D 4.3 Cost and performance model – Ship

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

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Release approval

1 | Release approval

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Executive summary

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

Necessary data has been and will be collected in the course of the SYNERGETICS project and gradually added to the model. Past experience has shown that cost assumptions in particular can change very quickly. The values given are therefore a snapshot used at the time the model was developed. To prevent the data used by the model from becoming obsolete, a link was established with the database from WP4.1 (the "Database").

Furthermore, this deliverable describes the exact steps for calculating the individual cost assumptions and determining performance, fuel consumption and the resulting emissions for various greening measures. The formulae used are described and preliminary starting values for assumptions are indicated.

Another requirement was the connection to the DST Voyage Simulation tool Fluvial. This tool was used to create typical operational profiles for the ships from the respective fleet families. These are correspondingly stored in the Database and can therefore also be changed or added to quickly. The model is therefore open to other operational profiles from different sources and it is not necessary to always use a profile created with Fluvial. This is especially important, when it comes to the use of the model in other SYNERGETICS Tasks:

The described method is also the basis for the fleet model in WP4, Task 4.4 and the decision support tool in WP5, Task 5.1. The fleet model will consist of many individuals created with the model described here to simulate the behaviour of the fleet in the future. For example, it can be shown what impact the mass rollout of various technologies would have or how much funding would be needed in the future. These findings are also important for decision-makers.

In Task 5.1, the model will be used to demonstrate to the user, or ship owner, the impact of choosing different greening options on pollutant and CO_2 emissions as well as on investment and operating costs.

The method described in this deliverable can be used for both inland and coastal vessels. However, the values given initially only refer to inland navigation, as many data are available. Transferability to coastal vessels is possible at any time with the corresponding entries in the Database.

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1. Introduction

The aim of the SYNERGETICS project is to promote greening measures for retrofits and new builds for inland and coastal vessels. This work package 4 will develop a programme to calculate the impacts of greening measures as a retrofit or as an installation in a newbuild.

In Work Package 1 (*exploration*), important data on technologies, fleets and energy carrier production were compiled. Work Package 2 focuses on the *synchronisation* of previous findings from pilot applications and Work Package 3 focuses on the *demonstration* of selected retrofit measures. The aim of Work Package 4 is to *integrate* the knowledge acquired to this point. In Task 4.1, the structures for the database have been created and data collection has begun, and in Task 4.2 fact sheets on the 8 most important retrofit measures have been created.

The third task of Work Package 4 focuses on developing a comprehensive tool for evaluating the performance and costs of greening technologies for individual ships. This tool will integrate and enhance existing resources, such as DST's web-based tool from the E-Binnenschiff project and the Fluvial voyage simulation environment, while connecting them to the newly created database in Task 4.1. The model is therefore open to other operational profiles from different sources and it is not necessary to always use a profile created with Fluvial. This is especially important, when it comes to the use of the model in other SYNERGETICS Tasks.

In this deliverable, the focus is primarily on the *methodology* of the calculation programme, i.e. the backend development. The described model is the engine behind the Decision Support Tool in WP5, Task 5.1 and the coming modelling of the fleet in WP 4, Task 4.4. It is not foreseen as a standalone application. Nevertheless, connectivity and functionality were tested with the database and a minimalistic GUI for debugging.

1.1 Outline

Within D4.3, Section 1.2 takes stock of existing web tools for inland navigation and describes the lessons learnt. Chapter 2 then describes the requirements for the new programme and the important interfaces with the database. This is done in the form of a requirement and functional specification. By leveraging this database, the tool enables quick and effortless modifications to input values, facilitating more efficient and accurate assessments of green retrofit options. The sustainability of the maintenance of the database is particularly important in order to quickly adapt to cost changes in the future. Section 3 then focuses on the description of the methodology. Here, there are sections on the cost estimation and the performance prediction method. Finally, Chapter 4 ends with an outlook.

1.2 Lessons learned from other models

Since the mid-2010s, more and more web-based tools, often called decision support tools, have been created for calculating the effectiveness of greening measures for inland navigation. Such a tool could not be found for coastal shipping. In order to avoid parallel development in SYNERGETICS and also to avoid repeating mistakes made in the past, an inventory of known web tools was carried out first.

Most of the tools offer the skipper various retrofit options and then calculate the investment, operational costs and potential savings. The GRENDEL project analysed the following tools in 2018 [1]:

- Econaut
- I-STEER app
- IWT-Greening Tool
- TCO Tool
- Funding Database
- Innovation Radar
- Energy efficient navigation tool (ENAT)
- E-Binnenschiff online tool

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The following is a brief description of the functionality of the tools and also shows which problems have occurred.

2 | Tools analysed in the GRENDEL project

Name	Project	Web address	Focus	Maintenance after project runtime
Econaut	-	https://econaut.nl	Calculation of CO_2-Emissions for individual ship for ship owners, also as mobile app, Registration with ENI necessary	App not available any more
IWT greening tool	PLATINA II	https://indanube.eu	• Liquefied Natural Gas (LNG) • Gas to Liquids (GTL) • Selective Catalytic Reduction (SCR) • Fuel-water emulsion (FWE) • Diesel particulate filters (DPF) • Propeller optimisation • Propeller outflow optimisation	No
I-STEER app	-	https://www.inland-waterways.nl/	• Same functionality as the IWT greening tool	No, input not possible anymore
TCO model	Break-through LNG deployment in IWT	https://tcomodel.eu/	LNG engine	No
Funding database	-	https://eibip.eu/funding/	Funding options	No
Innovation radar	-	https://eibip.eu/innovation-radar/Funding	• Vessel concepts, • Energy consumption, • Alternative fuels, • Logistic concepts, • Cargo flows and • Air pollutant emission reduction.	No, outdated after 2019
ENAT	PROMINENT	https://www.iwtnavigator.eu	Help planning sailing a stretch and give advice on reducing emissions	Website down

As it can be clearly seen from the table, the tools have some interesting functionalities to calculate emissions or the effectiveness. What can also be seen, is that they all were developed in a time, when the latest greening options in focus today were still totally out of scope. And there is a clear tendency towards LNG for IWT, which was present in the mid-2010s. The costs assumed at the time have not been updated over the years and are therefore outdated. Nor have the tools been supplemented by new technologies such as fuel cells.

For all tools, it was not possible to keep them up to date in the long term beyond the project duration or the funding period. This is often due to the fact that the programming of the sometimes complex websites was outsourced to an external service provider and the former project partners can no longer make any changes to the stored data or the website itself. It is precisely this problem that SYNERGETICS aims to solve with the following approach. The programming is done completely by the lead partner DST. The data is stored in the Database and can later be supplemented or revised. Ensuring up-to-datedness is also important with regard to the decision support tool that will be developed in WP5, Task 5.1. This will then also not suffer the same fate as the tools described above. The following describes exactly how the new approach will work.

