D4.4 Cost and performance model on fleet level

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

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AUTHOR	Friederike Dahlke-Wallat - DST Marko Josipović - DST
CO-AUTHORS	Michiel Katgert, MARIN Martin Quispel, EICB

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Release approval

1 | Release approval.

Name	Role	Date
Juha Schweighofer	Reviewer 1	24-06-2025
Niels Kreukniet	Reviewer 2	24-06-2025
Igor Backalov	WP Leader	30-06-2025
Benjamin Friedhoff	Coordinator	30-06-2025

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List of abbreviations

2 | List of abbreviations.

Abbreviation	Definition
CAPEX	Capital Expenditure
CO_{2e}	Carbon Dioxide Equivalent
CCNR	Central Commission for the Navigation of the Rhine
DPF	Diesel Particulate Filter
GT	Gross Tonnage
H2FC	Hydrogen Fuel Cell system
ICE	Internal Combustion Engine
ISO	International Organization for Standardization
IWT	Inland Waterway Transport
LHV	Lower Heating Value
MEGC	Multiple-Element Gas Container
NO_x	Nitrogen Oxides
OPEX	Operational Expenditure
PM	Particulate Matter
SCR	Selective Catalytic Reduction
TCO	Total Cost of Ownership
TTW	Tank-to-Wake
WTW	Well-to-Wake
WP	Work Package

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Executive summary

This deliverable describes the development of the cost and performance model on fleet level. The focus is clearly on the methodology, i.e. the basic structure and working method of the model.

Building upon the methodology from D4.3, the model features a modular structure encompassing dataset creation, performance prediction, cost estimation, and scenario comparison. This flexible architecture allows for easy adaptation as new data or technologies emerge.

The model integrates technical, operational, and economic parameters to provide a detailed assessment of decarbonization strategies. It estimates emissions from both Tank-to-Wake (TTW) and Well-to-Wake (WTW) perspectives, and calculates key cost indicators, including CAPEX, OPEX, and total cost of ownership (TCO), across predefined vessel families for both coastal and inland vessels. This comprehensive approach enables detailed benchmarking and comparison of various greening pathways under realistic conditions.

Furthermore, the model will be the basis for the decision-support tool in WP 5, guiding the sector towards effective and economically viable decarbonization. A key strength of the model is its support for flexible scenario configuration, allowing users to simulate the impacts of technological advancements, regulatory changes, and market developments up to 2050 and beyond. This capability empowers policymakers, fleet operators, and industry stakeholders to make informed decisions and strategically analyse scenarios for the transition to sustainable maritime transport.

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1. Introduction

The objective of Task 4.4 is to develop a methodology to assess the potential for implementing sustainable propulsion alternatives and energy-saving technologies through retrofitting in both inland and coastal fleets. Building on the methodology developed in Deliverable 4.3 (see [1]), which focused on individual vessel analysis, Deliverable 4.4 (D4.4) expands the cost and performance assessment to the fleet level. The model will be used for example in WP5 to build and analyse the scenarios for future fleet development.

The model applies a range of greening technologies and renewable energy options across predefined vessel categories ("fleet families"), using their technical characteristics as input. It also relies on baseline values from the SYNERGETICS database to estimate energy demand, emissions to air, and cost indicators. The baseline scenario is defined for the year 2025, with projections extending to 2050. In addition, the model supports configurable forecast parameters such as technology adoption rate and fleet renewal assumptions. Key elements from D4.3 are reiterated where needed, ensuring this deliverable can serve as a standalone reference.

1.1 Functional specification

To ensure that the model supports a wide range of cases, several functional requirements were defined. These requirements outline the model's key functions for fleet level assessment. An overview is provided in the table below.

3 | Overview of the key functional requirements implemented in the Fleet model.

Functionality	Description
Modular structure	The model comprises interconnected modules: datasets creation, performance prediction, cost prediction, and scenario comparison.
Support for multiple vessel segments	Covers both inland and coastal fleets, structured according to predefined fleet families.
Dynamic dataset creation	Generates fleet datasets based on internal or external sources.
Scenario configuration	Enables input of parameters such as fleet family, country of registration, vessel age, etc.
Forecast scenario configuration	Allows configuration of forecast year, technology uptake (share of green technologies), and new-build rate.
Performance and emission estimation	Estimates annual energy demand and emissions by adjusting reference diesel values for technology efficiency and fuel properties.
Cost calculation	Computes CAPEX, OPEX, and TCO at the individual vessel level and aggregates them at the fleet level.
Flexibility	Due to the connection between the model and the Database, all values (e.g. costs, efficiency, emission factors) can be easily updated without affecting the functionality of the model.

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1.2 Lessons learned from other models

In the past, two models have been created that enable the simulation (of parts) of the European fleet. The model for the CCNR serves as the basis for the creation of the model in this deliverable. The NEEDS project is particularly interesting for identifying promising trends in the future.

1.2.1 CCNR study

Within the framework of the CCNR study [2], a spreadsheet-based model of the European inland waterway fleet was created to simulate how the fleet can achieve climate neutrality by 2050. The fleet data was based on the previous work done in the FP7 project MOVE IT! [3] and the H2020 Project PROMINENT [4]. The fleet was divided into 12 families of type ships. These were assigned the adoption of new technologies in 5-year increments. The development of the fleet structure was also anticipated with the help of an assessment by a stakeholder group of experts. Three scenarios were created, where the Business as usual was used to set a baseline for the case that no greening activities with a roll-out of new technologies would happen. The two pathways had the strict boundary condition to reach the goals of the Mannheim Declaration:

1. Business as usual, where only policies in place were included and the rest of the fleet remained with conventional fossil fuel propulsion.
2. "The conservative pathway refers to a pathway in which mainly alternative fuels and techniques are considered which are relatively easy to implement and cost efficient at the short term. This concerns alternatives like advanced biodiesel (in the following summarised as HVO for simplification) that can be used in existing diesel internal combustion engines or liquified bio-methane (LBM) that can be used in gas engines. These are called 'drop-in' solutions. These are fuels and techniques which have a high TRL and are already available on the market.
3. The innovative pathway takes a more innovative approach with less internal combustion engines into account. The innovative pathway includes fuels and techniques which are currently still in their infancy stage (TRL 5-7) and are significantly more expensive as compared to advanced biodiesel and LBM. As result, the amount of biodiesel used in the innovative pathway will be significantly less as compared to the biodiesel consumption in the conservative pathway. These concern alternative technologies with a currently lower TRL like fuel cells and battery-electric propulsion systems." [2]

The study described here for the CCNR answered the question of greening measures for inland waterway transport from a technological perspective and provided an assessment of the financial costs involved. There was a large catalogue of questions, the answers to which were then incorporated into the CCNR Roadmap [5].

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1.2.2 NEEDS project

In earlier research performed in the NEEDS project [6], experience has been gained with cost and performance modelling. In this project, a simulation framework was developed in which the impact of certain retrofit technologies on the fleet and its surrounding infrastructures (bunkering ports) can be assessed.

These simulations are performed by setting up a 'traffic network' of a certain region, in which ships perform their daily operations. Simulations were made for the Rhine region for inland vessels and for the Greek Islands for coastal vessels. The energy consumption of these ships is calculated taking into account environmental conditions, and resulting bunker actions both influence the rest of the fleet as well as the bunker ports.

The impact of the retrofit technologies on ship properties such as payload (decreased cargo volume due to the presence of extra technology on board, such as battery packs or hydrogen containers), endurance (decrease in bunker capacity or having lower density energy carriers on board) and average speed (due to decreased engine power), and port properties such as bunkering times are all taken into account in the model.

By creating scenarios, in which certain parameters (such as energy prices, or selected retrofit technologies) in the model are changed over time, the impact of these scenarios can be assessed on a technological, environmental as well as on an economic level.

From these simulations, several lessons can be learned: Retrofit technologies with long bunkering times can cause a chain effect when applied to a larger fleet, where bunker ports get blocked by bunkering ships, ultimately decreasing the transport capacity of the entire fleet. This can be counteracted by adding more ships to the fleet, but this does not solve the root problem (namely, limited bunkering capacity) and negatively impacts the possible emission reduction from the new technology. Sufficient bunkering and recharging capacity need to be available in ports. TEN-T and AFIR policies as well as EU funding provide support for building such a network.

