D4.5 The Catalogue of greening retrofit solutions

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

The aim of the Innovation Action SYNERGETICS is to support and accelerate the green transformation of the European Inland and Coastal shipping using retrofit solutions. Work Package 4 aimed to consolidate the insights gathered in WP1, WP2, and WP3, culminating in the development of a database, the so-called Catalogue of Greening Retrofit Technologies. This Catalogue is designed for use both within and beyond the SYNERGETICS project. Given the rapid evolution of greening technologies, it was crucial to avoid relying on a static snapshot of their development status. Instead, a dynamic database and linked derivatives were established, serving as a toolbox for various outputs and target groups in WP5 and 6.

The D4.5 Catalogue document is primarily a summary of the current numerical values used in SYNERGETICS for the tools. Even after three years of research, it remains challenging to compile reliable assumptions about costs for retrofitting measures, as most of the technologies, with the exception of drop-in fuels, are not yet widely used. This means that the individual system installed on a ship is still rather a prototype compared to a conventional diesel engine, even if the components and systems themselves are market-ready. All costs listed here are based on numerous sources within and outside the SYNERGETICS consortium. They were discussed with technology providers and consolidated in workshops. As soon as new findings become available, the data in the database will be updated.

In addition to the costs of the technologies, the emission factors of the energy sources are also important. These have already been partially investigated and calculated in *D1.2 Report on suitability of identified technical solutions*. At present, there is no truly standardised source or methodology for calculating well-to-tank emissions. Therefore, various sources are compared here, also to illustrate to the reader the problem of the near impossibility of standardising fuel supply paths. For the future it was agreed to synchronize the database with the emission factors published in the context of EcoTransIT World. It is expected that future releases of EcoTransIT World will cover more and more relevant alternative energy carriers and are consistent with upcoming updates of ISO14083 for the reporting of Greenhouse Gas Emissions in the Transport Sector.

In addition, the costs associated with the use of the technologies are listed. The SYNERGETICS consortium has invested a considerable effort in establishing reasonably uniform assumptions while maintaining a reasonable balance between high complexity and simplification.

This deliverable is closely linked to deliverables published before or in parallel, which can be read in addition:

- The technologies listed are described in detail in *D1.1 Relevant identified technical solutions*. Initial cost assumptions have also been made here, but these are now being updated with D4.5.
- *D1.2 Report on suitability of identified technical solutions* reports the emissions as well as the costs of several energy carrier supply paths assessed from a Well-to-Wake perspective using a comprehensive, modular Well-to-Tank model as well as preprocessed Tank-to-Wake data for the years 2020 (status quo), 2035 and 2050.
- *D4.1 Specification and Creation of the Database* provides the concept and implementation background of the database.
- *D4.2 Fact sheets of most promising retrofit measures* describes the first set of outputs that are linked to the database.
- *D4.3 Cost and performance model – ship* describes the methodology and calculations based on the database.
- In parallel to this D4.5 the first deliverable of WP5, *D5.1 Decision Support Tool for Vessel Owners,* is submitted. It is one of the most relevant outputs of SYNERGETICS to the end-users in inland and coastal shipping but also useful to other stakeholders in the sector.

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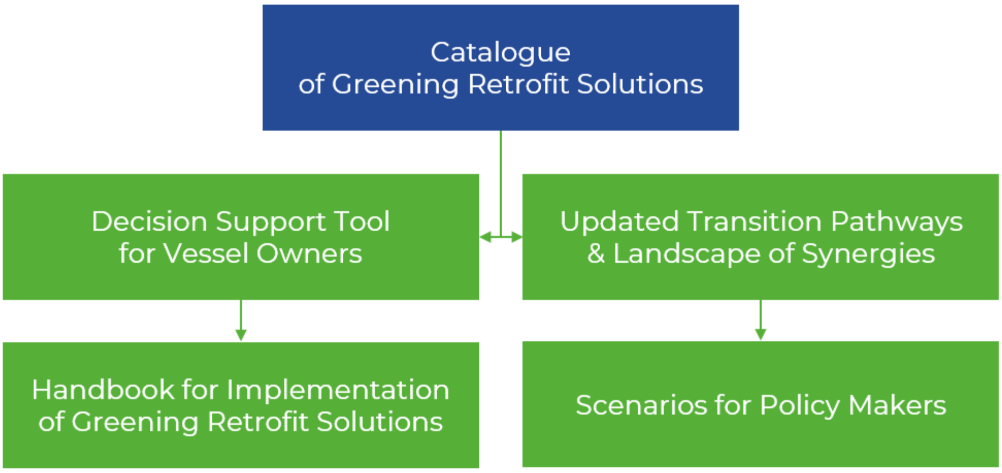
1. Introduction

This deliverable offers a comprehensive summary of the emission values and costs associated with the technologies featured in the SYNERGETICS Decision Support Tool for vessel owners, for the Scenarios for Policy Makers and the Technology Fact Sheets. The presented data serves as a reference point, reflecting the most current information available at the time of publication.

It is important to note that these values represent a snapshot in time. SYNERGETICS is committed to maintaining the accuracy and relevance of this data, recognizing that technological advancements, regulatory changes, and market dynamics can influence emission levels and costs over time. To ensure ongoing reliability, all data is centrally managed and regularly updated within a dedicated database.

The following illustration clearly shows how the catalogue is embedded in the SYNERGETICS project. It incorporates all findings regarding the numerical values for the technologies from work packages 1, 2 and 3 and summarises them clearly in tabular form. Based on these data, the *Decision Support Tool for Vessel Owners (T5.1)* can then be fed with assumptions for emissions and costs. The fleet model, which will show possible development scenarios for the entire European inland and coastal fleet, will also be filled with the values shown here (*T5.2 Updated Transition Pathways & Landscape of Synergies*). Building on these two tasks, the *Scenarios for Policy Makers (T5.3)* and the *Handbook for Implementation of Greening Retrofit Solutions (T5.4)* can then be developed.