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2. Requirement and functional specification

Some requirements for the tool can be derived from the findings of the inventory. The creation of a requirement and functional specification (Table 3) helps to define the desired functionality and to find solutions for implementation. The requirements specification describes the entire functionality that the software should fulfil. The functional specification presents the software solution and describes how the functions requested in the functional specification are to be realised. This method is primarily used for communication between the manufacturer and the customer. As in SYNERGETICS both the definition of the functionality and the solution approaches lie with the project partner DST, both are presented together in one table.

3 | Requirement and functional specification

Requirement specification	Functional specification
Allow quick adjustments of data sets	Data is stored in the Database and linked to calculation
Use operational profile	Suitable operational profiles from DST Fluvial tool and other sources are stored in a database and linked to calculation
Use up to date cost figures	Cost figures are stored in Database with easy access for change
Use engine characteristics for CO_{2e} emission calculation	Engine characteristics/fuel consumption map are stored in Database and linked to calculation
Consider the upstream emissions	Store upstream emissions in the Database

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3. Methodology

The tool developed in Task 4.3 for evaluating the performance and costs of greening technologies for individual ships forms the basis for the fleet model in Task 4.4 and the decision support tool in Task 5.1. This section describes the underlying methodology of the simulation. The basic idea is that a greening measure is selected for a ship in a fleet family and the costs and emission reduction potential are calculated for it then.

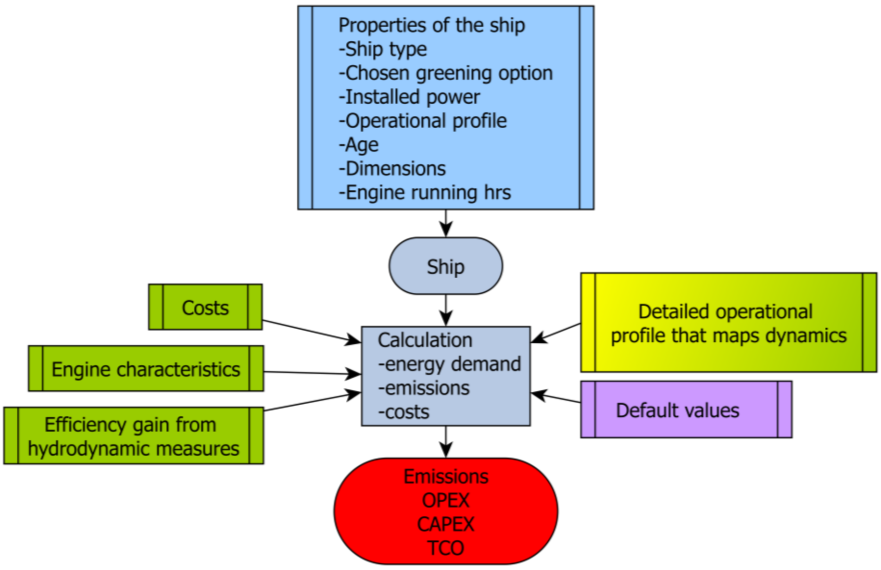
3.1 Basic structure of the model

This initial explanation of the functions is only intended to give a rough overview of how the various elements work together and how important the connection to the Database is. Details will be explained in the following sections.

The figure 1 shows that the basic data is defined first (light blue box). The modelled ship shall have certain properties. The user can enter a ship type, and the installed power. Also, a greening option and a matching operational profile can be chosen from a list.

Then, the calculation model receives further input: the current costs for the greening measures are taken from the Database (green boxes) and a corresponding operating characteristic of the selected energy converter is also selected.

Other input data includes, for example, a selected measure to increase energy efficiency or prescribed actions that, for example, prevent the selection of an unsuitable measure (purple box). These prescribed actions in particular are also important for later use in Task 5.1, as the skipper is to be supported in the selection of a suitable greening concept. The last source that is linked to the calculation is the above-mentioned operational profile in energy per stretch resolution (yellow-green box). This data comes from the DST tool Fluvial. Now, the emissions and costs can be determined using the input data described.



1 | Flow chart of the programme

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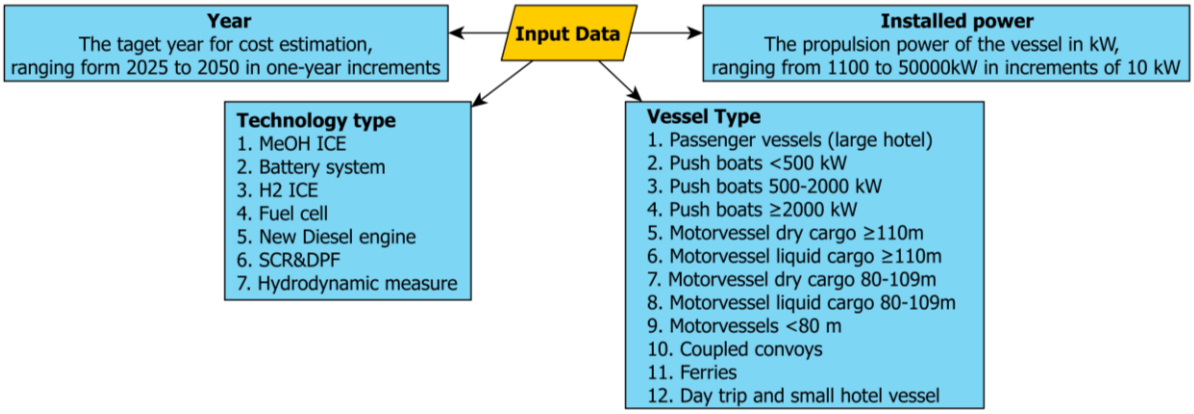
3.2 Cost and performance model – Ship

The cost and performance model - Ship has been developed using *Python*, with the *Streamlit* library providing an interactive and dynamic user interface. The model is structured into two primary modules: cost prediction and performance prediction. Each module applies systematic methodologies to evaluate both financial and environmental implications of implementing green technologies.

The cost prediction module utilizes data from the SYNERGETICS database (described in Deliverable 4.1), which includes baseline costs for various technologies and vessel types, along with projections for future years based on estimated annual cost development. Baseline costs and estimated annual cost development can be easily modified within the database without affecting the model's functionality.

The model requires user input for vessel type, technology type, installed power, and target year for cost estimation, as illustrated in Figure 2.