Within the NEEDS project, the original CCNR Roadmap scenarios have been implemented in the model. From these runs, it became clear that the financial incentives as described in the CCNR Roadmap scenarios did not have the expected effect. For a long time in the future, fossil diesel proved to be the preferred option by most ship owners, since the negative financial side effects of new technologies and renewable energy overshadowed the technological advantages.

One of the most promising technologies for the Rhine region is using swappable battery containers. The upfront investment of the electric propulsion train can also be limited by using pay-per-charge battery containers. This solution however requires a dense charging network, with swapping terminals in most ports along the Rhine, which requires large upfront infrastructure investments.

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2. Methodology

While Deliverable D4.3 introduced the structure of the cost and performance model at the level of an individual vessel, the methodology developed in Task 4.4 expands this concept to the fleet level. The objective is to enable an assessment of the impact of green technologies and renewable energy options across entire segments of inland and coastal fleets, disaggregated by vessel type (i.e. fleet family), with a time horizon extending up to 2050.

The model uses data from the SYNERGETICS Database [7], which includes structural, technical, and operational parameters, as well as baseline cost assumptions and projections.

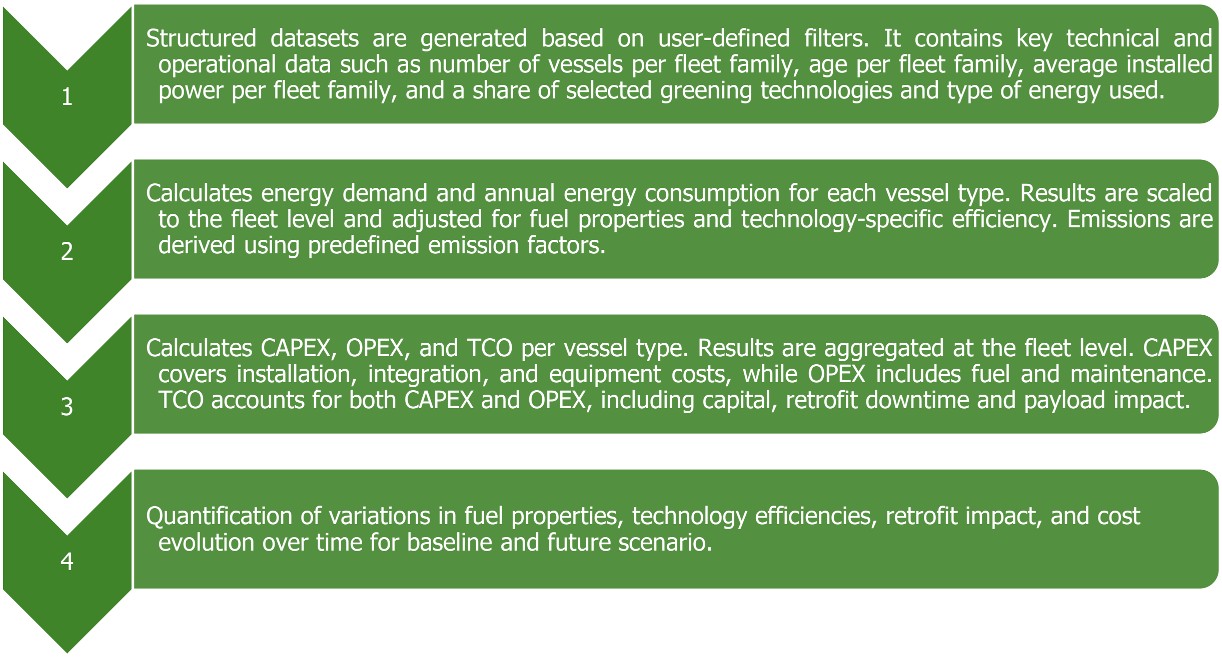
The focus of this deliverable is on the modelling framework itself. Some representative values are included for demonstration purposes, but these will be reviewed and updated, and missing data will be added in future project phases. Due to the link between the model and the Database, keeping the same structure, both cost inputs and fleet datasets can be updated without affecting the model's functionality. The methodology will be used (with possible refinements) in WP5 as part of the Decision Support Tool (Task 5.1), Transition Pathway updates (Task 5.2), Policy scenario analyses (Task 5.3) and other applications.

2.1 Structure of the model

The fleet model developed in Task 4.4 consists of four main modules:

1. Dataset creation,
2. Performance prediction,
3. Cost prediction,
4. Scenario comparison.

The general workflow is organized as follows:



1 | Workflow of the model

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The model allows both baseline assessment for 2025 and projection of future scenarios. The baseline reflects the current fleet development trends taking into account the 'business as usual' regarding the policy and measures, while scenarios represent possible shifts due to green technology and renewable energy uptake and fleet renewal. This structure enables comparison of future options against the baseline and supports evaluation of greening strategies for inland and coastal fleets. It helps to assess policy options and measures which can be taken to stimulate the uptake of greening technologies and renewable energy.

2.1.1 Vessel segmentation

The model classifies vessels into predefined fleet families based on their technical and operational characteristics. To assign a vessel to a specific category, either in the inland or coastal domain, minimum data requirements include vessel length, propulsion power, and type of operation (e.g. cargo, passenger, service). For coastal vessels also the unit Gross Tonnes (GT) is used. The concept of this measure is explained below. This segmentation enables the application of average values for installed power, fleet size per family, and other parameters, which are used as inputs (in the dataset creation process, described in the next section) for performance and cost calculations.

The fleet families are divided into two main domains:

- **Inland vessels**, including:
  1. **Motor vessels dry cargo (L ≥ 110 m)**: a vessel equal to or longer than 110 m, intended for the carriage of dry goods and/or containers and built to navigate independently under its own motive power;
  2. **Motor vessels liquid cargo (L ≥ 110 m)**: a vessel equal to or longer than 110 m, intended for the carriage of goods in fixed tanks and built to navigate independently under its own motive power;
  3. **Motor vessels dry cargo (80 m ≤ L < 110 m)**: a vessel with length between 80 and 110 m, intended for the carriage of dry goods and/or containers and built to navigate independently under its own motive power;
  4. **Motor vessels liquid cargo (80 m ≤ L < 110 m)**: a vessel with length between 80 and 110 m, intended for the carriage of goods in fixed tanks and built to navigate independently under its own motive power;
  5. **Motor vessels (L < 80 m)**: a vessel shorter than 80 m and longer than 19 metres, intended for the carriage of all types of goods and built to navigate independently under its own motive power;
  6. **Push boats (P < 500 kW)**[1]: a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of less than 500 kW;
  7. **Push boats (500 ≤ P < 2000 kW)**: a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of at least 500 kW but less than 2000 kW;
  8. **Push boats (P ≥ 2000 kW)**: a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of more than 2000 kW;
  9. **Coupled convoys**: a motor vessel (generally longer than 95 m) intended to be operated with one or several lighters;
  10. **Ferries**: a vessel providing a service crossing the waterway;
  11. **Large cabin vessels**: a passenger vessel longer than or equal to 86 m and with overnight passenger cabins;

[1] Push-tug boats, capable of both pushing and towing, are included in the corresponding power class of Push boats (categories 6 - 8) based on their installed propulsion power.

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12. **Day trip and small cabin vessels**: a passenger vessel for day-trip operation as well as a passenger vessel with overnight passenger cabins but shorter than 86 m.

- **Coastal ships**, including:
  1. **Offshore supply vessels (OSVs)**:
     - below 2000 GT[2]
     - 2000 to 3000 GT
     - 3000 to 4000 GT
  2. **Ferries**:
     - 0 to 999 kW installed power of the main engine
     - 1000 to 1999 kW installed power of the main engine
     - 2000 to 2999 kW installed power of the main engine
  3. **Cargo ships**:
     - up to 79.99 m length
     - 80 to 89.99 m length
     - 90 to 99.99 m length
     - 100 to 138 m length
  4. **Fishing vessels**:
     - VL0012 vessels less than 12 metres in length
     - VL1224 vessels between 12 metres and 24 metres in length
     - VL2440 vessels between 24 metres and 40 metres in length
     - VL40XX vessels greater than 40 metres in length
  5. **Tugboats**
  6. **Cruise ships**
  7. **Dredgers**
  8. **Pilot boats**
  9. **Workboats**

The current segmentation into fleet families has been defined for the purposes of this methodology; however, this classification may be refined or expanded in future phases of the project, depending on available data or analytical needs. Definitions of inland vessel types are adapted from the CCNR studies for the energy transition [2]. For the coastal ship fleet families, mostly customised groupings were used, based on statistically determined typical ship sizes. Best suitable indicators were the installed power of the main engine or the gross tonnage for the coastal vessels.

