D5.1 Decision Support Tool for Vessel Owners

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 report presents the SYNERGETICS Decision Support Tool for Vessel Owners; a specific tool that is made for owners of inland and coastal vessels. It reflects the work done in WP5 Task 5.1. The inland vessels tool and coastal vessels tool are accessible from the same weblink. To access the tools the following link can be used which will then guide the user to the version for inland vessels or the version for coastal vessels: https://www.synergetics-project.eu/dstool

The tool will also be accessible via the Tools section of the SYNERGETICS website: https://www.synergetics-project.eu/

The tool presents a step-by-step approach to provide the required input and the results. A good balance was sought between user friendliness and complexity/accuracy of the calculations. A user manual as well as information boxes are included in the tool itself to provide explanations and guidance for the user. The tool is based on information from the SYNERGETICS catalogue and calculation methodologies developed in WP4, which are presented in the public deliverables D4.3, D4.4 and D4.5.

In the Task 5.1, particular attention was paid to the dimensions and weight of the renewable energy propulsion systems, to account for payload loss and to monetise the impacts. Also, attention is paid to the impact of additional bunker time in relation to productivity loss of the vessels. The validation of the data used for the tools in Task 5.1 is presented in D4.5. Extensive research was also done on the energy price scenarios, which is being reported in the D5.2 (planned for April 2026). However, these energy price scenarios are already integrated into the decision support tool for vessel owners.

The tool calculation takes into account the fleet family and the operational profile, with key parameters such as the required autonomy and the energy consumption per year. Attention is also paid to new business concepts such as pay-per-use of swappable battery containers and swappable hydrogen Multi-Element-Gas-Container (MEGCs), to reduce the investment barrier of vessel owners.

The tools serve as a first indication for the vessel owners to get an idea of possible technologies and energy types which can be suitable to reach emission reduction. The emission reduction targets can be set by the user and the tool will present the solutions which meet the specified emission reduction targets and sorts these shortlisted solutions on their costs.

Detailed results are made available in the tool by means of tables and graphs which can also be exported and saved locally in MS Word, PDF and CVS formats. The tool also presents all underlying data and is therefore fully transparent. Furthermore, follow-up guidance is provided with links to the catalogue, factsheets, and the Handbook for Implementation of Greening Retrofit Solutions (as soon as available, expected by April 2026).

For the continuation of the tool, DST and SPB/EICB will work together closely after the project end to maintain, update and further develop the database and tool. Specific funding opportunities are already identified, such as new Horizon Europe Innovation Actions and more tailor-made, national applications for Germany and in the framework of the upcoming Dutch grant scheme (240 million euro) and through funding via the EICB Innovation Lab collaboration and the Port of Rotterdam.

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1. Introduction

1.1 Background and purpose

As deliverable for the SYNERGETICS Task 5.1, the Decision Support Tool for Vessel Owners has been developed. It is designed for vessel owners of both inland and coastal vessels. The core motivation for creating this tool is to address a persistent challenge in the inland waterway sector: vessel owners and operators face an increasingly complex landscape of technologies, regulations, and investment decisions when seeking to reduce emissions. Seen the challenge and increasing urgency to transition to cleaner and decarbonised shipping operations, industry actors need practical guidance to navigate the wide range of available alternatives. It is a complex matter because of the differences between capital and operational costs, varying operational implications and also seen the regulatory requirements and maturity.

The inland waterway and coastal shipping sectors each operate under very different financial conditions, technical constraints, and policy frameworks. To genuinely support decision-making in both contexts, the project therefore developed two separate tools, one for inland vessels and one for coastal vessels. Each tool is designed to reflect the realities and challenges of its respective segment. This tailored approach ensures that the guidance provided is realistic, relevant, and actionable for the users concerned.

The primary goal of the Decision Support Tool is to help vessel owners and operators to identify the technological emission-reduction strategies that best suit their individual needs and circumstances. Rather than advocating for one universal solution, the tool helps users explore a wide spectrum of technological and operational options, filtered and presented according to the requirements and boundary conditions they define. These requirements and boundary conditions are related to the vessel type, the operational profile, and financial constraints as well as the required emission reduction which needs to be achieved, while differentiating between greenhouse gas emissions and air pollutant emissions. By offering structured comparisons, transparent insights, and accessible supporting information, the tool enables users to better understand the trade-offs and advantages associated with each potential pathway.

In particular, attention was paid to operational elements such as the possible loss of payload and the additional bunkering time which may be required when using other energy types compared to diesel and drop-in fuels. Additional weight and space required can have significant impacts on the payload which can be carried and thus can lead to reduced productivity and thus to higher costs for the clients. Furthermore, the diesel can be bunkered quite rapidly, even during sailing operations, while the energy density is very high. But other options such as methanol, hydrogen or electricity have lower energy densities and do require significantly more time to replenish the energy storage on board. Again, this also can lead to reduced productivity of the vessel (more idle time for bunker) and can affect the productivity and costs of transport for the clients.

Crucially, the Decision Support Tool is not intended to make final decisions or recommendations for the vessel owners. Its purpose is to support, not replace, the human decision-making process. It provides clarity in a complex environment, helping stakeholders move towards emission reduction with greater understanding. It shall be seen as a tool which presents a short-list of most suitable technological options to meet the emission reduction targets set by the vessel owner, focussing on the most cost-effective solutions to reach the emission reduction goals. Afterall it is the business case and thus the total cost of ownership which is crucial for the decision making. Through this guidance, the tool contributes to a more informed and accelerated transition toward sustainable shipping practices across both inland and coastal shipping. Next to this tool also a Handbook for Implementation of Greening Retrofit Solutions is being prepared in WP5 of SYNERGETICS to provide further guidance and context as added value to the tool.

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1.2 Scope

The scope of Task 5.1 entails a combination of the exploration work that has been done in WP1 and the catalogue developed as part of WP4. The work done in those work packages resulted in a selection of viable technological options to green the fleet. For consistency the renewable technologies that were considered in the scope for the IWT and coastal sector are mostly the same but specifics of the coastal sector have been considered, such as the different fuel and engines types which can be used in coastal vessels because of the different regulatory framework.

Between the tools there is a slight difference in technology options, which is that for the coastal vessels solar panels are included in the tool and for IWT vessel not. The reason for this is, although solar panel systems for IWT vessel are considered as a viable option they have to be specifically designed per vessel which made it too complex to model solar panel systems for the IWT vessels in a general tool. However, for coastal vessel more standardised systems can be used for which cost-prices were available and thus could be installed.

For the reference engines there is, however, a difference between the coastal and IWT sector. The reason for this difference is the engine classification. Coastal vessels fall under the worldwide IMO regulations, while the IWT sector falls under the European regulations. The difference between these two regulatory frameworks is that the emission limits of the EU are stricter compared to those of the IMO. This results in different types of reference engines with different emission factors and efficiencies.

Another difference between the IWT sector and the coastal sector is the fuel used in both sectors. The IWT sector used mostly diesel with a sulphur content of less than 10 ppm since 2011, which is the same requirement as road diesel. As a result, the SOx emissions of inland vessels are not significant. The coastal vessels on the other hand can use fuels with higher sulphur contents like Heavy Fuel Oil (HFO), or Marine Diesel Oil (MDO), with a maximum share of 0.1 % of the fuel mass. The coastal vessels considered in SYNERGETICS, however, sail in a SOx restricted area, meaning that they either need scrubbers of use low sulphur fuels like Ultra Low Sulphur Fuel Oil (ULSFO) or Very Low Sulphur Fuel Oil (VLSFO). It is assumed that scrubbers are not used in the vessel types that are included in the coastal vessel tool, so these vessels must use ULSFO or VLSFO instead of the cheaper HFO or MGO for which scrubbers are required.

For the IWT tool the reference diesel engines that are used are:

- Unregulated diesel (build before year 2003)
- CCNR1 diesel engines (2003-2007)
- CCNR2 diesel (2008-2019)
- Stage V diesel (>2019)

For coastal vessel tool the reference diesel engines that are used are:

- IMO tier II with ULSFO
- IMO tier II with VLSFO
- IMO tier III with ULSFO
- IMO tier III with VLSFO

The selection of greening technologies that are used in the decision support tool are technologies that either already exist on the market or have sufficiently high TRL to be used for full scale demonstration projects.

The distinguished technologies and energy types are:

- Stage V engines (for IWT)
- Tier III engines (for coastal)
- SCR after treatment (for coastal)
- DPF and SCR after treatment for engines
- HVO as drop-in fuel: renewable diesel which can be replaced by e-diesel on longer term

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- Methanol Dual Fuel combustion engines, both grey and green methanol
- Methanol Single Fuel combustion engines, both grey and green methanol
- Hydrogen combustion engines, swappable or fixed containers, both grey and green hydrogen
- Hydrogen fuel cell, swappable or fixed containers, both grey and green hydrogen
- Full battery electric propulsion with a choice between pay-per-use model or fixed battery packs
- Liquid methane (LNG), both grey and Bio-Methane (Bio-LNG)
- Solar panels (for coastal)
- MeOH Fuel Cell

Technologies which are not mentioned above, like ammonia for example, can still be added to the selection of technologies in a later stage, for example as soon as the TRL is more mature and information is available on costs and emission factors. The database and the Decision Support Tool have been designed in such a way, that adding or removing technologies is possible without the need to restructure the entire tool. This makes the tool resilient to evolutions on the technological landscape.

In both the coastal and IWT sector many different vessel types exist, and hardly any ship is the same as another ship. Therefore, the concept of 'fleet families' was introduced to be able to classify vessels into a category and to provide default values based on averages seen in the market for a particular fleet family. The default values for example are about the average installed power, average fuel consumption, and several cost values. Fleet families for the IWT sector have been developed during the EU funded project PROMINENT in 2015, which include different vessel types with similar dimensions and engine powers. Later on, the fleet families have been further checked and refined in a CCNR study [1] on energy transition. The distinguished fleet families for the IWT sector are:

- Large cabin vessels: a passenger vessel longer than 86 m and with overnight passenger cabins.
- Push boats ($P < 500$ kW): a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of less than 500 kW.
- Push boats ($500 \leq P < 2000$ 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 ($P > 2000$ kW): a vessel specially built to propel a pushed convoy and equipped with a total propulsion power of more than 2000 kW.
- Motor vessels dry cargo ($L \geq 110$ m): a vessel equal to or longer than 110 m, intended for the carriage of dry goods and containers and built to navigate independently under its own motive power.
- Motor vessels liquid cargo ($L \geq 110$ 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 vessels dry cargo ($80 \text{ m} \leq L < 110$ 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 vessels liquid cargo ($80 \text{ m} \leq L < 110$ 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 ($L < 80$ 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.
- 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.
- 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.

For the coastal vessel sector there was however no such knowledge base from previous studies. Another complexity is that there is no exact definition of a coastal vessel. Therefore, also no fleet families were mapped and identified yet for the coastal sector. In the exploration work package of SYNERGETICS

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(WP1) research has been done to define the coastal vessel sector, which now led to a definition of fleet families for the coastal vessel sector in the published Sustainability paper by SYNERGETICS [2]. The defined fleet families currently in SYNERGETICS are:

- Dry cargo vessels up to 79.99m
- Dry cargo vessels between 80 to 89.99m
- Dry cargo vessels between 90 to 99.99m
- Dry cargo vessels over 100m and <5000 GT
- Ferries with an installed power between 0-999 kW
- Ferries with an installed power between 1000-1999 kW
- Ferries with an installed power between 2000-2999 kW
- Ferries with an installed power between 3000-3999 kW
- Ferries with an installed power between 4000-8000 kW
- Ferries with an installed power above 8000 kW
- Ferries High Speed Ferries
- OSVs weighing <2000 GT
- OSVs weighing between 2000-3000 GT
- OSVs weighing between 3000-4000 GT
- OSVs weighing over 4000+ GT
- Fishing vessels of the type VL0012
- Fishing vessels of the type VL1224
- Fishing vessels of the type VL2440
- Fishing vessels of the type VL40XX

Narrowing down the number of different vessel types using fleet families not only makes the tool user friendly, but it also reduces the required calculation time. The consequence of this chose, however, is that price ranges have to be used in order to account for the differences in vessel types within these fleet families. Other settings like installed power and yearly fuel consumption can be changed by the user to tailor the input setting towards their vessel specifics.

1.3 About this deliverable

This deliverable is the first of the series of deliverables within WP5 of SYNERGETICS and it describes the work that has been done for Task 5.1. This deliverable D5.1 includes an extensive documentation of the relevant information regarding the Decision Support Tool. It is however not a stand-alone deliverable. Important work done in SYNERGETICS which already has been documented in different deliverables is referenced, in order to prevent unnecessary repetition of information. This concerns mainly the work done in WP4. In Deliverable D5.1 references are therefore made to WP4 deliverables D4.3, D4.4 and D4.5. As preparatory work for Task 5.1 and Task 5.2, in-depth research was done to develop energy price scenarios for the period 2025-2050. The research done on this has been included in a separate document, which will be part of the Deliverable for Task 5.2. The energy price scenarios are however applied in the Decision Support Tool for Vessel Owners. The focus of this deliverable D5.2 is therefore mainly to provide a guideline on use of the decision support tool and the used approach and methodology to develop the tool.

The main body of this deliverable starts with Chapter 2, which encompasses a detailed user manual on the Decision Support Tool for Vessel Owners. The goal of this user manual is to make the tool accessible for everyone. The user manual describes the use of the interface; it outlines the meaning of the different options that can be selected, and it shows an exemplary result which can be used to test the tool. The user manual is also included in the tool itself as a separate document.

In chapter 3, this report subsequently continues with the description of the used methodology and assumptions. The groundwork of the methodology has already been done and reported in WP4 with the Deliverables D4.3 and D4.4. These deliverables present in detail the equations for the capital cost with the corresponding depreciation assumptions, the maintenance cost, the fuel consumption, the

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downtime cost, the bunker time loss, other fixed costs and the emission performance. For completeness of the deliverable the equations stemming from D4.3 and D4.4 are summarized in chapter 3. The remaining parts of the methodologies that have been specifically developed for D5.1 are described more detail. The main addition to the methodology in D5.1 compared to D4.3 and D4.4 is the loss of payload, the rest mainly entails updates and adjustments that were made during the development of the tool and checking and validating the input data, involving also many external experts and stakeholders from the industry.

Next, the chapter 4 presents the business case for the continuation of the Decision Support Tool after the duration of the SYNERGETICS project (from July 2026 onwards). This includes agreements on the ownership of the tool, the development and maintenance responsibilities, and plans for future funding required for the development and maintenance work of the tool.

Chapter 5, the final chapter of the report, concludes all the work done for Task 5.1. In the Annex extra information is included on the development of the payload loss methodology and extra information is presented on the validation process of the Decision Support Tool and the stakeholder involvement.

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2. Decision Support Tool layout

This chapter presents the user manual of the Decision Support Tool for Vessel Owners.

2.1 General information

The following vessel has been used as example to explain and illustrate the steps the user follows in the decision support tool, to generate the results and how to interpret the results for identifying possible solutions to reach emission reduction targets.

2 | Input values for the example used in the user manual.

Parameter	Value
Vessel type	Dry cargo motor vessel 80 m < L ≤ 110 m
Length (m)	105
Default engine	Old diesel engine CCNR2
Power (kW)	750
Fuel consumption per year in tonnes	135
Autonomy in days	1
Depreciation period in years	20
Interest rate %	7
Yearly profit in €	14000
Yearly insurance costs in €	30000
Yearly personnel costs in €	170000
Yearly revenue in €	366000
Yearly capital costs in €	62000
CO2e reduction %	90
Nox reduction %	50
PM reduction %	50
Subsidy %	80 on battery electric and hydrogen
Maximum deadweight in tonnes	2000
Maximum capacity %	60
Payload loss	Included
Bunker time loss	Included
Applicable scenario	STEPS

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The tools are developed and programmed using "Streamlit", which is a framework within Python containing modules to build basic interfaces for on-line applications. Python is a programming language used for automation, data analysis, and web development. Both decision support tools have basically the same functionalities and interface. Therefore, to avoid repetition, the tool developed for the inland waterway vessels is used throughout the user manual to explain the steps and the user interface of the decision support tool.

"Streamlit" was selected as it provides a suitable instrument for developing and maintaining the decision support tool. The framework itself is easy to use and it includes all the necessary and relevant functions which are needed for a well-functioning tool. However, it is important to note that "Streamlit" is a straightforward but basic application and there are limitations as well. Functionalities like making specific user accounts and storing data are not possible. But this also avoids sensitive issues like data protection and access. Furthermore, the input and the results can be exported and saved locally, to allow the user to still store the data and to make further analyses, e.g. using MS Excel, Word or PDF. Moreover, when using the tool, the user can navigate between the different tabs and the input data will be stored temporary. However, once the browser is closed and re-opened the tool has to be filled in again from the start.

The tool allows only one set of input settings to be evaluated at a time. Users must complete all tabs and download the results from these settings in Excel, PDF or Word format. To assess the solution of a different set of input settings, the tool must be restarted and the entire workflow must be repeated in order to save the new results. As a next step, the user can for example compare the MS Excel, PDF or MS Word outputs to create the overall picture in case the user wants to explore different settings, such as the energy price scenarios or emission reduction targets.

In order to provide full transparency on the used data for the calculations in the tool, a functionality was included to have access to the data used in the background. Besides transparency the level of understanding is also an crucial factor in ensuring a wide user range. To facilitate this the IWT tool is available in three different languages. For the coastal tool it was decided that only English would be enough. As shown in figure 1 the language can be selected by clicking on the desired language in the grey box appearing in the left. Ones the language is selected this grey box can be hidden by clicking on the arrow sign at the right to op the grey box.