2 | Schematic illustration of required input data with the plots

The fleet families shown in Figure 2 are taken from [2] and are defined as:

- Motor cargo vessels (MCV) >= 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;
- Motor tankers (MT) >= 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;
- Motor cargo vessels (MCV) 80-109 m: a vessel with length between 80 and 109 m, intended for the carriage of dry goods and built to navigate independently under its own motive power;
- Motor tankers (MT) cargo 80-109 m: a vessel with length between 80 and 109 m, intended for the carriage of goods in fixed tanks and built to navigate independently under its own motive power;
- Motor vessels (MV) < 80 m: a vessel shorter than 80 m and longer than 19 metres, intended for the carriage of all type of goods and built to navigate independently under its own motive power;
- Push boats with P< 500 kW: a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of less than 500 kW;
- Push boats with 500 < P < 2000 kW: a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of more than 500 kW but less than 2000 kW;
- Push boats with P > 2000 kW: a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of more than 2000 kW;

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- Coupled convoys: a motor vessel (generally longer than 95 m) intended to be operated with one or several lighters;
- Ferries: a vessel providing a service crossing the waterway;
- Large cabin vessels: a passenger vessel longer than 86 m and with overnight passenger cabins;
- 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.

The technologies that are currently available are the following and more on these technologies can be found in D1.1 [3]:

- MeOH ICE
- Battery system
- H2 ICE
- Fuel cell
- New Diesel engine
- SCR&DPF
- Hydrodynamic measure

3.3 Cost estimation methodology

Within SYNERGETICS, the partners have made new, updated cost assumptions based on the CCNR study [2]. The costs are stored in the Database.

Baseline capital expenditures (CAPEX) for 2025 are detailed in Table 11 (page 28) and include costs for installation, integration, and equipment. Equipment costs account key propulsion components such as electric engines, batteries, fuel cells, and hydrogen tanks. Notably, equipment costs vary with installed power, while installation and integration costs remain fixed, but are given a minimum and maximum value.

The integration costs cover piping for fuels and electric installations in the engine room and also on the bridge. The model outputs contain information on the estimated cost for the selected technology, vessel type, installed power, and year. It provides a breakdown of minimal and maximal capital, maintenance, fuel and depreciation costs, offering an understanding of potential financial variations. The idea is to give the user possibility to compare all the costs between the selected years and between the selected technologies. The user will be able to see the data visualized in both graphs and tables.

Maintenance costs range between 7% and 10% per year over the system lifetime of the total investment, depending on the selected technology. Depreciation assumes a service life of 20 years.

To account for potential cost variations, the model provides both minimum and maximum estimates for capital, maintenance, and depreciation costs.

There is also a forecast for the costs in 5-year increments up to 2050, with linear interpolation in between. As past forecasts have shown how uncertain long-term assumptions can be, the reduction in the cost of the technologies is assumed to be low. The prognosis can be seen in Figure 3.

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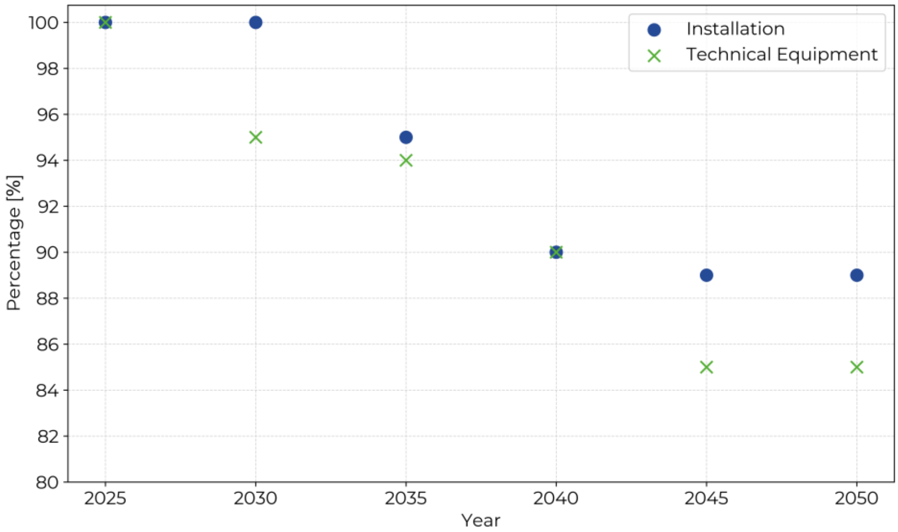

3 | Example of estimated development of costs for installation and technical equipment for alternative technologies

Future price prediction

Looking back on cost predictions in the above mentioned CCNR study in 2020, it can be said that a price forecast is extremely uncertain, as it has been shown that countless external factors, including the global political situation, can have an influence on costs. This means that aspects such as cost reductions through higher unit production, i.e. economies of scale, do not necessarily have to be the case. Of course, this view is very pessimistic and it is always possible that the predicted economies of scale will materialise exactly as predicted. Nevertheless, it is generally important to bear in mind that the predicted price change may not materialise.

Data Selection

The model filters cost reference data based on user-selected technology and vessel type. The estimated annual cost development (see Figure 3) is applied to project costs for the selected year, adjusting baseline values accordingly.

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3.3.1 Default values

However, there are some default values for the size of retrofit options. The item "default values" in Figure 1 describes all fixed specifications that are intended to prevent incorrect entries on the one hand and map anticipated developments in the fleet on the other. All these assumptions are start values for building the model and can be overruled later. Some of these specifications are, for example

- The default size of the battery when switching to a battery-electric ship is set to the energy requirement for 2 days of the type ship from the fleet family. The same applies to the hydrogen tank. The value of 2 days was chosen because it gives a reasonable size of the energy storage that is typically installed.
- A newly installed engine is always smaller than that of the type ship in the fleet family. This is because experience shows that many inland vessels are overpowered. Especially for the fleet model in Task 4.4 this "right sizing" may have a significant influence.
- When converting to fuel cell propulsion, 60 % of the previously installed engine power is replaced by the fuel cell. In addition, a battery with a capacity in kWh corresponding to 60 % of the formerly installed engine power is foreseen for peak shaving. This is just an averaged rough estimate. An optimized system will deviate from this based on the operational profile and further details [4].