[2] GT = Gross Tonnage, see next page.

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Definition of Gross Tonnage applied for fleet segmentation of the coastal vessels

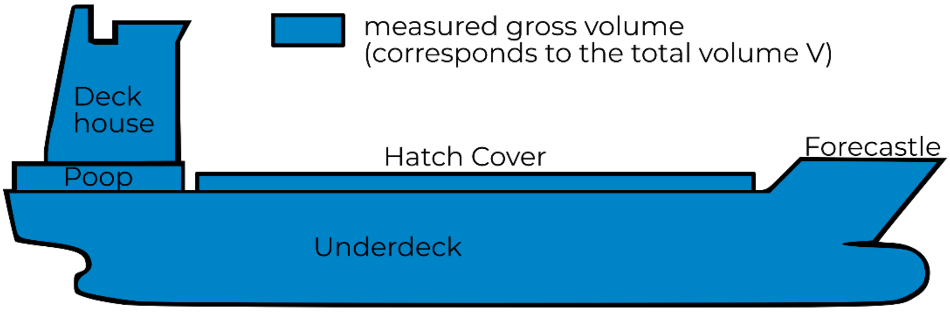
Gross Tonnage (GT) is a dimensionless measure of a ship's overall size. Unlike what is often mistakenly assumed, it does not represent the ship's weight or cargo-carrying capacity, but rather the total enclosed volume. GT is primarily used for regulatory purposes, such as determining port fees and safety requirements.

In accordance with the International Tonnage Convention (ITC) of 1969 [8], Gross Tonnage is calculated using the following formula:

$$\mathrm{GT} = \mathrm{K}_1 \cdot \mathrm{V}$$

where:

- K_1 is a coefficient that depends on the volume of the enclosed space, typically ranging between 0.22 and 0.32,
- V the total volume of all enclosed spaces on board (in cubic meters).



2 | Volumes included in Gross Tonnage of seagoing ships [9].

2.1.2 Technology options

The model includes a predefined set of sustainable propulsion alternatives and energy-saving technologies through retrofit, which can be assigned to any vessel type. The technologies and renewable energy options to be made available in the model are:

- HVO (renewable diesel)
- BioLNG/e-LNG
- MeOH ICE (methanol in internal combustion engine, both mono- and dual fuel)
- Battery system
-
- H_2 ICE (hydrogen in internal combustion engine, both mono- and dual fuel)
- H_2FC (hydrogen fuel cell system)
- New Diesel engine (Stage V or Euro VI)
- SCR & DPF retrofit on existing diesel engine (selective catalytic reduction and diesel particulate filter)
- Hydrodynamic measures (e.g. energy-saving devices, hull optimization)
- Fixed and swappable storage options for hydrogen and batteries

These technologies and renewable energy solutions represent the current potential range of solutions under consideration for decarbonizing inland and coastal shipping. They are the condensed results from work done in the work packages 1, 2 and 3. More information on the technical characteristics and applicability of these technologies can be found in [10] and [7].

Since each technology is added modularly, future technologies like redox-flow batteries or ammonia can be easily added, as soon as they are available for IWT or coastal vessels.

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3. Dataset creation

To estimate the impact of greening technologies and renewable energy options at the fleet level, the model relies on structured data describing the number and technical characteristics of vessels per fleet family. The methodology developed in Task 4.4 allows the model to dynamically generate datasets based on configurable parameters.

To ensure that the 2025 baseline reflects realistic conditions, the dataset creation process is linked with the pilot database developed in WP2 (see [11]). This database includes vessels/pilots where green technologies have been implemented. The pilot database is accessible at: *T2.1 Pilot_Database*.

Unless defined otherwise, the model will use default values derived from statistical sources and internal assumptions for each fleet family. However, all parameters listed below can be adjusted to reflect specific configurations:

1. **Inland or coastal ships**
   The model distinguishes between inland and coastal vessels. Each domain follows its own fleet family classification, as defined earlier.
2. **Fleet family**
   Vessels are grouped into predefined fleet families, which serve as the primary unit of analysis. The model enables inclusion or exclusion of specific fleet families depending on the assessment scope.
3. **Country of registration**
   If national registration data is available, the model enables country assessments. Otherwise, all vessels in the database are considered.
4. **Age of the fleets**
   Fleet age filters can be applied based on the year of construction for each fleet family.

For simulations beyond 2025, the following parameters can be configured to reflect assumptions on forward-looking scenario development:

5. **Selection of target year**
   Defines the future year for which the scenario is to be simulated (e.g. 2030, 2040, 2050).
6. **Share of greening technologies and renewable energy types**
   Specifies the adoption rate of greening technologies for each fleet family.
7. **Rate of newbuilds**
   Determines the share and characteristics of new vessels entering each fleet. This rate can also be overridden globally for all fleet families.
8. **Different assumptions on cost estimations** for both fuels / energy carriers and investment costs (minimum and maximum cost scenario)
9. **Assumptions to simulate also the impact of grants and taxes / subsidies** on energy types on costs matrices.

Based on the selected parameter combinations, the model generates two input datasets: one for the baseline year 2025 and one for the target year. The target-year dataset depends on the scenario-specific parameters (e.g. technology and energy share, newbuild rate), but also inherits baseline settings such as fleet selection and estimated running hours of the main engine based on the average vessel age family (as shown in Figure 3). It should be noted that vessels previously filtered based on age thresholds are assumed to be decommissioned in accordance with the selected target year. The age threshold can be defined by the user, or the model can apply the default average age of each fleet family (as shown in Figure 3). Both datasets serve as direct input to the performance and cost calculation modules of the model.

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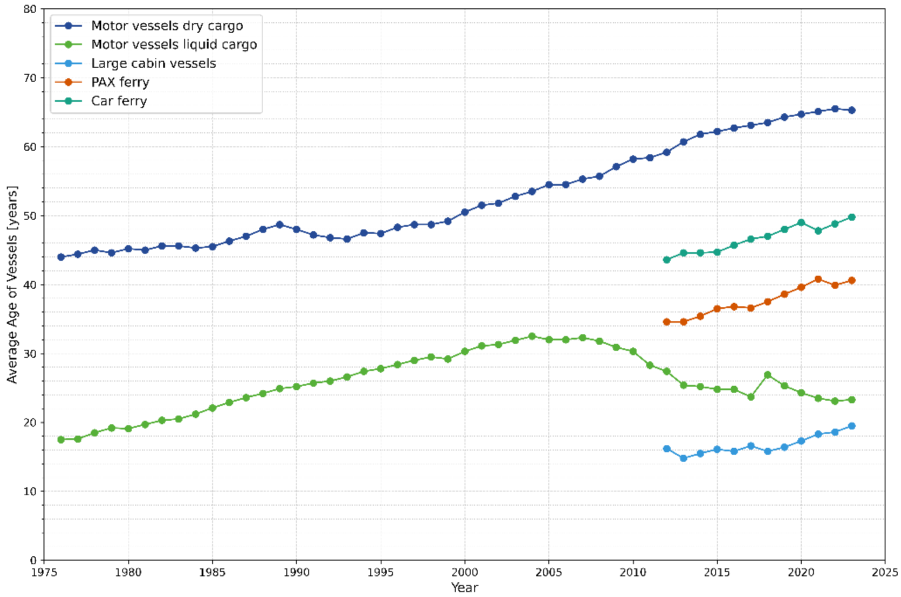

3 | Average age of selected inland vessel types in Germany, based on data from annual reports the Wasser- und Schifffahrtsverwaltung des Bundes (WSV)

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4. Performance prediction

In order to evaluate the impact of greening technologies on operational performance, the fleet model estimates the annual energy (fuel and electricity) consumption and associated emissions for each vessel type (fleet family).

The methodology builds upon available data for diesel fuel consumption, which are converted into a standardized annual energy demand. This value is then adjusted to reflect the energy content and efficiency of alternative fuels and technologies.