The tools are divided into five different tabs where, as shown in figure 1, the names of the tabs can be seen at the top of the screen. The circles next to the names of the tabs show the active and inactive tabs. The active tab is highlighted by the red circle, whereas the inactive tabs are white. In case of figure 1, the current tab that is active is tab 1 *Vessel type*.

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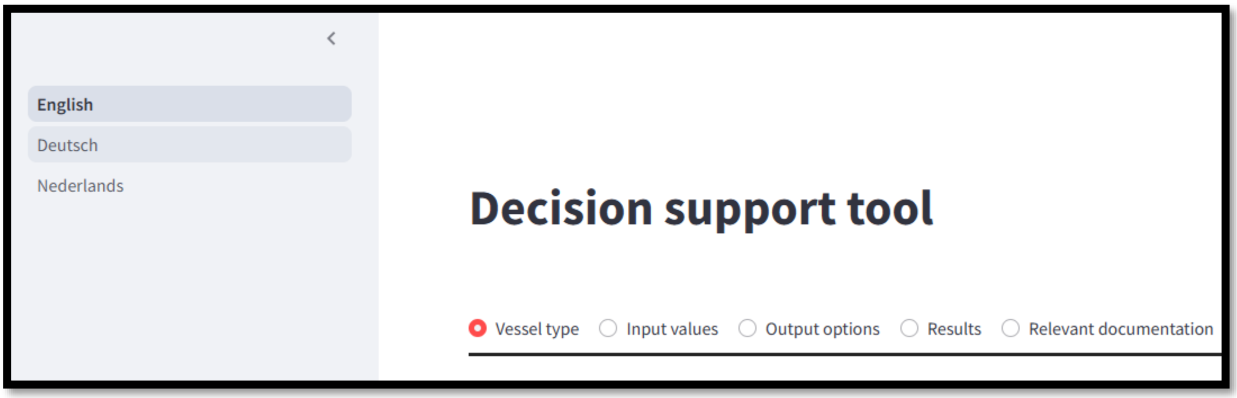
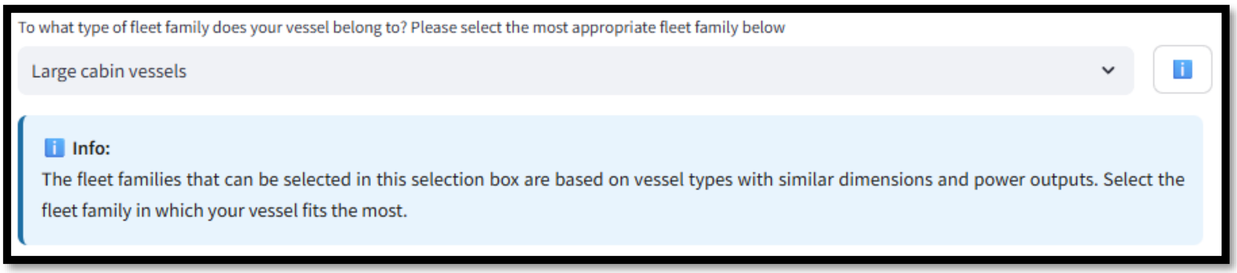


1 | Visualisation of the tab menu.

The user can navigate between different tabs, either by clicking on the circles next to the tab names, or by clicking on the Next and Previous buttons (1) at the bottom of the page, which are shown in figure 2. There are five different tabs of which the first three tabs define the input, the fourth shows the results and the last included extra information to better interpreted the results. All the first three tabs have to be filled-in properly first to generate reliable results.

2 | Visualisation of the Next and Previous buttons

Figure 2 shows another feature that can be found throughout the tool. On the right side of the page, a blue square box with an "i" in the middle (2) is visualised, which is an information box. When the user clicks on this element, extra information will appear in a blue field below the option, as shown in figure 3.



3 | Visualisation of the information field.

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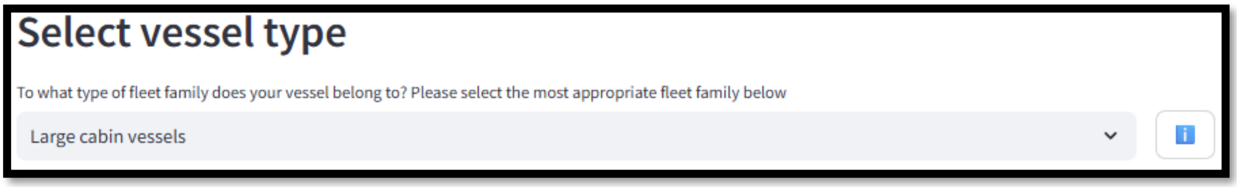
This information box is developed to help the user understand better what they have to fill in. In some cases, it also provides examples to clarify the different options for the vessel owner and to support them in selecting the correct options. In some cases, the info boxes include abbreviations with a dotted line under them. By hovering over these abbreviations with the mouse the full meaning of the abbreviation is shown.

2.2 Tab 1, Vessel type

SYNERGETICS includes both inland vessels and coastal vessels, which both have different financial structures and operational profiles. Therefore, two separate tools have been developed. To receive the correct solutions, it is important for the tool to receive accurate information on the type of vessel from the shipowner. Therefore, the appropriate selection box appears to select the fleet family in which the vessel of the shipowner fits best. Figure 4 shows the selection box for inland waterway vessels.



4 | Visualisation of the vessel type selection box.

Besides the vessel type, the current type of engine that is installed on the vessel is included, to use as a reference for the advice on the alternative options. Therefore, the user has to select the default engine at the beginning of the tool, which is shown in figure 5.

5 | Visualisation of the diesel reference engine selection box

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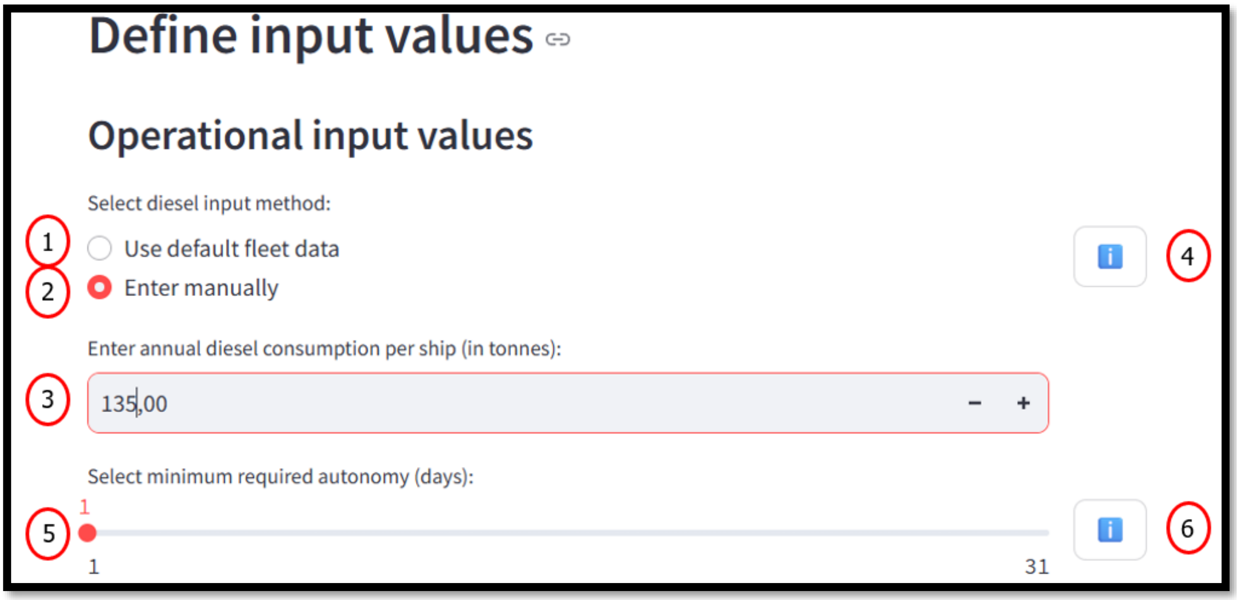
2.3 Tab 2, Input values

In tab 2, Input values, the user can select all the required input values for the Total Cost of Ownership (hereafter TCO) calculation. This tab is subdivided into four different parts: Operational input values, Additional input values, Emission requirements and Cost input values.

In the first section the user can select the specific operational input values, which is shown in figure 6. The first input value in this section is to select whether the user wants to use default values for the fuel consumption (1) or use a manual yearly fuel consumption value (2). If the user selects default values the TCO calculation will use the average fuel consumption from the database corresponding to the correct vessel type. If the user selects the button "Enter manually" a selection box will appear (3) where the user can define its own yearly fuel consumption. Some explanation on what these two options mean is included in the tool (4).

The final parameter in the operational input values section is the autonomy (5) that is preferred by the shipowner. The shipowner can choose between an autonomy of 1 to 31 days by the means of a slider as shown in figure **Fehler! Verweisquelle konnte nicht gefunden werden.**. An advice given is that the user should try different autonomy days, for example, to see whether certain solutions will be possible if the user chooses to reduce its autonomy (6).



6 | Visualisation of the operational input values section.

In the second section the user can select the additional input values, which is shown in figure 7. The first step of this section is to select the desired installed power on the vessel. The next step is to select the applicable interest rate of the Capital investment. Lastly for this section, the depreciation period in years has to be selected. In this case the economic depreciation period is meant, so not the lifetime of the technology itself. The TCO calculation uses default values for the installed power per fleet family (1) [3], an interest rate of 6 % (2) and a default depreciation period of 20 years (3). In case the shipowner has different preferences on the installed power or uses different interest rates and depreciation periods they can alter that by the means of a slider in the section shown in figure 7.

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Below every slider the tool shows the default values that match the selected vessel type and also shows a box that indicates whether the selected value matches the default values or not. If the value matches the default value the box turns green and it says "The selected power/interest rate/depreciation year matches the default value.", if value is below the default value the box turns yellow and says "The selected power/interest rate/depreciation year is lower than the default value.", and if the value is above the default value the box turns blue and says "The selected power/interest rate/depreciation year is higher than the default value.".

7 | Visualisation of the additional input values section.

In the third section the user can select which minimum emission reduction it wants to acquire. As shown in figure 8 there is a slide bar for CO_2e Well-to-Wake (1), NO_X (2) and PM (3) emissions going from 0 % to 100 %. What is meant by CO_2e Well-to-Wake is that all CO_2e emissions are included from producing the fuel up until using the fuel, so just not only the emissions that are emitted from the tailpipe. Based on the emission selection the user makes the TCO calculation engine filters out solutions that do not meet this requirement. The emission reduction selection is thereby the first filter of the possible greening technology solutions.

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8 | Visualisation of emission reduction input values section.

In the fourth section the cost input values need to filled in. This includes the yearly revenue (1), the yearly profit made (2), the yearly capital cost of the entire vessel (3), yearly personnel costs (4) and yearly insurance costs (5) as shown in figure 8. There is also an option to include CAPEX subsidies (6), if applicable.

9 | Visualisation of the input values section for personalising the installed power, interest rate, and depreciation default settings.

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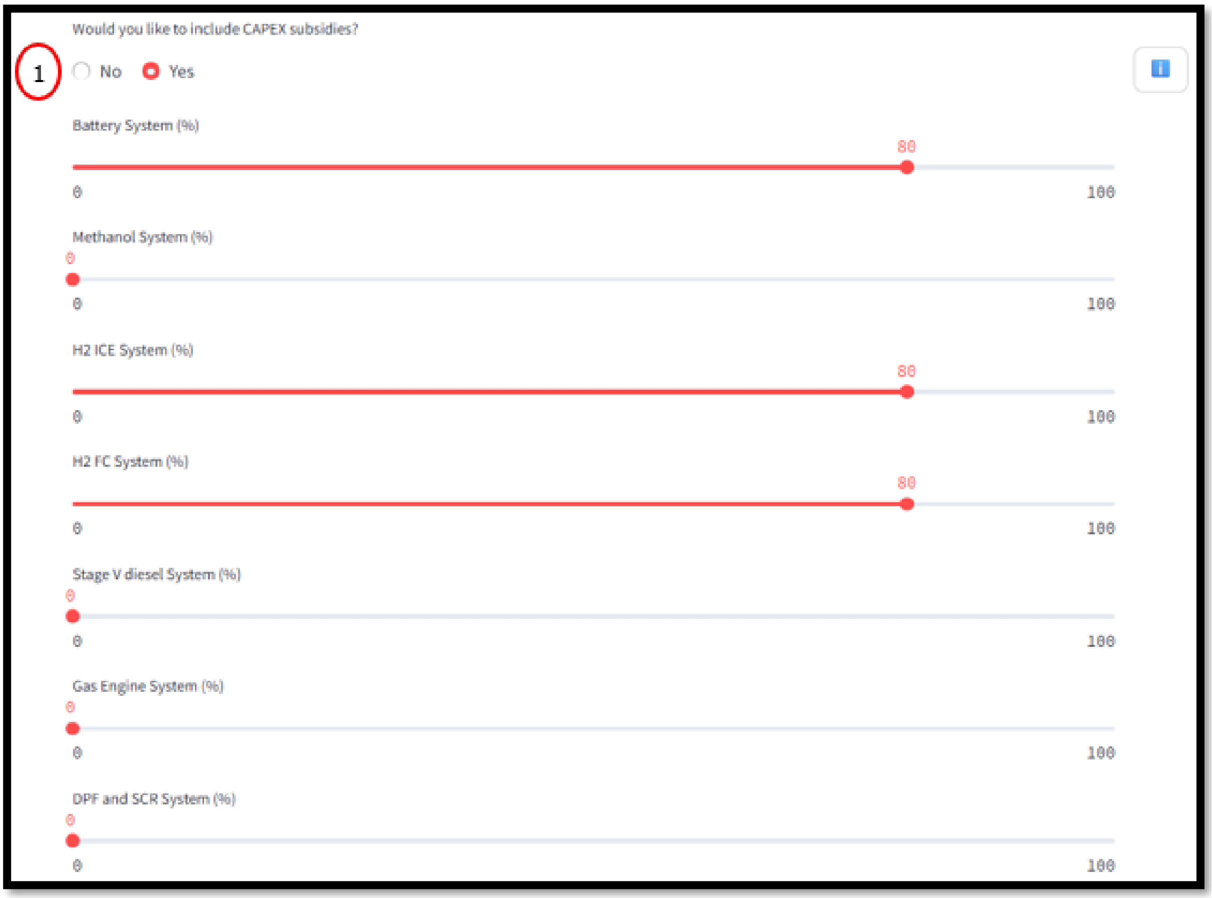
After the user has selected "Yes" (1) they can subsequently select the technologies to which the subsidy would apply to, which is shown in figure 10.



10 | Visualisation of subsidy input sliders

2.4 Tab 3, Output values

In tab 3 the user can select whether they want to include the cost of payload loss (2), the cost due to the loss in bunker time (3), none of these parameters (1) or both parameters (4) as shown in figure 11. The reason for providing this option is because not for all vessel types all options are relevant to be included in the TCO calculation.

In the case of payload loss, larger vessels or vessels that often do not sail on maximal capacity for example, a loss in maximal volumetric of weight capacity will have little effect on the total profit of the vessel. In case for the cost due to the potential extra bunker time, vessels that for example sail on a fixed route with plenty of time to bunker, one or two hours of extra bunkering a day would also hardly result in a loss of profit. However, for some vessels these two parameters could have a significant effect on their profit. Therefore, tab 4 is designed so that the user can decide whether they expect some of these two parameters to affect their profit and whether they would like to include them or not. An extensive explanation on this is given in an information box, together with some examples (5).

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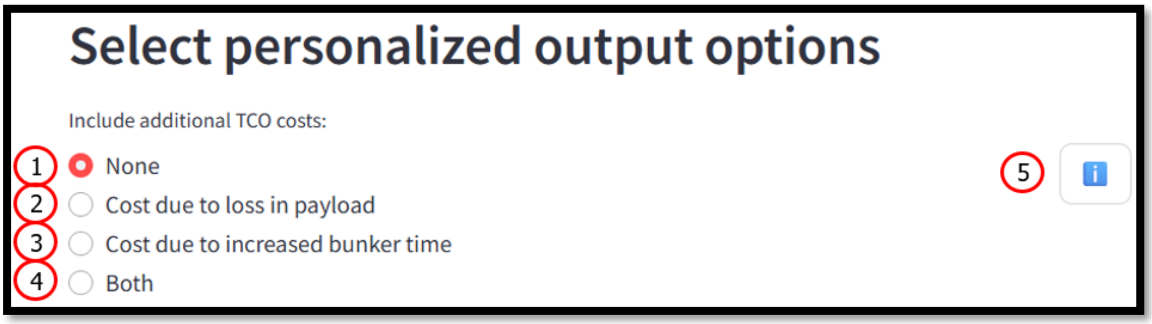
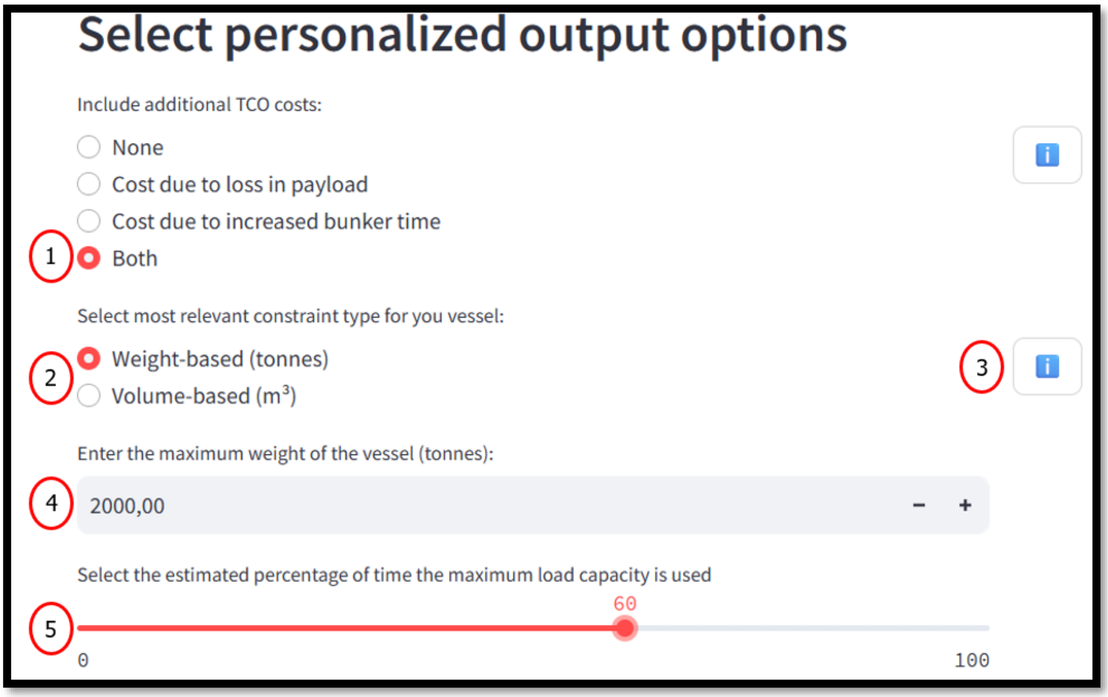


11 | Visualisation of the personalised output values.