3.3.2 Maintenance cost estimation

MeOH system: Calculated as 7% per year of the MeOH ICE [€] cost, computed based on user-defined installed power P_I. The following formulas are used:

$$\text{Maintenance Costs}_{\,min}\,[€] = \text{MeOH ICE}_{\,min}\left[\frac{€}{kW}\right]\cdot P_I\,[kW]\cdot 0.07$$

$$\text{Maintenance Costs}_{\,max}\,[€] = \text{MeOH ICE}_{\,max}\left[\frac{€}{kW}\right]\cdot P_I\,[kW]\cdot 0.07$$

Battery system: Calculated as 10% per year of the combined cost of the electric engine *Electric Engine*$_{min,max}$ and battery costs *Battery*$_{min,max}$. As a default value, the size of the newly installed engine is 85 % of the original installed power. The battery size is set as a default of the energy demand of the fleet family for two days (see table 7). Both these values can be overruled later. The following formulas are used:

$$\text{MaintenanceCosts}_{\,min}\,[€] = \left(\text{Battery}_{\,min}\left[\frac{€}{kWh}\right]\cdot EnergyDemand_{2days}[kWh] + \text{ElectricEngine}_{\,min}\left[\frac{€}{kW}\right]\cdot P_I\,[kW]\cdot 0.85\right)\cdot 0.10$$

$$\text{MaintenanceCosts}_{\,max}\,[€] = (\text{Battery}_{\,max}\left[\frac{€}{kWh}\right]\cdot EnergyDemand_{2days}[kWh] + \text{ElectricEngine}_{\,max}\left[\frac{€}{kW}\right]\cdot P_I\,[kW]\cdot 0.85)\cdot 0.10$$

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$\mathbf{H_2\ ICE}$: Calculated as 7% per year of the combined cost of the H_2 ICE [€] cost and hydrogen tank cost. H_2 ICE [€] costs are computed based on installed power P_I defined by the user, while hydrogen tanks are assumed to have a capacity to serve the hydrogen demand $H_2Demand_{2days}$ of the type vessel for 2 days (see table 7). The following formulas are used:

$$\text{MaintenanceCosts}_{min}\,[€] = \left(\text{H}_2\ \text{ICE}_{\ \text{min}}\left[\frac{€}{\text{kW}}\right]\cdot \text{P}_\text{I}\,[\text{kW}] + \text{H}_2\ \text{Tank}\left[\frac{€}{\text{kg}}\right]\cdot \text{H}_2\text{Demand}_{\text{2days}}[\text{kg}]\right)\cdot 0.07$$

$$\text{MaintenanceCosts}_{max}\,[€] = \left(\text{H}_2\ \text{ICE}_{\ \text{max}}\left[\frac{€}{\text{kW}}\right]\cdot \text{P}_\text{I}\,[\text{kW}] + \text{H}_2\ \text{Tank}\left[\frac{€}{\text{kg}}\right]\cdot \text{H}_2\text{Demand}_{\text{2days}}[\text{kg}]\right)\cdot 0.07$$

Fuel cell: Calculated as 10% per year of the combined price of the fuel cell, battery, and hydrogen tank costs, computed based on user-defined installed power P_I. For dimensioning values, the figures described under 3.3.1 apply. The following formulas are used:

$$\begin{aligned}\text{Maintenance Costs}_{min}\,[€] &\\ = \Big(&\text{FuelCell}_{\text{min}}\left[\frac{€}{\text{kW}}\right]\cdot \text{P}_\text{I}\,[\text{kW}]\cdot 0.6 + \text{H}_2\ \text{Tank}\left[\frac{€}{\text{kg}}\right]\cdot \text{H}_2\text{Demand}_{\text{2days}}\,[\text{kg}]\\ &+ \text{Battery}_{min}\left[\frac{€}{kW}\right]\cdot P_I\,[kW]\cdot 0.6\Big)\cdot 0.10\end{aligned}$$

$$\begin{aligned}\text{Maintenance Costs}_{max}\,[€] &\\ = \Big(&\text{Fuel Cell}_{\text{max}}\left[\frac{€}{\text{kW}}\right]\cdot \text{P}_\text{I}\,[\text{kW}]\cdot 0.6 + \text{H}_2\ \text{Tank}\left[\frac{€}{\text{kg}}\right]\cdot \text{H}_2\ \text{Demand}_{\text{2days}}\ [\text{kg}]\\ &+ \text{Battery}_{max}\left[\frac{€}{kW}\right]\cdot P_I\,[kW]\cdot 0.6\Big)\cdot 0.10\end{aligned}$$

New diesel engine: Calculated as 10% of the Stage V, Euro VI [€] engine cost per year and computed based on user-defined installed power P_I. The following formulas are used:

$$\text{Maintenance Costs}_{min}\,[€] = \text{Stage V, Euro VI}_{\text{min}}\left[\frac{€}{\text{kW}}\right]\cdot \text{P}_\text{I}\,[\text{kW}]\ \cdot 0.10$$

$$\text{Maintenance Costs}_{max}\,[€] = \text{Stage V, Euro VI}_{\text{max}}\left[\frac{€}{\text{kW}}\right]\cdot \text{P}_\text{I}\,[\text{kW}]\cdot 0.10$$

3.3.3 Estimation of financing costs

Capital cost

A variable annual interest rate is applied to the total investment cost. Total investment costs are including installation, integration, and equipment costs depending on the selected technology. The acquisition costs are depreciated on a straight-line basis per year, so the value to be considered for the capital costs is half of the acquisition costs. The following formula is used:

$$\text{Capital Costs}_{min}\,[€] = \frac{\text{Total Investment Costs}_{min}\,[€]}{2}\cdot \text{Annual Interest Rate}\,[\%]$$

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Depreciation cost estimation

The depreciation cost per year in IWT is typically calculated based on an assumed service life of 20 years of a technology. The following formulas are used:

$$\text{Depreciation Costs}_{min}\,[€] = \frac{\text{Total Investment Costs}_{min}\,[€]}{20}$$

$$\text{Depreciation Costs}_{max}\,[€] = \frac{\text{Total Investment Costs}_{max}\,[€]}{20}$$

The model outputs contain information on the estimated cost for the selected technology, vessel type, installed power, and year. It provides a breakdown of minimal and maximal investment cost, maintenance, and depreciation costs, offering an understanding of potential financial variations.

Additionally, the model generates comparative cost estimates for multiple technologies and selected years, which are presented both graphically and in tabular format to enhance data interpretation.

3.3.4 Annual fuel costs

The calculation of the annual fuel demand is described in section 3.4.4. In the following table exemplary fuel costs can be seen. As the data is stored in the Database, adjustment can be made. Currently, there is no data for green methanol. However, this will be added at a later stage, once a reliable source is found.