1 | The Catalogue of Greening Retrofit Solutions embedded in the SYNERGETICS project.

2. Database

The SYNERGETICS Database (SDB) itself is an online SQL database in which all factors and costs are stored. Easy access to the data means that updates can also be made beyond the project duration. Follow-up projects are of course helpful here in order to improve the data collection. There are links to both the fact sheets and the decision support tool in Task 5.1.

2.1 SYNERGETICS Database Specification

The SYNERGETICS database is built on a selection of elements and parameters, ensuring both comprehensiveness and direct relevance to the advancement of greening technologies. The focus is on parameters that enable robust analysis and support informed decision-making in the development and adoption of sustainable maritime solutions.

The database prioritises the following key areas:

- **Technology Profiles**: Clear descriptions of operational principles and practical applications for alternative fuels.
- **Energy Carrier Characteristics:** Performance metrics for carriers such as methanol, hydrogen, and biofuels, including energy density (volumetric [MJ/m^3] and gravimetric [MJ/kg], Well-to-Tank emission factors).
- **Energy Converter Specifications:** Input energy (calorific value [MJ]), mechanical output ([kWh]), and emission factors (CO_2e, NO_x, PM).
- **Adoption Trends:** Analysis of technology uptake within the fleet, drawing on insights from the T2.1 Pilot Database and covering a wide range of use cases—from established solutions like LNG to emerging options such as hydrogen.
- **Innovation Timeline:** Estimates of technology readiness levels (TRL) and the pace of progression from concept to market.
- **Integration Costs:** Assessment of capital expenditures (CAPEX) for retrofitting, including variations by vessel type, operational profile, and energy requirements, as well as downtime and opportunity costs.
- **Operational Impact:** Evaluation of operational expenditures (OPEX), fuel and maintenance costs, and the effects of energy storage systems on vessel payload (weight and volume).
- **Bunkering Time Efficiency:** Comparison of bunkering times and logistical requirements, e.g swapping of energy containment systems for alternative fuels versus traditional options.
- **Regulatory Landscape:** Tracking of current and upcoming regulations, their impact on alternative energy adoption, and the development of supportive bunkering infrastructure.

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2.2 Ensuring the Longevity and Effectiveness of the SYNERGETICS Database

To maintain the database's efficiency, security, and relevance to the SYNERGETICS project, a proactive and structured maintenance strategy is essential. This approach ensures the database remains a reliable and high-performing resource.

Key Maintenance Strategies

- **Performance Optimization:** Implementation of indexing, data partitioning, and query optimization to enhance speed, scalability, and responsiveness—especially when handling large datasets.
- **Data Normalization:** Organising the data into dedicated tables to minimize redundancy and streamline database structure.
- **Data Quality Assurance**: Enforcement of validation rules, error detection, and regular data cleansing to maintain accuracy and reliability. In cases where full validation is not feasible, a separate schema is used to preserve data integrity.
- **Change Management:** Management of the database evolution through a structured process for schema updates, including additions or removals of tables and columns. Each change undergoes review, testing, and approval to ensure smooth implementation and data consistency.
- **System Integration:** The database is designed for seamless connectivity with external systems via APIs and standardized data exchange protocols, enhancing its utility and scalability.
- **Backup and Recovery:** Protection against data loss with scheduled backups, efficient storage solutions, and rapid recovery procedures, ensuring minimal downtime and continuous operational reliability.

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3. Fact Sheets

The fact sheets were the Deliverable D4.2 “Fact sheets of most promising retrofit measures”. They provide an overview of the following topics

1. | Methanol ICE
2. | H2 ICE
3. | Drop-In Fuels
4. | Batteries
5. | Hydrodynamic Improvements
6. | Solar
7. | Electrification of Propulsion
8. | Fuel Cells

and address the sub-items (where applicable):

- Technical details and physical properties
- Emissions
- Regulations for inland and seagoing vessels
- Technical concepts for the integration on board
- Bunkering and Infrastructure
- Economics
- Considerations for Deployment
- Deployment examples

Tool

Catalogue

The Catalogue of Greening Retrofit Solutions ("the Catalogue") describes and arranges the suitable retrofit technologies for greening of the fleets, and outline their maturity, TRL, possibilities for deployment (infrastructure), cost-effectiveness, etc.

To explore the available retrofit solutions, click on the links below to access detailed information about specific technology.

2 | Screenshot of the SYNERGETICS website, the URL to the fact sheets is https://www.synergetics-project.eu/tools/

What makes this online publication unique is its ability to stay up to date. While many of the technologies are already on the market, their adaptation for maritime use is still evolving. To keep pace, the fact sheets are directly connected to a live database (Task 4.1). Each document also includes links to relevant regulations, scientific studies, and other useful resources.

This approach ensures that readers have immediate access to a solid introductory overview. For those seeking deeper insights, the linked references provide a clear path to more detailed information.

4. Emission Factors

The emission factors refer to both WTW and TTW shares. Since SYNERGETICS does not develop its own emission factors for the tool, it was necessary to find a data source that was as complete and sustainable as possible. Another important criterion was that this source should receive regular updates, which would then be incorporated into SYNERGETICS. Regular updates are provided as part of the EcoTransIt World studies in Germany, which are closely linked to the EU project CLEVER and the ISO standard 14083 [1].

There is another valuable source available from the Netherlands, the STREAM dataset and model by CE Delft. This refers to fuels bunkered at Dutch sea and inland ports.

Since there is not “one” source for the European fuels’ emissions pathways and also not only one way to calculate, both sources are included into the tool. The emission factors used in SYNERGETICS take into account the entire chain of fuel emissions. Emissions generated during the production of energy/fuel storage devices and energy converters, however, are not taken into account.

4.1 Description of sources

4.1.1 EcoTransIt world

The methodology, provided by independent scientific institutes (Ifeu, Infras and Fraunhofer IML), is continuously updated and validated with every leap in innovation. All assumptions are freely accessible and are published in a methodology report.

