEX, TCO) while including market value considerations (value retention, value added) often omitted in traditional cost analysis.

Collectively, the KPI framework addresses the measurement gap identified in Chapter 2 by providing theoretically grounded, practically applicable indicators at the vessel and component levels where standardised indicators were previously absent.

Chapter 5 applies this KPI framework to a real-world case study presented in Chapter 4. The case study serves as both validation and demonstration of the framework's utility for supporting circular refit decision-making in shipyard practice.

4

Case Study

This chapter implements Step 1 of the methodological framework by identifying the feasible circular refit strategies for the Damen 3110 ASD Tug and defining the comparison framework used in Step 2. The Damen 3110 ASD Tug serves as the reference case for evaluating the strategic, environmental and economic impact of these strategies against modern newbuild alternatives.

Based on the vessel's condition and the technological possibilities within Damen's current tug portfolio, three feasible strategies are identified in Step 1: refurbish, remanufacture to hybrid, and remanufacture to electric. These strategies correspond to the main propulsion concepts available in Damen's Tug designs.

To allow a fair comparison in Step 2, each refit strategy is linked to a representative newbuild vessel with the same propulsion concept. This structure allows the study to examine the trade-offs between circular strategies and newbuild procurement while controlling propulsion concepts.

Because the Damen 3110 ASD Tug is no longer in production, representative comparison vessels are selected from the current Damen portfolio based on similarities in bollard pull, propulsion concept, and operational relevance. These vessels and the resulting comparison setup are introduced in Section 4.2, forming the foundation for the quantitative analysis in Chapters 5 and 6.

4.1. Reference Vessel: Damen 3110 ASD Tug

The reference vessel for this case study is a Damen 3110 ASD Tug, delivered in 2006 to the Port of Djibouti, where it has operated since. It was selected because DFS Maritime Solutions is currently assessing options for this vessel, making it a relevant and timely case to investigate the potential benefits of refitting. Due to prolonged periods of inadequate maintenance, the vessel has been out of service for at least eight years and is currently out of class. As a result, the vessel requires full reclassification regardless of the strategy. Key vessel specifications are shown in Table 4.1.

Table 4.1: Sultan Habib A. Houmed 3110 Vessel Specifications

Specs	Value	Unit
Build Year	2006	
Length	30.82	m
Beam	10.20	m
Displacement	602	tonnes
Bollard Pull Ahead	54.7	tonnes
Bollard Pull Astern	49.8	tonnes
Speed Ahead	12.9	knots
Speed Astern	12.2	knots

The vessel operates according to one of Damen's standardised operational profiles based on the behaviour of harbour tugs in the Port of Rotterdam. According to this operational profile, the vessel spends approximately 43% of its annual operational time in free sailing condition, and 57% in bollard pull condition. The detailed operational profiles for each of these modes are shown in Figures 4.1 and 4.2.

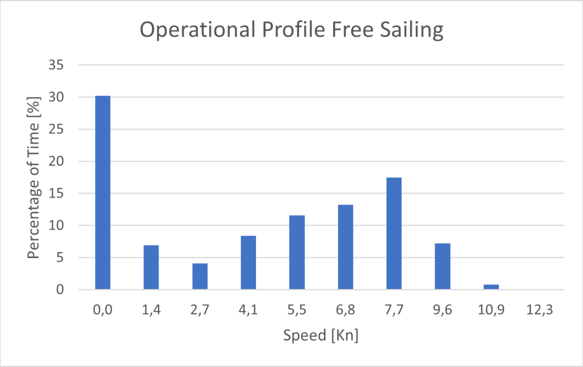


Figure 4.1: Operational Profile Free Sailing

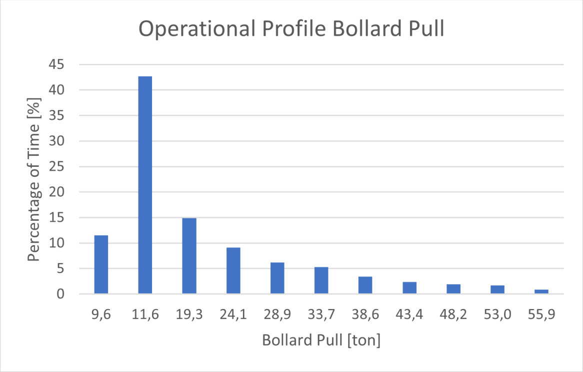


Figure 4.2: Operational Profile Bollard Pull

4.2. Comparison Framework and Vessels

Following Step 1 of the methodological framework, the condition of the 3110 ASD Tug limits the feasible circular strategies to refurbish and remanufacture. Within the remanufacture category, this study distinguishes between hybrid remanufacture and electric remanufacture, even though both formally qualify as remanufacture under R-strategy definitions (see Section 2.2.4), as they produce upgraded vessels that exceed original specifications and meet current performance standards. The distinction is necessary because hybrid and full-electric refits involve substantially different technical complexities, spatial and integration requirements, cost structures and environmental impact. Differentiating these pathways provides a clearer analytical structure, ensures that results reflect the heterogeneity of technological interventions within the broader remanufacture category, and allows a more precise comparison of their economic and environmental implications.

This section, therefore, completes Step 1 by describing the three refit strategies and defining the comparison framework that forms the input to Step 2. To support the subsequent impact assessment, each refit strategy is paired with a representative newbuild vessel using the same propulsion concept. This comparison structure isolates the effect of applying a circular strategy, relative to acquiring a newbuild vessel within the same technology class. The resulting comparison setup is summarised in Table 4.2 and defines the scenarios that will be quantitatively evaluated using the KPIs in Step 2.

The three comparisons differ in their degree of comparability. Comparison 1 and 2 both use the Damen 2810 ASD Tug as the newbuild reference, ensuring high comparability through closely matched hull dimensions, and bollard pull. Comparison 3 presents unique challenges. The Damen 2513 E-RSD is smaller than the 3110 ASD Tug, resulting in different water displacement, and employs a different propulsion concept (RSD - Reverse Stern Drive versus ASD - Azimuth Stern Drive). This physical discontinuity means the electric comparison is less directly comparable than Comparisons 1 and 2. However, it remains valuable as it represents the current electric tug design. This limitation is acknowledged in the interpretation of the results in Chapter 6.

Table 4.2: Comparative Analysis Framework

	CE Strategy	Refit Vessel	Newbuild Reference	Comparability
1	Refurbish	3110 ASD to conventional diesel	Damen 2810 ASD	High
2	Remanufacture (Hybrid)	3110 ASD to hybrid	Damen 2810 ASD Hybrid	High
3	Remanufacture (Electric)	3110 ASD to electric	Damen 2513 E-RSD	Moderate

The following subsections detail each comparison, describing both the refit intervention and the corresponding newbuild reference vessel. Together, these vessels create a balanced comparison set reflecting current options in tug propulsion systems at Damen: conventional diesel, hybrid diesel-electric, and full electric.

4.2.1. Comparison 1: Refurbish (Refit to Conventional)

This comparison evaluates the refurbish strategy, by comparing the 3110 ASD Tug refitted to conventional diesel propulsion against a new conventional diesel vessel. The comparison isolates the economic and environmental benefits of restoring an existing vessel versus acquiring an equivalent newbuild.

Refit Variant

The refit restores the 3110 to operational condition while maintaining its original diesel propulsion concept (Figure 4.3). Key interventions include:

- Restoration of existing main engines or replacement with equivalent modern diesel engines
- Reclassification to current standards
- Structural repairs and systems overhaul
- Minimal technological upgrading beyond regulatory requirements

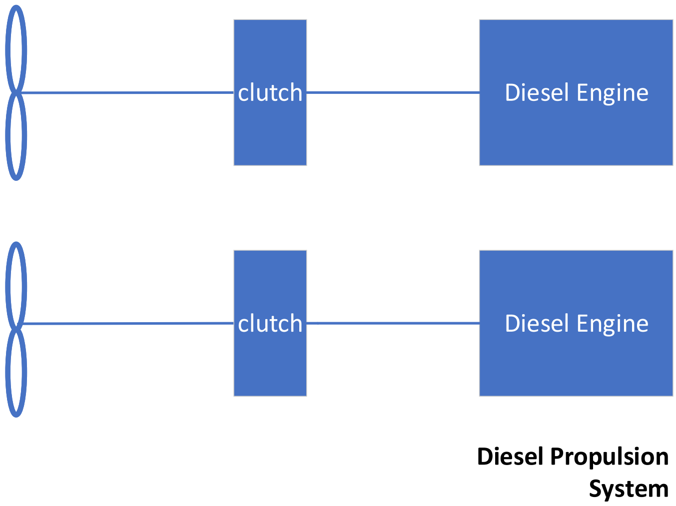


Figure 4.3: Diesel Propulsion System

Newbuild Reference: Damen 2810 ASD Tug

The newbuild baseline is the Damen 2810 ASD Tug. While the Damen 2811 ASD Tug would be the closest dimensional equivalent, it is only available in diesel configuration. The 2810 was selected instead because it offers both diesel and hybrid variants, enabling consistency across Comparisons 1 and 2 while using the same vessel. The 2810 ASD Tug features similar bollard pull to the 3110 (approximately 55 tonnes), providing an appropriate baseline for benchmarking CAPEX, OPEX, and emissions performance.

Comparison Purpose

This comparison represents the business case for the refurbish strategy. It tests whether circular strategies can compete with newbuild options when technological advancement is minimal and the primary benefit is material retention.

4.2.2. Comparison 2: Remanufacture Strategy (Refit to Hybrid)

This comparison examines the remanufacture to hybrid strategy by comparing the 3110 ASD Tug refitted with hybrid diesel-electric propulsion against a new hybrid vessel. The comparison evaluates whether upgrading an existing hull to hybrid technology is preferable to acquiring a newbuild hybrid tug.

Refit Variant

The refit upgrades the 3110 to hybrid propulsion, integrating diesel engines with electric generators and battery storage. A power take-in/power take-off (PTI/PTO) system is installed, as illustrated in Figure 4.4. This configuration enables dual operational modes: conventional diesel propulsion during bollard pull mode, and battery-electric propulsion for free sailing modes. Key modifications include:

- Installation of hybrid propulsion system (diesel-electric configuration)
- Integration of battery systems for peak shaving and zero-emission operations
- Upgraded electrical infrastructure and control systems
- Retention of structural hull and major hull components

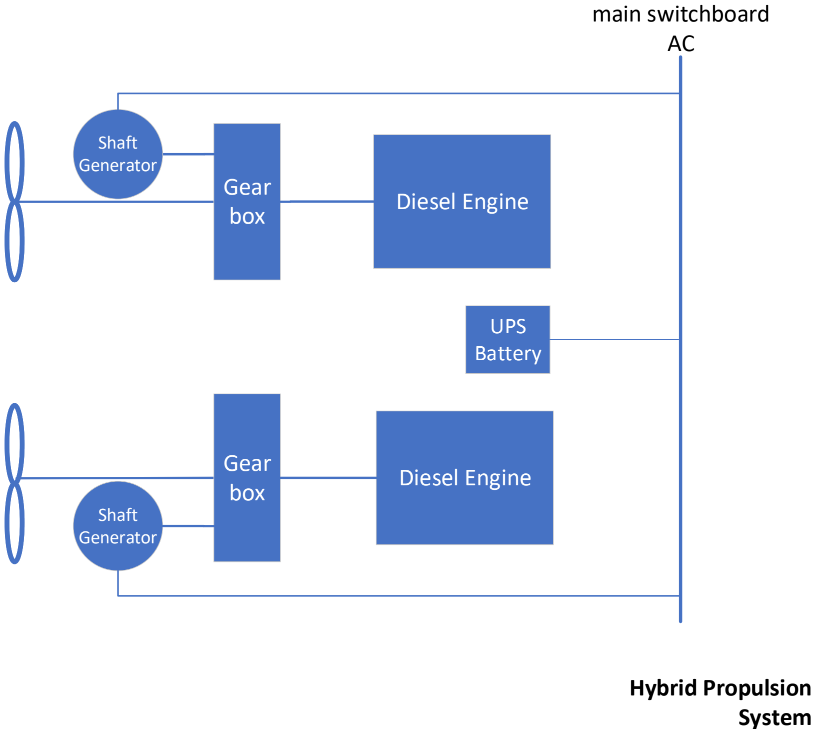


Figure 4.4: Hybrid Propulsion System

Newbuild Reference: Damen 2810 ASD Hybrid Tug

The Damen 2810 ASD Hybrid Tug serves as the newbuild reference. Currently it is the only tug in Damen's portfolio available in a hybrid configuration, making it the natural benchmark for hybrid propulsion comparisons. Using the same 2810 vessel as Comparison 1 ensures high comparability in hull dimensions and operational characteristics, allowing the analysis to isolate the effects of propulsion technology. The vessel enables direct comparison of material flows, cost structures, and operational performance between conventional and hybrid propulsion systems.

Comparison Purpose

This comparison illustrates whether the remanufacture to hybrid strategy is justified when measured against constructing a newbuild. It tests whether the material retention benefits and lower embodied energy of the remanufacture strategy offset the potential performance advantages and operational efficiencies of a newbuild hybrid tug.

4.2.3. Comparison 3: Remanufacture Strategy (Refit to Electric)

This comparison assesses the remanufacture to electric strategy, the most ambitious intervention, by comparing the 3110 ASD Tug converted to full electric propulsion against a new electric vessel. The comparison evaluates the feasibility and trade-offs of full electrification within an existing hull versus acquiring a newbuild electric tug.

Refit Variant

The refit converts the 3110 to full electric propulsion, eliminating all direct emissions during operations. The propulsion system shown in Figure 4.5 represents a fundamental transformation of the vessel's energy system, requiring extensive modifications:

- Complete removal of diesel propulsion machinery
- Installation of large-capacity battery systems
- Electric motors for propulsion
- Shore power infrastructure compatibility or onboard charging systems
- Significant internal reconfiguration to accommodate battery weight and volume

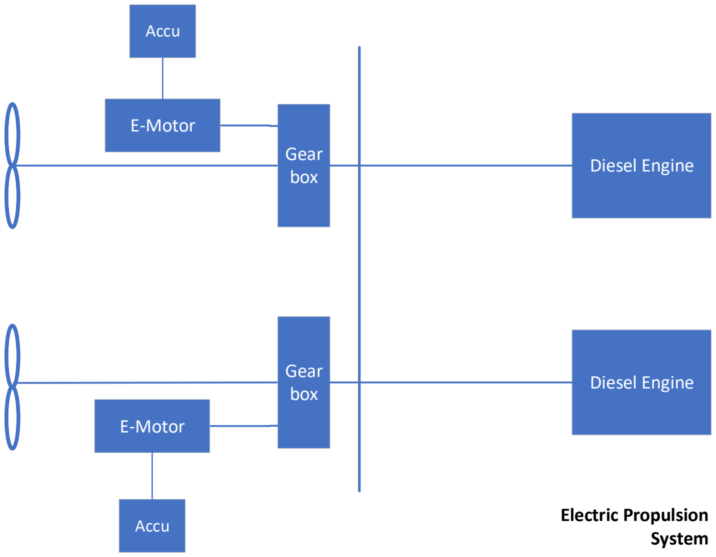


Figure 4.5: Electric Propulsion System

Newbuild Reference: Damen 2513 E-RSD Tug

The Damen 2513 E-RSD serves as the fully electric reference vessel. It represents the current state-of-the-art electric tug design, enabling assessment of the technical and spatial implications of electrification, particularly concerning battery capacity, machinery weight distribution, and layout constraints. Although classified as full-electric, the vessel does not rely exclusively on shore charging in all configurations. Some operational variants include auxiliary diesel generator sets that charge the battery bank, enabling extended operations or service in ports without adequate charging infrastructure.

Comparison Purpose

This comparison evaluates whether electric remanufacture of an ageing tug is feasible and economically viable compared to a newbuild electric tug. It tests the limits of circular strategies when technological transformation is extreme and when the newbuild alternative is specifically optimised for the new propulsion technology rather than being a like-for-like replacement.

4.3. Overview Comparisons

In contrast to Comparisons 1 and 2, this comparison features notable differences in both dimensions and design. The Damen 2513 E-RSD is shorter but broader than the 3110 ASD Tug (Table 4.3), yet this does not lead to a substantial change in maximum displacement, similar to what was observed in Comparisons 1 and 2. However, the 2513 E-RSD has a higher bollard pull than the 3110. Additionally, the vessels employ different propulsion concepts: the 2513 uses RSD (Reverse Stern Drive) configuration, while the 3110 uses ASD (Azimuth Stern Drive). These physical discontinuities reduce direct comparability. However, this comparison remains valuable because it reflects market realities: electric tugboats are typically purpose-designed with optimised hull forms, battery placement, and weight distribution rather than being direct conversions of diesel designs. The comparison thus evaluates real-world decision contexts where shipowners must choose between converting an existing vessel or purchasing a newbuild electric alternative.

Table 4.3: Vessel Specifications across Comparison Vessels

	3110	2810 (conventional)	2810 (hybrid)	2513 (electric)
Maximum Displacement	602	550	600	556
Bollard Pull	55	60.1	60.7	70
Length (L)	30.82	28.67	28.67	24.73
Beam (B)	10.2	10.43	10.43	13.13
Depth (T)	4.8	4.6	4.6	4.95

Figure 4.6 presents a visual overview of the various comparisons carried out in this study. It illustrates that each refit strategy is evaluated against its own dedicated newbuild reference vessel.

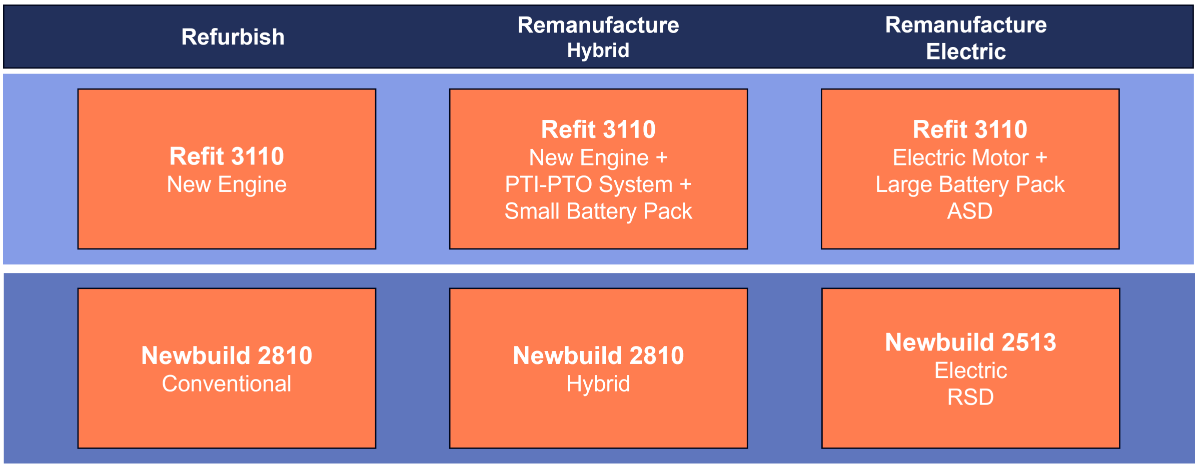


Figure 4.6: Refit Vessel Strategies and their Reference Newbuild Vessels

4.4. Case Study Boundaries

The case study applies the cradle-to-gate system boundary as defined in Section 2.4 to all vessel configurations assessed. This ensures consistency between the KPI framework and the comparative evaluation of refit and newbuild options.

Within this boundary, the assessment includes the production and replacement of materials and components, refit activities at the yard level, and associated energy use and costs required to bring each vessel configuration into operational condition. For refit strategies, this covers both retained and newly installed components, as well as refurbishment and remanufacturing processes, where applicable.

Processes that occur after delivery, such as maintenance during the service life and EoL treatment, are excluded from the system boundary. This boundary choice reflects the decision-making context of refit projects, where material use, investment costs, and upfront environmental impacts are most influential.

The strategies selected in this chapter serve as the input for Step 2 of the methodology, where the KPIs defined in Chapter 3 are calculated in Chapter 5, to evaluate their circular performance relative to the 3110 refit options.

5

Calculation KPIs

This chapter calculates the KPIs identified in Chapter 3. While the KPIs were selected based on literature and theoretical relevance, this chapter tests whether these indicators can be calculated with available data and whether they provide meaningful decision support in practice.

The documentation for each KPI includes the calculation and data sources used, assumptions made where data was limited or unavailable, challenges encountered during calculation, and an assessment of data quality and reliability. The question from Chapter 1 that is answered in this chapter is what difficulties arise in the calculation of the selected KPIs.

The intent is to do all assessments described in Section 3.5, so calculate both quick-assessment and in-depth KPIs. However, not all indicators can be computed due to data availability constraints. Where calculation proved impossible or insufficiently reliable, this is explicitly documented together with the root causes. These findings form the foundation of the evaluation in Chapter 7, where recommendations are made regarding which KPIs are suitable for inclusion in the final decision-support framework.

The chapter is structured into three sections addressing Strategic KPIs (Section 5.1), Environmental KPIs (Section 5.2), and Economic KPIs (Section 5.3). An overview of all successfully calculated results is presented in Appendix D.

Note: Due to sensitivity, all prices mentioned in this chapter are fictional, yet based on real-world data. Although prices are modified, ratios between the vessels are preserved. All values in this chapter are rounded, which means that some totals may deviate slightly, as the underlying calculations were performed using unrounded figures.

5.1. Strategic KPIs

The outcomes, including all intermediate values for the strategic KPIs, are presented in Appendix D.1. The rationale and calculation method for all 6 Strategic KPIs are detailed in this section.

5.1.1. Lead Time and Scheduling

This subsection addresses KPIs related to project timeline and vessel availability.

Vessel Lead Time

The Vessel Lead Time is calculated with Equation 3.1 and is based on the sum of the longest Component Lead Time and Time in Dock. The conservative assumption is made that all components need to have arrived before the Time in Dock starts. In reality, not all components are installed in the first month of Time in Dock and therefore the actual Vessel Lead Time might be shorter.

The Vessel Lead Time for refurbish is 10 months, for remanufacture to hybrid 12 months and for remanufacture to electric 14 months. Newbuild vessels have a lead time of 24 months. The construction of these values breakdown of these values is elaborated using the following two KPIs and is presented in Table 5.2.

Component Lead Time

The Component Lead Time is the time it takes for the component to be ordered and delivered. The component lead time is estimated per ship system using SFI based Damen system codes. These values are filled in based on expert knowledge and experience from the DFS operations team, and are represented in Table 5.1. The longest Component Lead Time is 6 months for all vessels, and is used to estimate the Vessel Lead Time.

Table 5.1: Component Lead Time [months] per System Group

Time [months]	**Refurbish** Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
100	0	1	0	1	0	1
200	6	6	6	6	6	6
300	0	1	0	1	0	1
400	6	6	6	6	6	6
500	0	2	0	2	0	2
600	3	2	3	2	3	2
700	0	2	0	2	0	2
800	0	6	0	6	0	6
000/900	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$	1

Time in Dock

Time in Dock is the total time the vessel undergoes yard works or transportation. For refits this represents the vessel's unavailability. The time in dock is estimated with the help of the operations team of DFS. For refits it is expected that the Time in Dock increases as the as the refit Complexity of Work increases. This results in 4 months for refurbish, 6 months for remanufacture to hybrid, and 8 months for remanufacture to electric. All newbuild vessels, have the same Time in Dock of 18 months.