Figure 11 shows that when the option "None" and also "Cost due to increased bunker time" is selected there are no other options to fill in. However, if the user selects "Cost due to loss in payload" or the option "Both" an extra set of selection boxes appear as shown in figure 12 (1).

At section (2) the user selects whether the parameter "weight" or "volume" will be the most relevant when looking at loss of payload. In case only the amount of TEUs that can be stored on board is known there is an information box which includes default values for calculating TEUs to volume or tons which are from the GLEC framework [4] (3). In section (4) the user then fills in either the current maximum payload in tons or in cubic meters depending on which parameter they have selected. Finally in section (5) the user can select an estimate percentage of how often they sail close to the maximum volumetric of weight maximum payload. After this is filled in, the tool has acquired all the information required to calculate the TCO.

When including payload loss into the TCO calculation a second filter method is initialised within the calculations. Here the technologies that have a larger weight of volume than the selected maximum weight or volume are removed from the analysis.



12 | Visualisation of the extended selection menu when the option "Cost due to loss in payload" or "Both" is selected.

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2.5 Tab 4, Results

2.5.1 Part 1: calculated top three technologies

In the fourth tab, the calculated results are presented based on the input values from tabs 1 to 3. The results are subdivided into two parts. The first part includes cost and emission results for the top three most cost-effective retrofit technologies, calculated based on the pre-defined input settings. The second part provides a more in-depth analysis of how the tool selected the top three most cost-effective solutions. In addition, the second part includes the cost and emission values for all feasible solutions within the pre-defined boundary conditions.

Firstly, to generate the results, the user has to choose which energy price scenario (1) they would like to use in the calculations as shown in figure 13. There are three scenarios to choose from:

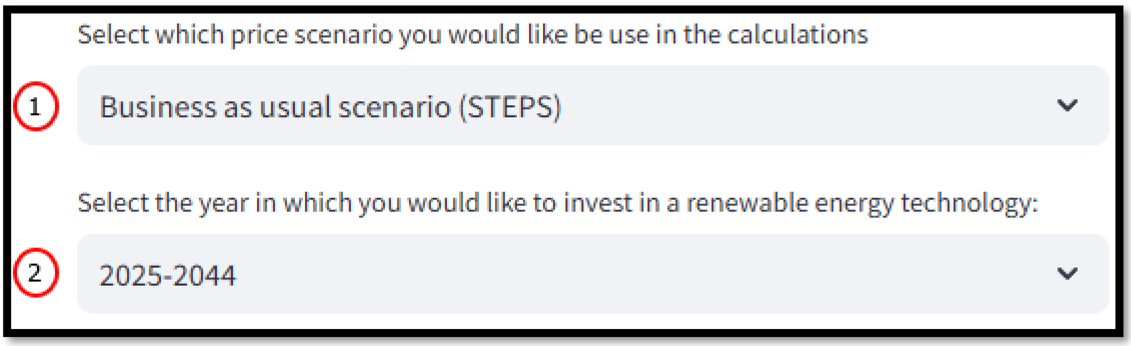
- Business as usual (Stated Policies Scenario STEPS);
- Increased policy measures (Announced Pledges Scenario APS);
- Net zero emissions (Net Zero Emissions Scenario NZE).

The "Business as usual scenario (STEPS)" is the least strict scenario and assumes into some extent the internalisation of costs of CO_2e emissions. The "Increased policy measures scenario (APS)" assumes more strict measures and higher costs of CO_2e which are internalised in the (fossil) energy prices. The "Net zero emission scenario (NZE)" assumes that more impactful measures are implemented to limit the global warming to the 1.5 degrees. In the NZE scenario the costs for CO_2e emissions are set at highest levels which results in higher prices for fossil fuels.

Across the scenarios, a set of differentiated OPEX (Operational Expenses) price levels is used to capture expected cost dynamics in the years ahead. The analysis spans a range from the current or "business-as-usual" trajectory, through a scenario characterized by tighter regulations and corresponding cost pressures, to an extreme scenario that illustrates the highest plausible escalation in operating expenses to achieve net zero emissions.

The user can choose which energy price scenario they expect to be applicable and see which technology is expected to be the best fit for their vessel within this scenario. This energy price scenario is used for the results in both part 1 and part 2. It is recommended to the user to experiment with these scenarios to see how the results change.

Besides the choice of an energy price scenario, the user also has to decide (2) in which year they would like to make their investment in a greening technology as shown in figure 13. In contrast to the energy price scenario this setting only effects the results in part 1. The investment time is a relevant parameter because energy prices and investment costs change over time for all solutions. This means that the most cost-effective solution when investing in 2025 could differ from the solution chosen for an investment in 2030. To investigate this effect, the year in which the user plans to invest in a greening solution can be changed as well.



13 | Visualisation of the fuel price scenario and the TCO period selection box.

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The top three most cost-effective solutions in the first part of the results are based on the average calculated Total Cost of Ownership (TCO). In this case, the TCO includes all costs related to the investment and use of the greening propulsion system and energy storage system over the full depreciation period, such as capital costs, operational costs and maintenance costs. It does not include costs related to the entire vessel, such as insurance and personnel costs. Since the TCO is calculated over the entire depreciation period, both the fuel price forecast scenario over time and the year of investment will affect the results.

In the first table in the results tab the user sees an overview of the different TCO scenarios for the top three most cost-effective solutions, based on the pre-defined input settings. This table contains five different cost scenarios, where the top three are calculated based on the average scenario (the first cost column). The average scenario is determined using a minimum cost value and a maximum cost value. Since the TCO is based on price forecasting, which is influenced by many uncertain parameters, the exact price scenario is difficult to predict. To show the range of possible outcomes, the second to fifth cost columns display the TCO difference for the following scenarios:

- Column 2: Minimum greening solution price and minimum reference diesel price scenario
- Column 3: Maximum greening solution price and maximum reference diesel price scenario
- Column 4: Minimum greening solution price and maximum reference diesel price scenario
- Column 5: Maximum greening solution price and minimum reference diesel price scenario

Columns 4 and 5 together represent the maximum price bandwidth. Column 4 shows the most favourable price scenario for the greening solution, while column 5 shows the least favourable scenario. The larger this bandwidth, the higher the uncertainty regarding the actual price scenario. This means that solutions with a smaller price bandwidth carry a lower risk of price deviations from the average scenario compared to solutions with a larger bandwidth.

When a TCO number is green this means that the TCO per day will reduce compared to the current diesel engine. When the TCO number is red this means that the TCO per day will increase compared to the current diesel engine.

Difference in TCO per day per technology for Motor vessels dry cargo (80 m ≤ L < 110 m) in the TCO period 2025-2044 for the top three technologies

System	Variant	Cost difference renewable(avg)-diesel(avg)	Cost difference renewable(min)-diesel(min)	Cost difference renewable(max)-diesel(max)	Cost difference renewable(min)-diesel(max)	Cost difference renewable(max)-diesel(min)
Battery System	pay-per-use	€210,-	€165,-	€255,-	€-1,-	€421,-
MeOH System	green Single Fuel	€449,-	€141,-	€757,-	€-25,-	€923,-
Battery System	charging	€580,-	€477,-	€683,-	€311,-	€849,-

Green numbers: this means that the TCO per day will reduce compared your current diesel engine
Red numbers: this means that the TCO per day will increase compared your current diesel engine

Click here for extra information on the table showing the TCO difference for the top three technologies

14 | Visualisation of the table showing the TCO difference per day between the reference diesel engine and the top three calculated best solutions based on the pre-defined settings and input values.

Besides the overview by means of the table, there is also a bar plot. This, in combination with the table shown in figure 16, shows the TCO per day averaged over the depreciation period for the top three most cost-effective greening retrofit solutions and the selected reference diesel engine. An example of the bar plot is shown in figure 15 which is obtained using the exemplary input data of table 2, with 2025-2044 as depreciation period.

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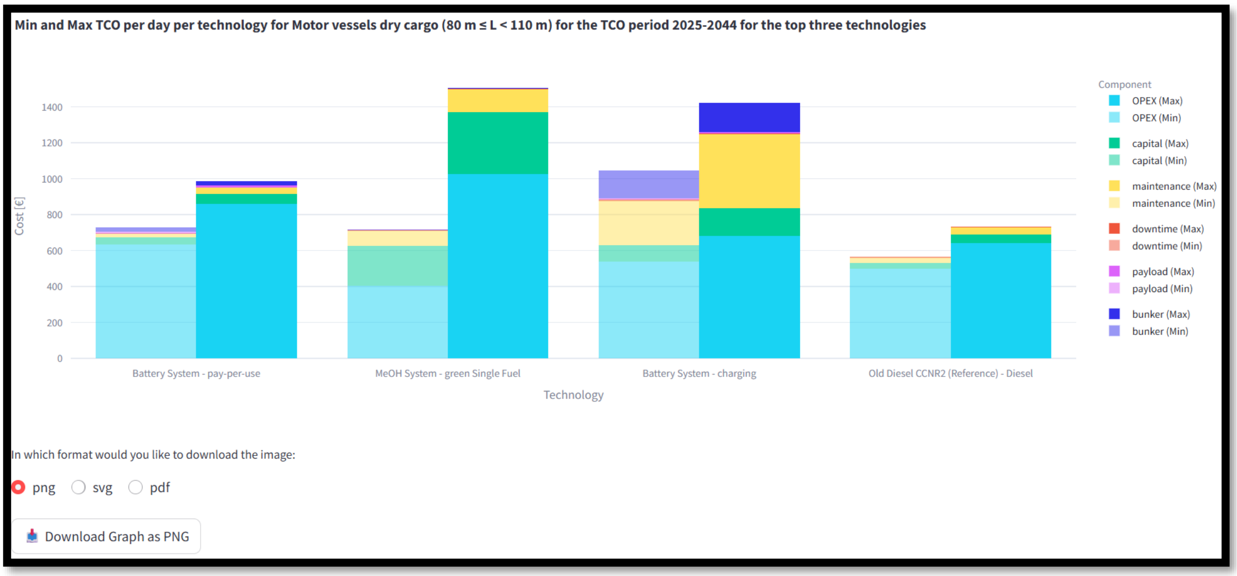
The bar plot displays both the minimum TCO (left bar) and the maximum TCO (right bar) to indicate the TCO bandwidth per technology, while the table also includes the average TCO value. As mentioned before, the TCO is the sum of different cost components. To illustrate the contribution of each component, the bar plot shows each cost component in a different colour, stacked on top of one another, which together make up the total TCO value. By placing the cursor over the different components, it is possible to see the cost associated with each specific component.

(1) By clicking on the cost components in the legend on the right side, the user can select which cost component they want to have in their overview.
(2) The user can also download the bar plot as a png, svg or pdf file, which is stated below the bar plot.



15 | Visualisation of the bar plot showing the minimum (left bar) and maximum (right bar) TCO per day for the top three calculated best solutions based on the pre-defined settings and input values, including the TCO of reference diesel engine. The different colours represent the cost values of the different cost parameter the TCO consist out of.

TCO per day per technology for Motor vessels dry cargo (80 m ≤ L < 110 m) for the TCO period 2025-2044 for the top three technologies

System	Variant	Average TCO per day	Minimum TCO per day	Maximum TCO per day
Battery System	pay-per-use	€857,-	€728,-	€986,-
MeOH System	green Single Fuel	€1,110,-	€716,-	€1,505,-
Battery System	charging	€1,232,-	€1,044,-	€1,420,-
Old Diesel CCNR2 (Reference)	Diesel	€647,-	€564,-	€730,-

16 | Visualisation of the table showing the absolute TCO per day between of the top three calculated best solutions based on the pre-defined settings and input values, including the TCO per day of the reference diesel engine.

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Finally, in the first part of the results the user can see a table with emission values, as shown below in figure 17. In this table the absolute CO_2e WTW and TTW emissions in tons per day, the NO_x emissions in kilograms per day and the PM emissions in kilograms per day of the top three calculated best solutions based on the pre-defined settings and input values are shown, including the emissions of the reference diesel engine. For the definition of WTW and TTW see chapter 2.3.

Absolute emissions per day per Technology for Motor vessels dry cargo (80 m ≤ L < 110 m) for the top three technologies

System	Variant	CO2e TTW [ton/day]	CO2e WTW [ton/day]	NOx [kg/day]	PM [kg/day]
Battery System	swappen	0.00	0.00	0.00	0.00
MeOH System	green Single Fuel	1.02	0.00	2.77	0.03
Battery System	charging	0.00	0.00	0.00	0.00
Old Diesel CCNR2 (Reference)	Diesel	1.13	1.48	14.13	0.23

Click here for extra infomration on the on the table showing the absolute emissions and the cost per saved emissions plot of the top three most cost effective solutions

17 | Visualisation of the table showing the CO2e WTW and TTW emissions in ton/day, the NOx emissions in kg/day and the PM emissions in kg/day of the top three calculated best solutions based on the pre-defined settings and input values, including the emissions of the reference diesel engine.

As an extra element to support the decision-making part 1 includes a graph on the cost per saved emissions, which is visualised in figure 17. The cost per saved emissions is a way to combine the emission performance with the cost of the technology and it can be used to further support the decision when doubting between one of the top three calculation most cost-effective solutions.

Figure **Fehler! Verweisquelle konnte nicht gefunden werden.** (top half) shows the bar plot of the cost per saved emissions results. In some cases, the emissions are equal or larger than the reference diesel. When this is the case, the cost per saved emission values are set to zero, since there is no emission saved. The cost per saved emissions shows reversed results compared to the emissions. Where, for example, the cost per emissions saved for PM are much larger than for CO_2e the absolute emission of PM is much lower. The reason for this is because the TCO cost difference remain the same while the emissions differ.

Just like in the emission bar plot this is solved by adding a table below the bar plot to see all the cost per saved emission values per technology, visualised in figure **Fehler! Verweisquelle konnte nicht gefunden werden.** (bottom half), or by removing the PM cost per saved emissions by clicking on "PM" below the legend. The user can also download the bar plot as a png, svg or pdf file, which is stated below the bar plot.

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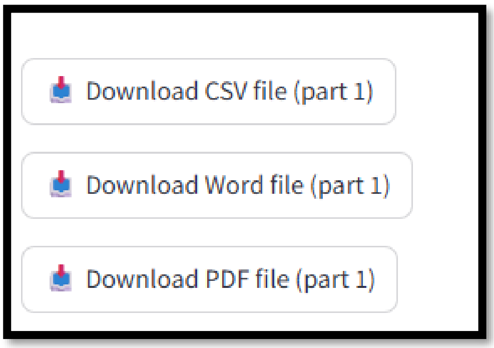
Cost per saved emissions for Motor vessels dry cargo (80 m ≤ L < 110 m) in the TCO period 2025-2044 for the top three technologies and cost scenario Cost per saved emission avg

System_Fuel_Variant	CO2e TTW	CO2e WTW	NOx	PM
Battery System - charging	€0.51,-	€0.39,-	€40.49,-	€2,453.03,-
Battery System - pay-per-use	€0.18,-	€0.14,-	€14.54,-	€881.00,-
MeOH System - green Single Fuel	€4.14,-	€0.31,-	€39.90,-	€2,202.42,-

18 | Visualisation of the bar plot showing cost per saved emission values for the CO2e WTW and TTW emissions, the NOx emissions, and the PM emissions of the top three calculated best solutions based on the pre-defined settings and input values, for the selected TCO price scenario.

While the application itself cannot store data, the results can be downloaded. For the results of the first part the user can download the data by clicking buttons shown in figure 18. There is an option to download the data in a CSV file, a word file and a PDF. The CSV file only includes the data presented in the table from figure 14, 16, 17 and the table from figure 18. The figures are part of the PDF and Word file, but can also be downloaded separately as mentioned before.



19 | Visualisation of the buttons to download the results from part 1 into a CSV, Word and PDF file.