4 | Estimated fuel prices in €/kg or €/kWh for the shipowner

	min						max					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Diesel	0.55	0.55	0.58	0.60	0.60	0.60	0.68	0.70	0.81	0.91	0.91	0.91
HVO	1.11	0.91	0.90	0.86	0.74	0.74	1.79	1.81	1.75	1.67	1.43	1.43
Electricity, €/kWh	0.09	0.09	0.09	0.09	0.09	0.09	0.12	0.12	0.12	0.12	0.12	0.12
H_2, grey	2.75	2.75	2.75	2.75	2.75	2.75	6.00	6.00	6.00	6.00	6.00	6.00
H_2, green	10.00	10.00	8.00	6.00	6.00	4.00	12.00	12.00	10.00	8.00	8.00	6.67
Methanol, grey	0.57	0.32	0.32	0.32	0.32	0.32	1.14	0.56	0.59	0.62	0.62	0.62

3.3.5 Future functions for estimating costs in WP4.4

Some cost elements are very important for the OPEX costs and also for the investment, especially in Task 5.1. However, as this requires very detailed information on individual financial data, these functions will be available in the model in Task 4.4, but are not active yet.

Total fixed cost per year

$$\sum Total\ fixed\ cost = Insurance + Depreciation + Interest\ cost + Repair\ \&\ Maintenance + Other$$

The insurance is a percentage of the vessel's insurance value, the depreciation and the interest cost are defined in the formulas above. The repair and maintenance cost are dependent on the ship type and the installed propulsion system.

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Downtime cost

In addition to the installation costs also the downtime costs, i.e. the time when the vessel is at the yard for retrofit must be considered. Those are calculated by multiplying the sum of the daily fixed costs and the daily opportunity costs with the downtime days. The opportunity costs are the daily profit minus variable/operational costs:

$$Downtime\ cost\ [€] = \left(\frac{Total\ fixed\ cost\ [€]}{365} + Profit_{day} - Variable\ Cost_{day}\right) * Downtime\ days\ [d]$$

5 | Downtimes for different retrofit options [5], [6]

Retrofit Option	Downtime in days
MeOH System	42
Battery System	42
H2 ICE	42
Fuel Cell	42
New Diesel Engine	14
DPF and SCR	5
Hydrodynamic measures	14 to 30

Payload loss due to space loss

A payload loss due to space/tonnage loss for fuel storage is possible for hydrogen and fully electric propulsion power sources. So far, a cost estimation per tonne lost cargo per year is stored in the Data-base. Nonetheless, this function is not active, yet, since there is more data needed to quantify the lost space/tonnage per ship type.

AdBlue consumption

For the exhaust after treatment in the SCR, urea (or AdBlue) is needed. The following table gives the AdBlue demand related to the yearly fuel consumption.

6 | AdBlue consumption per emission level [6], [7]. For CCNR I and II engines, the consumption is related to a reduction of NO_X to 1.8 g/kWh.

Engine emission level	AdBlue consumption [% of annual fuel demand]
CCNR I	9.00 %
CCNR II	4.8 %
Stage V	No data yet
Euro VI with EGR	3 %
Euro VI without EGR	6 %

Leasing cost/Pay-per-use cost for energy storage

If a vessel owner decides to lease hydrogen or battery containers, there is no investment in the storage, but an additional OPEX cost. This function is not yet active, but is foreseen to be used in task 5.1.

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3.4 Performance prediction

The performance prediction module focuses on evaluating the environmental and operational efficiency of various green technologies by assessing fuel consumption and emissions. This evaluation leverages operational profiles generated from the Fluvial voyage simulation environment, developed by DST. These profiles provide detailed data on power demand (P_D) and operational times for different vessel types across a variety of navigational routes and environmental conditions.

Once the fuel consumption is determined for each operational segment, the model calculates emissions based on emission factors for CO_{2e} and pollutants such as NO_X (nitrogen oxides), and PM (particulate matter).

The model outputs contain information on the estimated fuel consumption and corresponding emissions from different technologies. Also here, different years can be chosen and compared. The user will be able to see the data visualized in both graphs and tables.

3.4.1 Simulation of operational profiles

Operational profiles are created for specific vessel types based on input parameters such as installed power, navigational routes, and operational conditions. The routes are segmented into smaller stretches, each defined by parameters like operational time, power demand, and water depth. These simulations account for both upstream and downstream navigation and incorporate varying environmental conditions, such as fluctuating water levels and current speeds across multiple days.

Currently, the model imports data from Fluvial text files, automatically filtering relevant columns to focus on power demand and operational time per segment. At a later stage, also input from other sources, entered in a certain format, can be used for calculation.

Figure 5 illustrates a sample simulation output for one day, highlighting power requirements and operational time variations during upstream and downstream trip. In the following, previously used approaches are briefly described in order to contextualise the new approach.

In the models used to date, the energy requirements of a ship were assumed to be rather simplified. Two examples are shown below and then the new approach in this tool is described. In the CCNR study [2], the energy demand is taken from the average fuel consumption per fleet family. Also, the power of the main engine is given.

7 | Average energy demand and installed power per ship per fleet family in 2015

Fleet families	Fleet 2015	Average fuel consumption per year per Ship (in m³)	Average power installed (in kW)
Passenger vessels (large hotel)	346	500	1000
Push boats <500 kW	890	32	247
Push boats 500-2000 kW	520	158	847
Push boats ≥2000 kW	36	2070	3458
Motorvessel dry cargo ≥110m	610	339	1742
Motorvessel liquid cargo ≥110m	602	343	1780
Motorvessel dry cargo 80-109m	1802	162	764
Motorvessel liq. cargo 80-109m	647	237	954
Motorvessels <80 m	4463	49	302
Coupled convoys	140	558	2237
Ferries	103	99	374
Day trip and small hotel vessel	2207	54	500