Table 5.2: Vessel Lead Time [months] breakdown using Time in Dock and Component Lead Time

Time [months]	**Refurbish** Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
Vessel Lead Time	10	24	12	24	14	24
Time in Dock	4	18	6	18	8	18
Component Lead Time	6	6	6	6	6	6

5.1.2. Project Complexity

This subsection addresses KPIs related to the complexity of the project.

Complexity of Work / SFI

Complexity of work for the vessel refits is classified in low-medium-high categories. This is filled in per SFI system code, after which an overall complexity score is determined based on the number of times a certain score was given. The results, presented in Table 5.3, show that for systems 100, 600, and 000/900, complexity increases for more substantial R-strategies.

The complexity categories are defined as follows:

- **Low:** simple replacement or inspection (e.g. repainting or lighting)
- **Medium:** minor modification or component upgrade
- **High:** full system overhaul, or re-engineering

Table 5.3: Complexity of Work Refit Scenarios

	Refurbish Conventional	**Remanufacture** Hybrid	**Remanufacture** Electric
Overall Complexity of Work	**Medium**	**Medium-High**	**High**
100 - Tanks, Hull, Superstructure, Deck, Mast	Low	Low	Medium
200 - Engines, GB, Generators, Steering Gear, Bow Thrusters, Shafts	High	High	High
300 - Primary Ship Systems	Medium	Medium	Medium
400 - Electric Equipment	High	High	High
500 - Deck Equipment	Medium	Medium	Medium
600 - Auxiliary Systems	Medium	High	High
700 - Accommodation	Low	Low	Low
800 - Navigational Equipment	Medium	Medium	Medium
000/900 - General (reclassification/paperwork)	Low	Medium	High

Reclassification Required

The need for reclassification depends on the vessel's current class status (whether it is classified or not) and on the modifications being carried out. When the propulsion system is altered, reclassification is usually required. In this case study, the vessel is already out of class, so it will require reclassification regardless of the chosen refit strategy. Therefore, this KPI is *yes* for all refit strategies.

Reclassification Duration

The duration of the reclassification process is derived from the practical experience of the DFS Operations team. For refits, it is assumed that reclassification requires 10 days in total, with roughly 80% of this time spent during the refit itself on surveys, and the remaining 20% after the completion of the works. For newbuild vessels, the reclassification period is estimated at 30 days, following a similar proportional split.

5.2. Environmental KPIs

All calculated results can be found in Appendix D.2. The rationale and calculation method for all 13 Environmental KPIs are detailed in this section.

5.2.1. Total Emissions of Ownership

Analogous to the CAPEX, OPEX, and TCO used in the economic assessment, the environmental KPIs distinguish between capital emissions, operational emissions, and the Total Emissions of Ownership (TEO). Capital emissions (CAPEM) are defined as the environmental footprint associated with all materials added to the vessel and activities executed during the building/refit process. Operational emissions (OPEM) consist of all emissions resulting from fuel and electricity use during operation. Together, CAPEM and OPEM form the TEO presented in Table 5.4.

Table 5.4: Total Emissions of Ownership Breakdown with CAPEM and OPEM

Emissions tCO$_{2e}$	**Refurbish** Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
TEO	20.5 $\cdot 10^3$	18.8 $\cdot 10^3$	8.8 $\cdot 10^3$	9.2 $\cdot 10^3$	*6*	*0.65* $\cdot 10^3$
CAPEM	152	1013	*4.75*	*644*	*6.33*	*647*
OPEM	1016	887	438	426	0	0

Note: The TEO (Table 5.4) is calculated over 20 years (the expected service life of refits) to enable fair comparison. The actual TEO values for newbuild vessels are higher, because they are expected to sail 10 years longer.

Note: The results for the hybrid and electric comparisons for CAPEM are missing embodied emissions of the electric motors, battery systems and other related auxiliary equipment due to the absence of detailed outfitting BoMs, preventing an accurate estimation of the embodied emissions, as shown in Table 5.7.

5.2.2. Capital Emissions

This section addresses the embodied CO_{2e} emissions and the yard emissions that make up the capital emissions.

Embodied Emissions

Embodied emissions refer to the CO_{2e} emissions generated during the manufacturing of the materials used to construct the vessels. In refit scenarios, only the embodied emissions from materials added or replaced during the refit are considered. Emissions embodied in materials from the vessel's original construction phase are excluded from the analysis, consistent with the system boundaries specified in Chapter 4.

The calculation is based on a Bill of Materials (BoM) for a 2513 RSD diesel tug, which provides a detailed overview of the complete outfitting of a conventional tug, including material types and associated masses. In total, 113 different materials were identified. To enable linkage with life cycle inventory data, these materials were grouped into broader material categories aligned with those available in the EcoInvent database. For example, different steel grades such as S235 JR, S235 JR 3.1, and S235 GH were grouped under a single steel category. The full material grouping is presented in Table D.1 of Appendix D.

For each material category, the total mass was calculated using the SUMIFS function in Excel. The resulting mass (in kilograms) was then multiplied by the corresponding ECF, yielding the embodied CO_{2e} emissions per material category. The total embodied CO_{2e} emissions of the outfitting were obtained by summing the emissions across all material categories. The results are shown in Table 5.5.

Table 5.5: Embodied CO_{2e} Emissions by Material Category for Vessel Outfitting

	Material	**Mass [kg]**	**ECF**	**Embodied CO_{2e} [kg]**
Outfitting	Aluminium	7.0	6.85	48
	Brass	21.9	2.64	58
	Bronze	292.7	3.5	1024
	Carbon Steel	30885.3	1.84	56829
	Copper	949.2	2.71	2572
	Cast Iron	1540.2	2	3080
	Glass Fibre	183.9	1.4	257
	Nikkel-Chroom-Molybdeen	173.3	6.5	1127
	Nylon	18.4	3.1	57
	PVC	102.9	3.42	352
	Rubber	18774.5	2.547	47819
	Stainless Steel	5802.3	4.26	24718
	Steel	34657.5	2.38	82485
	Unknown	90591.8	1.64	148571
Total Outfitting [kg]		184001		368997
Total Outfitting [tonnes]		184		369

A substantial share of the outfitting mass (approximately 90 tonnes) could not be allocated to a specific material category. Approximately 90% of this mass was associated with the engines or engine-related components. This is probably because such components are purchased as complete systems without detailed material specifications. Given the importance of this share (around 50% of the total mass), it was retained in the analysis. Based on EcoInvent descriptions for engine components, the material was assumed to consist predominantly of engineering steel, applying an ECF of 1.64. This assumption introduces uncertainty and underlines the need for more detailed data at the component and material levels to enhance accuracy in future applications.

It is assumed that the outfitting of the conventional vessels (3110 ASD Refurbish and 2810 ASD) to be refitted is equivalent to that of a conventional 2513 RSD. This assumption is made because the BoM of the 2513 RSD was the only BoM available that included material types as well as corresponding mass. In reality, this will differ slightly due to a difference in propulsion method (propeller configuration). For the hybrid and fully electric configurations, the embodied emissions of the outfitting could not be quantified with the same level of detail, as the propulsion systems differ and not all component materials are known. Consequently, accurate estimation of embodied CO$_{2e}$ for these configurations would require a more detailed specification of components and material specifications. This highlights the need for improved data availability to support further application of the proposed methodology across different vessel types and configurations. The CAPEM values represented in Table 5.4 are conservative for the refurbished vessel, and a lower bound for all hybrid and electric vessels.

The embodied CO$_{2e}$ emissions of the hull are determined using Equation 5.1, where Mass Hull is based on the lightship weight of the vessel. This information was extracted from the Vessel Specification documents of the corresponding vessels. It is assumed that the difference between the lightship weight and the outfitting mass represents the mass of the hull.

$$\text{Embodied CO}_{2e}\text{ Emissions Hull} = \text{Mass Hull} \cdot ECF_{PlateSteel} = \text{Mass Hull} \cdot 2.38 \tag{5.1}$$

The resulting mass is multiplied by the ECF for plate steel to determine the embodied CO$_{2e}$ emissions of the hull. The use of plate steel as the representative hull material was confirmed in discussion with Dr. Carey Walters, Section Head Ship and Offshore Structures at Delft University of Technology. This approach is applied consistently to the reference vessel and all comparison vessels, ensuring a comparable estimation of hull-related embodied CO$_{2e}$ emissions.

Table 5.6: Lightship Weight Distribution Between Hull and Outfitting Components

Vessel Types	3110	2810 Conventional	2810 Hybrid	2513 Electric
Lightship Weight [tonnes]	429	450	*450*	451
Outfitting [tonnes]	184	184	*184*	*184*
Hull [tonnes]	245	266	*266*	*267*
Embodied Emissions Hull [tonnes CO$_{2e}$]	583	633	633	635

For the refurbish scenario (refit to conventional), it is assumed that the complete engine is replaced. In addition, minor replacements of deck equipment and small structural elements (e.g. railings) are expected. However, their associated masses are assumed to be negligible compared to the engine and are therefore excluded from the calculation. Consequently, the full allocation of the previously classified 'unknown' material category is included in the embodied CO$_{2e}$ calculation for the refit. Resulting in Embodied Emissions of **149 t CO$_{2e}$** for the refurbish scenario. As it is unlikely that all materials within this category are replaced in practice, this represents a conservative assumption.

Both remanufacture scenarios and their newbuild equivalent lack BoM data to fully capture the Embodied Emissions of these vessels. For the newbuild vessels, the hull embodied emissions are used as presented in Table 5.6, **633 t CO$_{2e}$** for the hybrid newbuild and **635 t CO$_{2e}$** for the electric newbuild. For the refits, only yard data can be used reliably. All embodied emission values for the hybrid and electric configurations are higher in reality due to the missing data.

Yard Emissions

Based on internal Damen data, total annual CO$_2$ emissions per shipyard were extracted from PowerBI. Newbuild tug vessels are predominantly constructed at Damen Song Cam (Vietnam), while the refit will take place at Damen Albwardy (Sharjah). Data about the total Gross Tonnage built at these shipyards was not available, so Equation 3.8 could not be calculated.

To get an estimate of the yard emissions attributable to a single vessel, the annual yard emissions are multiplied by the proportion of time the vessel occupies the yard and undergoes construction or refit activities.

For this assessment, a yard period of 4, 6 and 8 months is used for the different refit strategies and 18 months for new builds, according to the assumptions elaborated in Section 5.1. Applying this approach results in estimated yard emissions of **3.17 t CO$_2$** for refurbish, **4.75 t CO$_2$** for remanufacture to hybrid, and **6.33 t CO_2** for remanufacture to electric. Newbuild vessels all have equal yard emissions of **11.1 t CO_2**.

The embodied emissions for the newbuild are presented in Table 5.5. Since the refurbish strategy primarily involves an engine overhaul, it is assumed that the embodied emissions arise solely from the engine, as represented by the unknown embodied CO_2 entry in Table 5.5.

These values are based on the conservative assumption that each yard produces a single vessel at a time. In practice, multiple vessels are constructed or refitted concurrently, meaning that the actual emissions attributable per vessel are likely lower. However, due to limited insight into workforce allocation and project-specific energy use, this approach provides the most consistent and transparent estimation across all vessel configurations considered.

Table 5.7: Capital Emissions Breakdown with Yard Emissions and Embodied Emissions

Emissions t CO_{2e}	**Refurbish** Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
Capital	152	1013	>4.75	>644	>6.33	>647
Yard	3,17	11,1	4.75	11.1	6.33	11.1
Embodied	149	1002	*unknown*	*633*	*unknown*	*635*

Prevented CO_2 Emissions

The prevented CO_{2e} emissions KPI represents the difference in total Capital Emissions between a newbuild vessel and a refitted vessel. This KPI is calculated using Equation 3.9. The results for each comparison are presented in Table 5.8.

Note: The results for the hybrid and electric comparisons have limited reliability due to the absence of detailed outfitting BoMs, preventing an accurate estimation of the embodied emissions, as shown in Table 5.7.

Table 5.8: Prevented CO_{2e} Emissions per Refit Scenario (Comparison 1, 2, 3)

	Comparison 1 Conventional	**Comparison 2** Hybrid	**Comparison 3** Electric
Prevented Emissions [t CO_{2e}]	861	*639*	*640*

CO_2 Emissions per Unit of Value Added

This KPI represents the CO_2 emissions per Euro value added. The CAPEM of the refit and newbuild vessels are divided by the total amount [€] of value added to these vessels to calculate the CO_{2e} emissions per Euro value added using Equation 3.10.

The CAPEM for the hybrid and electric comparisons is incomplete, so the results for the Emissions per Value Added are not reliable for these configurations. Table 5.9 shows the results.

Table 5.9: Emissions per Unit of Value Added [t CO_{2e}/€] for each Vessel from all Comparisons

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
t CO_{2e}/€	0.35	0.87	*0.01*	*0.37*	*0.01*	*0.28*

5.2.3. Operational Emissions

This subsection presents the results for the KPIs used to calculate the operational emissions or that are related to the operation of the vessel.

Fuel Consumption

Fuel consumption is calculated based on the defined operational profile and vessel availability. The total running hours (H_i) from Equation 3.11 is calculated using equation 5.3. An annual availability of 95% is assumed, corresponding to 347 operational days per year (Equation 5.2). This availability factor represents typical operational practice for harbour tugs, accounting for scheduled maintenance, adverse weather conditions, and downtime, as confirmed by the DFS Operations team. On each operational day, the vessel is assumed to perform three jobs, each with a duration of three hours. This results in a total of 3,123 running hours per year (Equation 5.3).

$$\text{Yearly Availability [days]} = 95\% \cdot 365 = 347 \tag{5.2}$$

$$\text{Yearly Running Hours [hours]} = 347 \text{ days} \cdot 3\frac{\text{jobs}}{\text{day}} \cdot 3\frac{\text{hours}}{\text{job}} = 3123 \tag{5.3}$$

Fuel Consumption / hour from Equation 3.11 is extracted from the vessel-specific operational profile (presented in Chapter 4), resulting in different values for the 3110 (refit), 2811 (newbuild and hybrid), and the 2513 (electric) configurations. Multiplying the hourly fuel consumption by the annual running hours (Equation 5.4) yields a total yearly fuel consumption of **317 tonnes/year** of MGO for the refurbished vessel and **277 tonnes/year** of MGO for the newbuild vessel, shown in Table 5.10.

$$\text{Yearly Fuel Consumption} = \text{fuel consumption / hour} \cdot \text{running hours} \cdot \text{ \% running hours on MGO} \tag{5.4}$$

For the hybrid configuration, it is assumed that all towing operations are performed using MGO and that the vessel is equipped with the same diesel engine as the conventional configurations. Based on the operational profile, the vessel operates in towing mode for 57% of the total running time. This changes the calculation for the yearly fuel consumption into Equation 5.5. The annual fuel consumption of the refitted vessel is **137 tonnes/year** MGO and for the newbuild vessel **133 tonnes/year** MGO, shown in Table 5.10.

$$\text{Yearly Fuel Consumption} = \text{fuel consumption / hour} \cdot \text{running hours} \cdot 57\% \tag{5.5}$$

Additionally, the electricity consumption is assessed for the hybrid configurations, following the same operational profile assumptions used for fuel consumption. It is assumed that the vessels operate on electrical power during free sailing conditions, which account for 43% of total operational time.

The hourly electrical power demand during free sailing was derived from the operational profiles provided by Damen. For the *refitted hybrid vessel*, the average electrical demand is **111 kWh per hour**, while for the *hybrid newbuild*, this value is **70 kWh per hour**. The difference reflects variations in vessel configuration and system efficiencies.

The annual electricity consumption is calculated by multiplying the hourly electrical demand by the total yearly running hours and the share of time spent in free sailing, as expressed in Equation 5.6. The resulting electricity consumption values are reported in Table 5.10.

$$\text{Yearly Electricity Consumption} = \text{electricity consumption / hour} \cdot \text{running hours} \cdot 43\% \tag{5.6}$$

For the *fully electric* configuration, the hourly electricity consumption is determined based on the required propulsion power during operation. It is assumed that the installed electric motor operates with 95%-97% efficiency, allowing the required shaft power to be directly translated into electrical energy demand. Using the operational profile, the electricity consumption is **458 kWh per hour** for the refit and **465 kWh per hour** for the newbuild vessel. These values are multiplied by the total annual running hours, as calculated in Equation 5.3. The results are presented in Table 5.10.

Table 5.10: Annual Fuel and Electricity Consumption by Vessel Configuration

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
Fuel/hour [kg/h]	101	88.6	76.8	74.6	0	0
Fuel/year [t/year]	317	277	137	133	0	0
Electricity/hour [kwh/h]	0	0	111	70.1	458	465
Electricity/year [kwh/year]	0	0	$149 \cdot 10^3$	$94.1 \cdot 10^3$	$143 \cdot 10^4$	$145 \cdot 10^4$

Operational Emissions (per year)

The Operational CO_2 Emissions per year are calculated by multiplying the yearly fuel consumption by a fixed emission factor of 3.206 tonnes CO_2 per tonne of fuel (EF_{fuel} in Equation 3.12). This factor reflects the carbon content of MGO and is standard within Damen's emission calculations. The resulting OPEM values for all vessel configurations and scenarios are summarised in Table 5.11.

It is assumed that there are no emissions due to electricity used as per the current emissions reporting regulations. Therefore, the emissions for the remanufacture (refit to electric) strategy and the new electric vessel are zero.

Table 5.11: OPEM per Year by Vessel Configuration
*Operational Emissions are calculated Tank-to-Wake, by regulation, it is assumed electric vessels have 0 operational emissions.

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric*	**New** Electric*
CO_2 [t/year]	1016	887	438	42	0	0

Particulate Matter

Equation 3.13 is used to calculate the Sulphur emissions across all vessels. The Fuel Consumption per year from Table 5.10 is used as input. The results are shown in Table 5.12

Table 5.12: Particulate Matter Emissions per Year by Vessel Configuration
*Electric vessels use no fuel and therefore have 0 SO_2 emissions.

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric*	**New** Electric*
SO_2 [t/year]	619	541	267	259	0	0

EEDI and EEXI

EEDI and EEXI represent a similar value, where EEDI is applied to newbuild vessels and EEXI is applied to existing vessels.

EEDI and EEXI compliance is mandatory for ships with a Gross Tonnage of 400 and above (International Maritime Organisation (IMO), 2026). The tugboats considered in this study fall below this threshold and are therefore not subjected to EEDI or EEXI compliance. As a result, these KPIs are not calculated in this assessment, as they are not expected to influence decision-making for the vessel types and refit strategies evaluated.

When the method is used on other vessel types, it could be useful to include EEDI and EEXI if the vessels are required to comply due to size.

5.2.4. Resource Effiency

Percentage of Reused Components

The percentage of reused components is typically calculated as the ratio between the number of components reused after a refit and the total number of components installed on board the vessel.

However, as neither of these values is known with sufficient accuracy for the case study vessels, this indicator is estimated based on expert judgement from the DFS Operations team. The reuse rate is assumed to be 70% for refurbish, 50% for remanufacture to hybrid, and 30% for remanufacture to electric (Table 5.13). These estimates are based on the DFS Operations team's assessment of which vessel systems require replacement to achieve the desired propulsion configuration, with higher replacement rates corresponding to more extensive system modifications.

Table 5.13: Percentage of Reused Components per Refit Strategy vs. Newbuild Reference

	Refurbish Conventional	**Remanufacture** Hybrid	**Remanufacture** Electric	**New**
% Reused Components	70%	50%	30%	0%

For a more accurate qualitative assessment of this indicator in the future, improved record-keeping of the total number of components in each vessel is necessary. This may only become feasible in a few years, when vessels constructed during periods of comprehensive digital documentation become eligible for refitting.

Vessel Life Extension

Vessel life (extension) is defined as the expected remaining service life following newbuild or refit. For newbuild vessels, the design life is determined during the design phase, based on material selection, structural design, and operational experience from comparable vessels. For all tugboats, regardless of propulsion system, the design life is estimated at 30 years, in line with sector practice and the knowledge of the DFS Operations team.

For refitted vessels, it is assumed that the refit restores the vessel to a condition that enables an additional 20 years of operation from the moment of refit. This life extension estimate is likewise based on expert judgement from the DFS Operations team. The results are shown in Table 5.14.

Table 5.14: Life Extension per Refit Strategy vs. any Newbuild Reference

	Refurbish Conventional	**Remanufacture** Hybrid	**Remanufacture** Electric	**New**
Life Extension [years]	20	20	20	30

Resource Depletion

Resource depletion was included in the literature-based KPI selection to assess the consumption of scarce materials (e.g., rare earth elements, critical metals). The calculation requires detailed material specifications, for some vessels, beyond what is available in the BoM used in this study. The available BoM provides materials and their masses for a conventional outfitting. The materials and their corresponding masses could only be calculated for the conventional newbuild vessel. Therefore, the same limitations apply as for the Embodied Emission calculation.

Table 5.15: Resource Depletion

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
Outfitting	91	184	*unknown*	*unknown*	*unknown*	*unknown*
Hull	0	450	0	*unknown*	0	451

In this form the KPI misses insight into the scarcity of materials and therefore the potential impact of certain materials. Therefore, additionally Figure 5.1 is created to show the mass allocation per material. This is done for the conventional newbuild vessel. The resource depletion of the refurbished vessel is the same as the 'unknown' material mass in the figure.

The other vessels have too much unknown data to accurately display their Resource Depletion. Therefore, Resource Depletion in this format is recommended for exclusion from the decision-support framework for now. For future implementation, when digital product passports are integrated into data collection protocols, the KPI might be reintroduced.

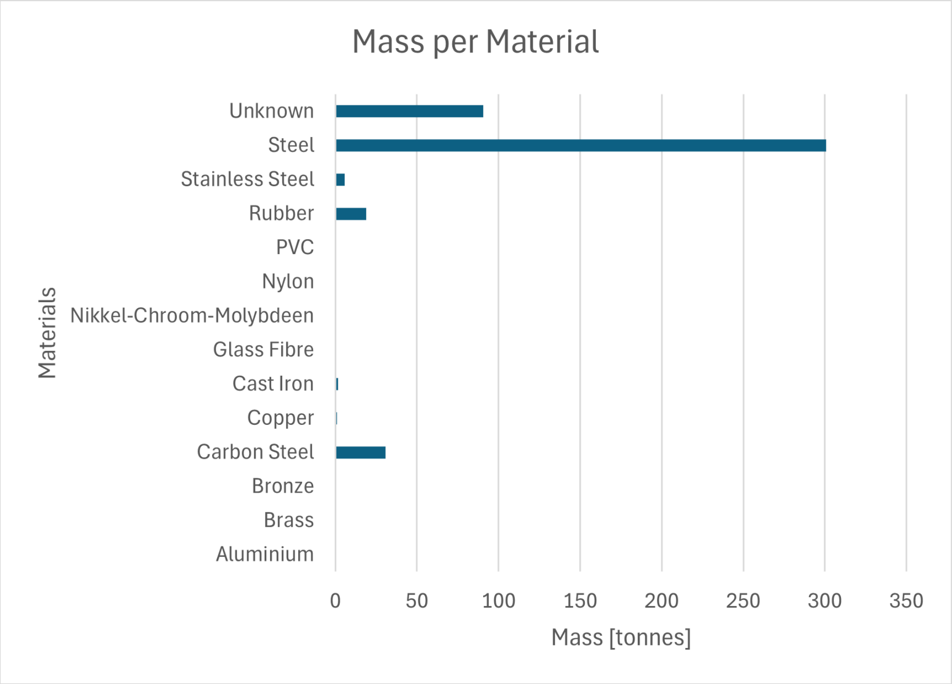


Figure 5.1: Resource Depletion per Material

5.2.5. Waste Reduction

Solid Waste Reduction

Waste reduction was proposed to quantify the environmental benefit of retaining existing vessel components through refitting. However, this KPI could not be calculated for the following reasons:

1. No detailed decommissioning records exist specifying which components are removed during refits
2. End-of-life treatment pathways (recycling, landfill, energy recovery) vary significantly between shipyards globally
3. Waste diversion rates depend on local reverse logistics infrastructure, which is unknown at the decision-making stage
4. No baseline exists for comparing waste generation between different refit strategies

While conceptually valuable, waste reduction requires systematic data collection during actual refit operations to be quantifiable. It is recommended for exclusion from the current framework, but should be considered for future inclusion once post-refit waste audits become standard practice within Damen.