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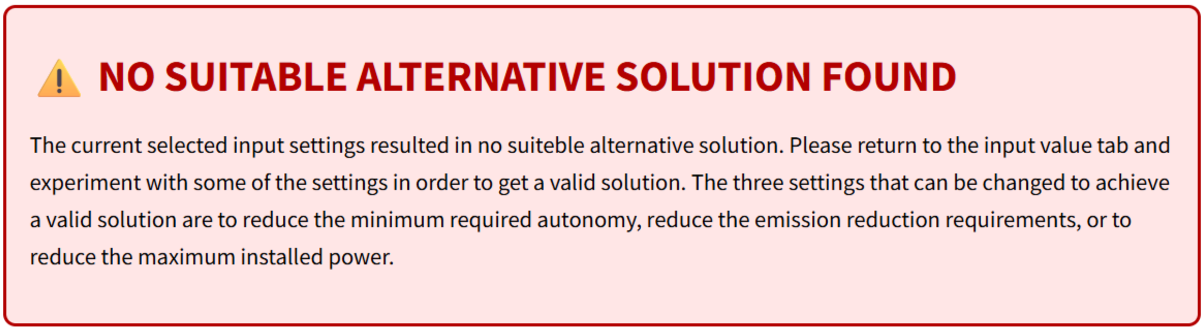
It can happen that there is no solution that fits within the set boundary conditions. The boundary conditions consist of the energy consumption, installed power, available space for energy storage, the required autonomy and required emission reduction for CO2e, NOx and PM emissions. In case no technology is suitable, a notification appears which urges the user to change some of the settings in order to get a viable solution, where the notification is shown in figure 20.



20 | Warning in case of unsuitable input parameters.

2.5.2 Part 2: In-depth analysis

The results presented in part 1 are based on a comparative analysis between all relevant technologies that fit within the pre-defined boundary conditions, which is outlined in part 2 in case more in-depth information is desired. As mentioned in chapter 2.5.1 the boundary conditions are defined by the emission reduction settings and if applicable by selection to include payload loss into the equation. Part 2 is intended to provide additional information, so if this does not interest the user part 2 can be skipped.

Part 2 is subdivided into multiple sections, which are: Total Cost of Ownership details, Capital cost details, Operational cost details, Absolute emissions details, and a Summary table. Depending on whether the bunker time loss, Payload loss, or both options are selected also a section including those costs appears in part 2. By clicking on the expander beneath the title of the specific sections the results with some explanation above it can be visualized, where the expander of the TCO details is visualizes in figure 20.

21 | Visualisation of the expander which shows the TCO details by clicking on it.

The first section is dedicated to the Total Cost of Ownership details. Figure 21 shows the ranking on technologies with respect to TCO. Each line in the graph shows the time evolution of the TCO depending on the year of investment, while each point represents the TCO over the full economic depreciation period. The table next to the graph, visualized in figure 22, shows the ratio between the TCO of the recommended technologies and the TCO of the reference diesel engine.

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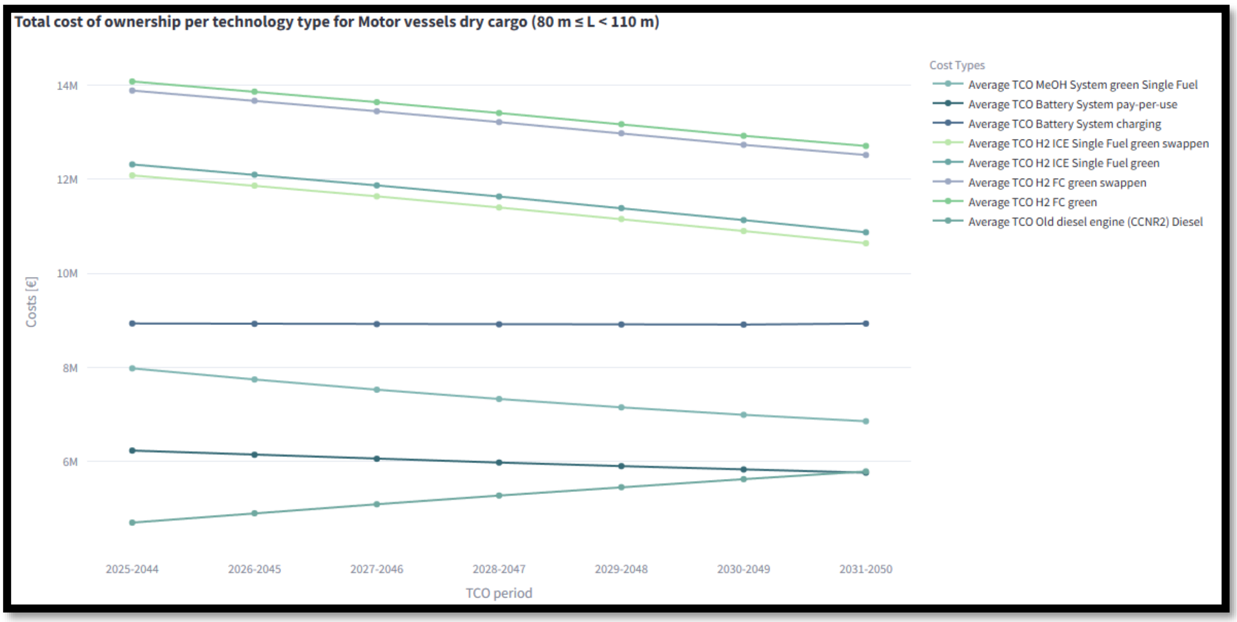
Besides the comparison between all recommended technologies within the boundary conditions, figure 21 and 22 provides information on the best possible investment time is one overview. This is done in two ways. Firstly, the lines shown in figure 22 might cross each other in a certain point in time. While this is not the case in figure 22 for some other examples it can happen. For example, in 2025 and 2026 batteries may be cheaper than a hydrogen ICE but from 2027 on, hydrogen ICE becomes the cheaper solution and using hydrogen as fuel would logistically fit your situation better. In this example the TCO lines would cross each other between the starting year 2026 and 2027 and it might strategically be a better decision to wait two years and invest in hydrogen ICE from 2027 onwards.



22 | Visualisation of the time evolution of the TCO, where each point corresponds to the TCO over the full economic depreciation period.

Secondly, it is possible to see when the prices will be low enough for a technology to become financially viable. For example, a client is willing to pay 20% extra for green transport. Then by changing the starting year in the selection box above the table shown in figure 23 it is possible to find from which year onwards there is a solution that fits within the boundary conditions that is maximum 20% more expensive then the reference diesel.

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Select the year for which you want to see the differences between the reference TCO and the system TCO:

2025

TCO Difference per Technology for Motor vessels dry cargo (80 m ≤ L < 110 m)

System	Variant	TCO difference
Battery System	pay-per-use	1.33
MeOH System	green Single Fuel	1.70
Battery System	charging	1.90
H2 ICE	Single Fuel green swappen	2.57
H2 ICE	Single Fuel green	2.62
H2 FC	green swappen	2.95
H2 FC	green	2.99

23| Visualisation of the table that included the ratio between the TCO of the allowed solutions and the TCO of the reference diesel engine.

The next section of part two depends on the selection made by the user, as it provides details on the extra bunker time costs, loss of payload costs or both. If none of the options are selected this section is removed from part 2.

In all three cases this section presents an information field and it includes a table. Figure 24 shows the information field that is included in the payload loss and bunker time section when both of these parameters are included. In case only payload loss is included only the first paragraph will appear and if only the bunker time loss is included only the second paragraph will appear.

Loss of payload cost and extra bunker time cost details

Click to expand for a more detailed analisys on the loss of payload and the required extra bunker time

General remarks on the loss of payload:

In the first two columns of the table below the extra cost associated with the loss of payload are shown. You have selected weight as the most significant parameter affecting your total profit. The loss in payload is calculated by adding the weight of the engine, which depends on the selected installed power, and the weight of the required fuel, based on the selected minimum required autonomy. When analyzing the cost associated with the loss in payload, keep in mind that only the extra weight of the engine and energy storage is used in the calculation. Since most renewable propulsion technologies require additional safety measures on board, especially hydrogen and methanol, the calculated cost associated with the loss in payload is likely an underestimation.

General remarks on the extra bunker time costs:

In the second two columns of the table below the extra cost associated with increased bunker time are shown. The cost due to the increased bunker time is calculated based on the loss in profit due to the additional bunker time required, as well as the hourly fixed costs, such as insurance cost, personnel cost, and Capital costs, that must be paid regardless of the downtime. When analyzing the downtime costs, keep in mind that for some technologies these values may not apply to your specific situation. For example, if a methanol dual-fuel vessel requires an extra 20 hours of bunker time per year, but you frequently rest for multiple hours near a bunker station, these additional hours do not affect your normal operation due to which the associated costs do not apply. Therefore, it is recommended to reconsider including bunker time loss costs once you have selected the technologies that best match your specific situation.

24 | Visualisation of the information field that appears when including bunker time loss, payload loss or both.

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Figure 25 shows an exemplary table for when the option to include both is selected. In this case all possible columns are included in the table. In case that only the bunker time loss was selected the required bunker time and the extra bunker time cost is included, and for the payload loss the fraction of payload that is lost and the associated cost are included.

Above the table visualized in figure 25 a selection box is shown. This selection box provides the option to sort the cost from low to high either based on the payload loss cost or the bunker time loss cost. In case only bunker time loss or payload loss cost is selected the table is automatically sorted from low to high cost.

Select here to wich parameter you would like to sort the table to

Average payload loss cost

Payload loss cost and bunker time loss cost per year per technology for Motor vessels dry cargo (80 m ≤ L < 110 m)

System type	Payload weight loss cost per year [€]	Payload weight loss fraction per year [%]	Bunkertime [hours]	Average extra bunker cost per year [€]
Baseline diesel	€0,-	0%	5 h	€0,-
MeOH System Single Fuel	€56,-	0.0256%	11 h	€495,-
H2 ICE Single Fuel	€1,135,-	0.5167%	214 h	€15,548,-
H2 ICE Single Fuel swappen	€1,135,-	0.5167%	58 h	€3,943,-
Battery System charging	€2,377,-	1.0826%	754 h	€57,162,-
Battery System pay-per-use	€2,377,-	1.0826%	126 h	€8,894,-
H2 FC	€2,608,-	1.1877%	171 h	€12,780,-
H2 FC swappen	€2,608,-	1.1877%	46 h	€3,156,-

25 | Visualisation of the table that appears when including bunker time loss, payload loss or both.

The following section compasses the Capital cost details of the allowed technologies within the boundary conditions. By clicking on the expander below the Capital cost details title an information field, a graph and a table appear. Figure 26 shows the explanation box that is included under the capital cost section.

Capital cost details

Click to expand for a more detailed analysis on the CAPEX

General remarks on the Capital cost calculations:

The figure in this tab shows the average calculated Capital cost for the different renewable propulsion systems based on your input settings, plus the Capital cost for emission and energy-saving measures. In this figure, if desired, you can remove Capital cost lines that are not of interest by clicking on the names in the legend. Double-clicking the names in the legend will restore all lines. The calculation predicts the Capital cost values from 2025 to 2050. By hovering the mouse over the Capital Cost figure, you can see the predicted cost values for each year. Keep in mind that these are estimated predictions based on forecasting the reduction of the Capital costs. Unexpected global or regional events may affect the actual Capital costs, resulting in deviations from the predicted values.

26 | Visualisation of the information field corresponding to the capital cost detail section.

The graph that is included in the capital cost details section is a cash flow plot of the calculated capital cost up until 2050 for the allowed technologies. A cashflow plot shows the predicted price over a period. With this cash flow plot shown in figure 27 the user can get extra insight in the predicted price drop over time. By hovering the mouse over the graph, the capital cost values per year are shown. Also, by clicking on the name under the legend the capital cost lines can be removed from the graph in case they are found not relevant. By clicking on the same name again the line can be added back.

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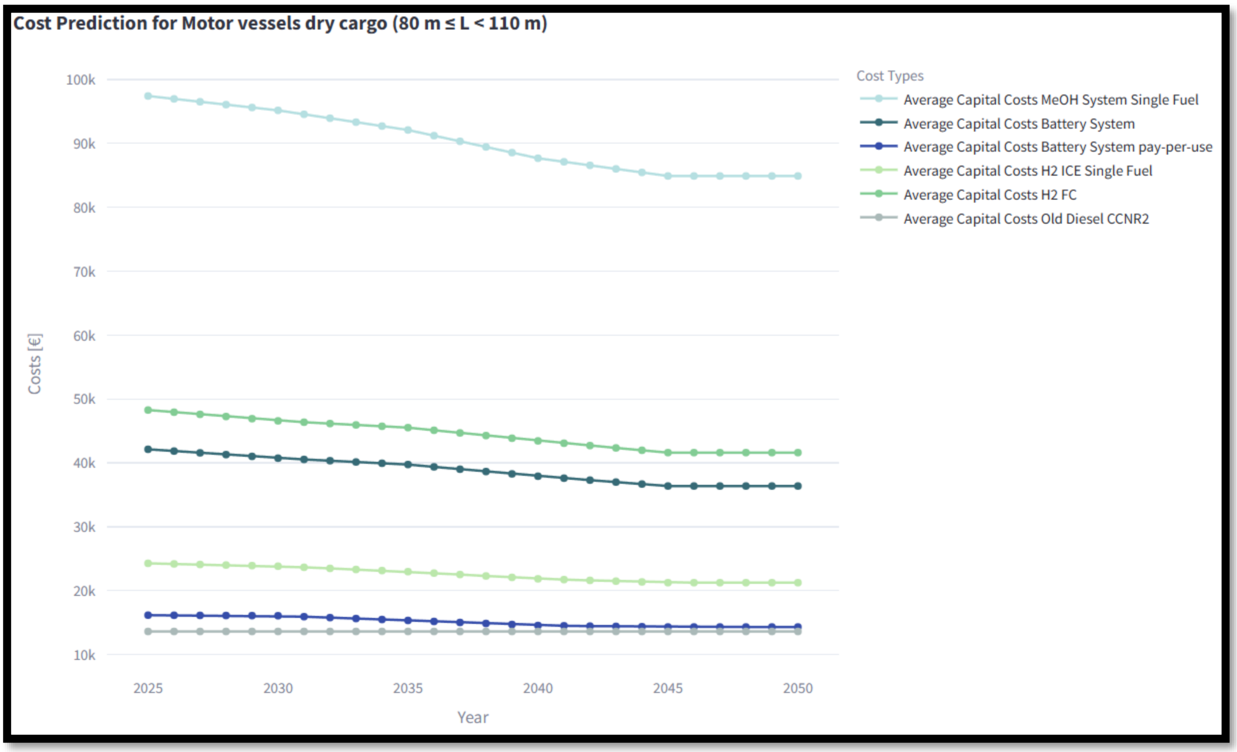

27 | Visualisation of the capital cost cash flow plot.

The table that is included in the capital cost details section shows the ratio between the capital cost of the allowed greening technologies and the capital cost of renewing the selected reference diesel engine. This table is shown in figure 28. Also, above this table of ratio values there is a selection box which allows the user to change the year in which they would like to see the capital cost ratio.

Select for which year you want to see the Capital cost differences values:

2025

Capital cost Difference per Technology for Motor vessels dry cargo (80 m ≤ L < 110 m)

System	Capital cost difference
Battery System pay-per-use	1.19
H2 ICE Single Fuel	1.78
Battery System	3.09
H2 FC	3.54
MeOH System Single Fuel	7.15

28 | Visualization of the capital cost ratio table.

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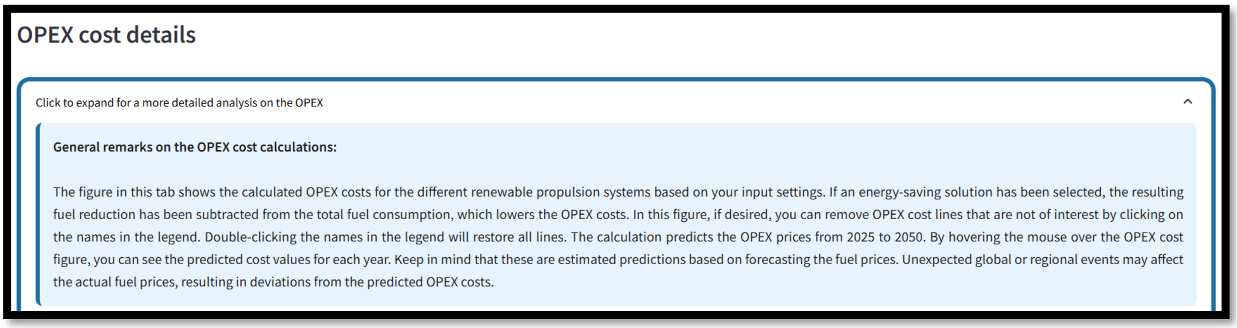
The fourth section that is included in part 2 of the results are the Operational details. Just as for the TCO and capital cost details the Operational details section included an information field, a graph, and a table. The information field included in the Operational cost details section is visualized in figure 29.



29 | Visualisation of the information field corresponding to the operational cost detail section.

The graph that is included in the operational cost details section is a cash flow plot of the fuel price predictions up until 2050 of the allowed technologies based on the boundary conditions. This graph is visualized in figure 30. In the operational cost lines in figure 30 the cost for AdBlue consumption is included for the applicable technologies.

These fuel price predictions are mostly taken from the 2024 world energy outlook predictions [5] and are dependent on the fuel price scenario that has been selected at the beginning of part 1 of the result section. The stricter the policy measures the larger carbon pricing will be and the more vessels switch to renewable fuels reducing their price. These consequences will alter the price predictions when the policy measures are becoming increasingly stricter.