Within the data set, the transport distances, energy consumption, greenhouse gases CO2 and CO2 equivalents, air pollutants SOx, NOx, NMHC and PM10 as well as external costs for every global transport chain are calculated:

“Energy chain of electricity production:

1. Exploration and extraction of the primary energy carrier (coal, oil, gas, nuclear etc.) and transport to the power plant
2. Conversion within the power plant (including construction and disposal of power stations)
3. Energy distribution (transformation and distribution losses)

Energy chain of fuel production:

1. Exploration and extraction of primary energy (crude oil) and transport to the refinery
2. Conversion within the refinery
3. Production and dismantling of energy source infrastructure
4. In the case of natural gas: compression (CNG) or cooling and liquefaction (LNG)
5. Energy distribution (transport to service station, filling losses)”. [2]

The emissions are determined on the basis of the energy requirement, the associated fuel, and other parameters such as the load factor or emission class. A carrier-specific internal routing is the basis for the identification of the route characteristics. Moreover, the methodology includes the ISO14083 and GLEC-compliant calculation. To ensure that it stays that way, the calculation sources used are continuously updated by our methodology partners. [2]

4.1.2 CO2emissiefactoren.nl

CO2emissiefactoren.nl originated from a Green Deal signed in March 2014 by the Dutch government, SKAO, Stichting Stimular, Connekt and Milieu Centraal.

The website states: Since 2014, CO_2 footprint calculations have become increasingly important and more and more calculation tools/instruments have been developed for this purpose.

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CO2emissiefactoren.nl provides all these calculation tools with a single, uniform list of the most up-to-date conversion factors. This makes it the foundation for CO_2 calculations in the Netherlands. A solid foundation shifts the discussion about the accuracy of figures to what really matters: reducing CO_2 emissions.

The emission factors presented have been calculated in Dutch scientific research and are representative of the Dutch situation. Since the Dutch seaports and inland ports play a dominant role in the bunkering of the inland vessel fleet and also coastal vessels, it is a very relevant source. These studies are based on international standards and data. As a result, many emission factors are also perfectly usable internationally, without any major deviations in the final total [3].

4.1.3 CLEVER Project

Led by a consortium of European experts, the project CLEVER (Creating Legitimate Emission Factors for Verified GHG Emission Reductions in Transport)—began in June 2024 and will run for three years, concluding in May 2027[4].

The key objectives of CLEVER are:

- Update existing emission factors to reflect current technologies and energy mixes.
- Develop new emission factors for previously uncovered categories, addressing both upstream and downstream emissions.
- Establish clear, standardized rules for emission factor development, including methodologies, calculation boundaries, fuel/energy specifications, and permissible assumptions—laying the groundwork for rapid, consistent assessments of emerging energy carriers.
- By aligning with the CountEmissionsEU framework, CLEVER seeks to foster harmonization and collaboration across the logistics sector, ensuring that organizations developing GHG emission factors for transport and logistics work from a common, robust foundation. [5]

The initiative is also closely connected to the international standard ISO 14083:2023 [1], which governs the quantification and reporting of GHG emissions from transport chain operations.

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4.2 Fossil fuels emission factors in SYNERGETICS

The emission factors from the EcoTransIt World 2024 for the fossil fuels in Europe are modelled using the ecoinvent database (version 3.9.1) and the internal ifeu refinery model. The upstream chain of the refinery, i.e. the crude oil supply is based on the ESU 2021 data. Detailed information on the refinery model can be found in [6]. Also, the data from the CO2emissiefactoren.nl is very relevant. Here the underlying dataset comes mainly from calculations done in [7] from CE Delft. As stated above, it was decided to put both datasets in the SYNERGETICS Decision Support tool. The functionality of the tool is described in detail in D5.1. The resulting emission factors for fuels relevant for IWT can be found in the following tables.

2 | CO2e emissions for fossil fuels from EcoTransIt World 2024

Fuel	Lower heating value MJ/kg_{fuel}	CO2e-factor kg_{CO2e}/kg_{fuel}		
		TTW	WTT	WTW
Diesel	42.8	3.221	0.966	4.187
Liquefied natural gas (LNG) (Otto dual fuel ship medium speed)*	49.1	3.647	1.265	4.912
Hydrogen (from SMR)	120	0	12.156	12.156
Very low sulphur fuel oil (VLSFO) (0.5% sulphur)	41.3	3.096	0.992	4.087
Ultra-low sulphur fuel oil (ULSFO (0.1% sulphur)	41.1	3.093	0.927	4.020

*For LNG ships, a methane-slip of 3.1 mass-% for an LNG ship using an Otto motor from Fuel.EU.maritime [8] was used.

For VLSFO and ULSFO also the IMO has published upstream values [9]:

3 | CO2e emissions for fossil fuels from IMO MEPC.376(80)

	Lower heating value MJ/kg_{fuel}	CO2e-factor kg_{CO2e}/kg_{fuel}
VLSFO	40.2	0.67536
ULSFO	42.7	0.75579

However, SYNERGETICS uses the values from the EcoTransIt World study, especially since the IMO also assumes different energy contents, which makes it even more difficult to compare the values.

4 | CO2e emissions for fossil fuels from CO2emissiefactoren.nl without biogenic emissions

	WTT	TTW	WTW
		kg_{CO2e}/kg_{fuel}	
Diesel (fossil) B0	0.966	3.131	4.097
H2 grey	12.516	0.000	12.516
LNG	0.706	2.945	3.651

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5 | WTT NOx and PM emissions for fossil fuels from EcoTransIT World 2024

Fuel	NOx kg/kg_fuel	PM kg/ kg_{fuel}
Diesel	1.673	0.295
LNG	1.390	0.240
H2 (SMR)	6.240	0.720
VLSFO	1.292	0.200
ULSFO	1.282	0.199

4.3 Fuels from renewable sources

The calculation approach aligns with the methodological framework set out in the RED and RED II directives. This includes the treatment of co-products, which are accounted for using allocation based on their lower calorific value. The method does not incorporate offsets or credits in the determination of emission factors. This applies to elements addressed in the RED, some of which have already been factored into actual value calculations. Specifically, it excludes credits for activities such as the use of captured CO_2 (CCR or CCU), soil carbon sequestration through improved agricultural practices, and the reduction of methane emissions by converting manure into biogas or biomethane. The green hydrogen upstream chain anticipates that only renewable electricity is used.