5.3. Economic KPIs

All final and intermediate values of the 13 Economic KPI calculations can be found in Appendix D.3.
Note: Due to sensitivity, all prices mentioned in this chapter are fictional, yet based on real-world data. Although prices are modified, ratios between the vessels are preserved.

5.3.1. Total Cost of Ownership

The total cost of ownership (TCO) is calculated as the sum of the initial CAPEX and the cumulative OPEX over the vessel's remaining service life. The assessment period extends to the end of the assumed vessel life: 20 years for refitted vessels and 30 years for newbuilds. The results at the end of the vessel's service life are shown in Table 5.16.

Table 5.16: Breakdown Total Cost of Ownership (TCO) at End of Refit Service Life
*Total OPEX and TCO are assessed over 20 years for all vessels to allow fair comparison.

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
TCO [€]	4,253	4,940	4,275	5,267	5,367	6,518
CAPEX [€]	517	1,164	862	1,724	1,379	2,328
Total OPEX* [€]	3,736	3,776	3,413	3,543	3,987	4,190
OPEX [€/year]	187	189	171	177	199	207

5.3.2. CAPEX

Acquisition Cost

The Acquisition Cost is calculated using Equation 3.19. The vessel was bought for €85 ($P_{purchase}$) and transportation costs were €26 ($T_{transport}$). The initial survey (F_{survey}) is done internally, bringing no additional costs to the project. The total Acquisition Costs for the vessel are €111.

Refit Cost / SFI

This KPI was proposed to provide transparency into how refit costs are distributed across vessel systems (using SFI system codes). This level of cost granularity is only available for the refurbish scenario (refit to conventional), where detailed quotations and invoices were accessible. Newbuild cost data for both conventional and hybrid vessels were available. Using the cost distributions from these known vessels, and assuming that hybrid and electric vessels are, on average, 1.7 and 2 times more expensive than conventional vessels, the cost shares per SFI group were derived for the hybrid remanufacture, electric remanufacture, and newbuild electric vessels. This KPI gives insight into cost-intensive systems (200 - Engine, Gearbox, Generators, Steering Gear, Bow Thrusters and Shaft) and differences between refit and newbuild (100 - Tanks, Hull, Superstructure, Deck, Mast).

Table 5.17: Refit Cost per SFI [%]

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
100	12%	37%	14%	31%	15%	31%
200	48%	36%	56%	23%	58%	23%
300	4%	5%	5%	5%	5%	5%
400	1%	6%	1%	16%	1%	16%
500	12%	4%	8%	9%	7%	9%
600	1%	2%	1%	1%	1%	1%
700	4%	2%	3%	2%	2%	2%
800	1%	2%	1%	2%	1%	2%
000/900	18%	5%	12%	11%	10%	11%

Total Refit Cost (CAPEX Shipyard)

For Damen, the total refit cost represents the internal cost price of executing the refit project or constructing a newbuild vessel. For refit projects, this also contains the acquisition costs of the vessel and transportation of the vessel to a refit shipyard. By subtracting the cost price from the expected market or sales value, the resulting difference indicates the profit margin associated with the vessel project. Results are presented in Table 5.18.

As shown in Table 5.18, detailed cost price data is only available for comparison 1 (refit to conventional and newbuild conventional). For hybrid and electric variants, internal cost structures remain under development as these represent emerging technologies for Damen. Consequently, profit margins for these scenarios could not be calculated. This limitation highlights the challenge of economic assessment for novel propulsion systems during the early adoption phase and suggests that profit margin analysis may have limited applicability until more cost data becomes available through operational experience.

Market Value

For the vessel owner, CAPEX is defined as the expected market or sales value. For newbuild vessels, this value is derived from historical sales records within Damen. For refitted vessels, the expected market value is estimated based on expert input from the DFS Operations and Trading teams. The resulting CAPEX values are presented in Table 5.18.

Table 5.18: Market Value Vessel Projects

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
Market Value [€]	517	1,164	862	1,724	1,379	2,328

5.3.3. OPEX

OPEX comprises four cost categories: crew costs, energy costs, maintenance costs, and insurance costs. The breakdown of these cost components is also provided in Table 5.19. **Crew costs** are assumed to be identical for all vessels (€121 per year) and are based on three rotating crews. The number of crew members is assumed to be independent of the propulsion system and whether the vessel is a refit or newbuild, as automation levels are comparable across all scenarios considered.

Maintenance costs are based on current records within Damen for vessels in operation. For conventional vessels, annual maintenance costs are estimated at €26, derived from actual costs across conventional tugboats. Operational costs for the hybrid and electric vessels are estimated at €22 per year, based on an operational 2513 E-RSD. The lower maintenance costs for electric/hybrid systems reflect reduced engine complexity and fewer moving parts.

As no hybrid tugs are currently in operation within Damen's fleet, this estimate represents a theoretical projection that will require validation through operational experience.

Insurance costs are calculated using the within Damen used rule of thumb that annual insurance amounts to approximately 1% of the vessel's sales or market value. Other operational costs (such as port fees, administrative costs, or emission fees) could not be quantified with the available data and are therefore assumed to be zero for this assessment. This assumption likely underestimates total OPEX, but the impact is expected to be proportionally similar across all scenarios, thus not significantly affecting relative comparisons.

Table 5.19: OPEX Breakdown with Crew, Energy, Maintenance, and Insurance Costs per Year

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
OPEX [€/year]	187	189	171	177	199	210
Crew	121	121	121	121	121	121
Energy	35	31	20	18	43	44
Maintenance	26	26	22	22	22	22
Insurance	5	12	9	17	14	23

5.3.4. Value and Lifecycle-based Indicators

Value Added

Value added represents the increase in vessel market value resulting from refit activities, calculated with Equation 3.27. This indicator was intended to assess whether refits create more economic value beyond cost recovery. The results are shown in Table 5.20.

Table 5.20: Value Added [€] across all Vessels

	Refurbish Conventional	**New** Conventional	**Remanufacture** Hybrid	**New** Hybrid	**Remanufacture** Electric	**New** Electric
Value Added [€]	432	1,164	777	1,724	1,294	2,328

This KPI is calculated to provide for the CO_{2e} emissions per Value Added. The KPI in this form does not account for the investment required to build or refit a vessel.

Value Retention

Value retention measures the proportion of the original vessel value that is preserved through refitting, calculated in Equation 3.28. This KPI aims to quantify the economic benefit of extending vessel life versus scrapping. The results are presented in Table 3.28.

Table 5.21: Value Retention [%] across all Refits

	Refurbish Conventional	**Remanufacture** Hybrid	**Remanufacture** Electric
Value Retention	44%	50%	59%

This KPI tells how much newbuild equivalent value the vessel holds after the refit. However, it does not consider the money invested and if the refit was worth it.

Therefore, a new KPI, presented in Equation 5.7, is recommended. This KPI combines the Value Added and the Refit Costs to define the Value Gain Ratio. Value Gain Ratio outcomes <1 indicate that less value was gained than money was invested. Value Gain Ratio outcomes >1 indicate a commercially attractive refit because every €1 invested returned more than €1 in vessel value.

$$\text{Value Gain Ratio} = \frac{\text{Value Added}}{\text{Total Refit Costs}} \tag{5.7}$$

Component Cost Share

The component cost share indicator was proposed to reflect how total costs are distributed across new, reused, repaired, refurbished, and remanufactured components. This KPI is intended to quantify circularity from an economic perspective, showing the financial benefit of component reuse strategies.

However, detailed calculation proved impossible because purchased components are not categorised by condition (new vs. refurbished vs. remanufactured) in procurement records. At the same time, many components undergo repair or refurbishment as part of standard refit practices, but these activities are not separately costed in project budgets.

For this reason, the KPI should be excluded until component product passports include clear labels indicating each item's R-strategy status. Without such information, applying the KPI imposes a substantial administrative workload on personnel involved in vessel repairs.

5.4. Data Quality Assessment and Limitations

This section provides a consolidated overview of data quality issues encountered during KPI calculation and their implications for decision-making reliability.

5.4.1. Data Availability

Table 5.22 summarises the availability and quality of data for each calculated KPI across the 6 vessels of the 3 comparisons.

Table 5.22: Data Availability and Quality Assessment

KPI	**Data Available**	**Quality**	**Limitations**
Strategic KPIs			
Vessel Lead Time	Yes	Medium	Based on expert estimates, not historical records
Component Lead Time	Yes	Medium	Aggregated estimates per system, not component-specific
Time in Dock	Yes	Medium	Estimation
Complexity of Work	Yes	Low	Subjective classification, no quantitative metrics
Reclassification Required	Yes	High	
Reclassification Duration	Yes	Medium	Practical Experience
Environmental KPIs			
TEO	Partial	Medium	BoM missing
Embodied Emissions	Partial	Medium	Generic ECF values, not supplier-specific
Yard Emissions	Partial	Medium	Gross Tonnage not defined
Prevented CO_2 Emissions	Partial	Medium	BoM missing
CO_2/Unit Value Added	Partial	Medium	BoM missing
Fuel Consumption	Yes	High	Based on reference data
OPEM/year	Yes	High	Based on established consumption models of reference data
Particulate Matter	Yes	High	Based on established consumption models of reference data
EEDI/EEXI	No	N/A	Not required for vessel type
% of Reused Components	Partial	Low	Based on expert estimates
Vessel Life Extension	Yes	High	Based on historical records
Resource Depletion	Partial	Medium	BoM missing
Solid Waste Reduction	No	N/A	No records of waste management
Economic KPIs			
TCO	Yes	Medium-High	Dependent on assumptions for hybrid/electric OPEX
Acquisition Cost	Yes	High	Based on historical data
Refit Cost/SFI	Yes	Medium	Based on assumptions of cost (share) data
Total Refit Cost	Yes	Medium	Based on assumptions of cost data
Market Value	Yes	High	Based on expert estimates
OPEX/year	Yes	High	Result of crew, energy, maintenance and insurance costs
Crew Costs	Yes	High	Based on historical data
Energy Costs	Yes	High	Based on established consumption models
Maintenance Costs	Yes	Medium	Based on historical data not available for hybrid
Insurance Costs	Yes	High	Rule of thumb of 1%
Value Added	Yes	Medium	Used in combination with CO_2/Value Added
Value Retention	Yes	Medium	Limited usefullness for interpretation
Component Cost Share	No	N/A	Procurement data insufficient

5.4.2. Key Uncertainties

The following uncertainties have the most significant impact on KPI reliability.

Hybrid and Electric System Costs: As Damen has not yet executed hybrid or electric refit projects for tugs, CAPEX and OPEX estimates for these scenarios rely on current vessel operations and theoretical performance models. Actual costs may differ significantly.

Maintenance Cost Projections: The €22 annual maintenance estimate for the hybrid system lacks empirical validation from Damen's operational fleet. This represents a critical knowledge gap that can only be resolved through actual operational experience. All maintenance costs are estimated based on newbuild vessels, so for refitted vessels, these values might also be higher in reality.

Embodied Carbon Factors: Generic EcoInvent database values were used where component-specific materials were unavailable. This introduces uncertainty for steel products. The materials and masses used in battery systems for the outfitting of hybrid and electric vessels are also unknown. Which introduces a significant uncertainty in embodied carbon for these propulsion systems.

5.5. Conclusion Decision-Making Implications

Despite data limitations, the calculated KPIs provide sufficient information for high-level strategic decisions regarding propulsion system selection and refit vs. newbuild trade-offs. However, the following limitations apply.

Strategic KPIs based on expert judgement should be validated through pilot projects before full-scale implementation. **Environmental KPI** results are more reliable for operational phases than for CAPEM/Embodied Emissions. Within **Economic KPI** results, TCO comparisons between conventional and alternative propulsion systems carry higher uncertainty than comparisons within the same propulsion type.

These limitations are input for the recommendations in Chapter 7 regarding framework refinement and data collection priorities.

6

Results and Analysis

This chapter presents the analysis of the KPI results calculated in Chapter 5. While the previous chapter focused on the calculation methodology and data quality assessment, this chapter interprets the KPI values to evaluate the performance of different refit strategies relative to newbuild alternatives and to each other. The analysis addresses the following questions from Chapter 1:

- How do the different refit strategies perform compared to each other, and how do they perform compared to newbuild reference vessels?
- How can the KPI results be used to identify the optimal circular strategy for vessel refits?

Rather than prescribing a single "optimal" solution, this chapter demonstrates how the calculated KPIs support multi-criteria decision-making by revealing trade-offs across strategic, environmental, and economic impact areas. The analysis is structured around three comparisons, corresponding to the R-strategies defined in Chapter 4:

Comparison 1 - Refurbish: Refit to conventional propulsion vs. newbuild conventional (Section 6.1)
Comparison 2 - Remanufacture (Hybrid): Refit to hybrid propulsion vs. newbuild hybrid (Section 6.2)
Comparison 3 - Remanufacture (Electric): Refit to electric propulsion vs. newbuild electric (Section 6.3)

Following the individual comparison analyses, Section 6.4 compares the three refit strategies to identify how the choice of R-strategy influences performance across impact areas. This cross-strategy comparison illustrates the trade-offs between minimising intervention (refurbish) and maximising environmental impact results (remanufacture to electric).

The analysis uses the following interpretation principles:
Time horizons: Refit strategies are evaluated over a 20-year remaining service life, while newbuilds are assessed over a 30-year design life. This reflects the different lifecycle assumptions established in Chapter 5 and ensures that comparisons account for the actual operational period relevant to each strategy.

Stakeholder perspectives: Economic KPIs are interpreted from both the vessel owner's perspective (market value, TCO) and the shipbuilder's perspective (cost price, profit margin). This dual perspective recognises that refit viability depends on value creation for both parties.

Data uncertainty: Where data limitations exist (particularly for hybrid and electric configurations), the analysis focuses on relative comparisons and directional insights rather than absolute values. Conservative assumptions are highlighted to indicate potential ranges.

Regulatory context: The analysis considers current emission reporting regulations, where electricity is assumed to have zero direct emissions. Future regulatory changes or lifecycle emission accounting may alter the environmental performance ranking, particularly for electric configurations.

Detailed calculations and intermediate results are provided in Chapter 5 and Appendix D. In this chapter, calculated values are repeated only when necessary for interpretation. Each comparison section concludes with key insights for decision-makers, while the overall chapter conclusion (Section 6.6) synthesises findings across all comparisons to answer the guiding research questions.

Note: Due to sensitivity, all prices mentioned in this chapter are fictional, yet based on real-world data. Although prices are modified, ratios between the vessels are preserved.

6.1. Comparison 1 - Refurbish (refit to conventional)

The first scenario considered is the Refurbish (refit to conventional) option. This scenario compares a refurbished 3110 ASD tug with a newbuild 2810 ASD conventional tug. The comparison is structured across the three impact areas: Strategic (Section 6.1.1), Environmental (Section 6.1.2) and Economic (Section 6.1.3).

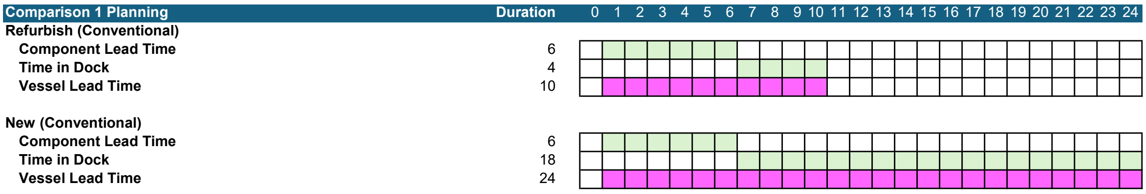
6.1.1. Strategic Impact Area

A strategic KPI for all refit strategies is **Time in Dock**, as it reflects the vessel's unavailability, and therefore impacts operational continuity and revenue generation. For the refurbish comparison, the average Time in Dock is approximately 4 months. This duration includes all physical refit activities required to restore the vessel to operational condition, upgrading the vessel to as-new state, without altering the propulsion concept. The newbuild vessel has an average Time in Dock of approximately 18 months. The results are visualised in Figure 6.1.

From a strategic perspective of a shipowner, a newbuild vessel may be preferred because fleet operations can continue uninterrupted, as the new vessel can replace the old one directly. In the refurbish scenario, however, this potential disadvantage can be mitigated by Damen by leasing a temporary vessel to the client for the duration of the time in dock, thereby maintaining operational continuity.

Regarding **Component Lead Times**, the results indicate that most major components commonly replaced during refits, such as the main engine and electrical systems, exhibit lead times comparable to those of newbuild projects. A notable exception is auxiliary systems, for which lead times are longer in refit projects (approximately three months) compared to newbuilds (approximately two months) (Figure D.1). The longest component lead time for both refit vessel and newbuild vessel is 6 months. The results are visualised in Figure 6.1.

For a refurbished vessel, the **Vessel Lead Time** is approximately 10 months, while for newbuild, the lead time is 24 months. Most of the refurbish vessel lead time coincides with component lead times, which can be organised in preparation. For newbuild vessels, most of the vessel lead time coincides with the time in dock.



Comparison 1 Planning	Duration	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
Refurbish (Conventional)																										
Component Lead Time	6		🟩	🟩	🟩	🟩	🟩	🟩																		
Time in Dock	4								🟩	🟩	🟩	🟩														
Vessel Lead Time	10		🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪														
New (Conventional)																										
Component Lead Time	6		🟩	🟩	🟩	🟩	🟩	🟩																		
Time in Dock	18								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Vessel Lead Time	24		🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪

Figure 6.1: Vessel Lead Time, Component Lead Time and Time in Dock Shown in Planning for Comparison 1

The assumption is made that equipment must be delivered before work can begin. Since the time in dock for a refit is shorter than for a newbuild, the schedule for ordering new equipment in a refit is more critical, and you need to start the ordering process earlier relative to the work start. For a newbuild, an engine might be installed in month 12, allowing you to place the order during construction, for example, in month 5 or 6. In contrast, for a refit where the engine has to be installed in month 2, you would need to place the order as early as month -4 or -5 to ensure timely delivery. Consequently, the ordering schedule for components is more time-critical in refit projects than in newbuilds because the overall time frame is shorter while lead times remain the same. The impact of this assumption is described in Section 6.5.

The project timeline, as depicted in Figure 6.1 remains unchanged across all newbuild vessels.

The overall **Complexity of Work** of the refurbished vessel is moderate. Because this KPI is not determined for the newbuild vessels, comparison is not relevant. The Complexity of Work is assessed across the different refit strategies in Section 6.4.

An important strategic distinction concerns **classification status**. For the refurbish strategy, reclassification requires 10 days, with 80% is integrated into yard activities, and 20% occurs after completion of the works. Consequently, an additional two days of post-refit downtime must be accounted for before the vessel can re-enter service. By comparison, reclassification for a newbuild vessel requires approximately 30 days, following the same 80/20 distribution. This translates to around six days of additional downtime after works are finished. From a strategic planning perspective, this highlights that refits generally have a lower risk of certification-related delay than newbuilds, even when reclassification is required.

Overall, the refurbish strategy demonstrates a relatively short time-to-service compared to newbuild alternatives, with strategic advantages in terms of reduced downtime and lower classification delays, provided that the component lead times are managed effectively.

6.1.2. Environmental Impact Area

The environmental performance of the refurbish strategy is assessed using **Capital Emissions** (CAPEM) (embodied emissions and yard emissions), **Operational Emissions** (OPEM), component reuse, and vessel lifetime, reflecting both short-term and lifecycle-oriented environmental impacts.

The refurbish scenario has an estimated 70% of **Component Reuse**. As the existing hull and a substantial share of onboard systems are retained, the **total embodied CO_{2e}** in materials is significantly lower for the refurbished vessel (149 t CO_{2e}) than for a newbuild vessel (1002 t CO_{2e}). This represents an environmental advantage of the refurbish strategy at the capital phase, as the emissions associated with primary steel production and large-scale fabrication for the hull and major equipment are largely avoided.

Based on the assumptions described in Section 5.2, the **Yard Emissions** are estimated at 3.17 tonnes CO_2 for the refurbished vessel and 11.1 tonnes CO_2 for the newbuild vessel. Although this absolute difference appears significant, yard emissions constitute only a minor share of total Capital Emissions when compared to the embodied emissions. As such, their influence on overall results is limited.

The **Operational Emissions** are based on the fuel consumption. Because the refurbished vessel and the newbuild reference vessel are equipped with different engine types, this leads to differences in fuel consumption, as shown in Table 5.10. Translating fuel consumption into Operational Emissions results in approximately 1,016 tonnes of CO_2 per year and 619 tonnes of SO_2 per year for the refurbished vessel. For the newbuild vessel, annual emissions are approximately 887 tonnes of CO_2 and 541 tonnes of SO_2 (Table 5.11).

These results indicate that, from an operational perspective, the newbuild vessel performs better in terms of efficiency. The refurbish strategy therefore exhibits higher operational emissions per year, despite its advantage in the capital phase. This is represented in Figure 6.2 by the **Total Emissions of Ownership** (TEO). The figure shows that after 6 years, the newbuild vessel becomes the preferred option over the refurbished vessel.

The figure illustrates the total emissions over the service life of each vessel, with CAPEM as the starting point. For refit strategies, a service life of 20 years is assumed, while newbuild vessels are evaluated over a 30-year lifetime. These assessment periods are based on the **Vessel Life Extension**, reflecting the remaining operational life after refit or newbuild. The impact of shorter or longer vessel lives is evaluated in Section 6.5.