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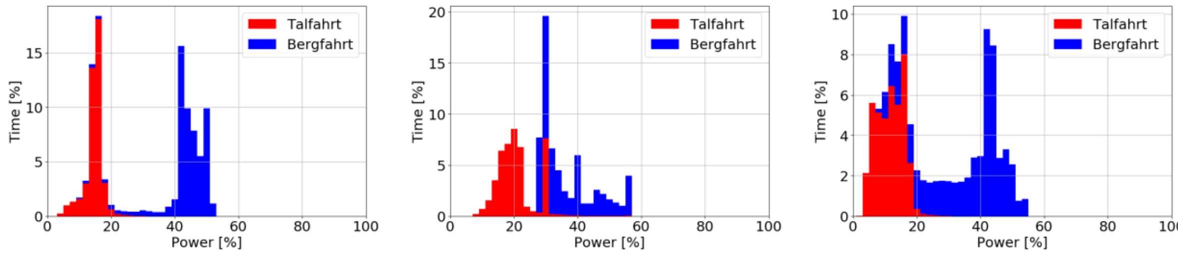
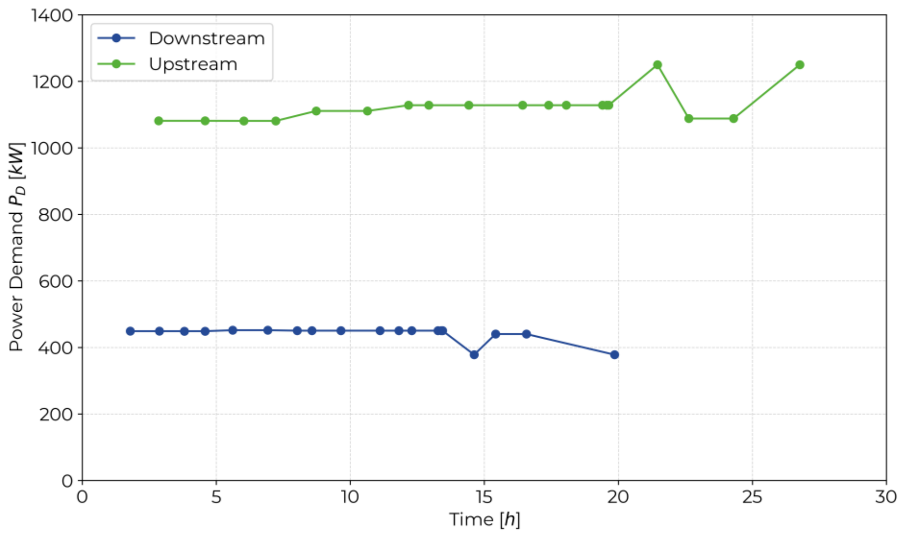
The E-Binnenschiff tool [8] uses a more differentiated variant, namely the distribution of the engine load over the voyage. The engine load is divided into different classes and then filtered according to these. This results in a distribution for the upstream and the downstream journey, as shown in the figure 4. Several journeys are required to create such a profile.



4 | Journey profiles in the E-Binnenschiff online-tool from Fluvial

However, this neglects the dynamics of operation. This is particularly important for inland waterway vessels, as they often travel on narrow waterways with currents and therefore have to manoeuvre almost constantly. The idea here is therefore to take an energy-per-stretch approach, whereby the waterway is divided into segments in which constant conditions are expected. Data for several decades is available for these segments so that a wide range of waterway conditions can be modelled. The following figure 5 shows an exemplary profile. More profiles for different routes and ship types are to be stored in the Database.



5 | Exemplary operational profile for the route between Duisburg and Rotterdam from Fluvial

So, within the newly developed tool, the operating profile comes from DST's internal programme Fluvial. It is created there according to the following methodology:

The behaviour of the boatmaster, the ship itself and the unloading are modelled for daily upstream and downstream journeys. Temporally and spatially resolved hydrological data is available for the German Rhine. Simplified assumptions or averaged data can be used for the Dutch waters. The simulation results can then be used with the assumptions for the emission behaviour of the various energy converters to create emission values. Figure 6 shows the functional diagram of the simulation.

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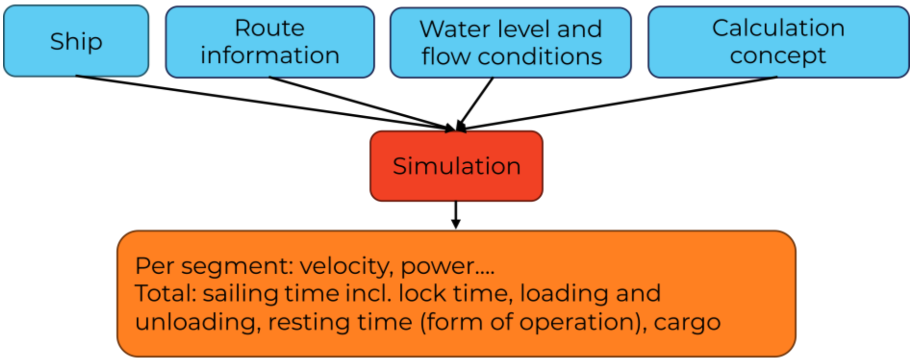

6 | Schematic illustration of the software for determining load profiles [9]. The green boxes show the calculation done in Task 4.3

Also, the information collected in the SYNERGETICS Deliverable D3.1 "SPEC analyses of full scale and model scale demonstrators" is to be considered, as some data from real vessels is collected.

3.4.2 Estimation of rotational speed and torque

Before utilizing brake-specific fuel consumption (BSFC) data, the model estimates rotational speed and torque when these values are not directly available. The BSFC is the specific fuel consumption of internal combustion engines that deliver power to a shaft. This estimation follows the propeller law defined in ISO 8178, Type E3, which is a widely adopted standard for marinized non-road engine exhaust emission measurement.

8 | Marine application propeller law – ISO 8178 [10]

Type E3, Mode	1	2	3	4
Power [%]	100	75	50	25
Rotational Speed [%]	100	91	80	63

For each power demand segment, rotational speed is calculated using these standards (see Table 8), while torque is derived as the ratio of power demand to rotational speed. Linear interpolation is applied when values fall outside predefined segments.

3.4.3 Engine Characteristics

The following propulsion technologies are addressed in SYNERGETICS: Fuel Cells, Methanol and Hydrogen internal combustion engines, Battery-electric propulsion systems and HVO. These are initially available as greening options. Of course, further technologies could be added at a later date. Within the SYNERGETICS project, a methanol engine has been on the test bed. Some of the results are presented in Deliverable D3.17 [11].

With the operational parameters defined, BSFC data for the selected technology is used to evaluate engine performance. The model identifies BSFC values for each power demand scenario by cross-referencing calculated torque and rotational speed.