6 | CO2e emissions for renewable fuels from EcoTransIt World 2024

Fuel	Lower heating value MJ/kg_{fuel}	CO2e-factor kg_{CO2e}/kg_{fuel}		
		TTW	WTT	WTW
HVO/ HEFA	44	1.257	0.051	1.308
Bio LNG (road)	50	1.443	0.047	1.490
Green Hydrogen	120	0	1.752	1.752

7 | CO2e emissions for renewable fuels from CO2emissiefactoren.nl

	WTT	TTW	WTW
		kg_{CO2e}/kg_{fuel}	
HVO	0.415	0.026	0.441
Bio-LNG	0.450	0.145	0.595
Green Hydrogen	1.080	0.000	1.080

8 | WTT NOx and PM emissions for renewable fuels from EcoTransIt World 2024

Fuel	NOx kg/kg_{fuel}	PM kg/kg_{fuel}
HVO/ HEFA* (50%rapeseed, 50% used cooking oil)	1.91E-03	1.53E-04
Bio LNG (40% maize, 40% manure, 20% biowaste)	2.56E-03	2.90E-04
Green Hydrogen	4.68E-03	1.68E-03

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4.3.1 Methanol

Methanol is not part of the EcoTransIt study yet and is not yet covered either in the CO2emissiefactoren.nl source. Therefore, the SYNERGETICS project makes use of the data collected and calculated in D1.2 [10]: From the variations modelled in D1.2, the "best guess" scenario 2020 values are selected. From those, few most likely pathways are used to derive averaged emission factors for E-Methanol and Bio-Methanol. Thus, those sets of emission factors can be regarded as representative for a European E-Methanol or Bio-Methanol mix, based on further assumptions as described in the specific chapters below.

The best guess scenarios for methanol are based on the following assumptions:

- For the hydrogen production (E-Methanol), wind onshore is preferred over wind offshore since it has higher annual electricity production capacities, both today as well as in the future.
- Decentralised electrolyses and methanol syntheses are chosen due to limited space at Rotterdam (or any other fuelling location).
- Methanol transported by vessels is preferred over lorries as vessels have higher transport capacities.

Methanol storage has been modelled (on-land and on-board) but plays a very minor role for the resulting emission factors as could be seen in the hot-spot analysis.

The chosen reference pathway for E-Methanol (#45) is one with the lowest identified costs for the methanol pathways. The "Direct Air Capture" and "Methanol Synthesis" contributions dominate the overall methanol emissions.

Bio-Methanol specifications

Assumptions:

- All biomass is from Europe, and it must be sustainable (low ILUC, usable after 2030) (European Union 21/12/2018, 27/06/2022, 01/10/2023).
- There is a focus on biomass with high availability. Residues from forestry and agriculture (especially straw) have the highest potential for sustainable biomass production [11] [12].
    - The production methods must have a high TRL: gasification of biomass, synthesis of biomethanol, hydrotreatment of used cooking oils and production of HVO [13].

Methanol can be produced from a wide range of biomass feedstocks (for example agricultural residues like straw, lignocellulosic biomass like forestry residues or biogas) through gasification of biomass and a synthesis of the resulting syngas to methanol [14]. The maximum possible bio-methanol production with a conversion rate of 35 % is 48 TWh/a (500 km radius around Rotterdam). For comparison: the current methanol market (2023) in the chemical industry in Europe is 62 TWh/a [15]. Thus, the demand for (renewable) methanol is already larger today than the maximum possible production capacity.

The capacity of existing and planned plants for "green methanol" in Europe until 2029 [16]. could only cover around a third of the current demand for methanol. The chemical industry is currently the largest consumer of methanol. It can be assumed that the demand in the chemical industry for sustainable raw materials such as methanol will increase in the future and that potentially interested parties, such as the shipping industry, will compete for these resources. Thus, due to the limited biomass capacity it is unlikely that the European coastal and inland shipping can rely to a large extend on bio-methanol.

The modelled biomass sources for Bio-Methanol are residual forest wood (RFW) and straw. The assumed average collection distances to the methanol synthesis plant are 500 km for RFW and 150 km for straw. Modelling of the biomass sources is based on [17], [18] and[19].

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E-Methanol specifications

Production of E-Methanol requires water and CO2.

Water: As freshwater resources are limited both in Europe as well as in MENA [20], only desalinated seawater is used. Reverse osmosis is chosen for all paths since it is the most common used desalination method [17].

CO2: To assure net zero CO2 emissions from the on-board combustion only direct air capture (DAC) is used where CO2 from the atmosphere is harvested. Therefore, point sources like cement plants or municipal solid waste treatment plants are not considered. Although emissions and costs are expected to decrease in the future, this process step will remain emission and cost intensive, amongst others due to the adsorption fleece [21], [17]. The following literature is used for modelling the water treatment and the carbon dioxide sources: [17], [22] and [23].

SYNERGETICS E-Methanol Pathway #45

To align the values from D1.2 with the slightly newer data from ISO 14083 and EcoTransIT World 2024, an interpolation for 2025 values could be done, lowering the values by half of a linear reduction 2020-2050 over 5 years. As an orientation: The values calculated in SYNERGETICS WP1 for e-methanol are quite high due to the assumptions and background described above. Most other sources assume the usage of flue gas for CO2 input today and DAC only later (in 2050). Then, e.g. GHG-E are about half in 2025 from the 2020 values in the table below.