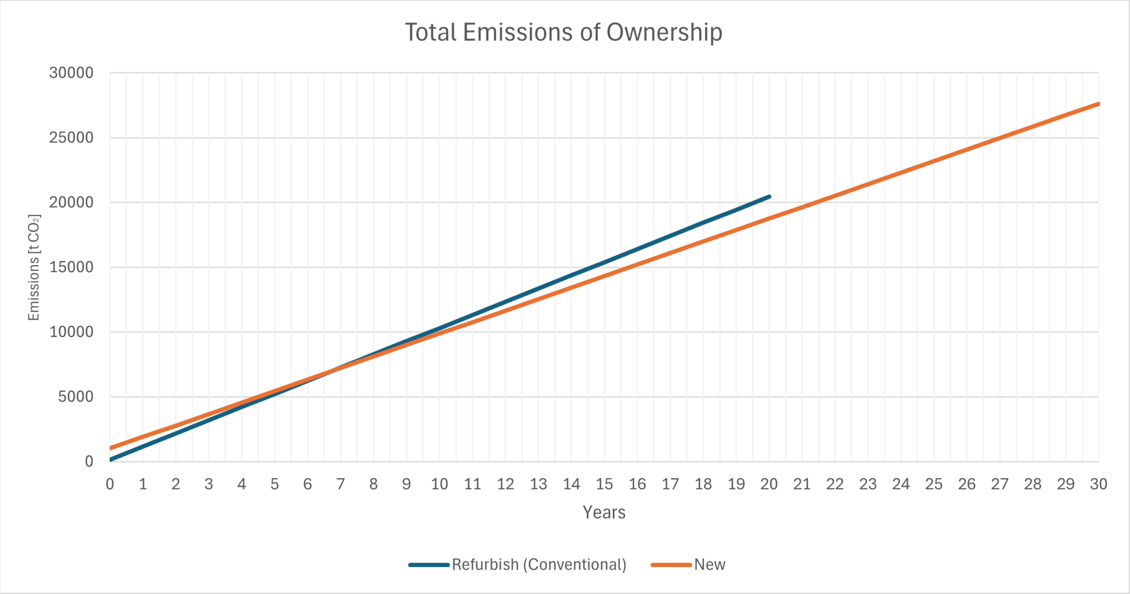


Figure 6.2: Total Emissions of Ownership over Service Life: Refurbish vs. Newbuild Conventional

6.1.3. Economic Impact Area

The economic performance of the refurbish strategy is assessed through Total Cost of Ownership (TCO) which is obtained by combining Capital Expenditure (CAPEX) (Table 6.1) and Operational Expenditure (OPEX) (Table 6.2). The results are compared against a newbuild conventional vessel to contextualise the economic implications for both the shipbuilder and the client.

The refurbish strategy requires an estimated €460 to be executed. The **CAPEX** for the client is based on the expected market or sales value. The expected market value of the refurbished vessel is approximately €517. In comparison, a newbuild conventional vessel has a cost price for Damen of approximately €1,070 and an expected sales value of approximately €1,164.

This results in a cost price difference of approximately €647 for the client in favour of the refurbish strategy. From a client perspective, refurbish therefore represents a substantially lower upfront investment, while still delivering a fully operational vessel with a remaining service life of 20 years.

Table 6.1: Capital Expenditure Comparison 1

	Refurbish Conventional	**New** Conventional
Expected Sales / Market Value [€] (CAPEX for Client)	517	1,164

Annual **OPEX** for the refurbish and newbuild vessels is comparable, with total OPEX estimated at approximately €187 per year for the refurbished vessel and €189 per year for the newbuild, shown in Table 6.2, based on Table 5.19.

Crew costs are assumed to be identical for both vessels, as crew size and operational profile remain unchanged. Maintenance costs are also similar, reflecting the use of the same conventional propulsion system and comparable maintenance regimes.

Differences in OPEX are primarily driven by energy costs and insurance costs. The refurbished vessel exhibits higher annual fuel consumption, as shown in Section 5.2, resulting in higher energy costs compared to the newbuild. The lower market value of the refurbished vessel leads to lower insurance costs (approximately €5 per year) compared to the newbuild vessel (approximately €12 per year). These effects partially offset each other, resulting in a difference in total annual OPEX of €2.

The combination of lower CAPEX and comparable OPEX results in a lower **TCO** for the refurbish

Table 6.2: Operational Expenditure Comparison 1

	Refurbish Conventional	**New** Conventional
Operational Expenditure [€/year]	**187**	**189**
Crew Cost [€/year]	121	121
Energy Cost [€/year]	35	31
Maintenance Cost [€/year]	26	26
Insurance Cost [€/year]	5	12

strategy over its remaining service life. The TCO comparison, illustrated in Figure 6.3 demonstrates that refurbish remains economically attractive despite its lower fuel efficiency, particularly in contexts where capital availability or investment risk is a dominant decision factor.

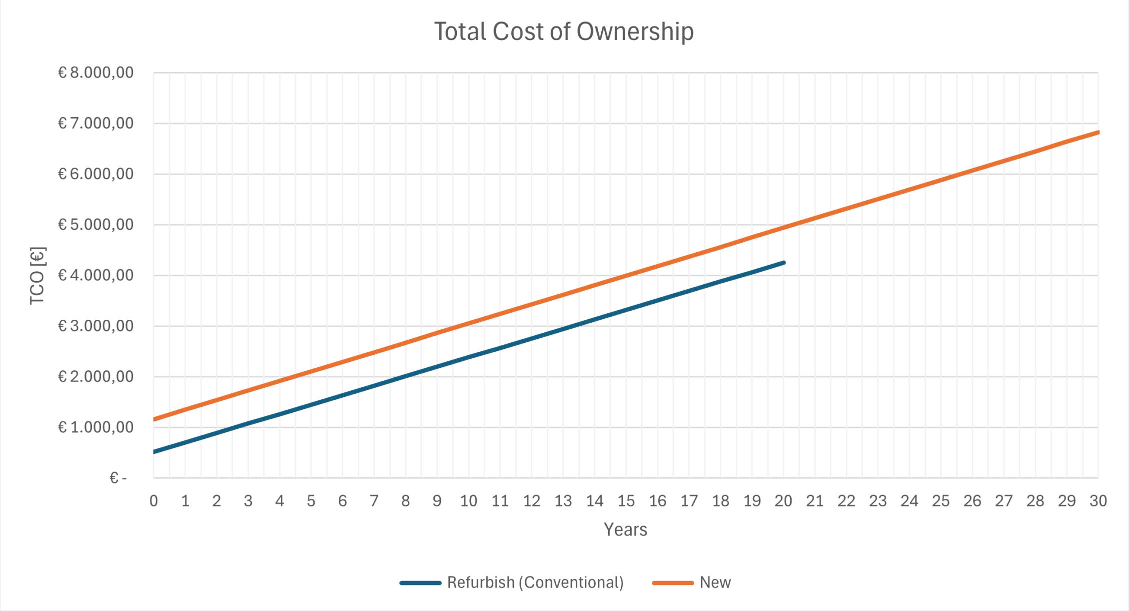


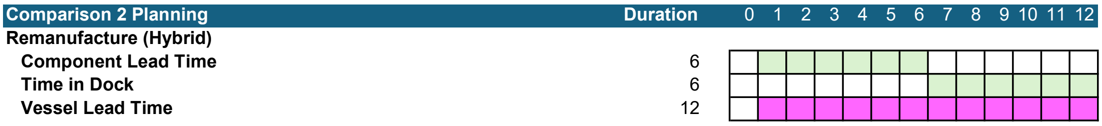
Figure 6.3: Total Cost of Ownership Over Service Life: Refurbish vs. Newbuild Conventional

6.2. Comparison 2 - Remanufacture (Refit to Hybrid)

The second comparison evaluates the Remanufacture (refit to hybrid) strategy. This comparison assesses a 3110 ASD Tug remanufactured with hybrid propulsion against a newbuild 2810 hybrid tug. The analysis follows the same structure as Comparison 1, examining Strategic (Section 6.2.1), Environmental (Section 6.2.2), and Economic (Section 6.2.3) impact areas. This comparison represents a more interventionist circular strategy than Comparison 1, with significant system replacement to achieve environmental performance.

6.2.1. Strategic Impact Area

Component Lead Times follow the baseline values established in Section 6.1.1. Time in Dock is extended with 2 months based on experience from Damen Hardinxveld. This leads to a Vessel Lead Time extension of 2 months. The time-related KPIs for the hybrid remanufacture are visualised in Figure 6.4, the newbuild hybrid vessel follows the same planning as the newbuild conventional from Figure 6.1.



Comparison 2 Planning	Duration	0	1	2	3	4	5	6	7	8	9	10	11	12
Remanufacture (Hybrid)														
Component Lead Time	6		🟩	🟩	🟩	🟩	🟩	🟩						
Time in Dock	6								🟩	🟩	🟩	🟩	🟩	🟩
Vessel Lead Time	12		🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪

Figure 6.4: Vessel Lead Time, Component Lead Time and Time in Dock Shown in Planning for Comparison 2

The key strategic differentiator is **Complexity of Work**, which increases to medium-high for the hybrid remanufacture strategy (Table 5.3). This indicates that more complex activities are executed within the same timeframe. The increase in complexity is mainly due to installation of electronics and energy management systems that increase the coordination effort and therefore increase risk of delays.

Although **Reclassification** is required, the propulsion configuration is based on previously approved hybrid systems, limiting additional regulatory uncertainty.

6.2.2. Environmental Impact Area

The remanufacture to hybrid strategy introduces lower **Capital Emissions** (CAPEM) than its newbuild equivalent. However, due to insufficient data on the materials and masses of the hybrid equipment, including batteries, power electronics, and hybrid-specific auxiliary equipment, the CAPEM of the hybrid vessels could not be fully quantified. The only conclusion that can be drawn is that the remanufactured hybrid vessel has around 633 tonnes CO_{2e} lower capital emissions than the newbuild vessel as this difference corresponds to the emissions attributed to the hull alone. Therefore, from a **Prevented CO_{2e}** perspective, the hybrid remanufacture strategy still achieves CAPEM savings relative to replacement through newbuild.

Operational Emissions (OPEM) of the hybrid remanufactured vessel (438 t CO_2) are slightly higher than those of the newbuild hybrid vessel (426 t CO_2). Calculations are based on the Fuel Consumption per hour extracted from the operational profile and the energy split assumptions between free sailing and bollard pull. Fuel consumption for the remanufactured hybrid vessel is approximately 137 tonnes MGO per year, compared to 133 tonnes MGO per year for the newbuild hybrid vessel. This shows that the difference in fuel consumption is smaller than for the refurbish scenario, indicating that the performance gap between refit and newbuild narrows significantly for hybrid configurations. The introduction of electric operation during free-sailing and standby conditions contributes to lower annual CO_2 emissions.

The relation between CAPEM and OPEM over the vessel's service lives is visualised through TEO in Figure 6.5. This figure shows that for a remaining service life of 20 years for the refit, and 30 years for the newbuild, the remanufactured hybrid vessel outperforms its newbuild equivalent up to at least 20 years.

The remanufacture (refit to hybrid) strategy achieves a **% of reused components** of approximately 50%. This is lower than the refurbished vessel due to the replacement of major propulsion-related

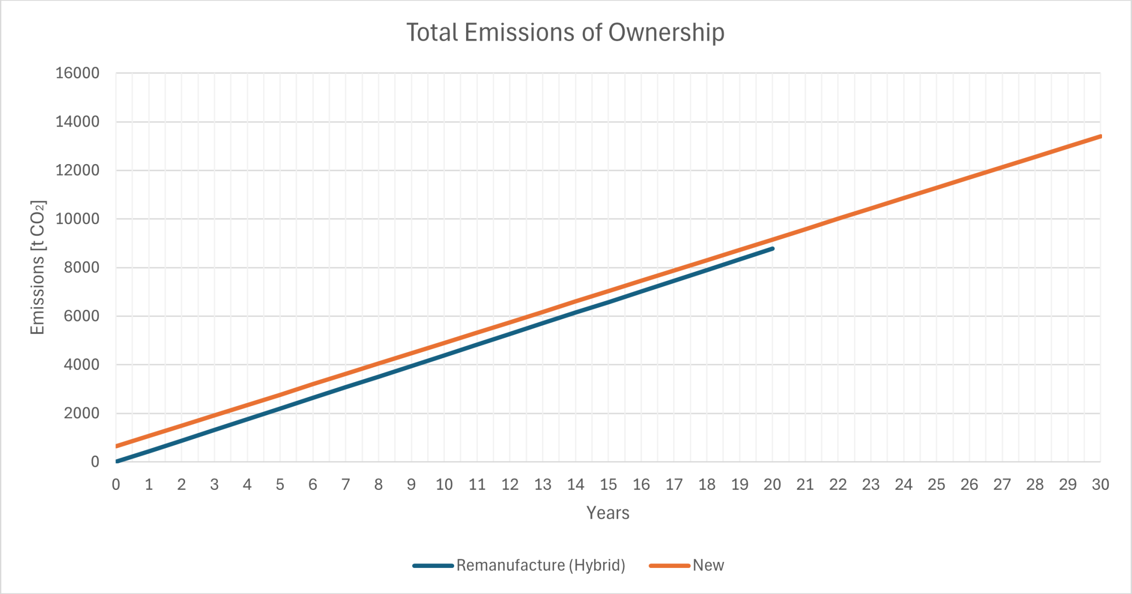


Figure 6.5: Total Emissions of Ownership Over Service Life: Remanufacture Hybrid vs. Newbuild Hybrid

systems. This results in increased material demand and resource depletion compared to refurbish, but still represents an improvement over newbuild.

6.2.3. Economic Impact Area

The remanufacture (refit to hybrid) strategy results in lower **CAPEX** compared to the hybrid newbuild. This is because the remanufactured vessel only replaces some systems. While the hull and some existing systems are retained, the extent of new equipment procurement increases overall CAPEX.

Compared to a newbuild hybrid vessel, the hybrid refit still benefits from avoiding full hull construction and complete outfitting. However, the CAPEX advantage relative to newbuild is smaller than for refurbish, reflecting the increased technical scope of the refit.

Despite the higher upfront investment, the hybrid refit introduces operational flexibility and emissions-reduction capabilities that may increase accessibility to ports with emission-based incentives or restrictions.

Table 6.3: Capital Expenditure Comparison 2

	Remanufacture Refit to Hybrid	**New** Hybrid
Expected Sales/Market Value [€] CAPEX (for Client)	862	1,724

Annual **OPEX** for the remanufacture (refit to hybrid) strategy is lower than for the conventional refurbish strategy due to reduced fuel consumption enabled by hybrid operation. Based on the operational profile, total energy costs for the hybrid refit are approximately €20 per year, which is higher than the €18 per year for the newbuild hybrid vessel. Crew costs remain unchanged, while maintenance costs are expected to decrease slightly in comparison with conventional vessels. Insurance costs remain lower for the hybrid remanufacture (€9) than for the newbuild hybrid (€17). This difference is bigger than the difference between energy costs, therefore, the insurance costs have the biggest impact on the OPEX of the hybrid vessels.

In general, the hybrid refit shows lower total OPEX per year (€171) than the hybrid newbuild (€177), as shown in Table 6.4.

Table 6.4: Operational Expenditure Comparison 2

	Remanufacture Refit to Hybrid	**New** Hybrid
Operational Expenditure [€/year]	**171**	**177**
Crew Cost [€/year]	121	121
Energy Cost [€/year]	20	18
Maintenance Cost [€/year]	22	22
Insurance Cost [€/year]	9	17

Figure 6.6 shows the trade-off between CAPEX and OPEX in the form of **TCO**. While TCO is similar as for refurbish, it may become competitive over longer operational periods or under certain operating areas with strict emission regulations. From an economic perspective, the hybrid refit offers an intermediate solution between short-term cost efficiency and long-term operational savings.

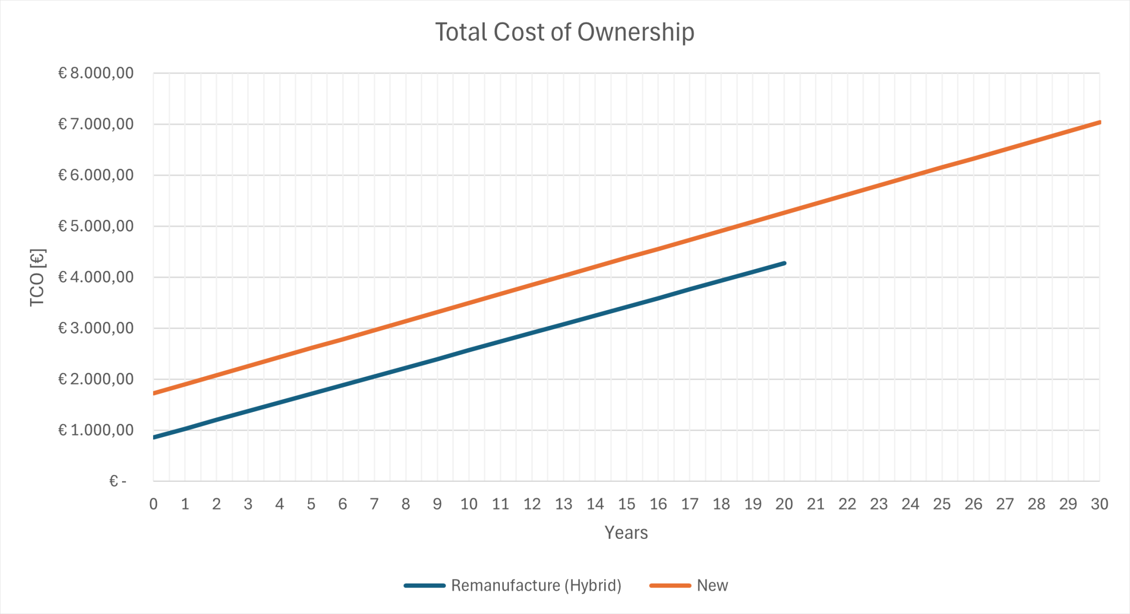


Figure 6.6: Total Cost of Ownership Over Service Life: Remanufacture Hybrid vs. Newbuild Hybrid

6.3. Comparison 3 - Remanufacture (Refit to Electric)

The third comparison examines the Remanufacture (refit to electric) strategy, representing the most interventionist approach among the assessed options. This comparison evaluates a 3110 ASD Tug remanufactured with fully electric propulsion against a newbuild 2513 E-RSD electric tug. Following the established structure, the analysis covers strategic (Section 6.3.1), environmental (Section 6.3.2), and economic (Section 6.3.3) impact areas. This strategy involves the most extensive system replacement and represents the maximum emissions reduction potential among refit options.

6.3.1. Strategic Impact Area

Component Lead Times follow the baseline values established in Section 6.1.1. Time in Dock is extended by 4 months compared to refurbish, based on experience from Damen Hardinxveld. This leads to a Vessel Lead Time extension of 4 months compared to refurbish. The time-related KPIs for the electric remanufacture of Comparison 3 are visualised in Figure 6.7. The newbuild electric vessel follows the same planning as the newbuild conventional vessel shown in Figure 6.1.

Comparison 3 Planning	Duration	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Remanufacture (Electric)																
Component Lead Time	6		🟩	🟩	🟩	🟩	🟩	🟩								
Time in Dock	8								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Vessel Lead Time	14		🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪

Figure 6.7: Vessel Lead Time, Component Lead Time and Time in Dock Shown in Planning for Comparison 3

The key strategic differentiator is **Complexity of Work**, which increases to high for the electric remanufacture strategy (Table 5.3). This indicates that even more complex activities are executed within the same timeframe. The increase in complexity is due to hull reinforcement works and installation of electronics and energy management systems that increase the coordination effort and therefore increase risk of delays.

Reclassification duration is similar as for the other comparisons. However, while the electric propulsion concept has precedent within classification frameworks, the extent of hull modifications results in increased regulatory scrutiny.

Strategically, the electric refit offers limited time advantages over other refit options while introducing higher execution and coordination risks.

6.3.2. Environmental Impact Area

The remanufacture to electric strategy is expected to result in the highest **Capital Emissions** among the refit options. This is primarily driven by the installation of large battery systems, high-voltage equipment, and other auxiliary systems. Although the hull and some structural components are retained, the material intensity of electrification likely leads to higher embodied CO_{2e} compared to refurbish and remanufacture to hybrid refits.

Despite this increase, Capital Emissions are expected to remain lower than those of a full newbuild vessel. The only conclusion that can be drawn is that the remanufactured electric refit has around 635 tonnes CO_{2e} lower capital emissions, as this difference corresponds to the emissions attributed to the hull alone. The **prevented CO_{2e}** benefit relative to newbuild is reduced compared to other refit strategies, as a larger share of new material is installed.

Operational emissions for the remanufacture to electric refit are the lowest among the refit options, as propulsion-related fuel consumption is eliminated. Direct CO_2 emissions during operation are therefore minimal (due to auxiliary engines) or zero when operating fully electric.

TEO reflect this shift in OPEM, making the CAPEM the main input for the TEO. The TEO is visualised in Figure 6.8. In this figure, the CAPEM for both the remanufactured and the newbuild vessel are missing the Embodied Emissions of the outfitting. Therefore, both these lines will translate upward in the graph, but the difference between the lines is expected to remain similar.

The remanufacture to electric strategy has the lowest **% of Reused Components** among the refit options, as major systems are replaced. The reuse rate is estimated on 30%, which indicates increased

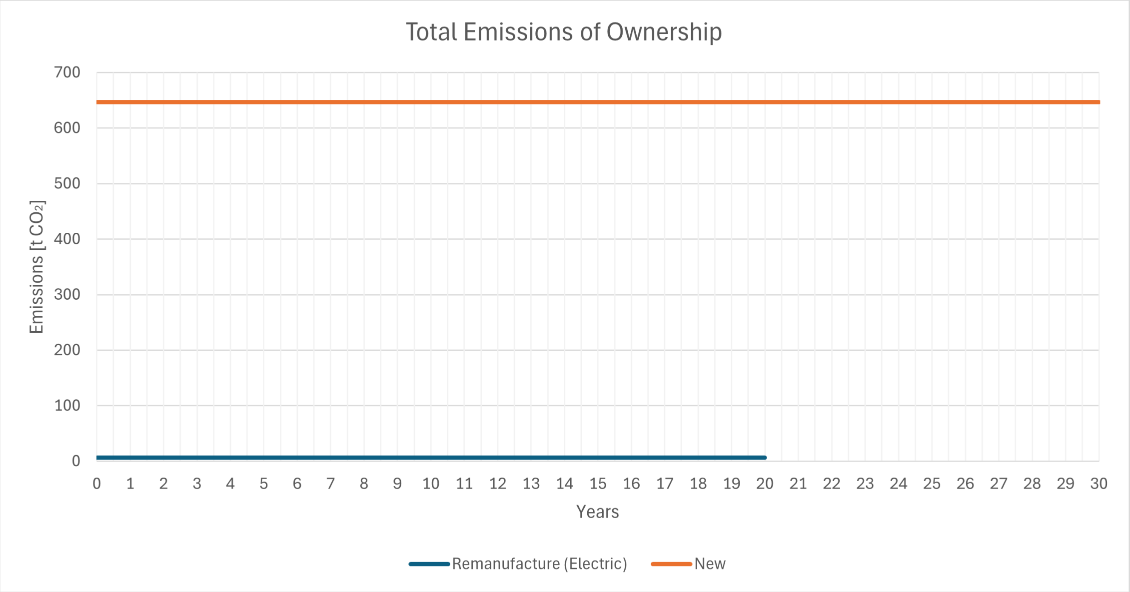


Figure 6.8: Total Emissions of Ownership Over Service Life: Remanufacture Electric vs. Newbuild Electric

resource depletion and upfront material demand. However, electrification may enable compliance with future emission regulations, potentially extending the vessel's functional relevance and environmental viability. From a lifecycle perspective, the electric refit represents a trade-off between high upfront environmental impact and near-zero operational emissions.