Just as for the capital cost graph by hovering the mouse over the graph the operational cost values per year are shown. Also, by clicking on the name under the legend the capital cost lines can be removed from the graph in case they are found to be irrelevant. By clicking on the same name again the line can be added back.

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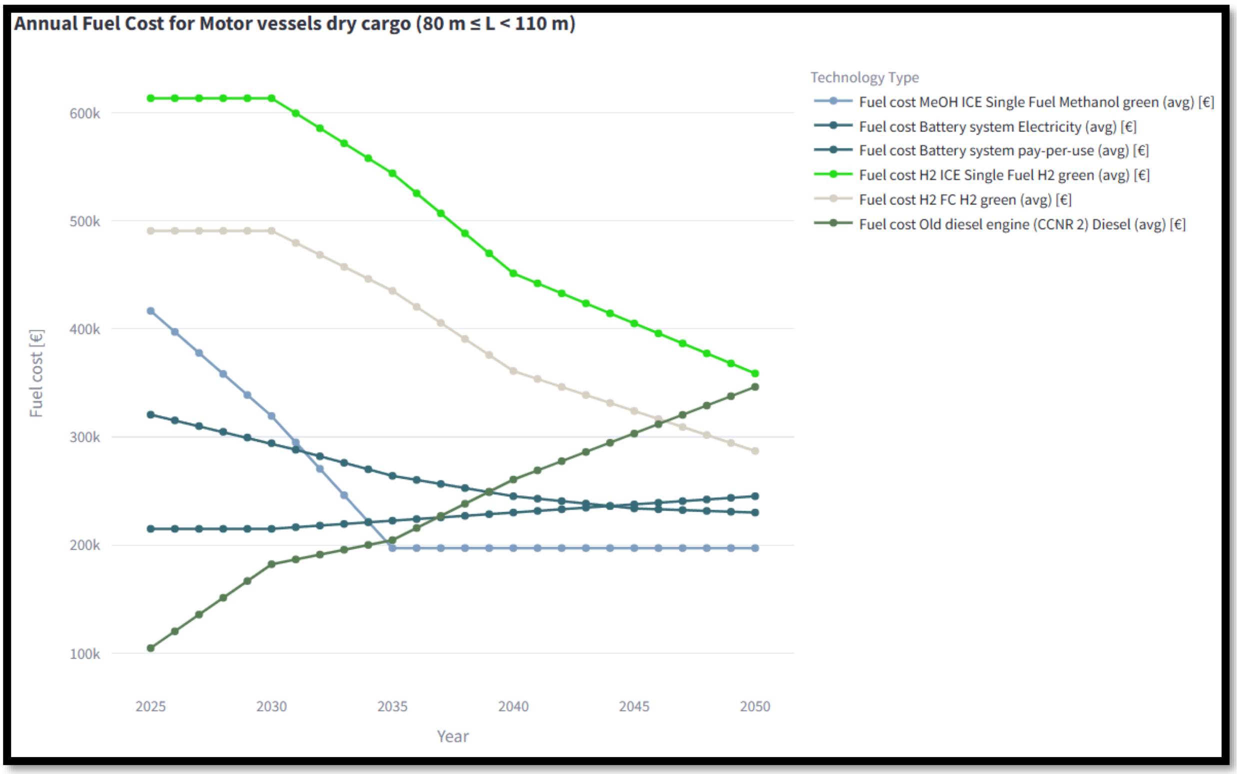

30 | Visualisation of the operational cost graph.

The table next to the graph in the operational section, shown in figure 31, again shows the ratio between the operational cost of the allowed greening technologies compared to the reference diesel engine for the selected year in the selection box above the table.

Select for which year you want to see the OPEX differences values:

2025

OPEX Difference per Technology for Motor vessels dry cargo (80 m ≤ L < 110 m) in 2025

System	Fuel type	OPEX cost difference
Battery system	Electricity [kWh]	2.05
Battery system	pay-per-use	3.06
MeOH ICE Single Fuel	green	3.98
H2 FC	H2 green	4.69
H2 ICE Single Fuel	H2 green	5.86

31 | Visualisation of the operational cost ratio table.

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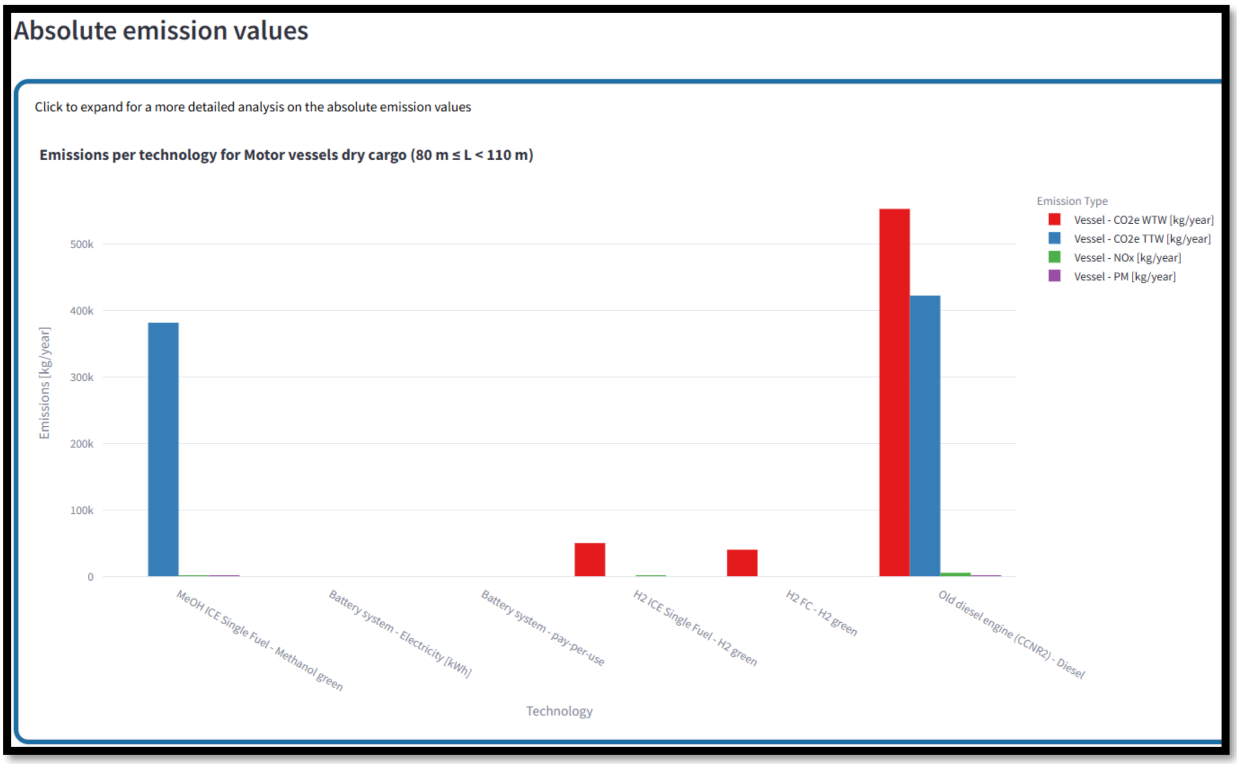
The next section shows a bar plot of the yearly emissions for the recommended technologies within the boundary conditions. The bar plot, shown in figure 32, includes CO_2e WTW and TTW, NO_x and PM emissions. Since CO_2e emissions are significantly higher than those of NO_x and PM, they are reported in tons per year rather than kilograms per year. By clicking on the emission names under the legend it is possible to remove the emission types that are not interesting for the user. By clicking again on the names, the emission type is readded.



32 | Visualisation of the emission bar plot (left) and the table with the emission values (right).

The final section of part 2 of the results includes a summary table presenting all the calculated KPIs. This includes the TCO, the capital cost, operational cost, the calculated emission reduction, and the cost per saved emissions as shown in figure 33.

In this summary table there are two parameters that can be adjusted. The first parameter is the investment starting year. This can be done by moving the circle in the slide bar above the table. The second parameter is to adjust which emission types the user would like to include. As a default all emission types (CO_2e WTW and TTW, NO_x and PM) are included. If the user is not interested in one of the emissions, they can be removed by clicking on the cross next to the name of the emission type in the red box. If later the user wants to add the emission types again this can be done by clicking on the arrow down and then click on the emission type.

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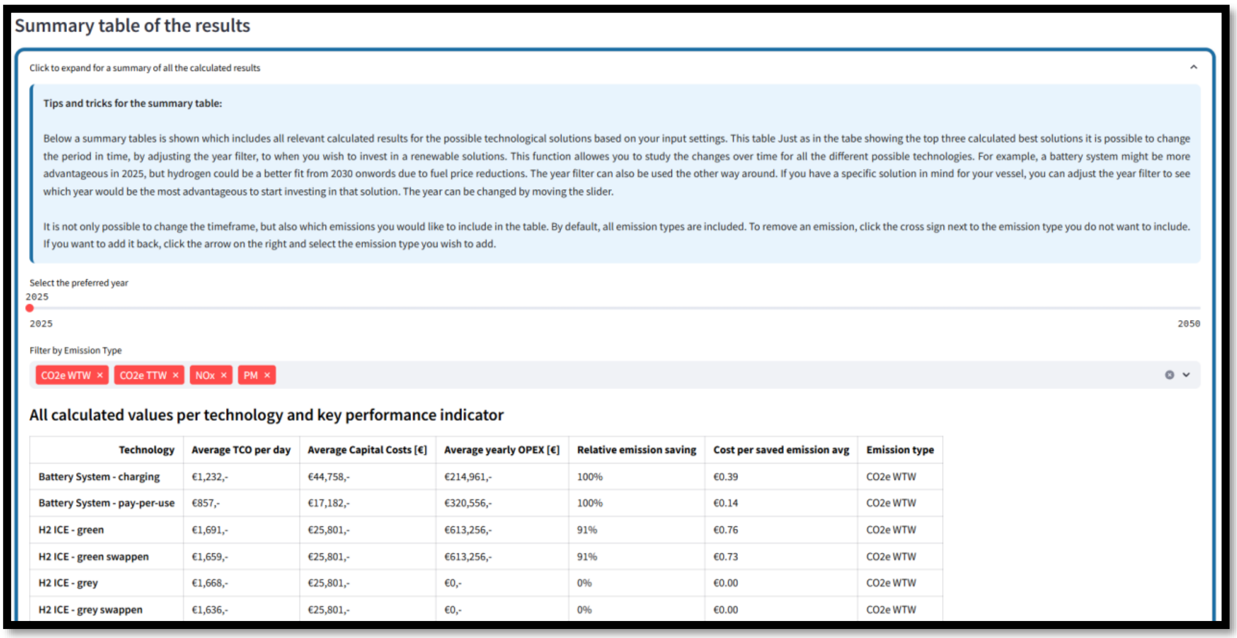
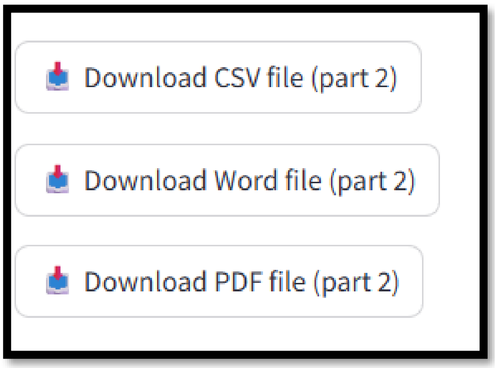


Technology	Average TCO per day	Average Capital Costs [€]	Average yearly OPEX [€]	Relative emission saving	Cost per saved emission avg	Emission type
Battery System - charging	€1,232,-	€44,758,-	€214,961,-	100%	€0.39	CO2e WTW
Battery System - pay-per-use	€857,-	€17,182,-	€320,556,-	100%	€0.14	CO2e WTW
H2 ICE - green	€1,691,-	€25,801,-	€613,256,-	91%	€0.76	CO2e WTW
H2 ICE - green swappen	€1,659,-	€25,801,-	€613,256,-	91%	€0.73	CO2e WTW
H2 ICE - grey	€1,668,-	€25,801,-	€0,-	0%	€0.00	CO2e WTW
H2 ICE - grey swappen	€1,636,-	€25,801,-	€0,-	0%	€0.00	CO2e WTW

33 | Visualisation of the first five rows of the summary table which includes the calculated KPI values for all possible technologies.

Just as for part 1 the results of the second part can be downloaded by clicking on the buttons shown in figure 34. There is an option to download the data in a CSV file, a word file and a PDF.



34 | Visualisation of the buttons to download the results from part 2 into a CSV, Word and PDF file.

2.6 Tab 5, Relevant documentation

Under this tab 5, the links to the data, methodologies and further information will be included. This is done to provide full transparency on the assumptions and cost and emission factors and the cost calculation methodologies and also to provide further guidance and technical information. For the latter, the links are provided to the WP4 catalogue and the individual factsheets for the technologies included in the Decision Support Tool. Furthermore, as soon as the Handbook is available (planned for April 2026), it will also be made available under this 5th tab in the Decision Support Tool for Vessel Owners.

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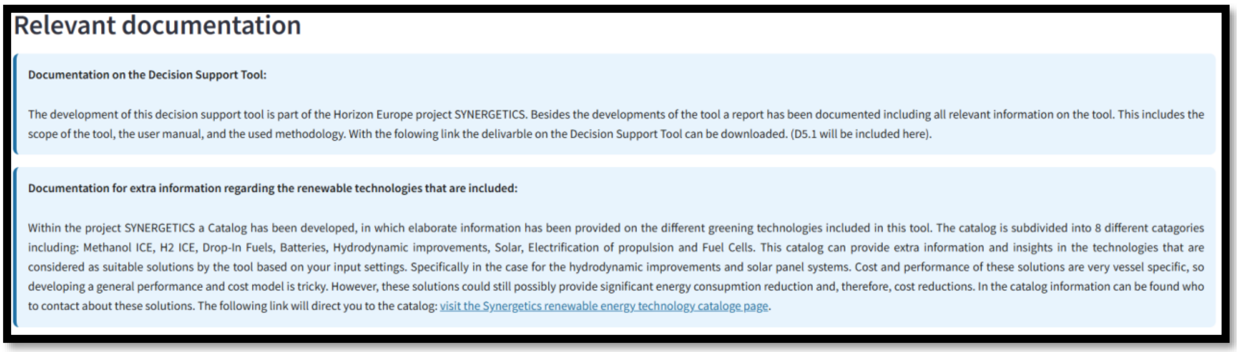
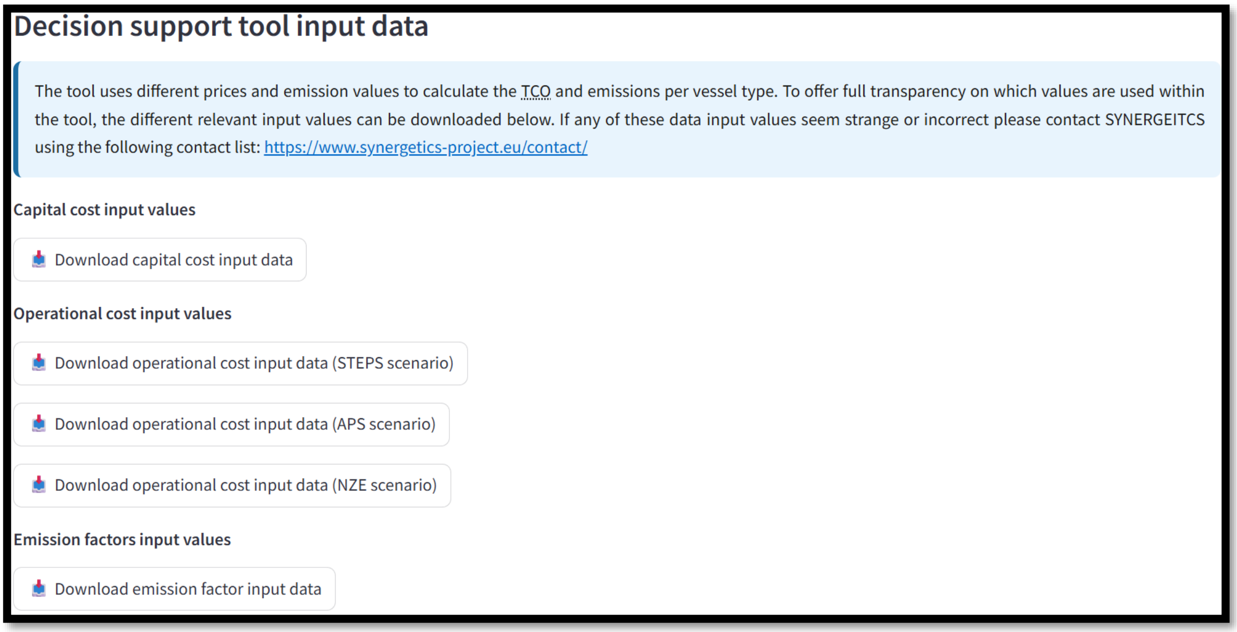


35 | Visualisation of the information field explaining about the SYNERGETICS catalogue on the different technologies that are included in the tool.

As mentioned in chapter 2.1, to ensure transparency a functionality was added to access the input values that are used within the decision support tools. The input values are included at the bottom of the relevant documentation tab and can be downloaded into a MS Excel file using the download buttons shown in figure 36.



36 | Visualisation of the buttons with which the input values used in the decision support tools can be downloaded into a MS Excel file.

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3. Methodology

In work package 4 of SYNERGETICS a methodology was developed to calculate the total cost of ownership for both a single vessel and for the entire fleet. This methodology described in SYNERGETICS Deliverable 4.3 and 4.4 forms the basis of the methodology used for the decision support tool. In this methodology the economic value is compared to the emission performance of the different greening retrofit technologies. This chapter summarizes the relevant equations from D4.3 and D4.4 and outlines the new developed equations in more detail. This chapter also described the assumptions made in methodology used for the decision support tool.