Once the fuel consumption is defined, the model calculates emissions based on emission factors for air pollution emissions, specifically nitrogen oxides (NO_x) and particulate matter (PM), and also for the climate change emissions (CO_2, CH_4). These estimates provide the basis for renewable energy and technology comparison and scenario-level emission impact assessments.

All values presented in the tables (e.g. lower heating values, energy conversion efficiencies, emission factors, and others) are used as reference inputs within the current version of the model. These have been integrated into the internal project Database and serve as indicative examples for the methodology.

4.1.1 Estimation of energy demand

For each fleet family, the model uses reference values of annual diesel consumption per vessel. These values are converted into energy demand expressed in megajoules per year using the lower heating value (LHV) of diesel fuel and an assumed efficiency for the diesel engine representing the ratio between the caloric energy value (LHV) and the mechanical energy output.

The following formula is applied:

$$Energy\ demand\ \left[\frac{MJ}{year}\right] = Diesel\ consumption\ \left[\frac{kg}{year}\right] \cdot LHV_{\ diesel}\ \left[\frac{MJ}{kg}\right] \cdot \eta_{diesel}\ [\%]$$

Average annual diesel consumption values per inland fleet families are listed in table 4 which are based on data from the CCNR Study [2]. For this calculation, a lower heating value of 43.1 $\left[\frac{MJ}{kg}\right]$ [12] was used for diesel fuel, and diesel engine efficiency was set at 38% [13]. The same method is applied to define energy demand for coastal vessel types, provided that representative fuel consumption data per fleet category is available.

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4 | Average annual fuel consumption and corresponding energy demand for inland fleet families [2].

Inland Fleet families	Average fuel consumption per year $[m^3]$	Avg. energy consumption per year [kWh]	Avg. energy consumption per year [MJ]
Passenger vessels (large hotel)	500	1,886,364	6,790,909
Push boats <500 kW	32	120,727	434,618
Push boats 500-2000 kW	158	596,091	2,145,927
Push boats ≥2000 kW	2,070	7,809,545	28,114,364
Motorvessel dry cargo ≥110 m	339	1,278,955	4,604,236
Motorvessel liquid cargo ≥110 m	343	1,294,045	4,658,564
Motorvessel dry cargo 80 m < L < 110 m	162	611,182	2,200,255
Motorvessel liquid cargo 80 m < L < 110 m	237	894,136	3,218,891
Motorvessels <80 m	49	184,864	665,509
Coupled convoys	558	2,105,182	7,578,655
Ferries	99	373,126	1,343,254
Day trip and small hotel vessel	54	203,727	733,418

4.1.2 Fuel consumption per technology

For each greening technology, the model calculates the required fuel or energy input by adjusting the baseline energy demand according to the fuel's energy content and the efficiency of the system. The model applies the following formula:

$$Fuel\ consumption\ [kg/year] = \frac{Energy\ demand\ [MJ/year]}{LHV_{\ fuel}\ [MJ/kg] \cdot \ \eta_{technology}\ [\%]}$$

Where:

$LHV_{\ fuel}$ is the lower heating value of the alternative fuel, while $\eta_{technology}$ is the efficiency of the greening technology. The used energy contents of different energy carriers and the efficiencies of different energy converters can be found in tables 5 and 6. The efficiency of the propulsion system refers not only to the engine but to the entire power train comprising energy pre-treatment, energy conversion, after-treatment and distribution.

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5 | Lower heating values (LHV) of selected fuels and their corresponding applicable technologies [14].

Fuel	$LHV_{fuel}\ [MJ/kg]$	Applicable Technology
Methanol, grey	20	MeOH ICE
Methanol, green	20	MeOH ICE
H_2 grey	120	H_2 ICE, Fuel cell
H_2 green	120	H_2 ICE, Fuel cell
Diesel	43.1	New Diesel Engine
HVO	44	New Diesel Engine
BioLNG/e-LNG	53	New Gas Engine

6 | Energy conversion efficiencies for each greening technology [13].

Greening Technology	$\eta_{technology}\ [\%]$
MeOH ICE	38
Battery system	90
H2 ICE	38
Fuel cell system	43
New Diesel engine	38 (inland), 44 (coastal)
Gas Engine	38 (inland), 44 (coastal)

The difference in the efficiency of diesel engines between coastal and inland vessels (see table 6) is due to the fact that an IWT require more power reserve to be able to safely manoeuvre and stop on rivers with current. Also, the engine cannot be operated steady state in the sweet spot for longer time periods, since the vessels constantly need to adjust the power demand when operating on restricted waterways.

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4.1.3 Emission estimation

In addition to fuel consumption, the model estimates the associated emissions based on the annual energy demand (converted into kWh) calculated for each vessel type and technology. The approach follows a standard emission factor method, where the total mass of emissions is computed by multiplying the annual fuel consumption by fuel-specific emission factors:

$$NO_X\ [g/year] = Energy\ demand\ [kWh/year]\ \cdot\ Emission\ Factor_{NOx}\ \left[\frac{g\ NOx}{kWh}\right]$$

$$PM\ [g/year] = Energy\ demand\ [kWh/year]\ \cdot\ Emission\ Factor_{PM}\ \left[\frac{g\ PM}{kWh}\right]$$

$$CO_{2e}[g/year] = Energy\ demand\ [kWh/year]\ \cdot\ Emission\ Factor_{CO_{2e}}\ \left[\frac{g\ CO_{2e}}{kWh}\right]$$

7 | TTW Emission Factors by Technology and Fuel for inland vessels. The values for PM and NO_X are derived from the Stage V emission limits [15]. Since the values for dual-fuel engine concepts can vary widely, they are not added here, but would be a combination of the share of pilot diesel fuel and the alternative fuel.

Technology	Fuel	NO_X $\left[\frac{g\ NOx}{kWh}\right]$	PM $\left[\frac{g\ PM}{kWh}\right]$	CO_{2e} $\left[\frac{g\ CO_{2e}}{kWh}\right]$
MeOH ICE	Methanol	1.525	0.035	0
Battery system	/	0	0	0
H_2 ICE	H_2	1.525	0.035	0
Fuel Cell	H_2	0	0	0
New Diesel Engine (Stage V)	Diesel	1.525	0.035	695 [12]
New Diesel Engine (Stage V)	HVO	1.525	0.035	0
Old diesel engine (unregulated)	Diesel	10	0.2	695 [12]
Old diesel engine (CCNR 1)	Diesel	9.2	0.54	695 [12]
Old diesel engine (CCNR 2)	Diesel	6	0.54	695 [12]
Gas engine	LNG	1.525	0.035	625 [2]

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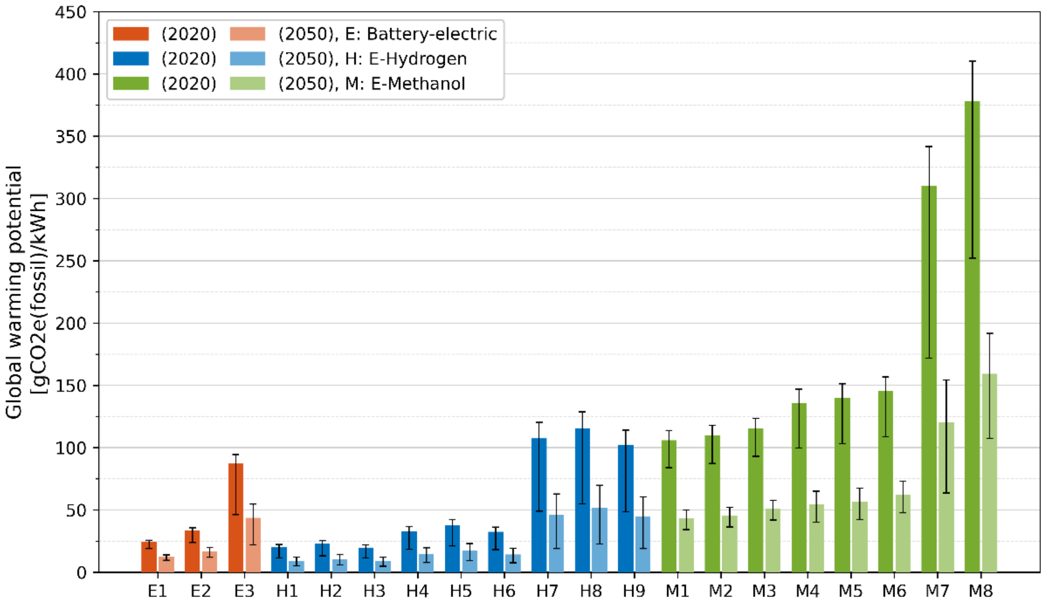
8 | **TTW Emission Factors by Technology and Fuel for coastal vessels.** The values for PM and NO_X are derived from the 4th IMO GHG study [16]. Since the values for dual-fuel engine concepts can vary widely, they are not added here, but would be a combination of the share of pilot diesel fuel and the alternative fuel.