6.3.3. Economic Impact Area

The remanufacture to electric strategy exhibits the highest **CAPEX** among the refit options (Table 6.5). This is driven by the installation of large battery systems, high-voltage equipment, and system integration. Although the hull is retained, the material and installation intensity of electrification significantly increase CAPEX.

Compared to a newbuild electric vessel, the refit avoids full structural construction. The relative CAPEX advantage for the client is bigger than for the other refit strategies due to the high cost of electric propulsion components.

Table 6.5: Capital Expenditure Comparison 3

	Remanufacture Electric	**New** Electric
Expected Sales/Market Value [€] CAPEX (for client)	1,379	2,328

Contrary to upfront beliefs, the remanufacture to electric strategy offers the highest **OPEX**, mainly due to high energy and insurance costs. Energy costs are largely dependent on electricity pricing and charging strategy, while crew costs remain unchanged. Maintenance costs may decrease due to fewer mechanical components, but could increase due to battery degradation and replacement requirements. These effects are not yet quantified and are therefore not included in the current OPEX estimates. The results are shown in Table 6.6.

Table 6.6: Operational Expenditure Comparison 3

	Remanufacture Refit to Electric	**New** Electric
Operational Expenditure [€/year]	**199**	**210**
Crew Cost [€/year]	121	121
Energy Cost [€/year]	43	44
Maintenance Cost [€/year]	22	22
Insurance Cost [€/year]	14	23

The relation between CAPEX and OPEX is visualised through TCO in Figure 6.9. This shows an increased TCO at the end of service for both vessels compared to the other comparisons. This makes electric vessels only an option in low-utilisation profiles and ports with favourable electricity pricing or zero-emission incentives.

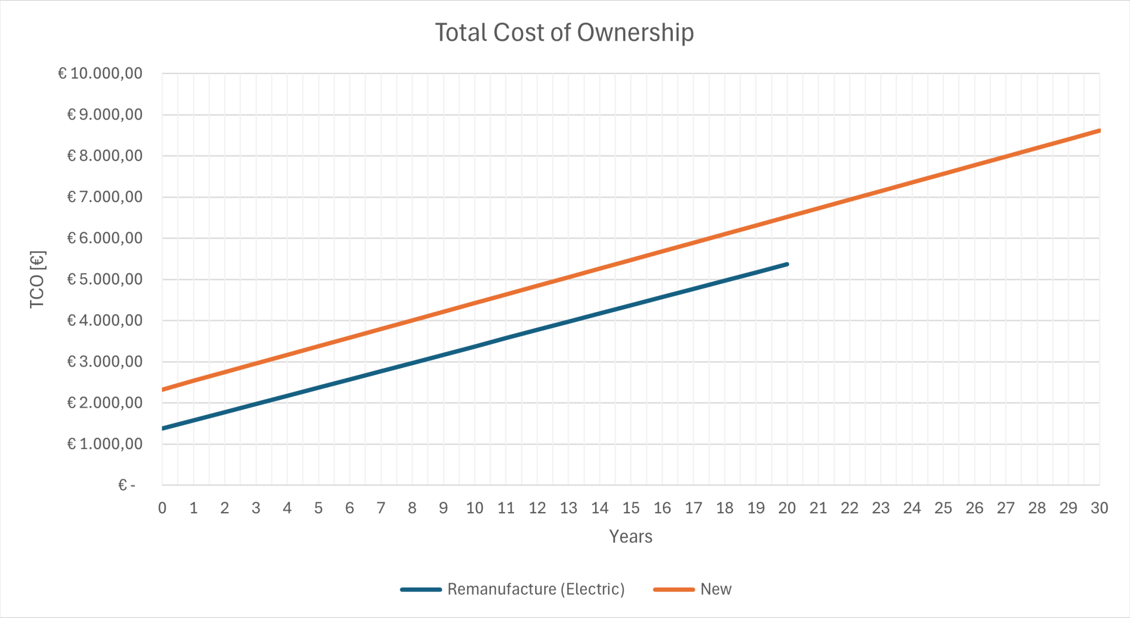


Figure 6.9: Total Cost of Ownership Over Service Life: Remanufacture Electric vs. Newbuild Electric

6.4. Comparison Refit Scenarios

This section compares the three refit strategies (refurbish, remanufacture to hybrid, and remanufacture to electric) to identify how the choice of circular strategy influences performance across strategic, environmental, and economic impact areas. Unlike the previous sections, which compared each refit strategy to its equivalent newbuild, this analysis focuses exclusively on the difference between refit approaches.

The comparison illustrates the fundamental trade-off in circular economy strategies: minimising intervention (refurbish) versus maximising performance improvement (remanufacture to electric). The hybrid remanufacture represents an intermediate position along this spectrum.

6.4.1. Strategic Impact Area

Time in Dock is estimated at 4 months for refurbish, 6 months for remanufacture to hybrid, and 8 months for remanufacture to electric. The longest **Component Lead Time** remains 6 months across strategies. Consequently, **Vessel Lead Time** is increases from 10 months for refurbish to 12 months for remanufacture to hybrid and 14 months for remanufacture to electric.

These results indicate that the propulsion system configuration influences the project duration when the refit works impact the structure of the vessel. The time-to-service benefit of refits compared with newbuilds (10–12–14 months versus 24 months) is therefore reduced for Remanufacture to Hybrid and Electric, yet a time advantage still remains.

With the timeline increase, **Complexity of Work** increases as well as the R-strategy moves from refurbish to remanufacture to electric, as shown in Table 6.7.

Table 6.7: Complexity of Work Refit Strategies

	Refurbish Conventional	**Remanufacture** Hybrid	**Remanufacture** Electric
Overall Complexity	**Medium**	**Medium-High**	**High**

This increase in complexity primarily stems from:

- **System integration requirements:** Hybrid and electric configurations require integration of power electronics, energy management systems, and battery management systems.
- **Structural modifications:** Electric retrofits may require hull reinforcement to accommodate battery weight and volume.
- **Coordination complexity:** More interfaces between new and existing systems increase coordination effort.

Higher complexity translates to increased execution risk and potential for schedule delays. This is reflected by longer timelines for higher R-strategies.

From a strategic perspective, refurbish represents the lowest-risk refit option, while remanufacture to electric introduces the highest execution risk. The choice between strategies therefore depends on the organisation's risk tolerance and technical capability.

All refit strategies require **Reclassification**, with an estimated duration of 10 days regardless of the propulsion configuration. This indicates that the choice of R-strategy does not significantly impact regulatory timeline, as classification societies have established frameworks for evaluating conventional, hybrid, and electric propulsion systems.

6.4.2. Environmental Impact Area

Capital emissions increase progressively from refurbish to remanufacture to electric due to increased material replacement. While the hull is retained in all cases (saving approximately 633-635 tonnes CO_{2e} compared to newbuild), the total capital emissions vary due to different outfitting.

- **Refurbish:** Lowest capital emissions (152 tonnes CO_{2e}) - only propulsion system and minor components replaced
- **Remanufacture to Hybrid:** Higher capital emissions due to battery systems and power electronics (specific value unavailable due to data limitations)
- **Remanufacture to Electric:** Highest capital emissions due to large battery banks and high-voltage equipment (specific value unavailable)

Despite data limitations preventing precise quantification for hybrid and electric configurations, the directional trend is clear: more extensive system replacement increases embodied emissions. However, all refit strategies achieve significant capital emissions reductions compared to newbuild alternatives.

Operational emissions exhibit an inverse relationship to capital emissions: strategies with higher upfront emissions deliver lower operational emissions. Figure 6.10 illustrates the Total Emissions of Ownership for the three refit strategies.

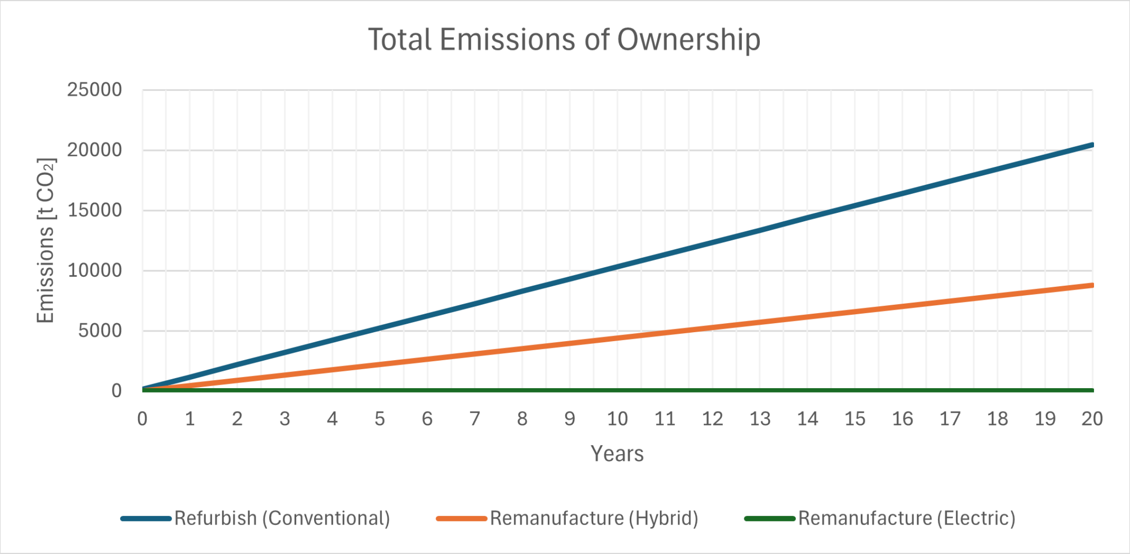


Figure 6.10: Total Emissions of Ownership Refit Strategies

Annual operational CO_2 emissions show a clear progression:

- **Refurbish:** 1,016 tonnes CO_2/year (highest operational emissions)
- **Remanufacture to Hybrid:** 438 tonnes CO_2/year (57% reduction vs. refurbish)
- **Remanufacture to Electric:** 0 tonnes CO_2/year under current reporting regulations (100% reduction)

The crossing point where higher capital emissions are offset by lower operational emissions depends on the assumed service life and operational profile. Given the 20-year remaining service life assumption, Hybrid and Electric strategies accumulate lower total emissions over their lifecycle despite their anticipated higher upfront impact.

The percentage of reused components decreases the R-strategy becomes more interventionist:

- **Refurbish:** 70% component reuse
- **Remanufacture to Hybrid:** 50% component reuse
- **Remanufacture to Electric:** 30% component reuse

This reflects the fundamental tension in circular economy strategies: achieving high performance improvements (emissions reduction, energy efficiency) often requires replacing more components, thereby reducing material reuse. The optimal balance depends on whether the priority is minimising resource extraction (favouring refurbish) or minimising lifecycle emissions (favouring remanufacture to electric).

6.4.3. Economic Impact Area

The economic comparison reveals a clear CAPEX-OPEX trade-off across the three strategies. Figure 6.11 illustrates the TCO for each refit option.

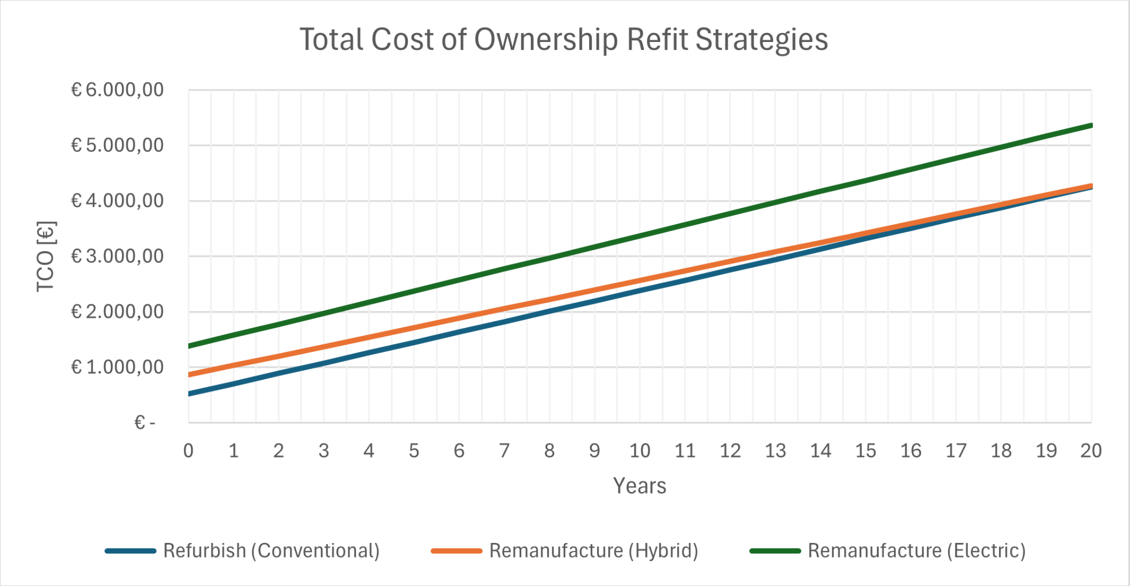


Figure 6.11: Total Cost of Ownership Refit Strategies

The starting point of Figure 6.11 is the expected market value of the vessel. Market values (CAPEX for the client) increase with propulsion system sophistication. Compared to Refurbish, Remanufacture to Hybrid yields a 67% increase in upfront investment and Remanufacture to Electric yields a 167% increase. These differences are visualised in Figure 6.12.

The increase in market value reflects both the higher cost of advanced propulsion components and the increased value proposition of emissions-reduced vessels. From the client's perspective, the higher upfront investment must be justified through operational savings, regulatory compliance benefits, or strategic positioning in emission-sensitive markets.

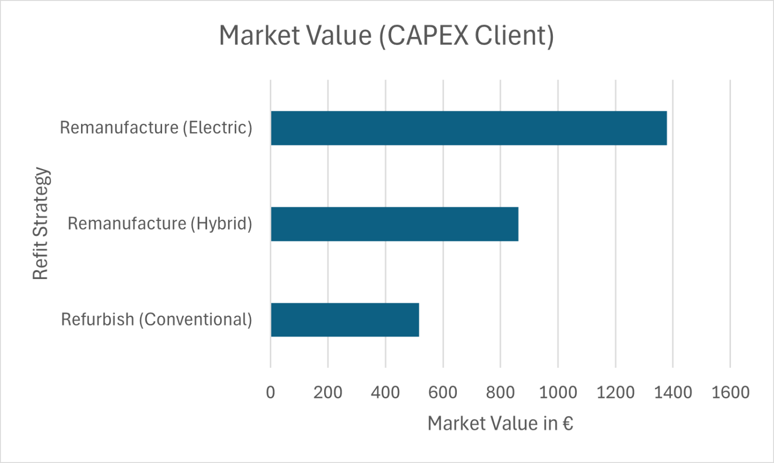


Figure 6.12: Market Value [€] (CAPEX for the Client) across all Refit Strategies

The slope gradient of Figure 6.11 is represented by the OPEX/year. Compared to Refurbish, OPEX/year decreases by 8% for Remanufacture to hybrid, and increases by 8% for Remanufacture to Electric.

The end point of Figure 6.11 represents the total TCO at the end of the vessel's 20-year service life. Refurbish results in the lowest TCO. The TCO for remanufacture to hybrid is similar to that of Refurbish.

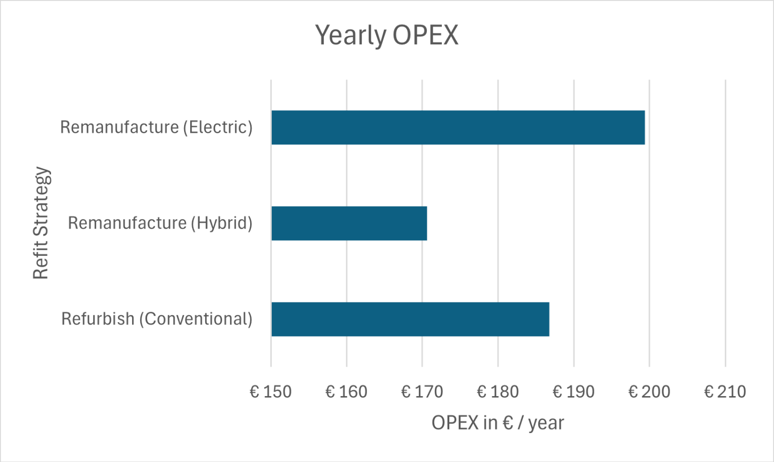


Figure 6.13: OPEX [€/Year] across all Refit Strategies

In contrast, remanufacture to Electric leads to a 26% increase in TCO relative to Refurbish. The large gap in TCO between Remanufacture to Electric and the other strategies arises from a higher OPEX in combination with a significant difference in market value between the vessels.

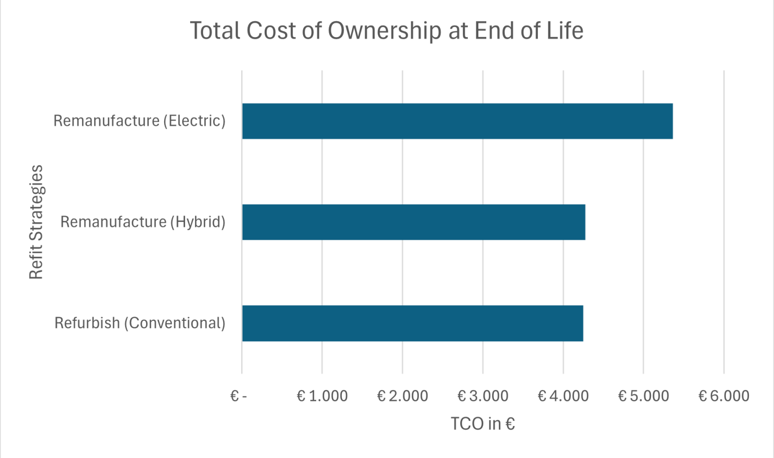


Figure 6.14: Total Cost of Ownership [€] at EoL across all Refit Strategies

These results indicate that under current economic conditions and the 20-year service life, Refurbish and Remanufacture to Hybrid strategies offer similar economic performance, while Remanufacture to Electric represents a premium option justified primarily by environmental or regulatory considerations rather than cost minimisation.

The cross-strategy comparison reveals distinct positioning for each refit option, summarised in Table 6.8. The optimal strategy depends on the stakeholder's strategic priorities, risk tolerance, capital availability, and operational context. No single strategy dominates across all dimensions, reinforcing the need for multi-criteria decision support tools that make these trade-offs explicit.

Table 6.8: Strategic Positioning of Refit Strategies

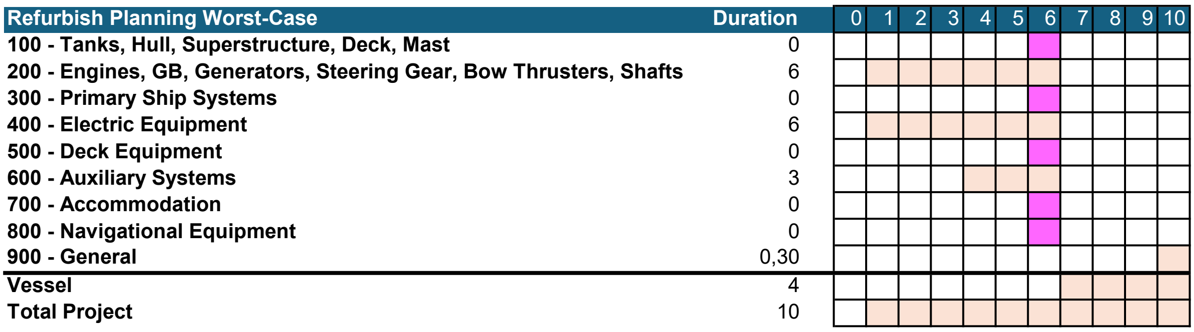
Strategy	Key Characteristics	Best Suited For	Trade-off
Refurbish	Lowest risk, lowest cost, fastest return on investment	Stable regulatory environments, cost-constrained operators, short remaining asset life	Higher operational emissions limit long-term environmental competitiveness
Remanufacture to Hybrid	Balanced risk-return profile, moderate cost increase, significant emission reduction	Operators anticipating regulatory tightening, emission-sensitive ports, medium-term investment horizons	Increased complexity without eliminating fuel dependency
Remanufacture to Electric	Highest risk and cost, maximum emission reduction potential	Zero-emission mandates, shore power availability, operators prioritising sustainability credentials	Economic viability dependent on favourable electricity pricing and regulatory incentives

6.5. Sensitivity Analysis

This section examines how robust the results are to some KPI assumptions by testing how changes in planning logic, vessel lifetime, and energy prices affect strategic, environmental, and economic impact areas. The sensitivity analysis follows the same underlying approach used in the baseline assessments. Therefore, only the resulting shifts in KPI performance are discussed. This section highlights where the preferred strategies remain stable and where they are most vulnerable to contextual changes.

6.5.1. Strategic KPI Sensitivity

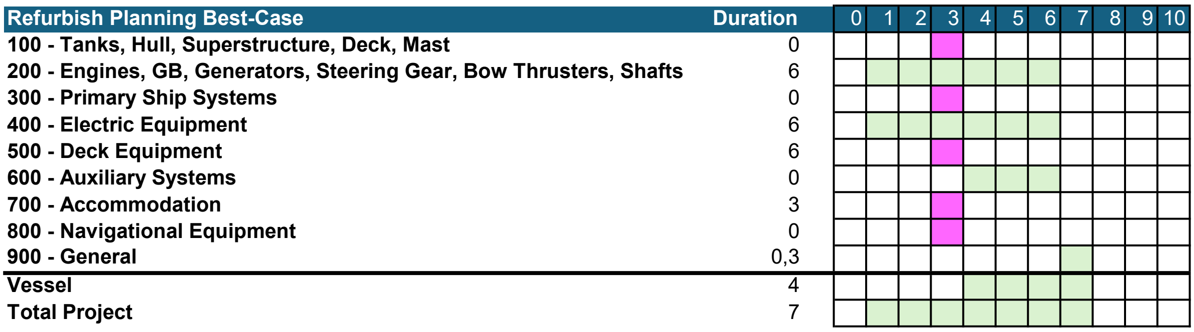
In the baseline planning assumption, the component with the longest lead time is ordered such that it arrives at the start of the vessel's Time in Dock, under the assumption that all components are required from the outset of installation. This conservative assumption is reflected in the longest (worst-case) planning depicted in Figure 6.15.



Refurbish Planning Worst-Case	Duration	0	1	2	3	4	5	6	7	8	9	10
100 - Tanks, Hull, Superstructure, Deck, Mast	0							■				
200 - Engines, GB, Generators, Steering Gear, Bow Thrusters, Shafts	6		▨	▨	▨	▨	▨	▨				
300 - Primary Ship Systems	0							■				
400 - Electric Equipment	6		▨	▨	▨	▨	▨	▨				
500 - Deck Equipment	0							■				
600 - Auxiliary Systems	3					▨	▨	▨				
700 - Accommodation	0							■				
800 - Navigational Equipment	0							■				
900 - General	0,30											▨
Vessel	4								▨	▨	▨	▨
Total Project	10		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure 6.15: Refurbish Planning Worst Case

In practice, however, not all components are necessarily required at the start of the refit or newbuild project. Certain components may only be needed at a later stage of the installation sequence. Therefore, the timing of component installation has a significant influence on the total vessel lead time. For the refurbish strategy, assuming a component installation offset of one month reduces the total project duration from ten months to seven months. The corresponding shortest possible (best-case) planning is shown in Figure 6.16.