In chapter 3.1 the economic part of the methodology is described and in chapter 3.2 the emission performance part of the methodology is described. Chapter 3.3 combines the findings of chapter 3.1 and 3.2 to construct a way of comparing cost and emission performance. The final chapter, chapter 3.4, explains the pay-per-use principle in more detail.

3.1 Total Cost of Ownership

The economic value of the different powertrain technologies is expressed in terms of the Total Cost of Ownership (TCO). The TCO consist out of all the cost that are made within the entire economic depreciation period of the system. The TCO comprises all costs incurred over the entire economic depreciation period of the system. Since the focus of the decision support tool is on the powertrain of the vessel, the TCO in the decision support tool includes all cost related to the fuel storage system, the propulsion system and all the related safety and energy management systems of the powertrain. The remaining cost like the insurance cost, the capital cost of the vessel, and the personnel cost are used within the methodology to calculate some of the cost factors, but are excluded from the final TCO calculation. This because they are not related to the cost of the powertrain. The TCO for the powertrain is calculated using the following equation:

$$TCO\ [€] = \left(\left(Capital\ cost\ \left[\frac{€}{year}\right] + maintenance\ cost\ \left[\frac{€}{year}\right] + Recharging\backslash bunkering\ cost\ \left[\frac{€}{year}\right] + Payload\ loss\ costs\ \left[\frac{€}{year}\right]\right) \cdot Depreciation\ years\ [years]\right) + Downtime\ costs\ [€] + OPEX\ [€] \qquad [1]$$

Equation (1) shows that the TCO consists out of six different cost components, which are the initial investment cost (Capital cost), the maintenance cost, the cost due the potential extra bunker or recharging time (Recharging\bunkering cost), the cost due to a potential loss of payload (Payload loss costs), the cost related to the downtime days to retrofit the vessel at the shipyard (Downtime costs), and the Operational related cost (OPEX). The parameter "depreciation period" represents the economic time frame to which the capital cost is paid off and is used as the time period for the TCO calculations.

As shown in equation (1) the Downtime cost and the OPEX are outside the depreciation period multiplication brackets. For the downtime cost the reason is that the retrofit construction work only happens once, so this is not a yearly reoccurring cost factor. The OPEX cost is taken outside the deprecation multiplication bracket because it is calculated using a cash flow prediction of the fuel prices (more on this in chapter 3.1.2). Since the OPEX is not constant per year it is calculated separately over the entire depreciation period. The rest of the cost values inside the depreciation period multiplication brackets are assumed to be constant per year and can therefore be directly multiplied by the depreciation period to calculate the total cost over the full period. The different cost parameters of equation (1) are explained in more detail below.

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3.1.1 Capital cost and maintenance cost

The Capital cost parameters include all costs related to the purchase and installation of the retrofit, or in other words it is the initial investment cost required to retrofit the vessel. The capital cost parameter can again be subdivided into multiple cost parameters. The first sub capital cost parameter is the hardware cost, which consist out of the cost for the engine and the cost of the energy storage system.

The cost of the engine is dependent on the installed power on board. The assumption made in the methodology is that the price of the hardware increases linearly with the installed power. The minimum and maximum hardware prices that are included in the tool accommodate for the fact that this assumption is not entirely accurate. The hardware cost for the energy storage system depends on the required capacity of the energy storage system, which in terms depends on the daily average fuel consumption and the required autonomy of the vessel. Here, the assumption is made that all parameters will linearly increase the hardware price, which is a realistic assumption. The more detailed hardware cost equations per technology, including the corresponding assumption per technology, can be found in SYNERGETICS D4.4, but the general equation can be expressed in the following way:

$$Harware\ cost = \left(power_{installed}\ [kW] \cdot \frac{cost}{power}\left[\frac{€}{kW}\right]\right) + \left(autonomy\ [days] \cdot \frac{energy}{day}\left[\frac{MJ}{day}\right] \cdot \frac{cost}{energy}\left[\frac{€}{MJ}\right]\right) \quad [2]$$

The other two sub cost parameters of the capital cost are the installation and integration cost of the retrofit. The installation cost includes all cost related to removing the old systems and installing the new systems. The integration cost includes all cost related to the safety measures and vessel redesigning. Combined, the hardware cost, installation cost, and the integration cost form the total initial investment cost, also referred to as the CAPEX of the powertrain.

Since most greening technologies require a large investment multiple subsidy schemes have been developed, both on a national and European level, to help shipowner to make these investments. To include these subsidy schemes in the decision support tool the user can select a percentage of the total CAPEX they can get subsidies. Combining this with the CAPEX calculation the following equation is obtained:

$$CAPEX = (Installation\ cost[€] + itergration\ cost[€] + hardware\ cost[€]) \cdot \left(1 - \frac{CAPEX\ subsidies\ [\%]}{100}\right) \quad [3]$$

The investment cost is typically financed through a mortgage, which is repaid over a predefined depreciation period at a fixed interest rate. The capital cost that has to be paid per year is then the total CAPEX divided by the depreciation period plus the yearly interest cost, which is a fixed percentage of the remaining total CAPEX. Since the interest rate remains constant over the depreciation period and the total CAPEX is reduced each year the interest cost decreases each year as well. By taking half the initial CAPEX cost and multiplying this value with the interest rate the average interest cost over the depreciation period can be determined. Combined, this gives the following equation for the average yearly capital cost:

$$Capital\ cost = \frac{CAPEX\ [€]}{2} \cdot Annual\ Interest\ Rate\ [\%] + \frac{CAPEX\ [€]}{Depreciation\ years\ [€]} \quad [4]$$

Even though equation (1) shows that the maintenance cost is an independent parameter within the TCO calculation, it is assumed that the maintenance cost is a fixed percentage of the total CAPEX. The exact percentage can be found in SYNERGETICS D4.4, but generally leighs between 7% and 10% for all technologies except LNG, where it is 2%. The maintenance cost can then be calculated using the following equation:

$$Maintenance\ cost = hardware\ cost \cdot estimated\ maintenance\ cost\ percentage$$

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3.1.2 Operational Costs

Operational costs consist of two possible components: fuel costs and AdBlue costs. The methodology used to calculate fuel costs is based on the lower heating value (LHV) of the fuel and the engine efficiency. These parameters are used to determine the required energy output of the reference diesel engine. This required energy output is then applied to calculate the corresponding fuel input for the different greening technologies.

Based on the yearly fuel consumption of the reference diesel engine, the following two equations are used to determine the required fuel input for the greening solutions:

$$Energy\ demand_{diesel}\left[\frac{MJ}{year}\right] = Diesel\ consumption_{yearly}\left[\frac{m^3}{year}\right] \cdot Density_{diesel}\left[\frac{kg}{m^3}\right] \cdot LHV_{diesel}\left[\frac{MJ}{kg}\right] \cdot \eta_{diesel}\ [\%] \quad [5]$$

$$Fuel\ consumption_{renewable}\left[\frac{kg}{year}\right] = \frac{Energy\ demand_{diesel}\left[\frac{MJ}{year}\right]}{LHV_{renewable}\left[\frac{MJ}{kg}\right] \cdot \eta_{renewable}\ [\%]} \quad [6]$$

As shown in equation (6) the unit of the fuel input for the greening technologies is [kg]. For electricity this is not a viable unit. Therefore, in the case for electricity the LHV in MJ/kg is substituted for the conversion factor 3.6 MJ/kWh so that the unit becomes [kWh] instead of [kg]. With the fuel consumption being calculated, the cost of the yearly fuel consumption can be calculated by using the price per kg for the different types of fuels.

In SYNERGETICS not only alternative fuels have been identified, but also solutions that can reduce the amount of energy input needed. The first solution to increase the energy efficiency that has been identified is the replacement of the aft ship to increase the hydrodynamic performance. This retrofit solution was done for the inland dry cargo vessel "Ernst Kramer" and it showed an energy efficiency increase of up to 30 % in shallow water and 16 % and 22 % in deep and moderate water conditions [6] (see D3.15).

The second solution is the installation of solar panels on the vessel. The solar panels can be used to power the hotel functionalities of the vessel which will reduce diesel use for the auxiliary engines. In combination with a battery, solar panel systems can potentially completely power the hotel functionalities. Combining the fuel cost calculation with the fuel use reduction measures gives the following equation for the total fuel cost:

$$Fuel\ cost_{yearly} = (Fuel\ consumption_{renewable}\ [kg] - fuel\ savings\ [kg]) \cdot fuel\ cost\left[\frac{€}{kg}\right] \quad [7]$$

Where:

$$Fuel\ savings\ [kg] = \left(Fuel\ consumption_{yearly}\ [kg] * r\right) + fuel\ saved_{solar\ panels}\ [kg] \quad [8]$$

In equation (8), the first part calculates the fuel saved by applying hydrodynamic improvements due to the aft ship replacement, where r is the efficiency gain in %, and the second part includes the fuel saved due to the installation of solar panels on board. Usually, energy savings from solar panels are measured in kWh, while except for the battery system the fuel is calculated in kilograms. When this is the case, the kWh needs to be translated to a fuel saving in kg by using the following equation:

$$Fuel\ consumption_{kWh} = Fuel\ consumption_{renewable}\ [kg] \cdot LHV_{renewable}\left[\frac{MJ}{kg}\right] \cdot \frac{1}{3.6}\left[\frac{kWh}{MJ}\right] \quad [9]$$

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From this the energy in kWh saved can be subtracted and converted back to fuel consumption savings in kg, using the following equation:

$$fuel\ saved_{solar\ panels} = (Fuel\ consumption_{kWh} - kWh\ saved) \cdot 3.6 \left[\frac{\text{MJ}}{\text{kWh}}\right] / LHV_{renewable} \left[\frac{MJ}{kg}\right] \quad [10]$$

The aft ship replacement solution is only a solution for inland waterway vessel and not for coastal. The solar panels can be installed both on inland vessels and coastal vessels. Since both the aft ship replacement and solar panel systems for inland vessels are tailor made to that specific vessel, also with different performance for each vessel, the tool does not include these options in the TCO calculation for inland vessels. On the SYNERGETICS website catalogues on the different technologies can be found including solar panels and hydrodynamic improvements for more information on these types of solutions (see link). For coastal vessels the solar panel systems are more standardised. For this reason, solar panels have been included as an option in the tool for coastal vessels.

Some technologies require next to fuel consumption also AdBlue (urea) consumption to reduce NO_x emissions. The amount of AdBlue that is consumed is a fix percentage of the total fuel consumption. The following equation can be used to calculate the AdBlue consumption:

$$AdBlue\ cost = Fuel\ cosnsumption_{yearly} \cdot \frac{liter\ AdBlue}{kg\ fuel\ use} \cdot \frac{cost}{liter\ AdBlue} \quad [11]$$

Table 2 shows the fixed percentages of AdBlue that are used for the different technologies. Table 2 shows that the DPF and SCR system in combination with a CCNR2 engine has a lower AdBlue consumption compared to the other two engines. The reason for this is because the CCNR2 engines are optimised to the lowest possible NOx emissions at the expense of the fuel consumption efficiency. The old engine types and the Stage V engines are optimised on efficiency, which results in a higher NO_x emission due to which more AdBlue is required. For Methanol Dual-Fuel the assumption is made that the same AdBlue percent as a Stage V engine is required.

3 | Fixed AdBlue consumption percentage of the total fuel consumed.

Technology	AdBlue consumption percentage
DPF and SCR systems in combination with a CCNR1 engine (Diesel and HVO)	10.5 %
DPF and SCR systems in combination with a CCNR2 engine (Diesel and HVO)	5.5 %
New Diesel Engine (Diesel and HVO)	10.5 %
Methanol Dual-Fuel (green and grey)	10.5 %

The total operational cost on annual basis can then be calculated using the following equation:

$$OPEX = Fuel\ cost_{yearly} + AdBlue\ cost \quad [12]$$

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3.1.3 Downtime costs

The capital cost, maintenance cost and operational cost are the main contributors to the total TCO. However, as equation (1) shows there are three more cost contributors that determine the total TCO. One of these cost contributions is the downtime cost, which is the cost arising from the vessel being at the shipyard for the retrofit construction work. During this construction work the capital cost and insurance cost still have to be paid, while it reduces the potential operational time and, therefore, the total revenue. At the same time, since the vessel is not being used, expense like fuel and personnel cost do not have to be paid. So, during the retrofit construction there is a reduction in the yearly profit, also referred to as opportunity cost, and they are fixed costs that always have to be paid. Combining this results in the following equation for the downtime cost:

$$Downtime\ cost\ [€] = \left(\frac{Capital\ cost\left[\frac{€}{year}\right] + Profit_{yearly}\left[\frac{€}{year}\right] + insurance\left[\frac{€}{year}\right]}{365\left[\frac{days}{year}\right]}\right) \cdot downtime\ days\ [days] \qquad [13]$$

In contrast with the capital cost and the operational cost, the downtime cost only has to be paid ones and is not a yearly reoccurring expense. Due to this, in combination with the fact that the downtime is generally not more than 1.5 months, it was found that its contribution to the TCO is relatively small.

3.1.4 Bunker time

The next cost parameter that is included in the TCO calculation is the potential cost due to increased bunker times. The energy density of each alternative fuel that is included in the tool is different. Thus, the amount of energy per unit of mass or per volume is different for each alternative fuel. This can result in larger amounts of fuel needed to be bunkered. Some alternative fuels like hydrogen also require special storage tanks, which are large and heavy, due to which more frequent bunkering is needed. The consequence of the difference in energy density and storage capacity is that the bunker time can increase.

To calculate the potential cost due to the increased bunker time, first the difference in bunker time for the different technologies needs to be calculated. This is done by subtracting the current diesel bunker time from the bunker time for the alternative fuels, as shown in the following equation:

$$Bunker\ time\ difference\left[\frac{hour}{year}\right] = bunkering\ time_{renewable}\left[\frac{hours}{year}\right] - bunkering\ time_{diesel}\left[\frac{hours}{year}\right] \qquad [14]$$

To calculate the bunker time of all the fuels the amount of energy present on board is required. For this the results from equation (5) and (6) can be used. The bunker speeds for the different alternative fuels that are used can be found in SYNERGETICS D4.4 and stem from the NEEDS project [7]. Diesel and methanol are bunkered per volume, which gives the following equation for the bunker time:

$$bunkering\ time_{diesel}\left[\frac{hours}{year}\right] = \frac{Diesel\ consumpiton_{yearly}\ [m^3]}{bunkering\ speed_{diesel}\left[\frac{L}{min}\right] \cdot 60\left[\frac{min}{hour}\right] / 1000\left[\frac{L}{m^3}\right]} \qquad [15]$$

and

$$bunkering\ time_{renewable}\left[\frac{hours}{year}\right] = \frac{Fuel\ consumption_{renewable}\ [kg] \ / \ Density_{renewable}\left[\frac{kg}{m^3}\right]}{bunkering\ speed_{renewable}\left[\frac{L}{min}\right] \cdot 60\left[\frac{min}{hour}\right] / 1000\left[\frac{L}{m^3}\right]} \qquad [16]$$

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Hydrogen and LNG are bunkered in weight, which gives the following equation for the bunker time:

$$bunkering\ time_{renewable}\left[\frac{hours}{year}\right] = \frac{Fuel\ consumption_{renewable}\ [kg]}{bunkering\ speed_{renewable}\left[\frac{kg}{min}\right]\cdot 60\left[\frac{min}{hour}\right]} \quad [17]$$

and electricity is bunkered in kWh per hour, which gives the following equation for the bunker time:

$$bunkering\ time_{renewable}\left[\frac{hours}{year}\right] = \frac{Fuel\ consumption_{renewable}\ [kWh]}{bunkering\ speed_{renewable}\left[\frac{kWh}{hour}\right]} \quad [18]$$

Just as for the downtime costs, the costs due to the potential increased bunker time can be constructed out of the opportunity cost due to a decrease in total revenue and the fixed cost. In this case not only the capital cost and the insurance have to be included in the fixed cost, but also the personnel cost. The total fixed cost can then be calculated using the following equation:

$$Total\ fixed\ cost\left[\frac{€}{year}\right] = Insurance\left[\frac{€}{year}\right] + Capital\ cost\left[\frac{€}{year}\right] + personnel\ cost\left[\frac{€}{year}\right] \quad [19]$$

The opportunity cost in this case is calculated from the yearly revenue instead of the yearly profit, since the operation time continues while bunkering. Combining this with the bunker time difference results in the following equation to calculate the potential cost due to bunker time loss:

$$Profit\ loss\backslash gain\left[\frac{€}{year}\right] = \frac{\left(Total\ fixed\ cost\left[\frac{€}{year}\right] + Revenue_{yearly}\left[\frac{€}{year}\right]\right)}{365\left[\frac{days}{year}\right]\cdot 24\left[\frac{hours}{day}\right]}\cdot Bunker\ time\ difference\ [hours] \quad [20]$$

In contrast to the capital cost, the operational cost, and the downtime cost, the cost due to the potential increased bunker time is a cost parameter for which the user can choose whether to include it in the TCO calculation or not, because the extra bunker time does not necessarily mean that extra costs are incurred. This is very dependent on the type of exploitation the vessel owner has.

If, for example, the vessel sails for eight hours a day and returns to the same location where bunkering is possible, a few extra hours of bunkering a day would not pose any problem in the operational time. In this case the same revenue can be obtained with these extra bunker times and no extra cost are made due to the increased bunker time. On the other hand, if the vessel is operated continuously on long sailing routes, it will affect its active operational time and, consequently, lead to a reduction in revenue. So based on the type of exploitation the vessel owner can decide whether extra bunker time will influence their normal operational time or not.