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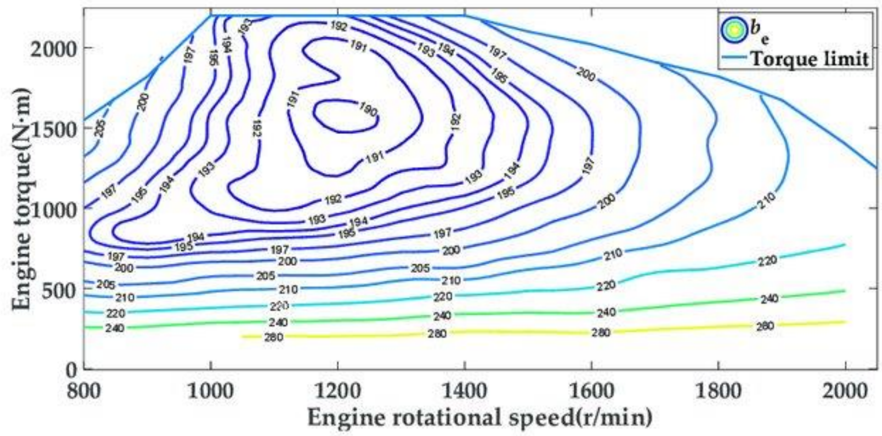
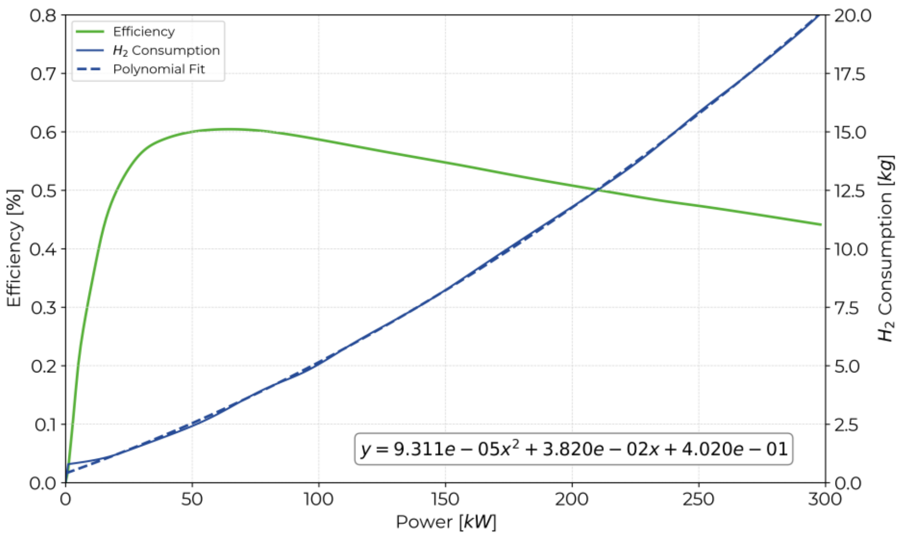
An example BSFC profile of an engine is presented in Figure 7, demonstrating how engine performance metrics are visualized. Since the used BSFC data is confidential, a diagram from the literature is shown. The model is adaptable to various engine formats, allowing for adjustments to accommodate different technological configurations.



7 | Exemplary BSFC diagram from literature [12]

For fuel cells, the hydrogen consumption is also dependent on the load. Figure 8 shows an exemplary characteristic.



8 | Efficiency and hydrogen consumption of a 300 kW heavy duty fuel cell [13].

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3.4.4 Fuel consumption

Fuel consumption is calculated based on the relationship between power demand, operational time, and BSFC values for each segment. The formula used is as follows:

$$\mathrm{FC}_i = P_{Di} \cdot t_i \cdot BSFC_i \cdot 10^{-3}$$

Where:

FC_i [kg] Total fuel consumption per segment
P_{Di} [kW] Power demand per segment
t_i [h] Operational time per segment
$BSFC_i \left[\frac{\mathrm{g}}{kWh}\right]$ Brake specific fuel consumption per segment

Total fuel consumption for a single day, whether upstream or downstream, is derived by summing the consumption across all segments. To obtain the fuel consumption for a specific operational route, the model averages the upstream and downstream consumption values.

$$FC_{Ti} = \sum FC_i \rightarrow FC_T = \frac{\sum FC_{Ti}}{Total\ number\ of\ days}$$

Where:

FC_{Ti} [kg] Total fuel consumption per day
FC_T [kg] Average total fuel consumption per operational route

3.4.5 Efficiency gain

In addition to new propulsion technologies, increasing energy efficiency is a very important measure for reducing emissions. Furthermore, reduced energy requirements also lower fuel costs. The calculation takes into account hydrodynamic measures, which are also associated with an investment. In the later fleet model, the timing of the investment (year of investment) is important for various aspects: on the one hand, of course, the financing requirements. On the other hand, the reduction in the fuel consumption of the entire fleet.

3.4.6 Emissions calculation

Emissions are calculated, whether upstream or downstream, by applying specific emission factors to the fuel consumption values. Emission factors *EF* represent the quantity of a pollutant released per unit of fuel consumed FC_T and are typically expressed in grams per kilogram of fuel. The following formulas are used for emission calculations:

$$\mathrm{NO_X}\ [\mathrm{g}] = \mathrm{FC_T}\ [\mathrm{kg}] \cdot \mathrm{EF_{NOx}} \left[\frac{\mathrm{g}}{\mathrm{kg}}\right]$$

$$PM\ [\mathrm{g}] = \mathrm{FC_T}\ [\mathrm{kg}] \cdot \mathrm{EF_{PM}} \left[\frac{\mathrm{g}}{\mathrm{kg}}\right]$$

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Emission factors are sourced from standardized datasets and are adjusted based on the selected technology and fuel characteristics. The model's flexibility allows for continuous updates of emission factors in response to new data, e.g. form the outputs of the CLEVER project (GA No 101146908) [14], or regulatory changes. The formation of both emissions during combustion is a very complex reaction process that cannot be estimated with an analytical approach. Apart from diesel and HVO, also for hydrogen and methanol in combustion engines, without those being reference fuels, the Stage V limits for engines larger than 300 kW for NO_X and PM are used [15].

9 | Emission factors in g/kWh

	NO_X	PM
CCNR Stage I	9.2	0.54
CCNR Stage II	6	0.2
Stage V	1.8	0.015
Euro VI	0.46	0.01

The performance module provides insights into the fuel efficiency and environmental impact of various greening technologies. These results are presented in both graphical and tabular formats, facilitating clear interpretation and supporting informed decision-making in the adoption of sustainable technologies.

The CO_{2e} emissions are calculated with the results from fuel consumption estimation and the following factors in table 10.

10 | CO_{2e} Emissions according to [16] and [17].

	kg_{CO2}/kg_{Fuel}
Diesel	3.74
Methanol, renewable	1.458
HVO	1.26

3.4.7 Upstream Chain Emissions

Of course, the upstream chain of all energy carriers used is important. For example, the emissions from the production of hydrogen and electrical energy must also be taken into account, even if no local emissions are generated during ship operation. Deliverable 1.2 [18] describes the determination of upstream chain emissions using many different pathways. The values are to be included later in the fleet model in Task 4.4. In the following diagrams the variability of the upstream chain emissions can be seen. This again underlines the need to store the data in the Database to make fast adjustments and additions.