Refurbish Planning Best-Case	Duration	0	1	2	3	4	5	6	7	8	9	10
100 - Tanks, Hull, Superstructure, Deck, Mast	0				🟪							
200 - Engines, GB, Generators, Steering Gear, Bow Thrusters, Shafts	6		🟩	🟩	🟩	🟩	🟩	🟩				
300 - Primary Ship Systems	0				🟪							
400 - Electric Equipment	6		🟩	🟩	🟩	🟩	🟩	🟩				
500 - Deck Equipment	6				🟪							
600 - Auxiliary Systems	0					🟩	🟩	🟩				
700 - Accommodation	3				🟪							
800 - Navigational Equipment	0				🟪							
900 - General	0,3								🟩			
Vessel	4					🟩	🟩	🟩	🟩			
Total Project	7		🟩	🟩	🟩	🟩	🟩	🟩	🟩			

Figure 6.16: Refurbish Planning Best Case

The actual vessel lead time is expected to fall between these two boundary conditions, depending on the specific installation sequence adopted. Applying this reasoning across all vessel scenarios yields the longest (worst-case) and shortest (best-case) lead time estimates presented in Table 6.9.

Table 6.9: Planning Range (Shortest-Longest) across all Refit Strategies

		Shortest Planning	**Longest Planning**	**Critical**
Refurbish	Conventional	7	10	Component
New		19	24	Dock
Remanufacture	Hybrid	7	12	Component
New		19	24	Dock
Remanufacture	Electric	8	10	Dock
New		19	24	Dock

The findings show that a tightly structured building or refit planning can significantly shorten the overall vessel lead time. Yet, a more compressed schedule is naturally more vulnerable to disruptions, since any deviation from the intended installation sequence can directly affect the final project completion date. In the refurbish and remanufacture to hybrid scenarios, component lead time is longer than the time in dock, meaning that the procurement schedule becomes the critical path and thus the main driver of potential delays. At the same time, assuming a shorter installation window reduces the available float to absorb unexpected disruptions in dock operations. In all other scenarios, newbuild vessels and remanufacture to electric, the time in dock exceeds the component lead time, making the time in dock the critical path instead.

6.5.2. Environmental KPI Sensitivity

The sensitivity of the TEO results to vessel service life was assessed by varying the remaining operational lifetime of both refitted and newbuild vessels around the baseline assumption of 20 and 30 years, respectively. Shortening the lifetime of newbuild vessels to 25 or even 20 years does not alter the conclusions. Only when the conventional newbuild has an unrealistically short service life of 6 years or less does the refurbish strategy become more favourable, an outcome not representative of real-world vessel lifetimes.

Figure 6.17 explores a scenario in which refitted vessels reach the end of their service life after 15 years and require renewal, either via a second refit (when possible) or by acquiring a replacement refitted vessel, while newbuild vessels retain their 30-year lifetime. The results show that the embodied emissions occurring at the beginning of the conventional vessel's lifetime are so small relative to operational emissions that repeating them after 15 years has a barely visible effect on the slope of the TEO line. For hybrid and electric refits, the lines lie so close to their newbuild equivalents that embodied emissions may influence results more strongly in those configurations than in the refurbish case. However, these effects could not be evaluated further due to missing BoM data, and additional research is therefore recommended.

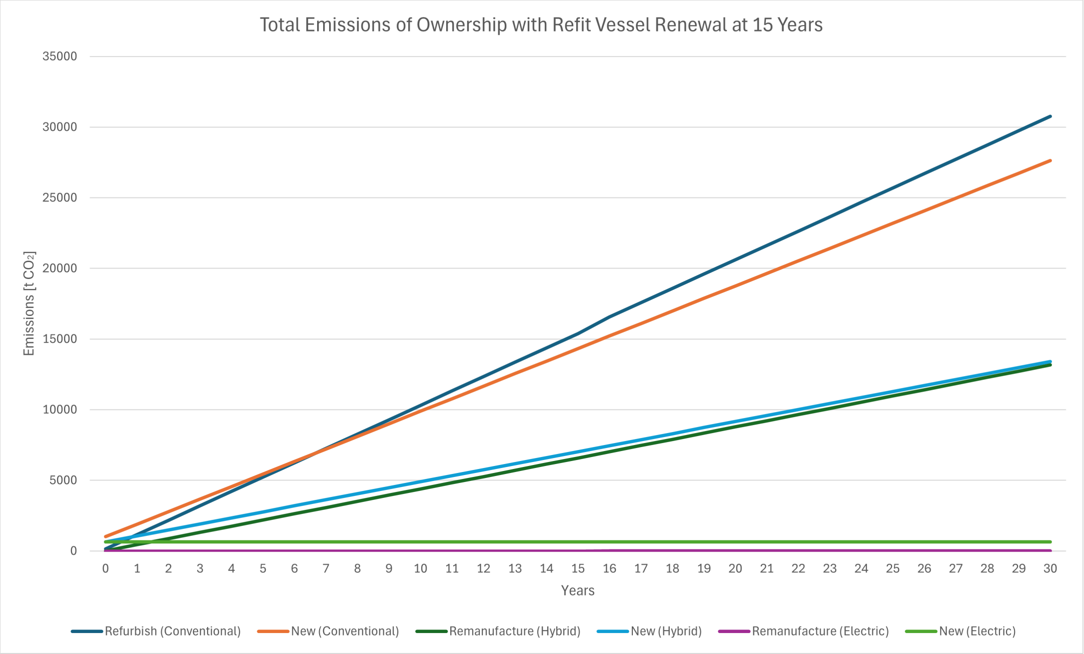


Figure 6.17: Total Emissions of Ownership [t CO_2] with Refit Vessel Renewal at 15 Years

6.5.3. Economic KPI Sensitivity

TCO Sensitivity to Vessel Lifetime

Following the TEO sensitivity assessment, the same variations in vessel service life were applied to evaluate how robust the TCO conclusions are under different lifetime assumptions. Because the methodological approach is identical to the previous analysis, only the results specific to economic performance are discussed here.

The results indicate that TCO is more sensitive to service-life changes than TEO. Reducing the operational lifetime of newbuild vessels from 30 to 25 or even 20 years does not alter the ranking of the strategies. Refit options remain cost-advantageous relative to newbuild, and the difference in cumulative cost remains similar to the baseline. The dominant role of CAPEX drives this stability. Even when operational life is shortened, the upfront investment required for a newbuild is sufficiently high that it continues to outweigh any cost disadvantages of refitting. Extending the service life of newbuild vessels likewise does not alter the current conclusions. Under current cost conditions, a new hybrid vessel would need to operate for at least 48 years to achieve better economic performance than a conventional newbuild.

A second scenario examined the case in which refitted vessels reach EoL after 15 years and require renewal, either through a second refit (if possible) or by replacing the vessel with another refitted alternative, while the newbuild retains its 30-year lifetime. Figure 6.18 shows that under this assumption, the refit TCO curves shift upward after 15 years. Even with a mid-life renewal, the position of the cumulative TCO of the refurbish and remanufacture to hybrid scenarios relative to their newbuild equivalents remains unchanged. For the electric vessels, mid-life renewal makes the electric refit less favourable than its newbuild alternative. The results show that even with the financial impact of a midlife renewal, refurbish and remanufacture strategies still have a competitive TCO.

The overall conclusion is that the TCO approach is robust to variations in vessel lifetime across all realistic scenarios. The big difference in CAPEX between refits and their equivalent newbuilds is not bridgeable by a small difference in OPEX. As a result, the economic preference for refit over newbuilds holds under both conservative and optimistic service-life assumptions.

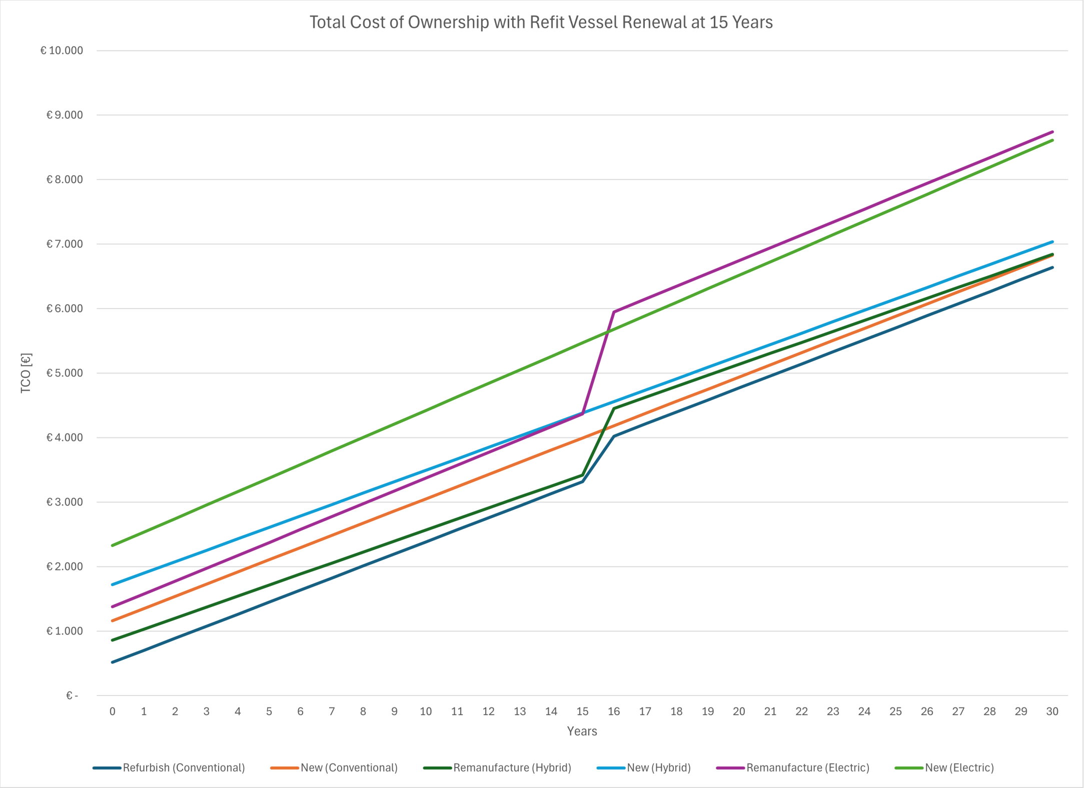


Figure 6.18: Total Cost of Ownership [€] with Refit Vessel Renewal at 15 Years

TEO Sensitivity to Energy Prices

Electricity and MGO are used as fuels, and both are commodities exposed to market fluctuations. Consequently, the assumed price levels may vary over time. Since energy costs account for a substantial share of the TCO, fluctuations in fuel and electricity prices can significantly influence TCO outcomes over the vessel's lifetime.

Both the hybrid and the fully electric vessel rely on electricity. In the current calculations electric vessels incur the highest operational expenses, partially because of high energy costs. Table 6.10 summarises how variations in fuel and electricity prices influence the TCO across the vessel's lifetime. The results show that a worst-case MGO price, when combined with either current or best-case electricity prices alters the relative cost trajectories of the three refit strategies. Similarly, current MGO prices paired with best-case electricity prices shift the TCO dynamics in favour of the hybrid vessel. Notably, the combinations *current electricity x worst MGO* and *current MGO x best electricity* produce similar outcomes, the difference being the height of the TCO at EoL (lower across all strategies for the second market scenario).

The most pronounced effect arises under the combination of worst-case MGO prices and best-case electricity prices, where the hybrid vessel becomes the most cost-effective option after approximately 17 years. In all other market scenarios, the cost curves may shift upward or downward, and in some cases become slightly more convergent or divergent towards the vessel's EoL. This divergence is particularly visible for the electric vessel. As electricity prices worsen, its TCO curve steepens more sharply than those of the hybrid and conventional vessels, indicating a higher sensitivity to adverse electricity price developments. Despite these variations, the overall TCO results for the different strategies remain unchanged for the majority of price combinations.

Table 6.10: Sensitivity analysis for fuel and electricity price scenarios

Fuel Price \ Electricity Price	Worst Case	Current Case	Best Case
Worst Case	No significant changes compared to the current situation.	After **19** years hybrid becomes favourable over Conventional. At EoL, the difference is marginal.	After **17** years hybrid becomes favourable over conventional.
Current Case	No significant changes compared to the current situation.	Current situation as calculated and analysed.	After **19** years hybrid becomes favourable over conventional refit. At EoL, the difference is marginal.
Best Case	At EoL, the cost gap between the vessels increases, with the electric even more expensive and the hybrid clearly the more expensive than conventional.	No significant changes compared to the current situation.	No significant changes compared to the current situation.

6.6. Conclusion

From the case study it can be concluded that refitting existing tugboats is a credible and often preferable alternative to newbuild vessels, when strategic, environmental, and economic impacts are considered together. Across all assessed scenarios, refits perform similarly or outperform newbuilds across the impact areas.

Strategically, refit projects offer 58% shorter lead times than newbuilds (10 vs. 24 months), enabling faster fleet availability. Although remanufacture to hybrid and electric increases project complexity, this does not translate into longer execution times and can be managed within existing yard schedules. Strategic risks associated with vessel unavailability during refit can be mitigated through temporary replacement solutions, making refits operationally feasible for shipowners.

Environmentally, the largest benefit lies in avoiding approximately 633-535 tonnes CO_2 in hull-related embodied emissions. Refurbish yields the lowest capital emissions, while hybrid and electric remanufacture introduce higher upfront emissions but deliver substantially reduced operational emissions. Operational emissions dominate Total Emissions of Ownership over the 20-year service life, making operational profile and fuel/electricity pricing decisive factors.

Economically, refits require significantly lower CAPEX for the client (€517 vs. €1,164 for conventional vessels). Total Cost of Ownership results show that refurbish and remanufacture to hybrid strategies perform similarly (€4,253 vs. €4,275), while remanufacture to electric has a significantly higher TCO over its service life (€5,367). This makes the choice for the electric remanufacture vessel primarily justifiable by environmental or regulatory considerations.

The analysis demonstrates there is no universally optimal strategy. Rather, the KPI results enable structured decision-making by making trade-offs explicit. Refurbish minimises cost and risk but has higher operational emissions. Hybrid balances cost and environmental performance. Electric maximises emissions reduction, but requires favourable economic conditions. The optimal choice depends on the stakeholders' coordination of strategic priorities, regulatory environment, capital availability, and operational context.

While successfully calculating most KPIs, the case study revealed data gaps for Solid Waste Reduction, Component Cost Share, and limited informational value for Value Added and Value Retention. Embodied CO_{2e} for hybrid and electric configurations could only be partially quantified due to insufficient material data for battery systems. These limitations indicate where enhanced data collection or standardisation (such as digital product passports) would strengthen future applications.

Overall, refit strategies represent a robust pathway toward sustainable fleet renewal. The framework demonstrates practical applicability for decision support, while highlighting areas requiring ongoing refinement as operational data from alternative propulsion systems becomes available. The next chapter evaluates the framework's effectiveness and provides recommendations for broader application.

7

Evaluation

This chapter evaluates the KPI-based framework developed and applied in this research. While Chapter 5 assessed the calculability and data quality of individual KPIs, and Chapter 6 demonstrated their application to the tugboat case study, this chapter takes a step back to evaluate the framework itself: its effectiveness as a decision support tool, its generalisability beyond the case study context, and its practical applicability in industry settings.

This evaluation informs the recommendations in Section 7.5 and provides context for interpreting the contributions and limitations of this research. Unlike previous chapters, that focused on specific KPIs and case study results, this chapter evaluates the methodology as a whole and its potential for broader application.

7.1. Framework Assessment

7.1.1. Effectiveness of the Multi-Criteria Approach

The framework's organisation around three impact areas, Strategic, Environmental, and Economic, proved effective in capturing the multi-dimensional nature of refit decisions. The case study demonstrated that no single strategy dominated across all dimensions, validating the need for multi-criteria evaluation rather than single-objective optimisation.

The framework successfully made trade-offs explicit. For example, the refurbish strategy emerged as the lowest-cost but highest operational emissions, while remanufacture to electric showed the inverse pattern. These trade-offs would remain hidden in single-criterion analyses focused only on cost or only on emissions. The strategic positioning table (Table 6.8) effectively synthesised these trade-offs into actionable decision support.

The framework does not prescribe weighting across impact areas. A decision-maker must still determine whether a 21% cost increase (refurbish to electric) is acceptable for 100% operational emission reduction. While this preserves objectivity and allows context-specific weighting, it also means the framework supports but does not replace managerial judgment.

The multi-criteria approach is appropriate for this decision problem. The three impact areas align with industry decision factors (time-to-market, regulatory compliance, profitability), and the balanced presentation of trade-offs enables informed decision-making without prescribing a single solution.

7.1.2. Applicability of R-Strategy Framework to Vessels

The research applied the circular economy R-strategy hierarchy (reuse, refurbish, remanufacture) from product-focused literature to vessel refits. This translation proved largely successful, with some important qualifications.

The R-strategy concept effectively differentiated between intervention levels. Refurbish (minimal intervention, retain propulsion concept) versus remanufacture (extensive intervention, change propulsion) represents a meaningful distinction that corresponds to different complexities, cost structures, and environmental outcomes. The hierarchy predicted that lower R-strategies (refurbish) would have higher component reuse and lower complexity, while higher R-strategies (remanufacture to electric) would have lower reuse but better environmental performance.

The R-strategy framework originates from product lifecycles measured in years, applied here to assets with 20-30 year lifespans. This creates tension because vessels have longer economic lives but shorter technological relevance cycles. A vessel refurbished in 2025 may be technologically obsolete by 2035 due to regulatory changes, even though structurally sound. This suggests that for long-lasting assets, technological upgrading (remanufacture) can in some cases be the more circular option, because it reduces the overall environmental impact more than a minimal intervention (refurbish), inverting the traditional hierarchy.

The R-strategies repair, repurpose, and recycle were not evaluated. Repair (fixing specific failures) was, in this case, too limited an option given the vessel's condition. However, for vessels that are still in service and remain in class, it would be the preferred strategy. Repurpose (changing vessel function entirely) and recycle (reuse materials of the vessel) represent end-of-life rather than life-extension strategies. This suggests the framework is specific to mid-life intervention decisions rather than applicable across the full R-strategy spectrum.

The R-strategy framework applies to vessels with contextual adaptation. The distinction between refurbish and remanufacture is meaningful and useful, but the assumption that ”lower is better” does not always hold for long-lived, regulation-sensitive assets.

7.1.3. Comparison Structure Validity

The three-comparison structure (conventional, hybrid, electric) effectively demonstrated how propulsion technology choices interact with the refit vs. newbuild decision. Each comparison included both a refit and a newbuild option with the same propulsion system, enabling a controlled comparison that isolated the refit/newbuild variable while holding propulsion constant.

This structure revealed that refit advantages (lower CAPEX, faster timeline) persist across propulsion types, while refit disadvantages (complexity increase, data gaps) scale with technological sophistication. This consistency across comparisons strengthens confidence in the findings.

The comparisons assumed the same operational profile of 43% of time spent free sailing and 57% in bollard pull, with a 95% availability and 3 jobs/day across all vessels. In practice, operators might adjust utilisation based on the area of operation (e.g., using electric only in emission-controlled areas). Sensitivity to operational assumptions was acknowledged but not quantified through scenario analysis.

The comparison structure was appropriate for the research question and yielded robust findings, though sensitivity analysis would strengthen future applications.

7.2. Generalisability and Boundaries

This section evaluates the extent to which the framework and findings can be transferred to other contexts beyond the tugboat case study.

7.2.1. Vessel Type Transferability

The framework's suitability differs across vessel types, primarily because of variations in design standardisation, refit market maturity, and the predictability of operational profiles. Although transferability is more limited for highly customised vessels when comparing refit and newbuild strategies, this limitation mainly concerns benchmarking refits against equivalent newbuilds.

Once a decision has been made to refit a vessel, the framework can still be used to quantify the effects of specific R-strategies and to help identify the most appropriate option for that vessel. Table 7.1 provides an overview of transferability across vessel categories for the refit versus newbuild comparison.

Table 7.1: Framework Transferability Assessment by Vessel Type

Vessel Category	Transferability	Key Considerations	Confidence
Similar Workboats (Anchor handling, port surveillance)	High	Standardised designs. Active second-hand markets. Regional operations with consistent regulations.	High
Short-Sea Commercial (Cargo vessels, ferries)	Moderate	Higher cargo capacity necessitates a detailed analysis of weight distribution. Hull modifications for electric propulsion have more impact. Variable operational profiles.	Moderate
Fishing Vessels	Moderate	Highly variable operational profiles complicate emission calculations. Different regulatory landscape.	Moderate
Deep-Sea Cargo	Low	Global operations span multiple regulatory regimes. Fuel efficiency dominates emissions profile. Less developed refit market.	Low
Specialised Vessels (Cruise, naval)	Very Low	Highly customised designs. Client-specific requirements dominate. Limited standardisation benefits.	Low

The full framework works best for vessel types with active refit markets, standardised designs enabling comparison, and regional operations where the regulatory context is consistent.

7.2.2. Geographic and Regulatory Context

The case study assumed European regulatory context (EU emission regulations, EU electricity costs, classification requirements). Table 7.2 assesses framework applicability across different regional contexts.

Table 7.2: Framework Applicability Across Geographic and Regulatory Contexts

Context Area	Region/Scenario	Applicability	Key Adjustments Required
Regulatory	Similar emission reporting (operational only)	Direct transfer	None - apply as-is.
	Lifecycle emission accounting	Modified	Increase the weight on capital emissions. May change strategy rankings.
	Different classification societies	Modified	Adjust reclassification requirements.
Economic	Low electricity, high fuel prices	Modified	Change the electricity and fuel prices. TCO of electric vessels improves significantly vs. case study.
	High electricity, low fuel prices	Modified	Change the electricity and fuel prices. TCO for electric vessels becomes less attractive. Conventional/hybrid favoured.
	Subsidy regimes for clean propulsion	Modified	Reduce electric/hybrid CAPEX disadvantage by subsidy amount
Market Maturity	Mature refit markets (Europe, SE Asia)	Direct transfer	Component availability, yard capability established
	Emerging markets (Latin America, Africa)	Limited	Component availability and yard capability may limit remanufacture options

7.2.3. Identified Limitations

The framework explicitly excludes several factors relevant to refit decisions. Table 7.3 categorises these limitations by impact on decision-making.