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3.1.5 Payload loss

The final cost parameter in the TCO, as shown in equation (1), is the cost associated with the potential loss of payload. The difference in energy density mentioned in Chapter 3.1.4, along with the example of hydrogen requiring special storage tanks, not only leads to a potential increase in bunker time but also to an increase in the space or weight required for the powertrain.

In the volumetric case, this can result in that some of the space used for cargo has to be used to accommodate the extra required space of the powertrain. Consequently, this will reduce the maximum cargo space. In terms of weight, it can result in that the maximum cargo weight is reduced since it is assumed in the tool that the draft of the vessel should remain constant. So, in this case the heavier the powertrain the more the maximum cargo weight capacity of the vessel is reduced.

The relevance of volume or weight varies depending on the vessel type. In case of, for example, container vessels volume would most likely be the relevant parameter, but for vessels that transport iron ore, for example, weight is usually the limiting factor. When the user selects volume as the most relevant parameter the following equations are used to calculate the require volumed of the different technologies [8] [9]:

$$Volume_{technology}[m^3] = \left(\frac{fuel\ consumption_{yearly}\ [MJ]}{Contained\ fuel\ volume\ \left[\frac{MJ}{L}\right]} \cdot \frac{minimum\ autonomy\ [day]}{365\ \left[\frac{day}{year}\right]}\right) + enigne\ volume\ [m^3] \qquad [21]$$

In equation (21) the engine volume for fuel cell system can be calculated using the following equations:

$$Engine\ volume_{FC}\ [m^3] = 0.0064\ \left[\frac{m^3}{kW}\right] * (power_{installed}\ *\ 0.6) \qquad [22]$$

where the installed power of the fuel cell is set to 60 % of the power of the electrical engines. For ICE engines the engine volume is calculated using:

$$Engine\ volume_{ICE}\ [m^3] = \left(9 \cdot 10^{-6}\left[\frac{m^3}{kW^2}\right] \cdot power_{installed}^2\ [kW]\right) - \left(0.0142\left[\frac{m^3}{kW}\right] \cdot power_{installed}\ [kW]\right) + 13.53\ [m^3] \qquad [23]$$

When the user selects weight as the most relevant parameter the following equations are used to calculate the require weight of the different technologies:

$$Weight_{technology}\ [kg] = \left(\frac{fuel\ consumption_{yearly}\ [MJ]}{Contained\ fuel\ weight\ \left[\frac{MJ}{kg}\right]} \cdot \frac{minimum\ autonomy\ [day]}{365\ \left[\frac{day}{year}\right]}\right) + engine\ weight\ [kg] \qquad [24]$$

In equation (24) the weight of the fuel cell system can be calculated using the following equation:

$$Engine\ weight_{FC}\ [kg] = 3.7162\ \left[\frac{kg}{kW}\right] \cdot (power_{installed} \cdot 0.6) \qquad [25]$$

where the installed power of the fuel cell is set to 60 % of the power of the electrical engines. For ICE engines the engine weight is calculated using:

$$Engine\ weight_{ICE}\ [kg] = \left(\left(3 \cdot 10^{-6}\left[\frac{ton^2}{kW^2}\right] \cdot power_{installed}^2\ [kW]\right) - \left(0.0048\left[\frac{ton}{kW}\right] \cdot\ power_{installed}\ [kW]\right) + 4.5524\ [ton]\right) \cdot 1000\ \left[\frac{kg}{ton}\right] \qquad [26]$$

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Equation (21) and (24), depending on the selected parameter, can be used to calculate the potential loss in payload. Based on the installed power the tool calculates the total weight or volume of the powertrain for both the reference diesel engine and the different greening technologies. By subtracting these two values the potential loss of payload can be calculated, using the following equation:

$$Payload\ loss = weight/volume_{renewable} - weight/volume_{diesel} \qquad [27]$$

To calculate the cost associated with the loss of payload the fraction of the total payload that is lost is required. In order to do this the user has to fill in the total DWT or the total available space. In the case of volume, the space that should be included is the space of the current engine room, other spaces that can be used for the powertrain system and, if applicable, the cargo space. The methodology for calculating the payload loss fraction for the parameters "weight" and "volume" differs slightly from each other. The reason for this is because for weight the DWT includes both the available cargo mass and the amount of fuel on board. However, for the payload loss fraction only the cargo mass should be used.

To calculate the initial maximum cargo mass first the maximum total mass of the cargo plus powertrain the engine weight is calculated. This is done by adding the engine weight of diesel, so the outcome of equation (26) for diesel, to the DWT. Then the weight of the diesel powertrain, so the outcome of equation (24), is subtracted from the total mass to calculate the initial maximum cargo weight. Combining this gives the following equation for the initial cargo mass:

$$Mass\ cargo_{diesel}\ [kg] = \left((DWT\ [ton] \cdot 1000\ \left[\frac{kg}{ton}\right] + Engine\ weight_{FC}\ [kg]\right) - Weight_{diesel}\ [kg] \qquad [28]$$

With the payload loss and the initial maximum cargo weight or volume known the payload loss fraction can be calculated using the following equation for volume:

$$Volume\ loss\ fraction = \frac{payload\ loss_{volume}\ [m^3]}{Total\ availible\ space\ [m^3]} \qquad [29]$$

and for weight the following equation can be used:

$$Weight\ loss\ fraction = \frac{Payload\ loss_{weight}\ [kg]}{Mass\ cargo_{diesel}\ [kg]} \qquad [30]$$

The final step is to use the payload loss fraction to calculate the cost that is associated with this. Unlike the case for the downtime cost (chapter 3.1.3) and the bunker time cost (chapter 3.1.4) there are no fixed cost involved in the potential cost due to the loss of payload. The cost associated with the loss of payload is all based on the loss in total yearly revenue compared to sailing on the reference diesel engine. The cost due to the potential loss of payload can be calculated using the following equation:

$$Payload\ loss\ cost = payload\ loss\ fraction \cdot Revenue_{yearly} \cdot correction\ factor \qquad [31]$$

Equation (31) shows that besides the payload loss fraction and the yearly revenue a third parameter is included in the final calculation step, which is a correction factor. This correction factor stems from the fact that vessels do not always sail with max cargo capacity. To explain this in more detail let's take a container vessel as an example.

After all parameters are provided by the user it turns out that in order to sail on electricity the space of 9 TEU needs to be sacrificed. In case that this vessel sails 100 % of the time on its maximum capacity it means that the revenue is reduced by the value corresponding to 9 TEU per trip. However, if the vessel only sails 60 % of the time on its maximum capacity (or close to) and the rest of the time not, it means that only 60 % of the time the 9 TEU space reduction results in a reduction of the total revenue.

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To account for this the user can select how often they sail on maximum capacity (or close to), which is then used as a correction factor. In the example, the correction factor would be 0.6.

The methodology for calculating the loss of payload as presented in chapter 3.1.5 is a first approximation, for which some assumptions have been made. One key assumption is that only the weight and volume of the engine and the energy storage tank are considered. This is not entirely accurate since some technologies require extra safety measures which, can increase the required space and weight substantially.

Another important assumption that any extra space or weight would result in a loss of payload. In the case of weight this assumption is quite accurate but in the case for volume this is really a first assumption.

There are several factors that explain this assumption. The first example arises due to the ES-TRIN regulations restrictions as to where energy storage systems can be located on the vessel. For battery containers, for example, they cannot be located inside the vessel and in case they are located in cargo hold no containers can be stacked on top of them. This means that if extra space is required as large as one 20-foot container, more container spots would be lost (the exact number depends on the number of container tiers/bays/rows the vessel is designed to carry) instead of one container spot calculated by the tool. On the other hand, it might be possible to locate this container at the deck of the vessel resulting in no cargo space lost.

The two above mentioned examples in practice both result in different loss of payload cost than calculated by the tool. Therefore, in the case of volume the tool should be used as a first approximation and not as a precise value. This first approximation is still of value since it gives an idea of whether a certain technology has a large or a small effect on the total yearly revenue. But for exact numbers more accurate vessel design models should be used. In Appendix 2 a more detailed analysis can be found on how the payload loss equations have been constructed and which assumptions are used.

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3.2 Emission factors

Besides costs, the emission performance of the greening technology is one of the most important factors in the retrofit decision. In policy regulations is has been determined that the emission performance of the greening technology is determined by three different emission types. These are, as already mentioned in chapter 2, CO_2e (which includes CO_2, CO and CH_4), NO_x, and PM. These three types of emissions are currently denoted as the main drivers for global warming and air pollution.

In the coastal vessel sector, SO_x emissions are important as well, due to negative impact on human health and environment. In the maritime sector, HFO, which contains large amounts of sulphur, used to be a commonly used fuel due to its low price. With the new IMO regulations that restricts the SO_x emissions in all of the sailing routes considered in SYNERGETICS coastal vessels either need scrubbers or use ULSFO or VLSFO. It has been concluded that scrubbers are only advantages for large seagoing vessels that spend a large amount of time at sea, so the assumption is made in SYNERGETICS that all coastal vessels use ULSFO or ULSD [10]. For this reason, SO_x is not included in the coastal vessel tool since it is not seen as relevant in coastal areas anymore.

The total emissions are calculated using the yearly fuel consumption and the corresponding emission factor for the specific fuel type. The following equation can be used to calculate the absolute emissions:

$$CO_2e\ [ton] = \left(Fuel\ consumption_{yearly}\ [kg] \cdot\ Emission\ Factor_{CO_2} \left[\frac{kg}{kg\ fuel}\right]\right) \cdot 1000\ \left[\frac{kg}{ton}\right] \quad [32]$$

$$NO_X\ [kg] = Fuel\ consumption_{yearly}\ [kg] \cdot Emission\ Factor_{NO_x}\ \left[\frac{kg}{kg\ fuel}\right] \quad [33]$$

$$PM\ [kg] = Fuel\ consumption_{yearly}\ [kg] \cdot Emission\ Factor_{PM}\ \left[\frac{kg}{kg\ fuel}\right] \quad [34]$$

As shown in equation (32) CO_2e is the only emission that is calculated in tons. The reason for this is because the absolute amount of CO_2e emission is much larger than that of NO_x and PM. The relative reduced emissions can then be calculated by dividing the emissions of the greening technology with the reference diesel engine emission performance, using the following equation:

$$Relative\ emission\ reduction_{CO_2e,NO_x,PM}\ [\%] = \left(1 - \left(\frac{Emission_{renewable}\ [kg,ton]}{Emission_{diesel}\ [kg,ton]}\right)\right) \cdot 100\ [\%] \quad [35]$$

The emission reduction as calculated with equation (35) is used as a filter method within the decision support tool. When the user selects a certain emission reduction target that they want or need to obtain the tool excludes the technologies that do not meet this requirement from the results.

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3.3 Cost per saved emission

By combining the calculated cost values with the emission values, a comparison can be made to see which technology is the most cost-effective way to reduce emissions. To combine the cost and emission values the cost per saved emissions can be used. The cost per saved emission can be calculated by dividing the cost difference and emission difference between the greening technologies and the reference diesel engine with each other, using the following equation:

$$Cost\ per\ saved\ emissions_{CO_2e,NO_x,PM}\left[\frac{€}{kg,ton}\right] = \frac{TCO_{renewable}\,[€] - TCO_{diesel}\,[€]}{Emissions_{diesel}\,[kg,ton] - Emissions_{renewable}\,[kg,ton]} \quad [36]$$

Generally, the lower the cost per saved emissions, the more cost-effective the solution is to reduce emissions. However, it is not always this straightforward. If, for example, the emission reduction of the renewable solution is low but at the same time the difference in TCO between the reference diesel engine and the greening technology is low, the cost per saved emissions could be low as well. It might look like a cost-effective way to reduce emissions, but in practice not much emissions reduction has been obtained. So, when using the cost per saved emission value to see which solution is the most cost effective also check the TCO and emission values that are used to calculate the value as a reference.

3.4 Pay-per-Use

Due to the large initial investment cost of zero emission technologies a new financial model has been introduced in the IWT sector, called "pay-per-use". In the pay-per-use principle the vessel owners do not own the energy storage system by itself, but they use the battery packs as a service for a certain time period. The benefit is that no investment cost and maintenance cost have to be paid by the vessel owner for the batteries, since this is done by the service providing company. The service providing company also takes care of the transshipment of the battery containers and recharging them and the logistics and maintenance. This option is only included in the IWT tool and not in the coastal vessel tool.

In the case for hydrogen the assumption is made that the hydrogen supplier also owns the energy storage tanks, so called Multi Element Gas Containers (MEGCs). The price of hydrogen, therefore, includes the cost related to all the hydrogen storage and logistics, crane cost, other related cost and a small profit margin.

For battery electric sailing the company Zero Emission Services (ZES) is currently the only supplier for swappable battery containers in Europe. The battery packs that ZES provides are battery systems packed into a 20-foot container that can be loaded and unloaded onto the vessel. The benefit of having the battery system in a 20-foot container is that charging can be done onshore without the need for the vessel to wait for it to be recharged at the port. This means that within roughly 30 minutes a battery charged with multiple MWhs electric power can be loaded onto the vessel. This will save a large amount of time compared to charging fixed battery from shore, especially for vessels which operate 24/7 and which have a high energy consumption.

In the case of ZES the vessel owner/operator pays for the electricity that is used from the battery and a fixed price per renting hours. The fixed price covers the capital investment in the batteries, crane cost, logistic expenses, other expenses and a profit margin. Since the fixed cost depend on how long the vessel owner rents the battery containers the eventual price is very dependent on the exploitation characteristics: how often a vessel owner can switch a battery pack, and how much battery packs are needed on board and for how long they are occupied. The actual pay-per-use price ZES applies is due to this reason tailor made per vessel and per transport route, depending on the operational profile and the facilities available in ports for transhipping the battery containers.

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To get an estimate price, ZES provided a bandwidth. These examples are selected based on suitable exploitation types and vessel dimensions. Since the tool predicts the cost up until 2050 the pay-per-use cost bandwidth that ZES made using these examples were not only calculated for the year 2025, but also for future years. ZES provided an indication up to the year 2035 based on their expected reduction in battery prices and increase in battery capacity. The pay-per-use price after 2035 is estimated based on the evolution factors that are also applied to the capital cost of batteries. In these evolution factors it is assumed that the lower bound has a 30 % price reduction every 5 years and for the upper bound a 20 % reduction is assumed. Using this the following pay-per-use values have been constructed, as can be seen table 4.

4 | Calculated pay-per-use cost bandwidth for the period 2025 to 2050.

Year	Minimum pay-per-use cost	Maximum pay-per-use cost
2025	0.35 €/kWh	0.50 €/kWh
2030	0.325 €/kWh	0.45 €/kWh
2035	0.30 €/kWh	0.40 €/kWh
2040	0.28 €/kWh	0.37 €/kWh
2045	0.27 €/kWh	0.35 €/kWh
2050	0.265 €/kWh	0.34 €/kWh

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4. Tool continuation

A goal of SYNERGETICS is not only to create a tool using an up-to-date cost and emission dataset, but also to ensure that this tool and the underlying database remains operational, relevant, and continuously updated well beyond the project's formal end. Sustaining the Decision Support Tool as an active and reliable digital service to the owners of inland and coastal vessels is a central strategy for achieving this long-term objective.

Upon the completion of the SYNERGETICS project, the Decision Support Tool will transition from a project-based prototype into a stable asset, designed for ongoing operational use. Its overarching purpose is to support vessel owners, operators, policymakers, and other stakeholders in identifying cost-effective, technically feasible pathways for emission reduction and compliance with evolving environmental regulations, standards, and technological developments.

To ensure continuity, operational and financial agreements are made, which defines responsibilities and tasks for maintenance, and mechanisms for future enhancement of the tool and the database. Regarding the governance, the organisations DST and SPB/EICB will be in charge together for the maintenance and development of the Decision Support Tools and they will regularly meet to discuss the status and development, at least once each two months. The costs will be covered from the budgets of SPB/EICB and DST for at least the next two years. The main distribution of tasks follows the structure of the division of work in the SYNERGETICS project:

- DST will focus on the database of costs and emission factors
- SPB/EICB will focus on the tool using data from the database

There is an in-depth mutual understanding and close collaboration between the two organisations.

Currently, the database runs on a rented server which is financed for by DST. Additional cost drivers include the staff hours required for periodic verification, quality control, technical maintenance, and functional updates. To address these recurring expenses, the ownership and maintenance responsibilities must be assigned to a designated organization or consortium capable of ensuring operational continuity.

The maintenance strategy goes beyond routine data updates. It includes a commitment to evolve the tool in response to market innovation and regulatory developments. For example, should new emission-reduction technologies become commercially available after the conclusion of the SYNERGETICS project, the decision support tool will be updated to incorporate these in both the database and assessment framework. This ensures that users continue to receive relevant and actionable guidance rooted in the latest industry knowledge.

From a business-continuation perspective, the current goal is to operate and support the decision support tool for a minimum of two additional years. During this period, the tool is expected to transition into a new project context, at the European level and/or within national or regional initiatives, where it can be further developed, repurposed, or integrated into broader innovation programs.

Through these measures, the SYNERGETICS Decision Support Tool is positioned not only as a temporary project output but as a long-term digital asset that continues to deliver operational, environmental, and strategic value across the inland and coastal waterway sectors.