Technology	Fuel	NO_x $\left[\frac{g\ NOx}{kWh}\right]$	PM $\left[\frac{g\ PM}{kWh}\right]$	CO_{2e} $\left[\frac{g\ CO_{2e}}{kWh}\right]$
MeOH ICE, single fuel	Methanol, green	1.525	0.035	Net zero
MeOH ICE, dual fuel	Methanol, green	1.525	0.035	Dependant on share of Diesel
Battery system	/	0	0	0
H_2 ICE	H_2	1.525	0.035	0
Fuel Cell	H_2	0	0	0
New Diesel Engine	Diesel	10.48	0.426	584 [12]
New Diesel Engine	HVO	10.48	0.426	Net zero
Gas engine	LNG	1.525	0.035	625 [2]

4.1.3.1 Well-to-tank upstream emissions

For the upstream chain of the fuels the pathways derived from D1.2 [11] are used. Here the best guess scenarios for the values are chosen.



4 | Global warming potential of the modelled supply paths for the years 2020 and 2050 from Well-to-Tank perspective. Bars correspond to the "best guess" values; bandwidths describe the "pessimistic" and "optimistic" assumptions.[13]

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It can be seen in figure 4 that the values can vary significantly depending on the path. Furthermore, it is intended to transfer the values from the ISO 14083 [17] and the currently ongoing CLEVER [18], [19] project into the Database.

4.1.4 Treatment of SCR & DPF and hydrodynamic measures and other measures

Some greening technologies do not directly influence the energy conversion efficiency of the propulsion system but still contribute to emission reduction or improved vessel performance. In particular, Selective Catalytic Reduction (SCR), Diesel Particulate Filters (DPF), and hydrodynamic improvement measures are handled differently in the model.

SCR & DPF: These are retrofitting options designed to reduce air pollutant emissions from conventional internal combustion engines, without significantly affecting the energy conversion process or fuel consumption. Fuel use remains more or less unchanged compared to baseline diesel operation. Increase of back pressure due to the SCR and DPF in the exhaust system may lead to increase of fuel consumption with a few percent. However, air pollutant emission factors are reduced using default abatement rates (e.g. NO_x reduction up to 95%, PM reduction up to 99% [2]). The SCR and DPF are integrated directly into engines type-approved for the 2016/1628 categories and fuel consumption is minimised. The consumption of urea also has a very limited CO2eq TTW emissions [20]. However, it is neglected here, as numbers of the annual consumption are currently not available for the sector.

Hydrodynamic measures: Aim is to reduce hull resistance (by optimized hull forms) and/or improve propulsion efficiency. While they do not modify engine technology or fuel properties, they indirectly lead to lower fuel consumption by reducing total energy demand. In the model, this is implemented by applying a correction factor r (e.g. 15% [2]) to the baseline energy demand:

$$Corrected\ energy\ demand\ [kWh/year] = Baseline\ energy\ demand \cdot (1 - r)$$

This reduction is then carried through the rest of the model, leading to lower annual fuel consumption, cost, and emissions.

Other measures

Logistics or operational efficiency measures can be simulated by adding another factor alike for the hydrodynamic factors. Also, the addition of solar panels might be such a measure.

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5. Cost prediction

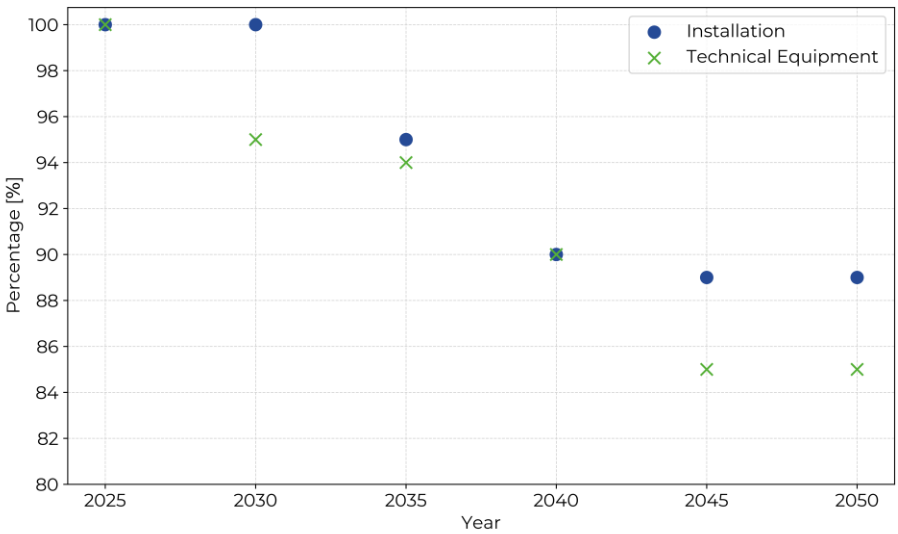
This section outlines the methodology applied to estimate the capital expenditures (CAPEX), operational expenditures (OPEX), and total cost of ownership (TCO) for various greening technologies. Cost calculations are conducted at the individual vessel and the technology level, and results are aggregated across the selected fleet segments.

5.1.1 CAPEX

As in Deliverable D4.3, the same principle is applied: baseline cost values for the year 2025 (see table 10) are used as the foundation for calculating CAPEX. This table only shows some of the items available. There is more data stored in the Database (Task 4.1) including fuel costs and swappable energy storage systems. These baseline values comprise both equipment and installation costs. Equipment costs vary depending on the installed power or energy capacity and are expressed as minimum and maximum values. In contrast, installation and integration costs are defined as fixed values per vessel type, also provided as minimum and maximum estimates.

To estimate future costs, scaling factors are applied to baseline values. These factors represent percentage changes and are defined in five-year steps up to 2050 (see figure 5). Linear interpolation is used for intermediate years. The model assumes moderate cost reductions over time, reflecting a conservative forecasting approach.

The cost module uses the tailored fleet datasets generated in the previous step. Average installed engine power values per fleet family are applied, as equipment costs are directly linked to installed power or required energy storage capacity.



5 | Example of estimated development of costs for installation and technical equipment for alternative technologies [1].

For each greening technology, the CAPEX is calculated as the sum of fixed installation and integration costs and variable equipment costs. The cost item *installation cost* is here related to the installation of an engine. The term *integration cost* refers to the integration of a whole fuel system including all electric installations, pipes, auxiliaries, control systems etc. For the fuel cell and the battery system no additional installation costs are foreseen. If a swappable system is applied, the integration costs also cover the tank connection spaces.

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Later in the scenarios developed in work package 5, some constraints regarding the installation of battery systems and H_2 tanks could be set, e.g. the swappable battery system and also the swappable hydrogen tank system could be applied to all large cargo ships as the charging or bunker times are, based on current assumptions, too high to enable a cost-effective use of fixed batteries on these ships (see also paragraph 5.1.4). The fixed battery and hydrogen tank systems would then be applicable to small passenger vessels, small push boats and ferries.

Below is a breakdown of the methodology per technology.