9 | E-Methanol (Pathway #45) (CO_2 only from DAC)

	Lower Calorific Value MJ/g	CO2e $\text{kg/kg}_{\text{fuel}}$	NOx $\text{kg/kg}_{\text{fuel}}$	PM $\text{kg/kg}_{\text{fuel}}$
WTT	0.0199	9.528	1.36E-02	4.87E-02
TTW	0.0199	Net Zero	1.10E-01	2.87E-03
WTW	0.0199	9.528	1.23E-01	5.16E-02

SYNERGETICS Bio-Methanol Pathway #51

To align the values from D1.2 with slightly newer data from ISO 14083 and EcoTransIT World 2024, an interpolation for 2025 values could be done, lowering the values by half of a linear reduction 2020-2050 over 5 years. As an orientation: The values calculated in SYNERGETICS WP1 for bio-methanol are quite low due to the assumptions and background described above, especially the choice of substrates.

10 | Bio-Methanol (Pathway #51) (only residual forest wood and straw)

	Lower Calorific Value MJ/g	CO2e $\text{kg/kg}_{\text{fuel}}$	NOx $\text{kg/kg}_{\text{fuel}}$	PM $\text{kg/kg}_{\text{fuel}}$
WTT	0.0199	1.433	2.87E-03	1.07E-02
TTW	0.0199	Net Zero	1.10E-01	2.87E-03
WTW	0.0199	1.433	1.12E-01	1.36E-02

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4.4 Electricity in Europe

4.4.1 Current EU-Mix

For the GHG emissions in g CO2e per kWh of electricity at medium voltage level (including infrastructure) for production and consumption mixes 2021 [6] states 334 gCO2e/kWh for the EU27 Mix. The ISO 14083:2024 gives the EU 28 Mix from 2019 with 349.2 gCO2e/kWh [1].

4.4.2 Renewable Electricity Mix in SYNERGETICS

To make battery-powered ships truly sustainable, they must also be powered exclusively by green electricity. Wind and water provide most renewable electricity; solar is the fastest-growing energy source: […] Wind and hydro power accounted for more than two-thirds of the total electricity generated from renewable sources (38.5 and 28.2 %, respectively). The remaining one-third of electricity generated was from solar power (20.5 %), solid biofuels (6.2 %) and other renewable sources (6.6 %). […][24]

When calculating a mix of renewable electricity in Europe, which in this model consists solely of wind, hydro and solar power, the proportions converted from the above figures would be as follows:

- Wind: 44.2 %
- Hydro: 32.3 %
- Solar: 23.5 %

From D1.2[10] the share of onshore wind is 82 % and offshore wind is 18 %. This then leads to:

- Wind Onshore: 36.24 %
- Wind Offshore: 7.95 %
- Hydro: 32.3 %
- Solar: 23.5 %

The emission factors for the sources are

- Wind Onshore: 17.7 gCO2e/kWh$_{el}$ [10]
- Wind Offshore: 9.7 gCO2e/ kWh$_{el}$ [10]
- Hydro: 24.0 gCO2e/ kWh$_{el}$ [25]
- Solar: 56.6 gCO2e/ kWh$_{el}$ [10]

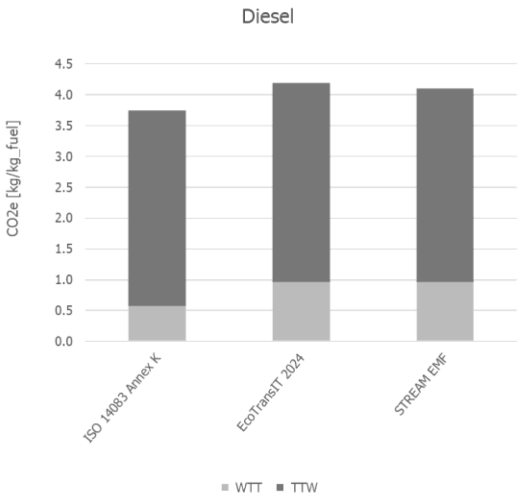
This leads to an averaged GHG emission factor for current renewable electricity in Europe of **28.2 gCO2/kWh$_{el}$**. Nonetheless, this mix contains a share of hydro power. Within SYNERGETICS, the renewable electricity shall consist solely of renewable sources with potential for expansion, i.e. wind and solar. As hydropower has only limited potential for expansion, it is excluded from the SYNERGETICS value. A renewable electricity mix with only wind and solar sources would have the following shares:

- Wind Onshore: 46.9 %
- Wind Offshore: 18.5 %
- Solar: 34.2 %

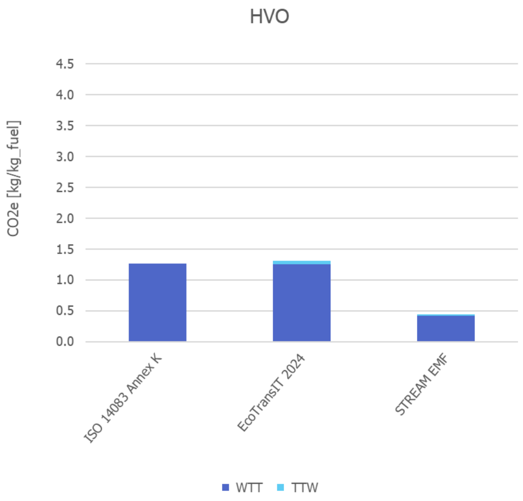
This would lead to an average emission factor per kWh$_{el}$ for renewable electricity from wind and solar only of **29.5 gCO2/kWh$_{el}$**.

4.5 Visual comparison of sources

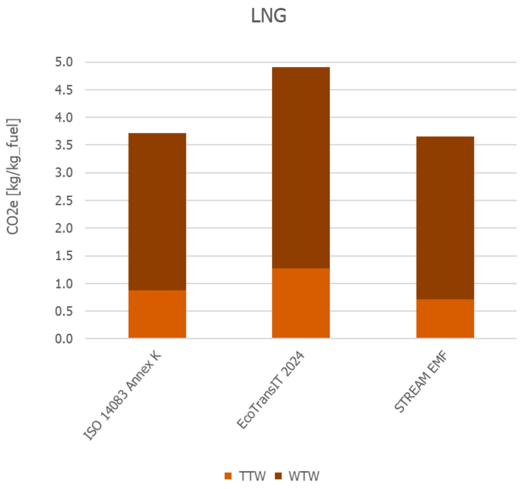
In the sources, the fuel supply chains are calculated using the same standards named above, but different assumptions are made along the paths, resulting in differing end results. This section therefore uses graphs to show the extent of the respective deviations.