Table 7.3: Framework Scope Limitations and Mitigation Strategies

Limitation Category	Excluded Factors	Decision Impact	Mitigation
Organisational & Stakeholder	Corporate sustainability commitments, ESG reporting, Financing structures, Crew training, Risk appetite, Innovation culture	High	Complement with stakeholder analysis
Technical Constraints	Classification society requirements, Shipyard capacity, Supply chain resilience, Vessel-specific barriers (space, weight, power)	Medium-High	Technical feasibility study before KPI analysis
Market Dynamics	Second-hand vessel market volatility, Fuel price forecasting (20-30 yr), Technological disruption (H_2, NH_3, batteries)	Medium	Scenario analysis with sensitivity bounds
Regulatory Uncertainty	Future carbon taxation, Emission trading schemes, Zero-emission mandates, Lifecycle vs. operational accounting	High	Incorporate regulatory roadmaps (IMO 2030/2050)
Client-Specific Requirements	Unique operational needs, Preferred suppliers, Performance specifications, Port access requirements	Medium	Customisation layer on top of framework

These exclusions do not invalidate the framework but define its boundaries: it provides systematic KPI-based comparison to inform decisions, but must be complemented with qualitative assessment of organisational, technical, and market factors. The Decision Impact column indicates which limitations most significantly affect outcomes, with organisational factors and regulatory uncertainty having the highest impact on real-world decision-making.

7.3. Methodological Reflection

Reflecting on the research methodology, several choices warrant evaluation. The use of one tugboat refit as the primary case study enabled deep analysis but limits generalisability confidence. A multiple case study design comparing different vessel types (e.g., tugboat, ferry, fishing vessel) would have strengthened transferability claims, at the cost of increased data collection burden and reduced depth per case. Given the exploratory nature of applying R-strategies to vessels and the data access challenges, the single-case approach was appropriate, though follow-up research should expand to multiple cases across different vessel types.

Chapter 6 acknowledged sensitivity of lead times, fuel/electricity pricing and lifetime extension and their impact on TCO. Incorporating sensitivity analysis with best-worst case variations in vessel life extension and fuel/electricity prices provided confidence intervals for TCO rankings and threshold conditions where strategy rankings change.

Many KPIs relied on expert judgement (complexity, component reuse, lead times) due to limited historical refit data. While expert estimates enabled KPI calculation, they introduce subjectivity and potential bias. As refit data accumulates, validation studies comparing expert estimates to actual outcomes would strengthen the methodology and improve future estimates.

The framework evaluates decisions at a single point in time under current regulations and prices. Incorporating collaboration with class societies and other sector stakeholders would improve the reflection on long-term environmental and investment decisions. This would strengthen the method for future sector wide implementation.

The methodology was appropriate for the research objectives, though future applications would benefit from multi-case validation.

7.4. Practical Applicability

For the framework to provide value beyond academic contribution, it must be usable by industry practitioners. Table 7.4 assesses implementation requirements, barriers, and pathways.

Table 7.4: Framework Implementation Readiness Assessment

Dimension	Requirements / Barriers	Assessment & Recommendations
Data Access	*Required:* BoM, cost data, operational profiles *Barrier:* Data scattered across departments	Available within large shipbuilders. External consultants face barriers. Develop a centralised KPI database.
Personnel	*Required:* Analyst hours Multi-disciplinary input *Barrier:* Accessing and delivering data is not prioritised	Feasible for large organisations. Smaller organisations may require external support. Consider phased implementation.
Tools	*Required:* Spreadsheet software *Barrier:* None - no specialised LCA software needed	Low barrier to entry. Improves accessibility vs. complex LCA tools.
Organisational Fit	*Required:* Impact areas map to existing functions (Operations, Finance) *Barrier:* These tasks are not prioritised within these functions	Aligns well with strategic planning processes. Facilitates cross-functional collaboration.
Cultural	*Required:* Prioritisation and presentation of findings *Barrier:* Data transparency norms, confidentiality concerns	May conflict with competitive secrecy. Framework deliberately doesn't prescribe a single answer - some prefer simpler tools.

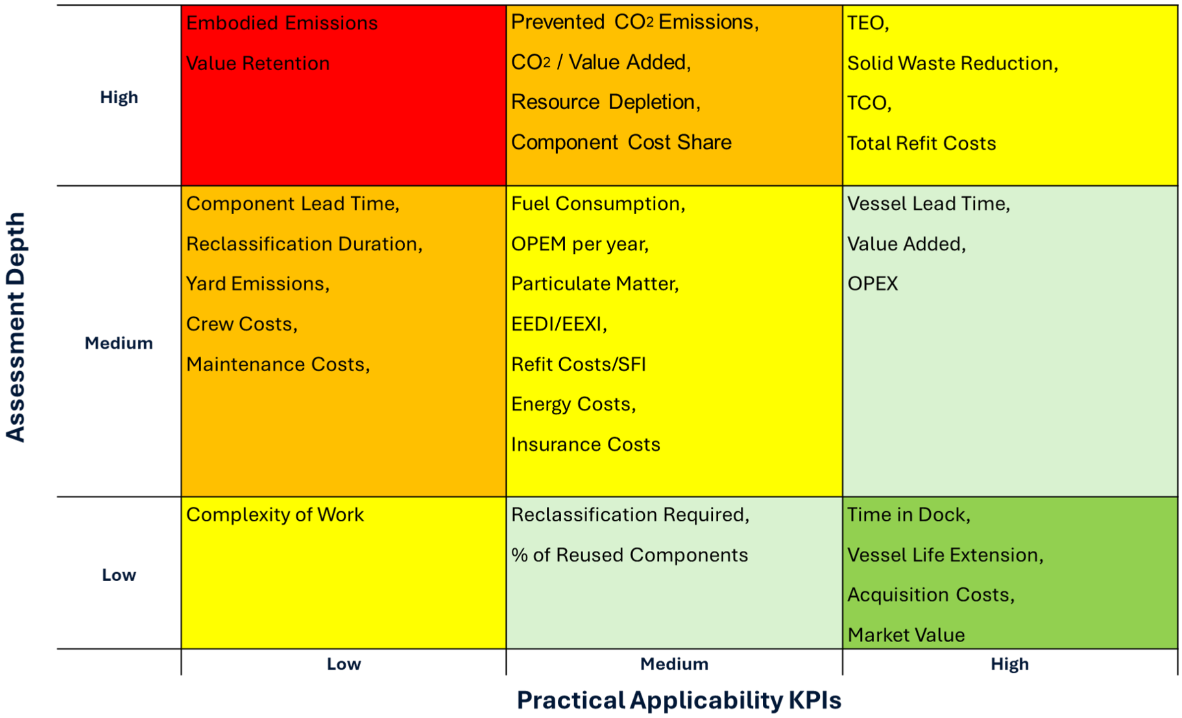
All KPI results were jointly reviewed with the DFS management team to identify which indicators they considered most meaningful and supportive in their decision-making. Using Table 3.7 to assess the depth of analysis required for each KPI, the KPIs were then positioned in a practical applicability matrix (low, medium, high). This resulted in the matrix depicted in Figure 7.1.

The matrix reveals a clear pattern: KPIs that combine moderate assessment depth with high practical applicability provide the strongest decision value for DFS. This prioritisation also preserves a balance across strategic, environmental and economic impact areas, ensuring that the decision framework does not become dominated by a single impact area. The limited amount of environmental KPIs in the high-applicability category is because the TEO indicator already captures much of the environmental insight the management team finds relevant.

For practical implementation, the KPIs in the lower-right half of the matrix should be prioritised. These medium-depth, high-applicability indicators (vessel lead time, value added, and OPEX) offer a strong balance between effort and decision value. Environmental KPIs such as OPEM and Particulate Matter form the next tier for adoption once additional data is available.

Time in dock, vessel life extension, acquisition costs, and market value constitute quick wins. They are easy to obtain and useful for initial screening, but they are not in themselves sufficient to choose between strategic options.

KPIs located in the upper-left part of the matrix largely represent intermediate values needed to calculate higher-priority KPIs in the middle or top right. This means that although some high-depth but low-applicability indicators must be computed as inputs, reporting them adds little value for decision-making.



Assessment Depth	Low	Medium	High
High	Embodied Emissions Value Retention	Prevented CO_2 Emissions, CO_2 / Value Added, Resource Depletion, Component Cost Share	TEO, Solid Waste Reduction, TCO, Total Refit Costs
Medium	Component Lead Time, Reclassification Duration, Yard Emissions, Crew Costs, Maintenance Costs,	Fuel Consumption, OPEM per year, Particulate Matter, EEDI/EEXI, Refit Costs/SFI Energy Costs, Insurance Costs	Vessel Lead Time, Value Added, OPEX
Low	Complexity of Work	Reclassification Required, % of Reused Components	Time in Dock, Vessel Life Extension, Acquisition Costs, Market Value

Practical Applicability KPIs

Figure 7.1: Assessment Depth versus. Practical Applicability KPIs

As CE practices become more embedded in regulations, intermediate indicators such as yard emissions and embodied emissions may gain importance in the future. Because the prioritisation incorporates DFS management's input alongside analytical criteria, the selected KPIs are not only technically justified but also more likely to be adopted in practice.

The two main limitations highlighted through this collaboration are the availability of electric charging infrastructure for hybrid and fully electric vessels, and the training of mechanics and electricians working on board. Non-standard configurations demand different competencies from staff. This situation motivates shipyards and educational institutions to cooperate in equipping the next generation with the skills needed to handle the technological advances implemented on vessels.

7.5. Recommendations

7.5.1. Framework Enhancements

Future applications should incorporate scenario analysis that varies regulatory assumptions and maintenance projections. Presenting results as ranges or confidence intervals rather than point estimates would better reflect uncertainty and strengthen decision-making robustness.

In addition to scenario analysis, the current TCO and TEO analysis apply undiscounted values over the vessel's lifetime, treating impacts in year 1 and year 20 equivalently. Incorporating net present value (NPV) or internal rate of return (IRR) methods with appropriate discount rates would better reflect the time value of money and emissions and improve environmental and economic decision-making. This is particularly relevant when comparing high-CAPEX/low-OPEX strategies against low-CAPEX/high-OPEX strategies (conventional).

The study also introduces the Value Gain Ratio (Value Added / Total Refit Costs), which directly assesses whether a refit produces more value than it costs. Because this KPI overcomes the interpretation limitations of Value Retention and Value Added individually, it is recommended that the Value Gain Ratio be incorporated as a core economic KPI for early-stage refit screening.

A second major enhancement relates to data quality and availability. The greatest data challenge encountered was quantifying embodied emissions for hybrid and electric components due to incomplete material specifications. Industry-wide adoption of digital product passports documenting component materials, masses, manufacturing emissions, and EoL pathways would dramatically improve framework accuracy and reduce analysis time. These passports should store component-level material data (weights, grades, suppliers, embodied CO_{2e}), circularity data (repair, refurbish, remanufacture labels), operational and maintenance logs, and regulatory/compliance certificates. This would enable more accurate TEO calculations, improve reuse rate KPIs and increase comparability across refit options.

Finally, discussions with the DFS management team indicate that the framework is practically applicable for large shipbuilders or operators with existing data infrastructure, but may pose challenges for smaller organisations. A phased implementation pathway can facilitate progressive adoption.

Phase 1: Simplified version (4-5 green KPIs Figure 7.1)
Phase 2: Internal database development (expand to yellow KPIs Figure 7.1)
Phase 3: Full framework adoption (all KPIs)

7.5.2. Future Research Directions

Future research can further strengthen the applicability and robustness of the developed framework. Several directions are recommended.

First, the boundary conditions of the environmental assessment can be expanded. Late in the research, it was decided that the vessel would be equipped with an SCR system to achieve IMO Tier III compliance. This modification affects all three impact areas: environmental performance (emission reductions), economic performance (increased CAPEX), and strategic performance (complexity of work, lead time). Because the SCR system was not included in this study's calculations, an assessment of its impact is recommended as future work. In addition, the current framework applies IMO Tank-to-Wake reporting, which assigns zero operational emissions to electric vessels. Future research should evaluate Well-to-Wake emissions by including grid carbon intensity or upstream fuel production emissions, allowing a more comprehensive comparison between propulsion types.

Second, as operational data for hybrid and electric vessels becomes available, retrospective analysis comparing projected versus actual performance, such as energy consumption, maintenance requirements, and reliability, would validate model assumptions and improve future TCO and TEO predictions.

Third, the long-term behaviour of energy storage systems requires deeper investigation. Battery degradation, mid-life replacement, and EoL scenarios were not evaluated in this study, but have a substantial influence on CAPEX, OPEX, embodied emissions and overall circularity. Future research should incorporate battery lifecycle modelling into TEO and TCO.

Fourth, although this study confirmed that the required hybrid and electric technologies are available and theoretically compatible with the vessel class, no stability assessments or spatial integration studies were performed. Future research should therefore evaluate the technical feasibility of implementing hybrid and electric refits for this vessel specification, including structural integration, weight distribution, and operational safety considerations.

Fifth, the framework could be enriched by incorporating perspectives from additional stakeholders, such as classification societies, regulators, financiers, and port authorities. Their requirements and decision criteria influence the feasibility of refits and the uptake of circular strategies. Investigating organisational adoption, through action research or applied case studies, would also reveal practical barriers, required process adjustments, and factors enabling successful implementation.

Finally, applying the framework to additional vessel types (e.g., ferries, fishing vessels, offshore support vessels) would test its transferability and may reveal vessel-specific KPIs needed for broader industry use.

7.6. Conclusion

This evaluation assesses the KPI-based framework developed and applied in this research. The framework demonstrates effectiveness in supporting multi-criteria refit vs. newbuild decision-making by making trade-offs explicit across strategic, environmental, and economic dimensions. The R-strategy concept from circular economy literature translates successfully to vessel refits, providing meaningful differentiation between refurbish and remanufacture approaches.

The framework is most applicable to standardised workboat categories operating in regional contexts with mature refit markets. Transferability to deep-sea vessels, highly customised designs, or regions with fundamentally different regulatory or economic conditions is limited. Methodologically, the single-case study approach was appropriate for this exploratory research, though sensitivity analysis and multi-case validation would strengthen future applications.

Practically, the framework is implementable within large shipbuilding organisations with established data infrastructure, though barriers exist for smaller companies. Key enablers for broader adoption include industry standardisation of sustainability-related data (e.g. in the form of product passports), which can be used to develop internal KPI databases over time.

Overall, the framework successfully achieves its research objective of providing systematic, multi-criteria decision support for circular vessel refit strategies, while acknowledging boundaries and areas for enhancement through future research and industry development.

8

Conclusion

This thesis addressed the research question: *How can the optimal circularity strategy for a vessel refit be chosen and evaluated from a strategic, environmental, and economic perspective?*

The answer is a structured KPI-based framework. It translates the abstract concept of the optimal circular strategy into measurable and comparable indicators. The framework demonstrates that ”optimal” cannot be universally prescribed. Instead, it emerges from the pattern of trade-offs across strategic, environmental, and economic impact areas, weighted according to specific operational, regulatory, and organisational contexts.

By applying circular economy R-strategies to vessel refits, the research reveals a critical insight. For long-lived and regulation-sensitive assets, minimising intervention does not always maximise circularity. A vessel refurbished today may become technologically obsolete within a decade due to regulatory changes, even while structurally sound. In such cases, substantial intervention through remanufacture can extend economic and regulatory relevance beyond structural lifespan. This inverts the traditional hierarchy that assumes lower R-strategies are inherently superior. This finding reframes the optimal circular strategy from ”minimise intervention” to ”maximise lifecycle value creation while minimising total environmental impact”. This definition sometimes requires significant technological upgrading.

The framework enables assessment through controlled comparison. It isolates the value of life extension from technology choice, revealing systematic advantages of refits in timeline flexibility and capital efficiency. The case study results show that refurbish offers the lowest CAPEX but the highest TEO, hybrid remanufacture achieves substantially lower TEO while maintaining competitive TCO, and electric remanufacture performs best environmentally (lowest TEO) but has the highest CAPEX and OPEX. Environmental performance depends critically on propulsion technology and operational profile. The case study quantified what was previously assessed only qualitatively. Refits deliver faster market entry and lower investment requirements. However, the choice between refurbish, remanufacture to hybrid, and remanufacture to electric depends on how organisations weigh cost efficiency against operational emission reduction and regulatory future-proofing. The framework's structured comparison methodology, evaluating each refit strategy against its equivalent newbuild while simultaneously comparing across refit options, enables this context-dependent assessment by making performance patterns across all three dimensions visible and comparable.

A fundamental contribution is making trade-offs explicit. The framework reveals conflicts that remain hidden in fragmented analyses: strategies minimising capital emissions maintain higher operational impacts, strategies minimising operational emissions require higher upfront investment, and strategies optimising cost sacrifice environmental positioning. No strategy dominates all impact areas, and sensitivity analysis shows that while the direction of results is robust, the magnitude, particularly for hybrid and electric vessels, depends on future fuel and electricity prices. This transparency shifts decision-making from seeking a universal ”best option” to identifying which trade-off pattern best fits the specific context. Different operators facing different regulatory environments and market conditions will rationally select different strategies.

The methodology proves functional despite incomplete data, enabling assessment through transparent uncertainty acknowledgement rather than demanding perfect information. This practical approach makes the framework applicable to emerging technologies where empirical data does not yet exist. By explicitly categorising data quality levels and applying conservative assumptions where needed, the framework allows meaningful analysis while avoiding false precision.

The case study validated the framework's effectiveness while the evaluation identified its boundaries. The methodology works best for standardised vessels in mature markets, but requires adaptation for deep-sea operations or highly customised designs. The single-case approach limits generalisability confidence, and several qualitative factors fall outside the framework's scope. Furthermore, the analysis of time-related KPIs, energy prices and lifetime extension provides confidence intervals for the results, but expanding sensitivity analysis to regulatory compliance pathways would strengthen future applications. These limitations do not invalidate the methodology but define where it delivers the highest value and where complementary analyses are needed.

The framework's contribution lies in providing a systematic methodology where current practice relies on fragmented, discipline-specific assessments that often yield contradictory recommendations. By integrating strategic, environmental, and economic perspectives within a unified structure, it enables transparent, comparable, and reproducible evaluation of vessel refits as circular economy interventions rather than repair activities. This positions life extension not as a cost-saving compromise but as a strategic instrument for sustainable fleet renewal.

Beyond its methodological contribution, the framework provides a foundation for Damen to work towards EU Taxonomy alignment for refit projects, as required by export credit insurers such as Atradius. Several KPIs directly correspond to the technical screening criteria, including fuel consumption reduction, operational CO_2 emissions, waste management, and the share of reused components. The case study demonstrates that both remanufacture strategies achieve measurable fuel efficiency improvements compared to the original vessel, which is an EU Taxonomy requirement.

However, the data gaps identified in Chapter 7, particularly around embodied CO_2 data, waste indicators, resource depletion, and the reliance on assumed rather than measured reuse percentages, indicate that Damen has not yet reached the data maturity required to fully benefit from the framework. The primary barrier is not the framework itself, but the absence of complete BoM documentation and component-level tracking for ageing vessels, a challenge explicitly identified in Section 2.3 as stemming from the lack of digital databases at the time of build. As data quality improves through structured refit documentation and internal digitisation efforts, the KPI framework presented here provides a credible and practical pathway toward meeting the evidence requirements for green financing eligibility.

Future developments will strengthen the framework's accuracy. The decision to install an SCR system to meet IMO tier III compliance, made late in the research, was not included in the quantitative assessment and should be analysed for its effects on CAPEX, OPEX, particulate matter emissions, and project complexity. Expanding the environmental boundary from IMO tank-to-wake to well-to-wake would better reflect upstream fuel and electricity emissions. Incorporating battery degradation, mid-life replacement cycles, and EoL scenarios would improve the assessment of hybrid and electric vessels. As operational datasets for these propulsion systems expand, retrospective validation will refine TEO and TCO projections and further strengthen the framework's applicability.

As the maritime industry navigates decarbonisation pressures while managing capital constraints, this research demonstrates that refits can be systematically evaluated to support evidence-based decision-making. Digital product passports containing component-level material data, circularity information, operational and maintenance logs, and compliance certificates will further increase material transparency and improve KPI accuracy. However, its core contribution remains: a practical method for choosing the optimal circular strategy for vessel refits and evaluating the impact of the strategy across strategic, environmental, and economic impact areas that matter for maritime sustainability.

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A

Sustainability Development Goals

Table A.1: United Nations Sustainable Development Goals (United Nations, 2024a)

1	No Poverty	End poverty in all its forms everywhere.
2	Zero Hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
3	Good Health and well-being	Ensure healthy lives and promote well-being for all at all ages.
4	Quality Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
5	Gender Equality	Achieve gender equality and empower all women and girls.
6	Clean Water and Sanitation	Ensure availability and sustainable management of water and sanitation for all.
7	Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all.
8	Decent Work and Economic Growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
9	Industry, Innovation and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation.
10	Reduced Inequalities	Reduce inequality within and among countries.
11	Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient and sustainable.
12	Responsible Consumption and Production	Ensure sustainable consumption and production patterns.
13	Climate Action	Take urgent action to combat climate change and its impacts.
14	Life below Water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
15	Life on Land	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
16	Peace, Justice and Strong Institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
17	Partnerships for the Goals	Strengthen the means of implementation and revitalise the Global Partnership for Sustainable Development.

B

9R Circularity Index

The method outlined in Chapter 2.5 presents a framework that is adapted from the 9R circularity index bottom-up approach from Muñoz et al. (2024) depicted in Figure B.1.