1. **MeOH System (single and dual fuel)**

$$CAPEX\ [€] = \ Installation\ cost\ [€] + \ Integration\ cost\ [€] + Engine\ cost\ [€]$$

Where:

$$Engine\ cost\ [€] = \ Unit\ cost\ per\ kilowatt\ \left[\frac{€}{kW}\right] \cdot \ Engine\ Power\ [€]$$

2. **LNG System (single and dual fuel)**

$$CAPEX\ [€] = \ Installation\ cost\ [€] + \ Integration\ cost\ [€] + Gas\ Engine\ cost\ [€]$$

Where:

$$Engine\ cost\ [€] = \ Unit\ cost\ per\ kilowatt\ \left[\frac{€}{kW}\right] \cdot Engine\ Power\ [€]$$

3. **Fixed Battery System**
The "Installation cost" covers the electrification of the vessel to be ready to be equipped with a battery pack (e.g. connections and also the energy management system).

$$CAPEX\ [€] = Integration\ cost\ \ [€] + \ Battery\ cost\ [€] + Electric\ Engine\ cost\ [€]$$

Where:

- The size of the fixed battery for the fleet families mentioned above is set as a default of the energy demand of the fleet family for a variable number of days:

$$Battery\ cost\ [€] = \ Unit\ cost\ per\ kilowatt\ hour\ \left[\frac{€}{kWh}\right] \cdot \ EnergyDemand_{X\ days}[kWh]$$

- As a default value, the size of the newly installed electric engine is 85 % of the average installed power:

$$Engine\ cost\ [€] = \ Unit\ cost\ per\ kilowatt\ \left[\frac{€}{kW}\right] \cdot \ Engine\ Power\ [€]\ \cdot\ 0.85$$

4. **Swappable Battery System**

For the swappable battery system, the battery costs are deducted from the CAPEX calculation.

$$CAPEX\ [€] = Integration\ cost\ \ [€] + \ Electric\ Engine\ cost\ [€]$$

Where:

$$Engine\ cost\ [€] = \ Unit\ cost\ per\ kilowatt\ \left[\frac{€}{kW}\right] \cdot Engine\ Power\ [€]\ \cdot\ 0.85$$

As a default value, the size of the newly installed electric engine is 85 % of the average installed power

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5. H_2 ICE (single and dual fuel)

$$CAPEX\,[€] = Installation\ cost\,[€] + Integration\ cost\,[€] + Engine\ cost\,[€] + Hydrogen\ tank\ cost\,[€]$$

Where:

$$Engine\ cost\,[€] = Unit\ cost\ per\ kilowatt\left[\frac{€}{kW}\right]\cdot Engine\ Power\,[€]$$

- The hydrogen tank for the fleet families mentioned above is dimensioned with the energy demand of the fleet family for a variable number of days:

  $$Hydrogen\ tank\ cost\,[€] = H_2\ Tank\left[\frac{€}{kg}\right]\cdot H_2 Demand_{X\ days}[kg]$$

  The tank cost equals zero if swappable tanks are applied.

6. Fuel Cell System

The “installation cost” also covers items like the energy management system, pipe and cable routing etc. The method for battery and fuel cell sizing is taken from [2].

$$CAPEX\,[€] = Integration\ cost\,[€] + Battery\ cost\,[€] + Fuel\ Cell\ cost\,[€] + Hydrogen\ tank\ cost\,[€]$$

Where:

- The battery is sized at 60% of the average installed power:

  $$Battery\ Cost\,[€] = Unit\ cost\ per\ kilowatt\ hour\left[\frac{€}{kWh}\right]\cdot AVG.Engine\ Power\,[€]\cdot 0.6$$

- The fuel cell is sized at 60% of the average installed power:

  $$Engine\ cost\,[€] = Unit\ cost\ per\ kilowatt\left[\frac{€}{kW}\right]\cdot AVG.Engine\ Power\,[€]\cdot 0.6$$

- The hydrogen tank for the fleet families mentioned above is dimensioned with the energy demand of the fleet family for a variable number of days:

  $$Hydrogen\ tank\ cost\,[€] = H_2\ Tank\left[\frac{€}{kg}\right]\cdot H_2 Demand_{X\ days}[kg]$$

  The tank cost equals zero if swappable tanks are applied.

7. New Diesel Engine

$$CAPEX\,[€] = Installation\ cost\,[€] + Engine\ cost\,[€]$$

Where:

$$Engine\ cost\,[€] = Unit\ cost\ per\ kilowatt\left[\frac{€}{kW}\right]\cdot AVG.Engine\ Power\,[€]$$

8. DPF and SCR

$$CAPEX\,[€] = Installation\ cost\,[€] + Equipment\ cost\,[€]$$

Where:

$$Engine\ cost\,[€] = Unit\ cost\ per\ kilowatt\left[\frac{€}{kW}\right]\cdot AVG.Engine\ Power\,[€]$$

9. Hydrodynamic Measures

$$CAPEX\,[€] = Installation\ cost\,[€] + Equipment\ cost\,[€]$$

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5.1.2 OPEX

OPEX refers to the recurring annual costs associated with the operation and upkeep of the installed technology over its lifetime. In this study, it is assumed that OPEX includes:

- Energy costs, based on estimated annual consumption per fleet family (outlined previously) and energy prices,
- Maintenance costs, defined as a percentage of the CAPEX, typically ranging between 7% and 10% per year, depending on the technology [2].
- If a swappable tank or battery system is applied, the leasing and rental costs are added to the OPEX while the energy costs are already included for refilling or recharging

5.1.3 Capital costs

Capital costs include both the depreciation of the system over time and the interest associated with financing the investment. In this study, capital costs are composed of:

- Depreciation, calculated on a straight-line basis over the expected service life of the equipment. This value is configurable and can be adapted depending on the scenario (e.g. default: 20 years).
- Interest, applied as a fixed annual rate over the average invested capital. The interest rate is configurable and can be adapted depending on the scenario (e.g. default: 6 %). Since depreciation is linear, the average capital is approximated as 50% of the total CAPEX.

The following formula is used to estimate annual capital costs per year:

$$\text{Capital Cost [€]} = \frac{\text{CAPEX [€]}}{2} \cdot \text{Annual Interest Rate [\%]} + \frac{\text{CAPEX [€]}}{\text{Expected Life Time}}$$

5.1.4 Downtime costs

As default value for the cost of vessels, the publication by Rijkswaterstaat [21] can be used as a first starting point: An excel is provided which gives indication for the vessel costs, depending on the type of vessel, type of operation and the sailing area. Although the dataset is already a few years old (from 2017) the costs during waiting can be derived as well as the full costs per year which serves as an indication of the turnover a vessel may generate per year. Inflation figures can be applied to correct the prices from 2017 for the prices today. Moreover, also other publications from Rijkswaterstaat are available with less detailed but more recent costs factors for IWT [22].

5.1.4.1 Due to bunkering/ recharging

Compared to vessels using diesel as fuel there can be a significant impact on the time required for the energy provision on board of the vessel. Bunkering diesel can be done relatively fast and can even take place while the vessel is sailing, resulting in no loss of productivity of a conventional vessel using diesel. However, when using other energy types than diesel, the bunkering or recharging can take a significant amount of time and might have to take place more often. This will have a negative impact on the productivity of the vessel. The additional time needed for bunkering shall be considered in the equation of economic impacts. The methodology is to assess the additional time per year and to value these hours based on the average hourly costs of the vessel excluding the annual energy costs for propulsion of the vessel.

The additional time needed depends on the energy consumption and the speed of transfer of energy to the ship. In the NEEDS project, Deliverable 3.1 the bunkering / recharging speeds were estimated [23].

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9 | Speed of bunkering per form of bunkering and speed of swapping [23]

Energy/fuel	Truck-to-Ship	Ship-to-Ship	Bunkerstation-to- Ship / Shore-to-Ship	Swapping energy container[3]
Fossil diesel		550 l/min	550 l/min	
HVO		550 l/min	550 l/min	
LNG	18 t/h	25 t/h [4]	250 kg/min	
LBM	18 t/h	25 t/h	250 kg/min	
Electricity			188 kW/h	30 min
H2	3,6 kg/min		3,6 kg/min	30 min
MeOH	550 l/min	550 l/min	550 l/min	

It is important to remark that the amount of fuel/energy to be transhipped, in terms of litres, tons, kWh, will depend on the energy density of the fuel type in comparison with diesel and also the efficiency of the energy conversion. Here it needs to be noted that diesel has a high energy density, therefore it is also important to take into account the Lower Heating Value of other energy types.

The presented information concerns the time required for the actual transfer of energy, any additional time that might be needed for, e.g., filling in checklists or the administrative time required for planning a bunker is not included. No clear information was available during the NEEDS project and these activities can also be done during the navigation of the vessel. But it is safe to assume that, especially in an initial phase, significantly more time will be involved in both the preparations and the actual bunkering, swapping, charging of alternative energy compared to fossil diesel. Furthermore, also the availability will be lower along waterways and in ports, therefore, possibly the vessels will need to make detours or more stops to arrive at a recharging, swapping or bunkering facility.