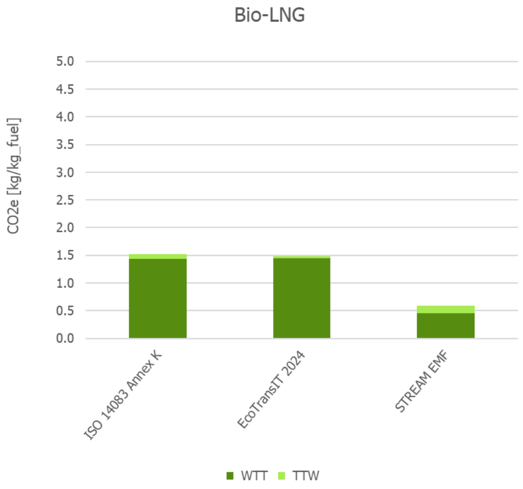
3 | WTT, TTW fossil Diesel



4 WTT, TTW HVO



5 | WTT, TTW LNG



6 | WTT, TTW Bio-LNG

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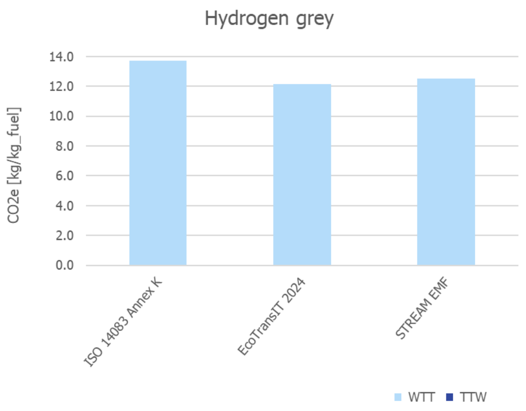
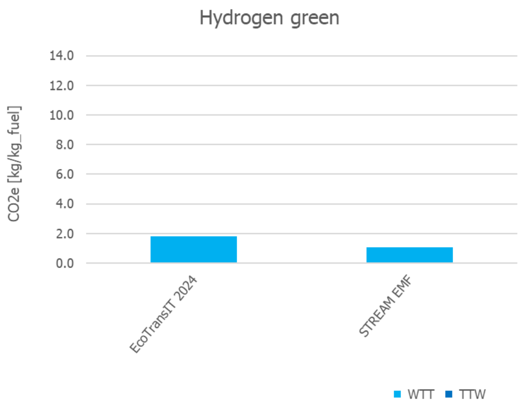
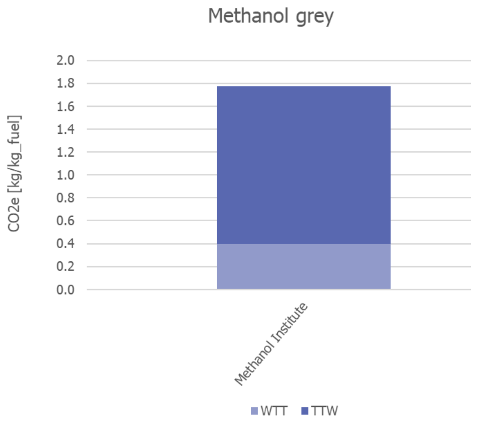


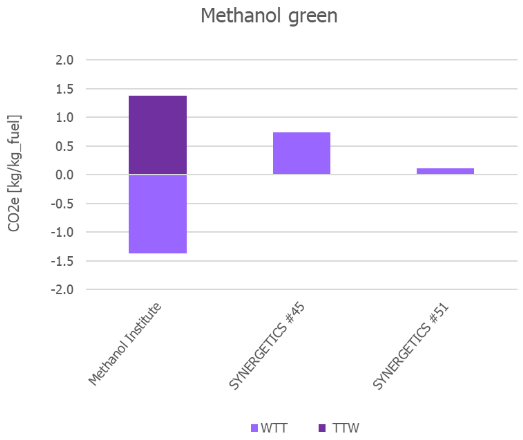
7 WTT, TTW grey Hydrogen



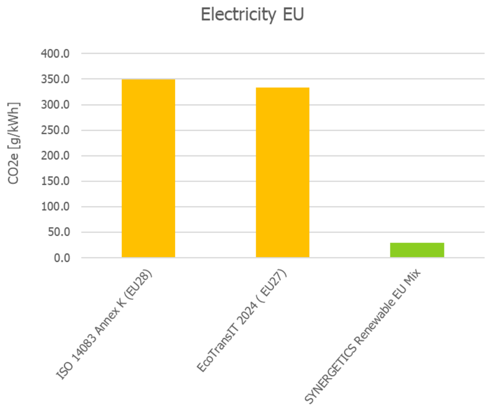
8 | WTT, TTW green Hydrogen



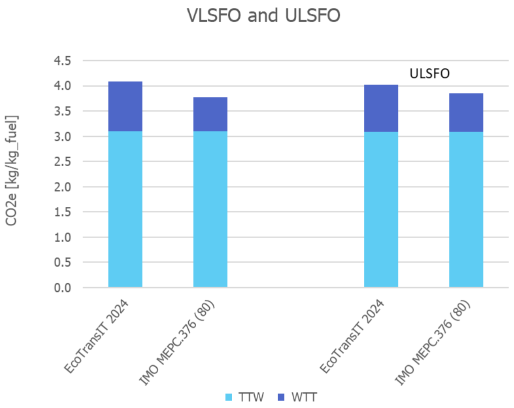
9 | WTT, TTW grey Methanol



10 | WTT, TTW green Methanol



11 | WTW Electricity EU



12| VLSFO and ULSFO

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4.6 TTW PM and NOx emissions of ICE inland vessels

The PM and NOx emissions from the usage on board depend on the energy converter. To set some benchmarks against current or old technologies, these are also included into the SYNERGETICS database.