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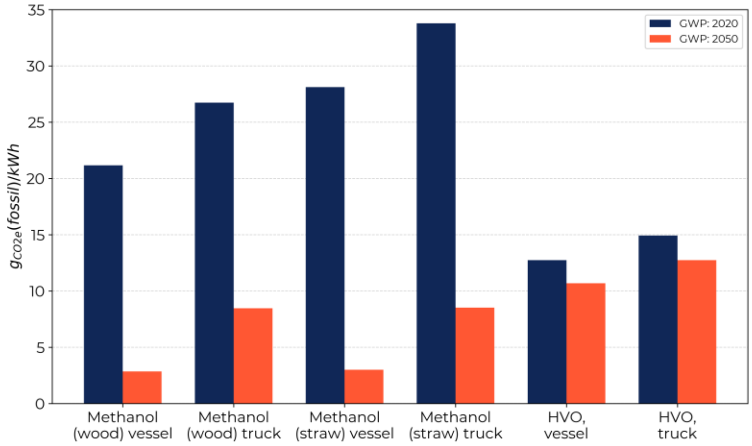
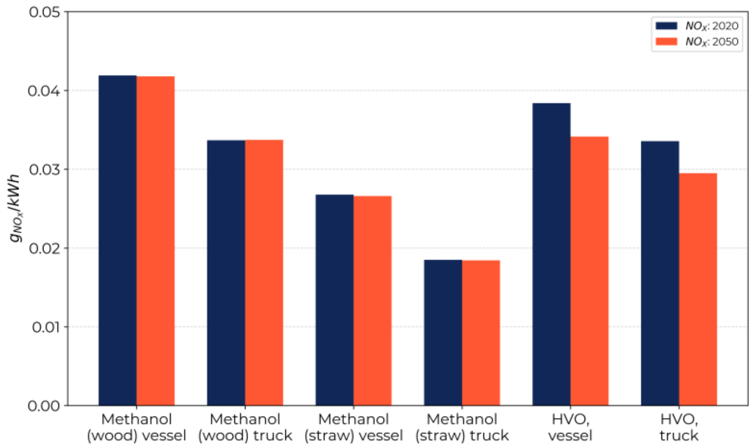
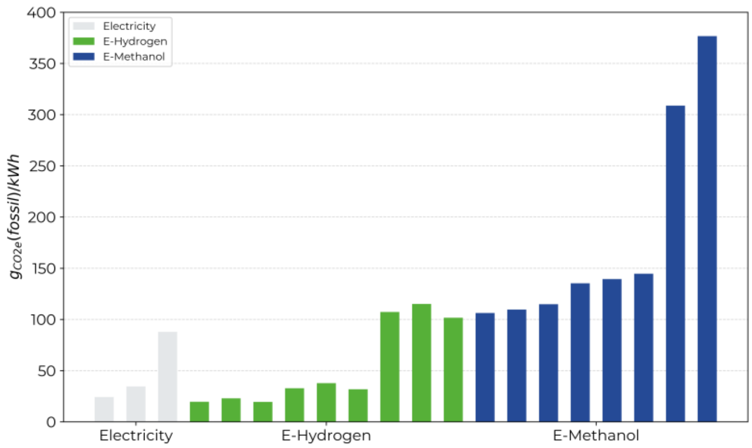


9 | CO_{2e} upstream emissions for biobased fuels from different sources and transported by different modes [18]



10 | NO_X upstream emissions for biobased fuels from different sources and transported by different modes [18]



11 | CO_{2e} upstream emissions for e-fuels from different sources. The different production paths from the D1.2 are not listed here, as only the variance in the values for illustration is important here.

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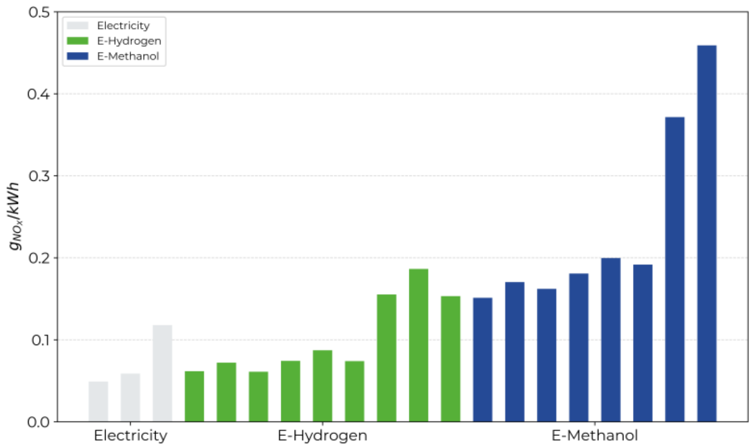
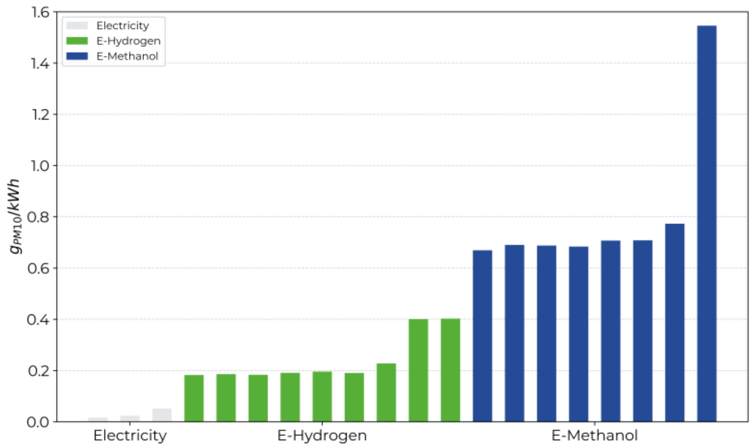


12 | NO_X upstream emissions for e-fuels from different sources. The different paths from the D1.2 are not listed here, as only the variance in the values for illustration is important here.



13 | PM10 upstream emissions for e-fuels from different sources. The different production paths from the D1.2 are not listed here, as only the variance in the values for illustration is important here.

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4. Considerations and future work

While the current model offers a robust framework for cost and performance prediction, the accuracy of calculations heavily depends on the resolution and quality of input data. Assumptions regarding baseline cost, estimated annual cost development, operational conditions, and engine characteristics influence the precision of results.

Currently, the model incorporates a single operational example to demonstrate its functionality. However future enhancements should focus on integrating a broader range of operational profiles for different vessel types and routes, as well as incorporating diverse engine configurations with varying power outputs for each greening technology. Adjustments to the code structure may be necessary to accommodate new data formats.

The result from Task 4.3 lays the foundation for the development of the fleet model. In the fleet model in Task 4.4, individual ships will form the fleet. This has the advantage that a greening timeline is stored for each ship to a certain extent. This can then be used to make various predictions for the entire fleet or individual segments. This can be used, for example, to illustrate the effectiveness of the focus on a particular measure or to determine future funding requirements.

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ANNEX

11 | Default values for investment costs for technologies in 1000€

	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 liq-uid 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 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
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
DPF and SCR												
Design and installation per unit (incl tank+compr)	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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