As example:

In case of 500m³ of diesel consumption per year, the bunkering speed would be 550 l/min (=0,55 m³ diesel per minute) and therefore take 909 minutes of time per year, which corresponds to 15.2 h.

However, when changing to methanol, the energy density is much less (19.9 MJ instead of 43 MJ/kg), resulting in 2.16 times the amount of kilograms needed of methanol compared to diesel. Methanol is a bit lighter compared to diesel. This is because methanol has a density of 791 kg/m³ compared to 840 kg/m³ for diesel. Therefore, more litres of methanol will be needed compared to the number of litres of diesel due to the difference in density. Thus, at the same speed of transhipment in terms of litres per minute (both 550 litres/minute) it will take a factor 2.3 more time to transfer the same amount of energy

[3] The swapping time includes (un)mooring and swapping the container. Each additional container will take around 10 minutes each. A vessel already calling at a container terminal where containers can also be swapped immediately does not have to deal with the additional (un)mooring time of around 20 minutes compared to a ship going specifically to a container terminal for a swap of energy container(s).The swappable container of 2MWh can recharged at the terminal within 2 hours (1MWh capacity)

[4] This speed applies to LNG pontoons supplying ocean-going vessels at relatively high speeds. In theory, these pontoons can also be used to supply inland vessels with LNG, but in practice this does not happen.

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(assuming similar efficiency of ICE diesel versus ICE methanol). In case of methanol 34.8 hours will be needed for bunkering, the added time will be 19.6 hours per year.

This is yet not very dramatic. However, when assuming a full battery application, the time loss will be much more significant:

500 m³ of diesel represents 420 t of diesel at 43 MJ/kg or 43 GJ/ton. Therefore, the caloric value is 420 * 42 GJ= 18060 GJ. Assuming an efficiency of 45 % for a diesel engine and 90 % for the electric propulsion, half of this amount is required as input electrical power: 9030 GJ per year. In terms of the amount of kWh electricity needed, this corresponds to 2,508,333 kWh.

The speed of transfer of electricity is clearly crucial. At the 188 kWh per hour, similar to current fast charging capacities of cars, as reported in the NEEDS study, the time needed to recharge would be 13342 hours per year. This is more time than actually is available in a year and therefore clearly not feasible. At 1 MWh charging, similar to current facilities for full electric heavy duty vehicles, the charging hours would be 2508 hours per year. This is quite significant and would lead to very high costs. For example, at a cost of 100 EUR per hour, this would be 250,833 EUR, which could be a quarter of the total costs per year and only the time loss would lead to 25 % higher costs.

Assuming however a 2 MWh swappable battery pack, each taking 10 minutes to transfer (6 containers in one hour), results in capacity of 12 MWh per hour. At this speed, the time to get the energy on board is roughly 14 times more than the time needed for bunkering diesel. The net additional time is 194 hours per year and could be 35 minutes per day. At a cost rate of 100 euro per hour, this would be an additional annual cost of 19,400 EUR which could be acceptable for client/ vessel operator.

5.1.4.2 Due to retrofitting works

Moreover, retrofitting a vessel to implement another technology will take time at the shipyard. While the vessel is at the shipyard, for example for a few weeks, it is assumed that costs at the shipyard comprise of the capital costs of the vessel. While being at the shipyard, there is no crew on board and no energy consumption takes place either. The capital costs of the vessel can be derived based on the value of the vessel in combination with an assumption of the applicable annual interest rate and the economic lifetime to represent the depreciation costs.

$$\text{Capital costs vessel per year } [€] = \frac{\text{Capital value } [€]}{2} \cdot \text{Annual Interest Rate } [\%] + \frac{\text{Capital value } [€]}{\text{Expected Life Time}}$$

Next this capital cost figure per year can be expressed in capital costs per day by means of dividing the figure by 365 days. Subsequently the capital costs during shipyard can be calculated based on the number of calendar days that the vessel is in the shipyard for the retrofitting works.

For example, in case a vessel has a capital value of 4 million EUR, assuming an interest rate of 5% and a 30 year expected life time, results in annual capital costs of 233,333 EUR. Per calendar day this amounts to 639 EUR. A retrofit work at the shipyard of 3 weeks would result in a cost of 13,424 EUR.

In addition, the insurance cost can be added as well, by dividing the annual insurance costs by the number of days and the days required for the retrofitting work.

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5.1.4.3 Costs due to loss of payload

As a result of using a different technology and energy carrier, the weight and size of the overall propulsion system including the energy storage can significantly affect the capacity of the vessel to transport goods or passengers. This may concern the volumetric capacity (m^3 or TEU) but may also have an impact on the maximum weight of goods which can be carried. It is therefore important to estimate the relative loss of productivity taking into account the average load rate and turnover (or annual costs) of the vessel. There are examples such as:

- vessels which lose 1/12 of the cargo space to accommodate a methanol tank (≙ 8.3 %)
- vessels which lose 9 TEU out of 132 TEU to accommodate exchangeable battery containers (≙ 6.8%)
- vessels which lose 16 TEU out of original 208 TEU to accommodate H_2 MEGCs and FC system (≙ 7.7%)

The freight rates will therefore be higher to compensate for the loss of payload. However, it will not always be the case the vessel uses the full capacity in terms of payload. Therefore, a factor needs to be applied to consider this.

For example, a container vessel can cost around 1 million euro per year. A loss of productivity of around 7 %, assuming that the vessel will always be fully loaded in terms of TEU capacity, will then lead to 70,000 EUR of costs. However, assuming being fully loaded at 25 % of the trips, the impact will only be 17,500 EUR.

5.1.5 TCO

TCO represents the cumulative cost of a technology over its entire economic lifetime of 20 years. It combines both investment related and operational costs, and integrates additional cost components that may affect the overall financial feasibility of the technology. In this study, it is assumed that TCO is defined as the sum of:

$$\text{TCO}\ [€] = \text{OPEX}\ [€] + \text{Capital Cost}\ [€] + \text{Downtime costs}\ [€] + \text{Payload loss costs}\ [€]$$

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6. Conclusion

This deliverable has presented a comprehensive cost and performance model designed for application at the fleet level, providing a robust framework for evaluating alternative propulsion technologies and retrofit solutions across both inland and coastal vessel segments. Building directly upon the methodology established in D4.3, the model advances previous work by introducing a modular architecture that enables detailed fleet scenario analysis. This modularity is achieved through the integration of four key components: dataset creation, performance prediction, cost estimation, and scenario comparison, each of which can be adapted or extended as new data or technologies become available.

By systematically incorporating technical, operational, and economic parameters, the model facilitates holistic assessments of fleet decarbonization strategies. It estimates emissions, including both Tank-to-Wake (TTW) and Well-to-Wake (WTW) perspectives, ensuring a comprehensive view of environmental impacts. Additionally, it calculates a range of cost indicators, such as capital expenditures (CAPEX), operational expenditures (OPEX), and total cost of ownership (TCO), across the predefined fleet families for inland and coastal vessels. This approach supports detailed benchmarking and comparison of different greening pathways under realistic operational conditions.

A notable strength of the model lies in its support for flexible scenario configuration. Users can define and simulate a variety of fleet evolution pathways, adjusting parameters to reflect technological advancements, regulatory changes, or market developments. This flexibility enables stakeholders to explore the impacts of different decarbonization measures and investment strategies, projecting their effects up to the year 2050 and beyond. As a result, the model will be the base to serves as a valuable decision-support tool in WP 5 for policymakers, fleet operators, and industry stakeholders seeking to navigate the transition toward sustainable maritime transport.

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7. Literature

[1] Friederike Dahlke-Wallat and Marko Josipović, 'D 4.3 Cost and performance model – Ship', SYNERGETICS, Feb. 2025.

[2] Friederike Dahlke-Wallat, Benjamin Friedhoff, Salih Karaarslan, Sophie Martens, and Martin Quispel, 'Study "Assessment of technologies in view of zero-emission IWT Edition 2", Part of the overarching study "Financing the energy transition towards a zero-emission Europe-an IWT sector"', CCNR, 2021.