All combustion engines newly launched on the market, including those running on alternative fuels, must comply with Stage V limits. Therefore, only these are listed here, since it is assumed, that the majority of the engines for alternative fuels will be new. However, there might also be the option, that a CCNR2 engine is retrofitted and might then reach those emissions levels with an alternative fuel. In practice, the limits can also be undercut with alternative fuels. Methanol, for example, burns almost soot-free and therefore produces no PM emissions. However, as these values depend heavily on the respective engine and also on the operating point, only the Stage V limits are used here, as mentioned above. Marinised Euro 6 engines can also be installed on inland waterway vessels. These limits are also used. Batteries and Fuel Cells are considered to produce no TTW NOx and PM emissions.

11 | TTW NOx and PM emissions for inland vessels

Technology	Fuel Type	NOx [kg/kgFuel]	PM [kg/kgFuel]
MeOH ICE Single Fuel	Methanol	0.0106	0.0001
MeOH ICE Dual Fuel*	Methanol, Diesel	0.0106	0.0001
H_2 ICE Single Fuel	H_2	0.0228	0.0004
H2 ICE Dual Fuel*	H2, Diesel	0.0093	0.0002
Stage V engine	Diesel, HVO	0.0077	0.0002
EURO VI engine	Diesel, HVO	0.0077	0.0002
Diesel Unregulated	Diesel	0.0470	0.0017
Diesel CCNR1	Diesel	0.0378	0.0005
Diesel CCNR2	Diesel	0.0335	0.0006
Diesel Unregulated	HVO	0.0423	0.0013
Diesel CCNR1	HVO	0.0340	0.0004
Diesel CCNR2	HVO	0.0301	0.0004
DPF and SCR	Diesel Unregulated	0.0470	0.0017
DPF and SCR	Diesel CCNR1	0.0077	0.0002
DPF and SCR	Diesel CCNR2	0.0077	0.0002
Gas Engine	LNG	0.0106	0.0001

* For the dual fuel engines, the shares are 30% diesel fuel / 70% methanol and 75% diesel fuel / 25% hydrogen.

The following specific fuel oil consumptions were used to convert the values from g/kWh to kg/kg.

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12 | Specific fuel consumptions

Technology	SFOC (g/kWh)
MeOH ICE Single Fuel	474
MeOH ICE Dual Fuel*	36.5 (Diesel), 395.5 (Methanol)
H2 ICE Single Fuel	79
H2 ICE Dual Fuel*	196 (Diesel), 9 (H2)
H2 FC	60
Stage V, EURO VI	199
Stage V, EURO VI (HVO)	195
Gas Engine	170
Old diesel engine (unregulated)	253
Old diesel engine (CCNR1)	246
Old diesel engine (CCNR2)	232

*For the dual fuel engines, the estimated average shares are 30% diesel fuel / 70% methanol and 75% diesel fuel / 25% hydrogen.

4.7 MARPOL Annex VI NOx emission limits

The coastal vessels addressed in SYNERGETICS fall under the IMO ship pollution rules. Those are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78. On 27 September 1997, the MARPOL Convention has been amended by the "1997 Protocol", which includes Annex VI titled "Regulations for the Prevention of Air Pollution from Ships". MARPOL Annex VI sets limits on NOx and SOx emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances from ships of 400 gross tonnage and above engaged in voyages to ports

r offshore terminals under the jurisdiction of states that have ratified Annex VI.

The IMO emission standards are commonly referred to as Tier I, II and III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by Annex VI amendments adopted in 2008, as follows:

- 1997 Protocol (Tier I)—The "1997 Protocol" to MARPOL, which includes Annex VI, becomes effective 12 months after being accepted by 15 States with not less than 50 % of world merchant shipping tonnage. From 18 May 2004, Annex VI was ratified by States with 54.57 % of world merchant shipping tonnage.
- Annex VI entered into force on 19 May 2005. It applies to new engines greater than 130 kW installed on vessels constructed on or after January 1, 2000, or which undergo a major conversion after that date. In anticipation of the Annex VI ratification, most marine engine manufacturers have been building engines compliant with the above standards since 2000.
- 2008 Amendments (Tier II/III)—Annex VI amendments adopted in October 2008 introduced
    - (1) new fuel quality requirements beginning from July 2010,
    - (2) Tier II and III NOx emission standards for new engines, and
    - (3) Tier I NOx requirements for existing pre-2000 engines.

The revised Annex VI entered into force on 1 July 2010. By June 2021, Annex VI was ratified by 100 countries (including the United States), representing 96.65 % of world merchant shipping tonnage. [26]

The NOx emission limits of Regulation 13 of MARPOL Annex VI apply to each marine diesel engine with a power output of more than 130 kW installed on a ship. NOx emission limits are set for diesel engines depending on the engine maximum operating speed. Tier I and Tier II limits are global, while the Tier III standards apply only in NOx Emission Control Areas (NECA).

All factors in the SYNERGETICS tools are used in the unit kg/kg$_{fuel}$. The values shown in Table 13 are converted using a specific fuel consumption of 180 g/kWh. Furthermore, only TIER II and III limits are used as a reference in the tools, as European coastal waters are all SECA zones.