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Annex 1: Payload loss analysis

As explained in chapter 3.1.5 a methodology has been developed to make some first assumptions on the loss of payload due to the increased weight or volume of the greening technologies. Parts of this methodology are taken from a previous European study done by H2SHIPS in 2020, where the weight and volume of ICEs and Fuel cells were calculated. In the applied methodology, weight and volume specifications of different system types from various system dealers were first acquired. These values were then plotted, and weight and volume trendlines were constructed to determine weight and volume per kW. The payload loss methodology implemented in the decision support tool is based on the same methodology and values from this study.

The values that the H2SHIPS study (Interreg, 2020) used originate from a different study done by Sandia National Laboratories in 2017 (Pratt, 2017). Fuel cell technology is still in development so the data from 2017 is probably not entirely accurate anymore, but it still provides a good approximation on the order of magnitude of the different parameters of a fuel cell system. For the ICE case the engines of today will most likely be close to the values from the Sandia report.

For the fuel cell systems, the required parameters have been acquired from the companies HYDROGEN-ICS, POWERCEL and US FUELCEL. Table 5 shows the parameters of the different fuel cell systems developed by these companies.

5 | Fuel cell system parameters, including fuel cell systems different companies and different types within these companies

Fuel cell system	Power [kW]	Volume [m^3]	Mass [kg]
HYDROGENICS HD90	93	0.594	360
HYDROGENICS HD180	198	1.19	720
HYDROGENICS CELERITY	60	0.294	275
HYDROGENIC POWER RACK	120	1.62	800
POWERCELL MS-100	100	0.293	98
US FUELCELL Fce 80	80	0.494	248
US FUELCELL Fce 150	150	0.660	474

The plots in figure 37 are made using the numbers in table 5.

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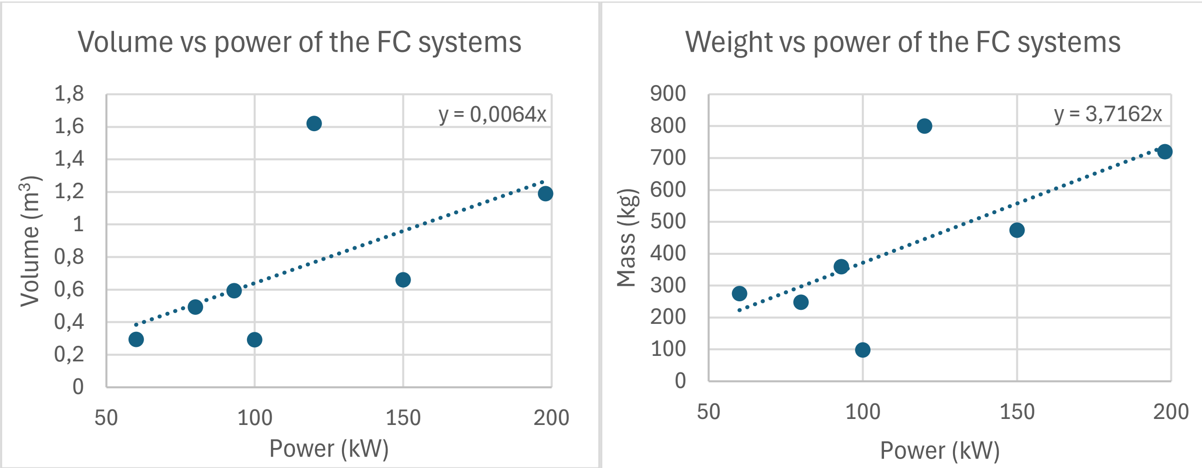

37 | Plot of the volume (left figure) and the weight (right figure) vs the power of the different fuel cell systems, with which the volume and weight per power slope has been determent.

Figure 37 shows that most of the fuel cell systems show a correlation between volume, weight and power except for the one system, which is the HYDROGENIC POWER RACK fuel cell. A possible explanation for this is that this system is a combined fuel cell system of 4x there HD30 fuel cell system instead of system on its own.

It can also be seen that for both volume and weight there is one system that is on the lower end of the volume and weight per kW. This is the POWERCELL MS-100 which is a new improved prototype. The current fuel cell systems are most likely to be in this weight and volume per kW category. However, this overestimation can partially offset the fact that the weight and volume of the required safety measures are not included.

For the parameters of the ICE the engines of different vessels have been studied, ranging from a small fishing vessel to one of the largest seagoing vessels. The values that resulted from this study are shown in table 6.

6 | ICE parameters for different vessel types ranging from a small fishing vessel to one of the largest seagoing vessels.

Vessel type	Length [m]	Power [kW]	Volume [m³]	Mass [ton]
Pride of Hull	215	37800	1660	521
Spiegelgracht	168	12100	470	149
Atlantic Klipper	165	14300	572	181
Capricorn	119	3800	89	30
Atlantic Dawn	112	4000	97	33
Maersk Frontier	83	5370	160	52
Zalophus	47	800	10	4
Northwestern	38	950	17	5
Trondheimsfjord 2	25	1620	12	4
Hein Senior	24	224	6	2
Trearddur Bay	21	1800	11	4

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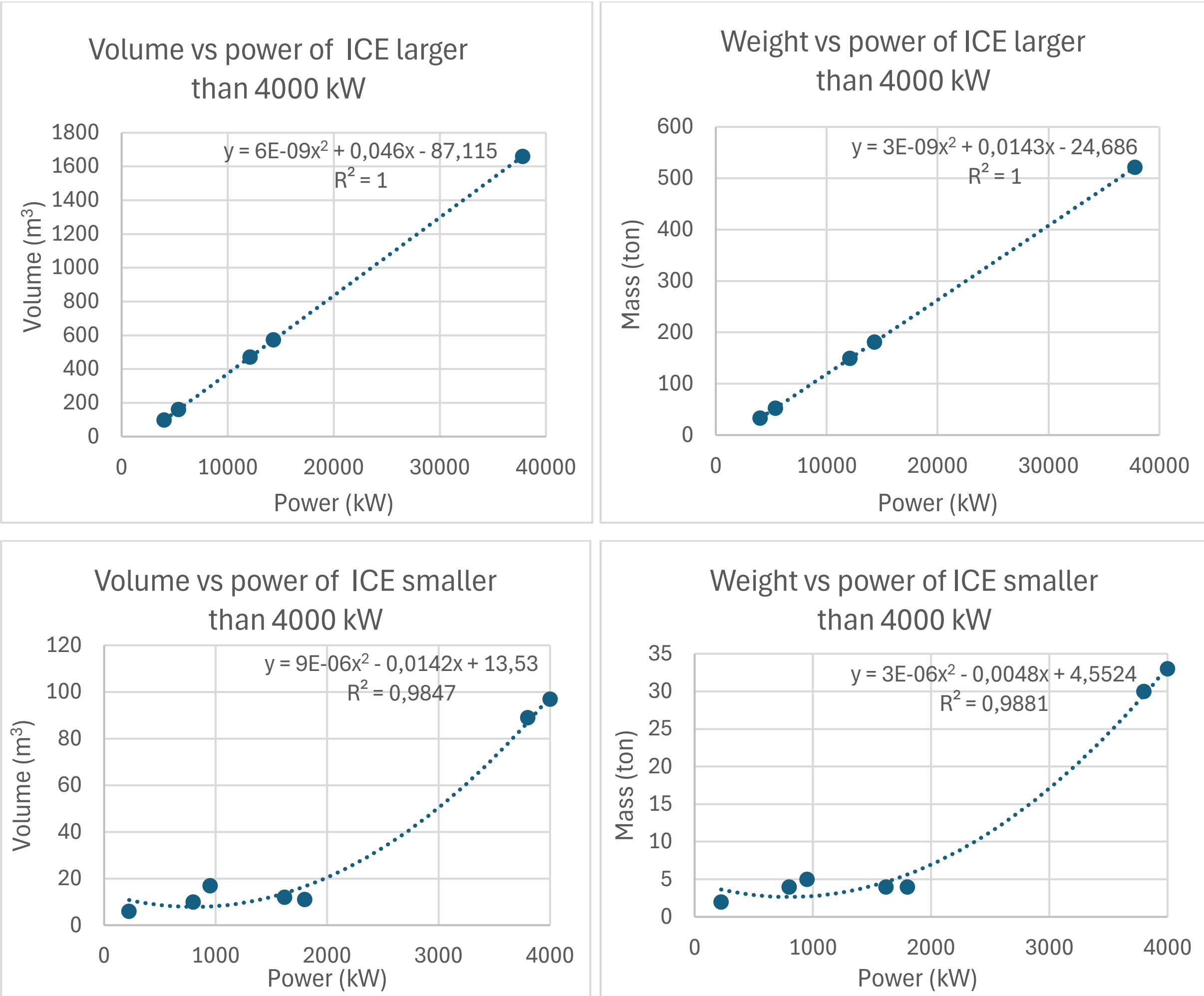
Based on the numbers in table 6 the plots shown in figure 38 is constructed.



38 | Volume (left figures) and weight (right figures) vs the power of the different engines that have been investigated, with which the volume and weight per power slope has been determined.

Figure 38 shows two plots for both weight and volume. One being for engines with a power above 4000 kW and one for engines equal or below 4000 kW. During the fitting of all datapoint in one plot it became clear the either an accurate trendline for values below 4000 kW could be obtained or one that showed accurate results for powers above 4000 kW, but not for all powers simultaneously. Due to this it was decided to create two trendlines for both weight and volume.

The R that is presented in the top right corner of the plots in figure 38 represents the accuracy of the trendline. The closer the R is to 1 the more accurate the trendline. For powers above 4000 kW it is shown that for both weight and volume the R is equal to 1. So, for these datapoints it is possible to construct an accurate regression. The trendlines for powers equal or below 4000 kW show an R of 0.9847 for volume and 0.9881 for weight. This means the trendline is not as accurate as that of above 4000 kW but still accurate enough to be used.

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Annex 2: Stakeholder verification

An essential step in the decision support tool development has been the validation of both the tool and the used data. The data that goes into the tool is discussed in SYNERGETICS D4.5, including the verification process, so only the verification process of the tool will be discussed here. In different stages of the tool development there has been a verification moment, which are outlined below.

Danube Ports Days, Constanta

The first time the decision support tool has been presented was during the 2025 Danube Ports Days in Constanta. Due to time limitations, there was no option to do a live demonstration at the event, but by the means of screenshots the fields of entry plus some results were presented. As preparation for this presentation the barge operator TTS provided an example for a typical vessel that sails in the lower Danube region. With this, a relevant example could be presented to the present stakeholders. The example included a push boat with 6 barge (3 wide, 2 long), where table 7 shows the corresponding data input values.

7 | Input parameters for the example used in the 2025 Danube Ports Days presentation on the decision support tool.

Input parameter	value	unit
Power output	2800	kW
Fuel consumption	3000	m^3/year
Required autonomy	7	days
Interest rate	6	%
Depreciation period	20	years
Yearly profit	250,000	EUR
Yearly personnel cost	350,000	EUR
Yearly insurance cost	100,000	EUR
Max capacity	9000	tons
Percentage of time the vessel sails on max capacity	60	%

The feedback that followed after the presentation was minimal. This was probably the results of the static presentation form through slides instead of using a life demo. Although the feedback during the Danube Ports Days was minimal, the use case given by TTS provided real life input values, which where useful to check and verify the outcomes of the tool.

PLATINA4Action second stage event, Budapest

The second validation moment was during the second stage event of PLATINA4Action in Budapest. This event consisted out of two days, where the first day was more focussed on the vessel owners in the Budapest region and the second day on policy makers. At this stage the tool had been verified using the input values from TTS, more functions were added to the tool and the design of the interface was completed. After this set of improvements, the decision support tool was ready to be presented as a first draft of the application.

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During the first day there was the opportunity to give a live demo. This resulted in more interaction between the presenter and the stakeholders, since they were provided the opportunity to use their own values. Valuable discussions were raised on the technology inputs, the price inputs, and some design improvements.

The goal of the second day of the PLATINA4Action stage event was to discuss the gap between diesel and zero emission solutions. The time schedule for day two was a bit stricter, so here again a static presentation on the tool was given, this time with more focus on the results. Since the topic was about zero emission technologies the presentation was adapted to a 105-meter dry cargo (containers) vessel that currently sails on ZES battery packs. The input values for this example are shown in table 8.

8 | Input parameters for the example used in the 2025 PLATINA4Action second stage event presentation on the decision support tool.

Input parameter	value	unit
Diesel baseline	Old diesel engine (CCNR2)	-
Price scenario	STEPS	-
Installed power	750	kW
Interest rate	6	%
Depreciation years	20	years
Minimum CO_2e reduction	90	%
Minimum NO_x reduction	50	%
Minimum PM reduction	50	%
Yearly profit	14,000	EUR
Yearly capital costs vessel	150,000	EUR
Yearly personnel costs	170,000	EUR
Yearly insurance	30,000	EUR
Manual diesel consumption	135	ton/year
Minimum autonomy	1	days
Max payload	2000	ton
Percentage of time the vessel sails on max capacity	60	%

When comparing table 7 with table 8 it is shown that more input values are included in table 8. This is the result of the further development of the tool between the first and second validation moment. The feedback from the stakeholders present at the second day of the stage event was just as in Constanța quite minimal. It is there proven that by presenting a live demonstration in a smaller setting will provide more input, than to present the tool through a slide show presentation to a larger group.

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Waterstofnet as project leader of the RH2INE collaboration

As a third verification moment a meeting was scheduled with Waterstofnet from their role as project leader in the RH2INE collaboration. Waterstofnet is a company that tries to increase the hydrogen industry within the logistic sector. Over time they have established a wide network in the hydrogen sector, ranging from vessel owners to hydrogen producers, making them a suitable candidate to verify the input values of the tool related to hydrogen.

In the meeting with Waterstofnet current hydrogen prices were discussed, the common use of the hydrogen tanks was verified, and how subsidy schemas are commonly implemented in TCO tools for the logistic sector. From this discussion the hydrogen prices were confirmed, it became clear that some vessel owners buy their own hydrogen tanks and some rent them, and based on their expertise it was decided to use CAPEX subsidies in the form of percentages instead of absolute numbers.

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Annex 3: Fuel price scenarios

In this report, the focus is on current fuel/energy prices and the future prognoses. For the future prices different scenarios are described to see what could happen to the inland shipping industry with a different set of regulatory rules and implementations.

The scenarios are based on the scenarios used in the World Energy Outlook 2024 published by the International Energy Agency (hereafter IEA) (International Energy Agency, 2024) with specific values for Europe. In the WEO 2024 there are three scenarios which are:

- Stated Policies Scenario (STEPS)
- Announced Pledges Scenario (APS)
- Net Zero Emissions (NZE)

The States Policies Scenario is a kind of business as usual scenario which takes into account the planned and confirmed policy measures. The Announced Pledges Scenario takes it a step further in terms of ambitions and uses the climate targets of countries as basis for the forecasts of energy prices. The Net Zero Emissions Scenario is the most ambitious one regarding the climate mitigation and assumes that the global warming will not exceed 1.5 degrees Celsius, which requires higher targets than foreseen in the APS.

Stated Policies Scenario

The Stated Policies Scenario (STEPS) provides a projection of the global energy system based on current policy measures and officially announced policy intentions. For Europe, this concerns policies such as as the revised RED lll Directive and the ETS. This scenario reflects the direction the energy system is likely to take under existing policies, without assuming that all announced targets will be fully achieved on time. Under STEPS, global energy demand is expected to grow by 0.7% per year between 2023 and 2030, about half the growth rate of the past decade. This slower growth is driven by improvements in energy efficiency, electrification, and the accelerated deployment of renewable energy. Electricity demand is projected to grow faster than total energy demand, driven by factors such as electrification of transport, data centres, and air conditioning. Renewable energy, particularly solar and wind, will contribute most to electricity generation growth, with a global market share exceeding 40% by 2035 and nearly 60% by 2050. Meanwhile demand for oil, gas, and coal is expected to peak before 2030, though the decline varies by fuel.

The STEPS scenario serves as a reference for the other two main scenarios in the World Energy Outlook 2024: the Announced Pledges Scenario (APS), which assumes full and timely implementation of all national energy and climate targets, and the Net Zero Emissions by 2050 Scenario (NZE), which outlines a pathway to net-zero emissions by 2050 to limit global warming to 1.5°C.Announced Pledges Scenario.

Announced Pledges Scenario

The Announced Pledges Scenario (APS) assumes that all current national energy and climate pledges made by governments including net-zero goals are met in full and on time. Under APS, policy ambition increases beyond what is already law or currently implemented (as in the Stated Policies Scenario), leading to deeper emissions reductions, faster deployment of renewable energy, and greater uptake of technologies like electric vehicles, efficiency improvements, and clean power generation.

While APS offers a more optimistic outlook than STEPS, it still falls short of the path required for limiting global warming to 1.5 °C. It shows what could happen if governments live up to their declared commitments, but also highlights the gap between ambition and what is needed for the most ambitious climate goals.

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Net Zero Emissions scenario

The Net Zero Emissions (NZE) Scenario outlines a pathway in which global CO_2 emissions fall to net zero by 2050, consistent with limiting global warming to around 1.5 °C. This scenario assumes that countries not only deliver on their existing pledges but also take additional actions, including a rapid scale-up of renewables, large-scale electrification, major efficiency improvements, and a sharp reduction in the use of fossil fuels.

In the NZE, electricity demand grows significantly, while total energy demand declines thanks to efficiency measures. Renewables, especially solar and wind, alongside nuclear, hydropower, and bioenergy, provide the bulk of the power mix. The use of unabated fossil fuels is almost entirely phased out, while technologies such as carbon capture, utilization and storage (CCUS) and clean hydrogen play a crucial supporting role. Due to the phasing out of fossil fuels, the wholesale price of crude oil will reach an all-time low.

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