[3] FP7 Grant agreement ID: 285405, 'MOVE IT! Modernisation of Vessels for Inland waterway freight Transport'. November 2011 to October 2014.

[4] B. Kelderman *et al.*, *PROMINENT - D1.1 List of operational profiles and fleet families*. 2016.

[5] Central Commission for the Navigation of the Rhine, 'CCNR ROADMAP for reducing inland navigation emissions', Mar. 2022. [Online]. Available: https://www.ccr-zkr.org/files/documents/Roadmap/Roadmap_en.pdf

[6] 'NEEDS project website'. Accessed: Jun. 10, 2025. [Online]. Available: https://waterborne.eu/projects/coordination-projects/needs/about-needs

[7] M. Josipović, 'D4.1 Specification and Creation of the Database', SYNERGETICS, Mar. 2024.

[8] 'International Convention on Tonnage Measurement of Ships', in *Commercial Shipping Handbook*, 0 ed., Informa Law from Routledge, 2014, pp. 232–232. doi: 10.4324/9781315774695-90.

[9] 'BSH - Internationales Vermessungsverfahren'. [Online]. Available: https://www.bsh.de/DE/THEMEN/Schifffahrt/Sportschifffahrt/Sportbootvermessung/Internationales_Vermessungsverfahren/internationales_vermessungsverfahren_node.html

[10] F. Dahlke-Wallat *et al.*, 'D1.1 Relevant identified technical solutions', SYNERGETICS, Jun. 2024.

[11] Florin Thalmann, Elimar Frank, Cornelia Moser-Stenström, and Almut Sanchen, 'D1.2 Report on suitability of identified technical solutions', Dec. 2024.

[12] 'EMEP/EEA air pollutant emission inventory guidebook 2019'. Oct. 17, 2019. Accessed: Apr. 30, 2025. [Online]. Available: https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2019

[13] I. Bačkalov *et al.*, 'Greening of Inland and Coastal Ships in Europe by Means of Retrofitting: State of the Art and Scenarios', *Sustainability*, vol. 17, no. 11, p. 5154, Jun. 2025, doi: 10.3390/su17115154.

[14] Friederike Dahlke-Wallat, Benjamin Friedhoff, and Sophie Martens, 'Study "Assessment of technologies in view of zero-emission IWT, Edition 1", Part of the overarching study "Financing the energy transition towards a zero-emission European IWT sector"', DST – Development Centre for Ship Technology and Transport Systems, 2020.

[15] ICCT, 'EUROPEAN STAGE V NON-ROAD EMISSION STANDARDS', 2016.

[16] International Maritime Organization, 'Fourth IMO GHG Study 2020 - Full report', International Maritime Organization, 2020.

[17] 'DIN EN ISO 14083, Treibhausgase –Quantifizierung und Berichterstattung über Treibhausgasemissionen von Transportvorgängen (ISO 14083:2023); Deutsche Fassung EN ISO 14083:2023'.

[18] 'CLEVER Project website', CLEVER. [Online]. Available: https://emissionfactors.eu/

[19] 'Creating Legitimate Emission Factors for Verified GHG Emission Reductions in Transport CLEVER', CORDIS | European Commission. [Online]. Available: https://cordis.europa.eu/project/id/101146908

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[20] 'Brandstoffen voertuigen - Hernieuwbare brandstoffen - Ad Blue (additief)', CO2 emissiefactoren. [Online]. Available: https://co2emissiefactoren.nl/factoren/2024/31/111/brandstoffen-voertuigen-hernieuwbare-brandstoffen-ad-blue-additief/

[21] 'Binnenvaarttool | RWSeconomie.nl'. Accessed: Jun. 11, 2025. [Online]. Available: https://www.rwseconomie.nl/documenten/2016/februari/kostenbarometer-en-binnenvaart-tool/binnenvaarttool

[22] 'Kostenkengetallen voor het goederenvervoer | Kennisinstituut voor Mobiliteitsbeleid'. [Online]. Available: https://www.kimnet.nl/documenten/2023/03/30/kostenkengetallen-voor-het-goederenvervoer

[23] Salih Karaarslan, Martin Quispel, and Niels Kreukniet, 'D3.1 Regional inland application of the model', NEEDS Project, Mar. 2023. Accessed: Jun. 11, 2025. [Online]. Available: https://www.waterborne.eu/images/D07_NEEDS_WP3-D3.1_Regional_inland_application_of_the_model.pdf

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ANNEX

10 | Default values for investment costs for technologies in 1000€ They are subject to further validation and revision under WP5

	Large cabin vessels	Push boats <500 kW	Push boats 500-2000 kW	Push boats ≥2000 kW	Motor-vessel dry cargo ≥110m	Motorvessel liquid cargo ≥110m	Motor-vessel dry cargo 80-109m	Motor-vessel liquid cargo 80-109m	Motor-vessel <80 m	Coupled convoys	Ferries	Day trip and small cabin vessel
MeOH-System												
Integration of MeOH-system, min	1000.00	250.00	312.50	437.50	500.00	500.00	450.00	450.00	250.00	450.00	250.00	250.00
Integration MeOH-system, max	3000.00	500.00	625.00	875.00	1000.00	1000.00	750.00	750.00	450.00	750.00	500.00	2000.00
Installation MeOH engine	68.00	16.80	57.60	235.14	118.46	121.04	51.95	64.87	20.54	152.12	25.43	34.00
MEOH ICE [€/kW] min	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
MEOH ICE [€/kW] max	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Battery System												
Electrification and Installation, min	1500.00	375.00	468.75	656.25	750.00	750.00	675.00	675.00	375.00	675.00	375.00	375.00
Electrification and Installation, max	4500.00	750.00	937.50	1312.50	1500.00	1500.00	1125.00	1125.00	675.00	1125.00	750.00	3000.00
Battery [€/kWh] min	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Battery [€/kWh] max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Electric engine [€/kW] min	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Electric engine [€/kW] max	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
H_2 ICE												
Electrification and Installation of H_2 System, min	1500.00	375.00	1406.25	1968.75	2250.00	2250.00	1687.50	1687.50	1012.50	1687.50	1125.00	4500.00
Electrification and Installation of H_2 System, max	4500.00	750.00	937.50	1312.50	1500.00	1500.00	1125.00	1125.00	675.00	1125.00	750.00	3000.00
Installation H_2 engine	68.00	16.80	57.60	235.14	118.46	121.04	51.95	64.87	20.54	152.12	25.43	34.00
H_2-Tank [€/kg] (20ft container, 500kg capacity)	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
MEOH ICE [€/kW], min	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
MEOH ICE [€/kW], max	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Fuel Cell												
Electrification and Installation of H_2 System, min	1500.00	375.00	312.50	656.25	750.00	750.00	675.00	675.00	375.00	675.00	375.00	375.00
Electrification and Installation of H_2 System, max	4500.00	750.00	937.50	1312.50	1500.00	1500.00	1125.00	1125.00	675.00	1125.00	750.00	3000.00
Battery [€/kWh] min	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Battery [€/kWh] max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
H_2-Tank [€/kg] (20ft container, 500kg H_2)	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Fuel Cell [€/kW] min	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Fuel Cell [€/kW] max	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
New Diesel Engine												
Installation Diesel engine	42.50	10.50	36.00	146.97	74.04	75.65	32.47	40.55	12.84	95.07	15.90	21.25
Stage V+, Euro VI [€/kW] min	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Stage V+, Euro VI [€/kW] max	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74

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	Large cabin vessels	Push boats <500 kW	Push boats 500-2000 kW	Push boats ≥2000 kW	Motor-vessel dry cargo ≥110m	Motorvessel liquid cargo ≥110m	Motor-vessel dry cargo 80-109m	Motor-vessel liquid cargo 80-109m	Motor-vessel <80 m	Coupled convoys	Ferries	Day trip and small cabin vessel
LNG												
System design and installation min	2000		1900	3100	1800	1800				2300		
System design and installation max	2300		2100	3300	2000	2200				2500		
Gas engine [€/kW] min	0.45		0.45	0.45	0.45	0.45				0.45		
Gas engine [€/kW] max	0.6		0.6	0.6	0.6	0.6				0.6		
DPF and SCR												
Design and installation per unit (incl. tank + components)	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50	32.50
Cost per kW installed	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Hydrodynamic measures												
Installation	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
Equipment Cost	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Saving potential [%]	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

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