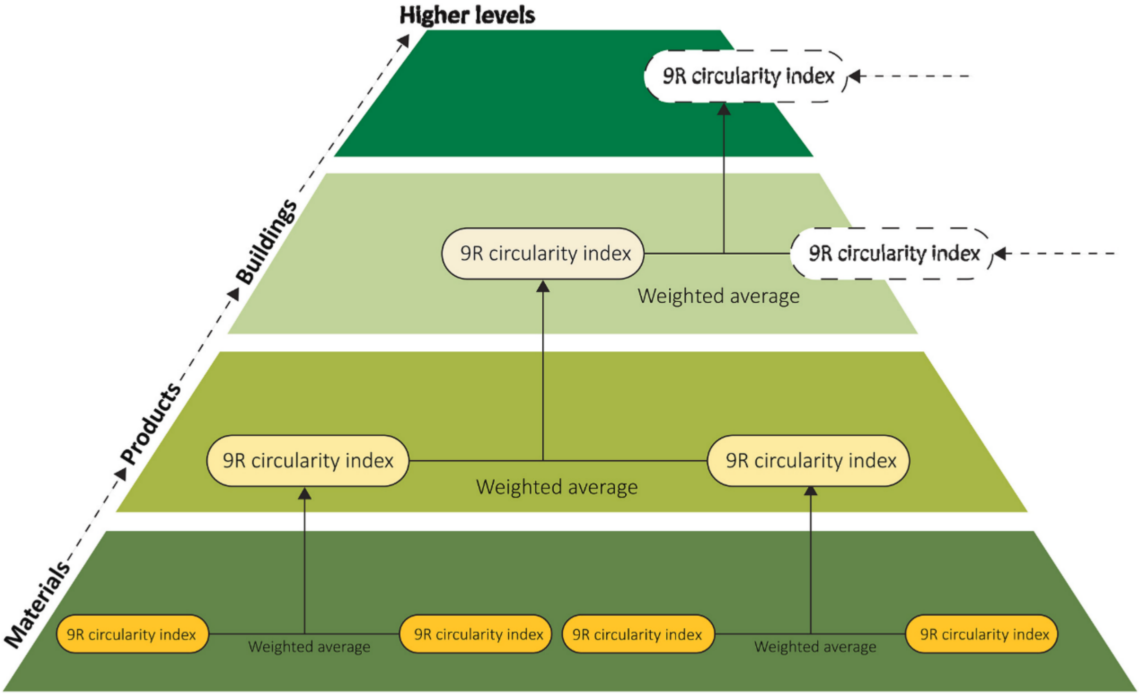


Figure B.1: Circularity index bottom-up approach (Muñoz et al., 2024)

C

Indicator Database

Table C.1: Indicator Database including Source, Code and Description

Source	Code	Indicator
Okumus, Andrews, and Gunbeyaz (2024)	SD-CM 1	Durability indicator, longevity of the design
	SD-CM 2	Modularity of Design Indicator
	SD-CM 3	The recycled-reused material proportion by mass
	SD-CM 4	Cost distribution of new, remanufactured, and reused onboard components
	SD-CM 5	Ratio of customers offered designs with circular products onboard
	OEM-CM 1	Advanced recycled content ratio (reused or remanufactured parts ratio by weight in products):
	OEM-CM 2	Durability and longevity metric - lifespan of equipment
	OEM-CM 3	Modularity, remanufacturability, and upgradability
	OEM-CM 4	Lead time of remanufactured/refurbished product compared to brand-new production
	OEM-CM 5	Quality of remanufactured products
	OEM-CM 6	GHG emission reduction due to restorative operations
	OEM-CM 7	Recovered waste due to restorative operations
	OEM-CM 8	Circular economy marketing practices
	OEM-CM 9	Hazardous waste generation ratio
	OEM-CM10	Remanufactured parts revenue compared to brand-new parts revenue
	BS-CM 1	Modularity of vessels built
	BS-CM 2	Recycled-reused material proportion by mass in ship construction
	BS-CM 3	Cost distribution of new, remanufactured, and reused onboard components
	BS-CM 4	Durability indicator, longevity of built vessels
	BS-CM 5	Ratio of customers ordering new vessels with circular products onboard
	BS-CM 6	Ratio of hazardous waste generated
	BS-CM 7	GHG emission reduction due to circular ship construction
	RS-CM 1	Spare parts lead time for maintenance and repairs

Continued on next page

Source	Code	Indicator
	RS-CM 2	Proportion of reused parts in repairs
	RS-CM 3	Proportion of reused parts in maintenance
	RS-CM 4	Volume of returns
	RS-CM 5	Quality of returns
	RS-CM 6	Circular revenue generated
	RS-CM 7	Ratio of customers who purchased circular parts and components
	RS-CM 8	Ratio of hazardous waste generated
	RS-CM 9	GHG emission reduction due to circular options
	CS-CM 1	Having rules, standards, or regulations regarding remanufactured components
	CS-CM 2	Having rules, standards, or regulations regarding refurbished equipment
	CS-CM 3	Having a standard process for certifying circular products
	CS-CM 4	Number of type approval tests for circular products
	CS-CM 5	Having rules, standards, incentives, or regulations regarding improving the reverse supply chain for onboard assets at the decommissioning stage
	OO-CM 1	Longevity of their fleet
	OO-CM 2	Circularity of operation and maintenance
	OO-CM 3	Circularity of design and shipbuilding
	OO-CM 4	Contribution to the Reverse Supply Chain
	OO-CM 5	Contribution to the Reverse Supply Chain
	OOCM 6	Ratio of solid waste generated during the decommissioning phase
	OO-CM 7	Ratio of hazardous waste generated during the decommissioning phase
	RF-CM 1	Circular revenue generated
	RF-CM 2	Value retention due to reuse, remanufacturing, and repurposing
	RF-CM 3	GHG reduction due to material recovery at end-of-life
	RF-CM 4	Ratio of solid waste generated during the decommissioning phase
	RF-CM 5	Solid waste reduction due to restorative EoL processes
	RF-CM 6	Ratio of hazardous waste generated during the decommissioning phase
	RF-CM 7	Volume of returns
	RF-CM 8	Quality of returns
	CO-CM 1	Circular freight ratio
	CO-CM 2	Reuse or recycle rate of packaging
	AUT-CM 1	Having standards or regulations regarding remanufactured marine equipment
	AUT-CM 2	Having standards or regulations regarding refurbished electronics onboard
	AUT-CM 3	Providing incentives for circular economy practices for vessels at the EoL stage
	AUT-CM 4	Defining a circular vessel to create a baseline standard
United Nations (2024a)	SDG 9.4	CO_2 emissions per unit of value added
	SDG 12.2	Material footprint
		Material footprint per capita
		Material footprint per GDP
		Domestic Material Consumption

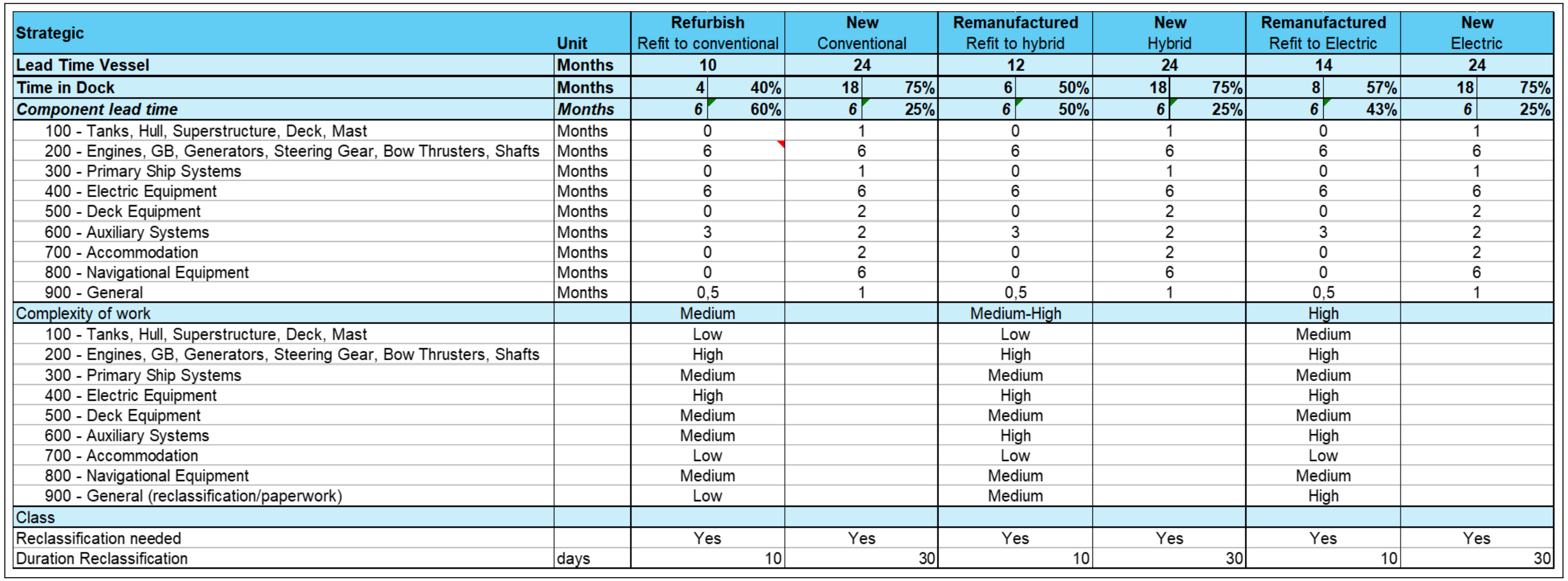
Continued on next page

Source	Code	Indicator
		Domestic Material Consumption per Capita
		Domestic Material Consumption per GDP
	SDG 12.5	National Recycing rate
		Tons of material recycled
	SDG 12.6	Number of companies publishing sustainability reports
	SDG 13.2	Total GHG emissions per year
LCA/LCC Favi et al. (2017)	TCO	Total Cost of Ownership
	CAPEX	Capital Expenditure
	OPEX	Operational Expenditure
Pero et al. (2024)	GWP	Global Warming Potential
		Resource Depletion
		Particulate matter emissions
Systems Perspective Khadim et al. (2022)	NANO	Recyclability
		Toxicity
		Embodied Energy
Khadim et al. (2022), Kristensen and Mosgaard (2020), and Moraga et al. (2019)	MICRO	Product Lifetime
		Repairability
		Reused Content
		Modularity
	MESO	
	MACRO	Policy
		Sectoral Material Use
		Economic Performance
		Readiness for the transition to circularity
EU Taxonomy (Commission, 2021)	EEDI	
		Fuel consumption

D

Results KPIs

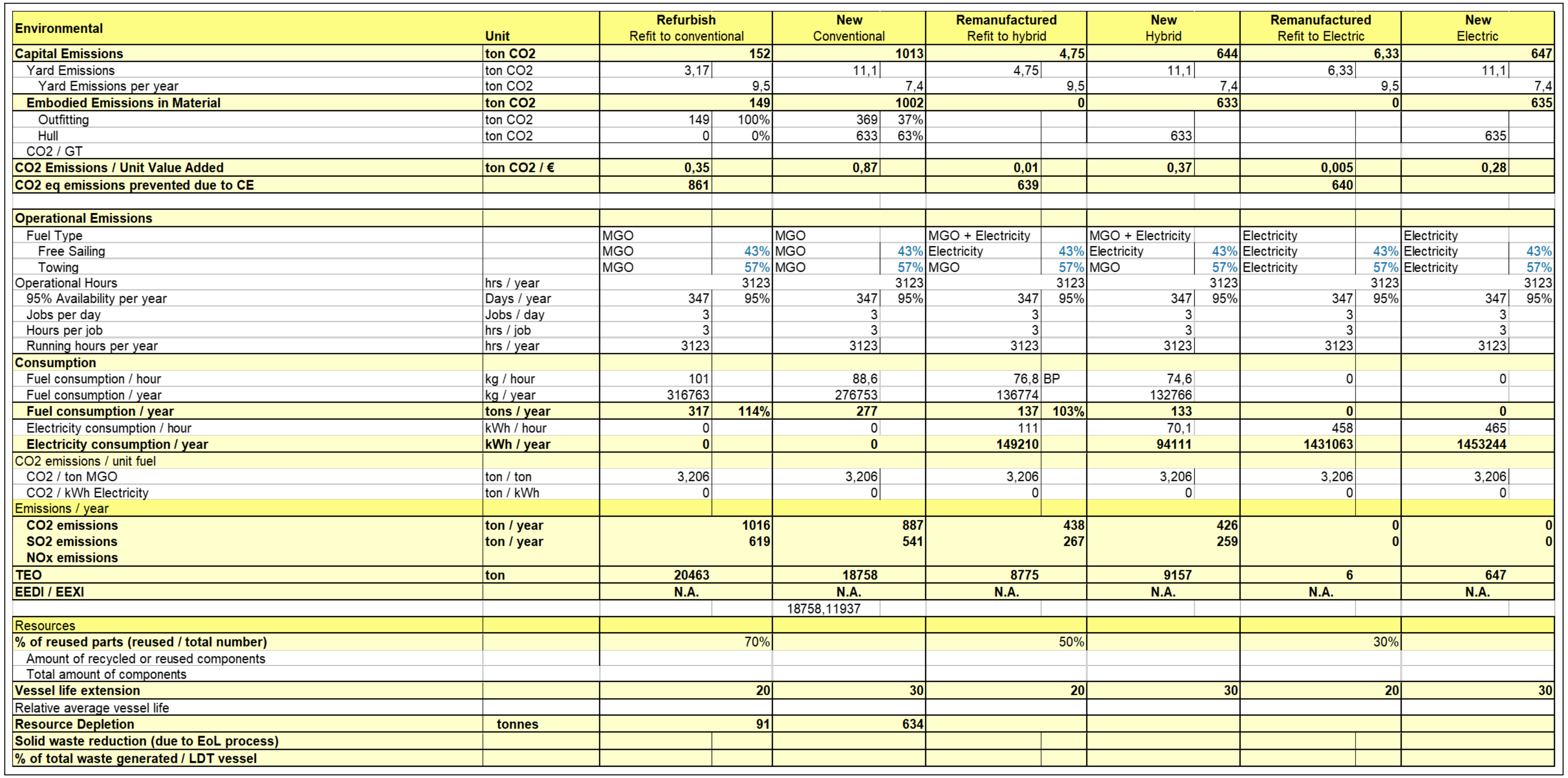
D.1. Strategic KPI Results



Strategic	**Unit**	**Refurbish** Refit to conventional		**New** Conventional		**Remanufactured** Refit to hybrid		**New** Hybrid		**Remanufactured** Refit to Electric		**New** Electric	
Lead Time Vessel	**Months**	**10**		**24**		**12**		**24**		**14**		**24**	
Time in Dock	**Months**	**4**	**40%**	**18**	**75%**	**6**	**50%**	**18**	**75%**	**8**	**57%**	**18**	**75%**
Component lead time	***Months***	***6***	**60%**	***6***	**25%**	***6***	**50%**	***6***	**25%**	***6***	**43%**	***6***	**25%**
100 - Tanks, Hull, Superstructure, Deck, Mast	Months	0		1		0		1		0		1	
200 - Engines, GB, Generators, Steering Gear, Bow Thrusters, Shafts	Months	6		6		6		6		6		6	
300 - Primary Ship Systems	Months	0		1		0		1		0		1	
400 - Electric Equipment	Months	6		6		6		6		6		6	
500 - Deck Equipment	Months	0		2		0		2		0		2	
600 - Auxiliary Systems	Months	3		2		3		2		3		2	
700 - Accommodation	Months	0		2		0		2		0		2	
800 - Navigational Equipment	Months	0		6		0		6		0		6	
900 - General	Months	0,5		1		0,5		1		0,5		1	
Complexity of work		Medium				Medium-High				High			
100 - Tanks, Hull, Superstructure, Deck, Mast		Low				Low				Medium			
200 - Engines, GB, Generators, Steering Gear, Bow Thrusters, Shafts		High				High				High			
300 - Primary Ship Systems		Medium				Medium				Medium			
400 - Electric Equipment		High				High				High			
500 - Deck Equipment		Medium				Medium				Medium			
600 - Auxiliary Systems		Medium				High				High			
700 - Accommodation		Low				Low				Low			
800 - Navigational Equipment		Medium				Medium				Medium			
900 - General (reclassification/paperwork)		Low				Medium				High			
Class													
Reclassification needed		Yes		Yes		Yes		Yes		Yes		Yes	
Duration Reclassification	days	10		30		10		30		10		30	

Figure D.1: Strategic KPI Results

D.2. Environmental KPI Results



Environmental	Unit	Refurbish Refit to conventional		New Conventional		Remanufactured Refit to hybrid		New Hybrid		Remanufactured Refit to Electric		New Electric	
Capital Emissions	**ton CO2**		**152**		**1013**		**4,75**		**644**		**6,33**		**647**
Yard Emissions	ton CO2	3,17		11,1		4,75		11,1		6,33		11,1	
Yard Emissions per year	ton CO2		9,5		7,4		9,5		7,4		9,5		7,4
Embodied Emissions in Material	**ton CO2**		**149**		**1002**		**0**		**633**		**0**		**635**
Outfitting	ton CO2	149	100%	369	37%								
Hull	ton CO2	0	0%	633	63%			633				635	
CO2 / GT													
CO2 Emissions / Unit Value Added	**ton CO2 / €**	**0,35**		**0,87**		**0,01**		**0,37**		**0,005**		**0,28**	
CO2 eq emissions prevented due to CE		**861**				**639**				**640**			
Operational Emissions													
Fuel Type		MGO		MGO		MGO + Electricity		MGO + Electricity		Electricity		Electricity	
Free Sailing		MGO	43%	MGO	43%	Electricity	43%	Electricity	43%	Electricity	43%	Electricity	43%
Towing		MGO	57%	MGO	57%	MGO	57%	MGO	57%	Electricity	57%	Electricity	57%
Operational Hours	hrs / year		3123		3123		3123		3123		3123		3123
95% Availability per year	Days / year	347	95%	347	95%	347	95%	347	95%	347	95%	347	95%
Jobs per day	Jobs / day	3		3		3		3		3		3	
Hours per job	hrs / job	3		3		3		3		3		3	
Running hours per year	hrs / year	3123		3123		3123		3123		3123		3123	
Consumption													
Fuel consumption / hour	kg / hour	101		88,6		76,8	BP	74,6		0		0	
Fuel consumption / year	kg / year	316763		276753		136774		132766					
Fuel consumption / year	**tons / year**	**317**	**114%**	**277**		**137**	**103%**	**133**		**0**		**0**	
Electricity consumption / hour	kWh / hour	0		0		111		70,1		458		465	
Electricity consumption / year	**kWh / year**	**0**		**0**		**149210**		**94111**		**1431063**		**1453244**	
CO2 emissions / unit fuel													
CO2 / ton MGO	ton / ton	3,206		3,206		3,206		3,206		3,206		3,206	
CO2 / kWh Electricity	ton / kWh	0		0		0		0		0		0	
Emissions / year													
CO2 emissions	**ton / year**		**1016**		**887**		**438**		**426**		**0**		**0**
SO2 emissions	**ton / year**		**619**		**541**		**267**		**259**		**0**		**0**
NOx emissions													
TEO	**ton**	**20463**		**18758**		**8775**		**9157**		**6**		**647**	
EEDI / EEXI		**N.A.**		**N.A.**		**N.A.**		**N.A.**		**N.A.**		**N.A.**	
				18758,11937									
Resources													
% of reused parts (reused / total number)			70%				50%				30%		
Amount of recycled or reused components													
Total amount of components													
Vessel life extension			**20**		**30**		**20**		**30**		**20**		**30**
Relative average vessel life													
Resource Depletion	**tonnes**		**91**		**634**								
Solid waste reduction (due to EoL process)													
% of total waste generated / LDT vessel													

Figure D.2: Environmental KPI Results

Table D.1: Materials Grouped

Materials	Grouped
316L/FG/316/316	Steel
A234WPB 3.1	Carbon Steel
Aluminium	Aluminium
Aramide NBR	Glasvezel
ASTM A106 Gr B 3.1	Carbon Steel
ASTM A-106 GR B 3.1	Carbon Steel
ASTM A-106 GR B 3.2	Carbon Steel
ASTM A182 F316	Carbon Steel
ASTM A182 F316L	Carbon Steel
ASTM A234 WPB 3.1	Carbon Steel
ASTM A234 WPB 3.2	Carbon Steel
ASTM A269 316/316L	Carbon Steel
ASTM A276 316	Carbon Steel
ASTM A312 316/316L	Carbon Steel
ASTM A36	Carbon Steel
ASTM B75	Carbon Steel
ASTM B88 K	Carbon Steel
Brass	Brass
Brass CuZn39Pb3	Brass
Brass CW617 N	Brass
Bronze	Bronze
Bronze RG10	Bronze
C22	Nikkel-Chroom-Molybdeen
Cast Steel	Carbon Steel
Copper	Copper
Copper CW024A	Copper
CrNiMo (1.4401)	Nikkel-Chroom-Molybdeen
CuNi10Fe1Mn 3.1	Copper
CuSn5Zn5Pb2-C	Copper
CuSn5Zn5Pb5-C	Copper
CuZn39Pb2	Copper
CuZn40Pb2	Copper
DELIVERY WINTEB	Aluminium
DIN2445/2 3.1	Steel
E235+N, 3.1	Steel
E235JR	Steel
E355+N 3.1	Steel
EN-GJMW-400-5	Cast Iron
EPDM-StSt AISI316Ti	Stainless Steel
GARLOCK 3300	Glasvezel
GARLOCK 5500	Glasvezel
G-CuSn12	Bronze
G-CuSn5Zn5Pb5-C	Bronze
G-CUSn5ZnPb	Bronze
GG 25	Cast Iron
GG-25	Cast Iron
GGG-40	Cast Iron
GG-40, EPDM	Cast Iron
GGG-40.3	Cast Iron
GGG40/EPDM	Cast Iron
GGG40/NBR	Cast Iron

Materials	**Grouped**
GP240GH	Carbon Steel
Graphite StSt 316	Stainless Steel
GRE conductive	Glasvezel
NBR	Rubber
Nitrile Rubber	Rubber
Nofirno Rubber	Rubber
Nylon	Nylon
P235GH	Carbon Steel
P235GH 3.1	Carbon Steel
P235GH 3.2	Carbon Steel
P245GH 3.1	Carbon Steel
PVC Glass Wool	Plastic
PVC-C	Plastic
PVC-C-StSt	Plastic
Roxylon Rubber	Rubber
S235 JR	Steel
S235 JR 3.1	Steel
S235 JRG2	Steel
S235 JRG2 3.1	Steel
S235 JRG2/GRADE A	Steel
S235GH	Steel
S235JR	Steel
S235JR/ H.D.G.	Steel
S235JR 3.1	Steel
S235JR/GRADE A 3.2	Steel
S235JRG2	Steel
S355J2G3	Steel
S355JR	Steel
SS316	Steel
St / StSt	Stainless Steel
St 35.4	Carbon Steel
ST 37-2	Carbon Steel
St st 316/316L	Stainless Steel
St st 316L	Stainless Steel
St St AISi 304	Stainless Steel
St St AISI 316L	Stainless Steel
St/StSt AISI 316Ti	Stainless Steel
St35.4 / AISI 316Ti	Stainless Steel
STEEL	Steel
Steel (35.4)	Carbon Steel
Steel 35.4	Carbon Steel
Steel E235+N	Steel
Steel Grade A	Steel
Steel P235GH	Steel
Steel P235GH 3.1	Steel
Steel P235GH 3.2	Steel
Steel S235JR	Steel
Steel S235JR 3.1	Steel
Steel, Brass	Steel
Steel+StSt	Stainless Steel
StSt	Stainless Steel
StSt 316L	Stainless Steel
StSt 316L 3.1	Stainless Steel

Materials	Grouped
StSt AISI 316 L	Stainless Steel
StSt AISI 316L	Stainless Steel
StSt AISI 316L 3.1	Stainless Steel
StSt AISI 316L, 3.1	Stainless Steel
StSt AISI 321	Stainless Steel
AISI 316L	Stainless Steel
AISI 316L 3.1	Stainless Steel
Blanks	Unknown
Steel	Steel

BoM Material	Material and Source	ECF
Aluminium	Aluminium (average) (EcoInvent)	6.854
Brass	Brass (EcoInvent)	2.64
Bronze	Bronze (from climatIQ)	3.5
Carbon Steel	Steel (Engineering, Rebar, Wire Rod (average)) (EcoInvent)	1.84
Copper	Copper (EcoInvent)	2.71
Cast Iron	Iron (from ClimatIQ)	2
Glass Fibre	Glass Fibre (EcoInvent) (from ClimatIQ)	1.4
Nikkel-Chroom-Molybdeen	(from Global LCA Data)	6.5
Nylon	Nylon (EcoInvent)	3.1
PVC	Plastics PVC (EcoInvent)	3.42
Rubber	Rubber (EcoInvent)	2.547
Stainless Steel	Stainless Steel (EcoInvent)	4.26
Steel	Steel Plate (EcoInvent)	2.38
Unknown	Engineering Steel (EcoInvent)	1.64

Table D.2: Corresponding Material and ECF

Yard Factors		
	Albwardy	Song Cam
2019	5.9	5.9
2020	4.6	4.6
2021	20	4.8
2022	23.5	4.7
2023	18.9	5
2024	9.5	7.4
2025	33.8	

Table D.3: Yard Factors Damen Albwardy (Sjarjah) and Damen Song Cam (Vietnam)

D.3. Economic KPI Results

Removed due to data sensitivity.