13 | MARPOL Annex VI NOx emission limits

Tier	Date	NOx Limit, kg/kg$_{fuel}$		
		$n < 130$	$130 \le n < 2000$	$n \ge 2000$
Tier I	2000	0.094	$0.250\ n^{-0.2}$	0.054
Tier II	2011	0.080	$0.244\ n^{-0.23}$	0.043
Tier III	2016†	0.019	$0.050\ n^{-0.2}$	0.011

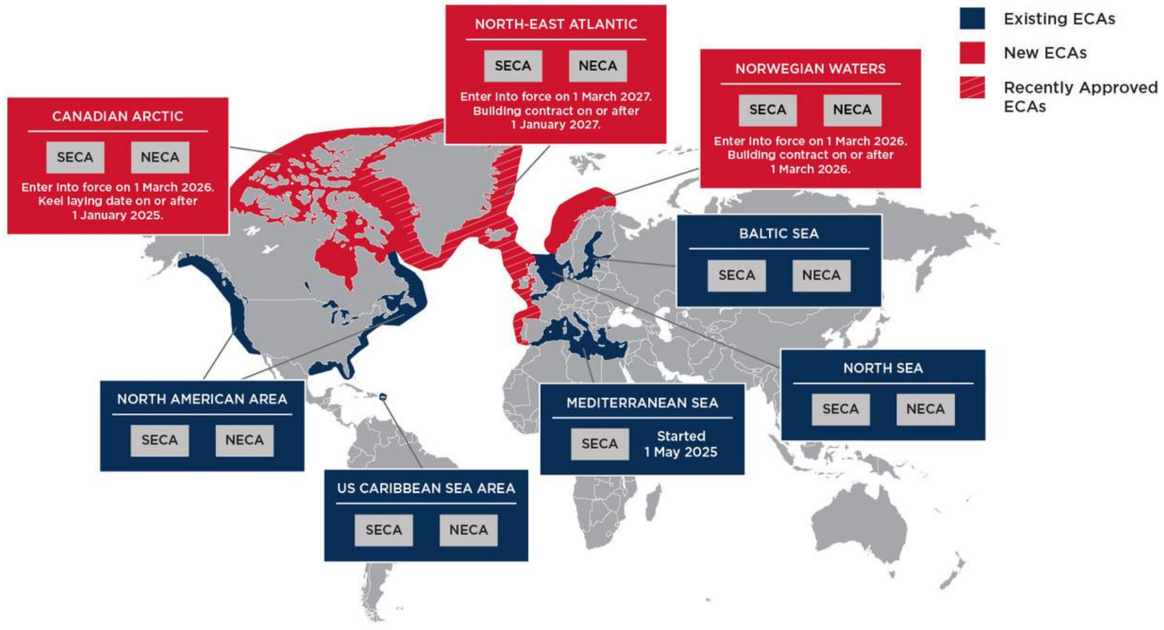
† In NOx Emission Control Areas (Tier II standards apply outside ECAs).

Since 2000, the sulphur content in marine fuels has been progressively reduced. The table below details these changes. While SOx emission limits in Sulphur Emission Control Areas (SECA) are not addressed here, they remain higher than those for inland waterway transport (IWT), though still significantly lower than the limits for deep-sea shipping.

14 | MARPOL Annex VI fuel sulphur limits

Date	Sulfur Limit in Fuel (% m/m)	
	SOx ECA	Global
2000	1.50%	4.50%
07/2010	1.00%	
2012		3.50%
2015	0.10%	
2020		0.50%

The map in figure 13 shows the worldwide NECA and SECA zones.



13 | SECA and NECA areas. Source: ABS

5. Costs

5.1 Fuel

The data for fuel costs in 2025 is derived from current prices, such as spot market values from Rotterdam. A forecast of future costs is based on various models, namely the STEPS, APS and NZE models. Due to the highly complex methodology, please refer to the SPB/EICB "Sub-report on energy prices and scenarios" as part of D5.2 which is expected to become available by May 2026.

15 STEPS Scenario , costs in €/kg

	min						max					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Methanol grey	0.65	0.88	0.95	1.12	1.29	1.45	0.85	1.17	1.23	1.4	1.57	1.74
Methanol green	0.85	0.65	0.4	0.4	0.4	0.4	2.15	1.65	1.02	1.02	1.02	1.02
Electricity	0.25	0.25	0.26	0.27	0.28	0.29	0.32	0.32	0.33	0.34	0.35	0.36
H2 grey	3.5	5.0	7.03	9.06	10.99	13.01	12.0	14.0	16.03	18.06	20.09	22.11
H2 green	5.5	5.5	5.5	5.5	5.5	5.5	21.0	21.0	18.0	14.0	12.0	10.0
Diesel	0.65	1.14	1.31	1.72	2.04	2.36	0.9	1.56	1.72	2.14	2.45	2.77
HVO	1.25	1.4	1.41	1.41	1.4	1.24	1.9	2.08	2.09	2.08	2.07	1.92
LNG	0.7	0.75	1.28	1.87	2.4	2.93	0.85	1.08	1.61	2.19	2.73	3.26
Bio-LNG	1.06	1.0	0.94	0.88	0.82	0.76	3.19	3.01	2.82	2.64	2.45	2.27
pay-per-use	0.35	0.33	0.3	0.28	0.27	0.265	0.5	0.45	0.4	0.37	0.35	0.34

16 APS Scenario , costs in €/kg

	min						max					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Methanol grey	0.65	1.1	1.45	1.79	2.14	2.48	0.85	1.39	1.74	2.08	2.43	2.77
Methanol green	0.85	0.7	0.6	0.5	0.4	0.3	2.15	1.2	1.1	1.0	0.9	0.8
Electricity	0.25	0.25	0.25	0.25	0.25	0.25	0.32	0.32	0.31	0.31	0.3	0.3
H2 grey	3.5	6.65	8.81	10.96	13.01	15.17	12	15.65	17.81	19.96	22.11	24.27
H2 green	5.5	5.5	5.5	5.0	5.0	5.0	21.0	9.0	9.0	8.5	8.5	8.5
Diesel	0.65	1.05	1.61	2.18	2.75	3.32	0.9	1.46	2.03	2.6	3.16	3.73
HVO	1.25	1.36	1.44	1.57	1.66	1.84	1.9	2.03	2.11	2.25	2.33	2.46
LNG	0.7	0.72	1.21	1.75	2.28	2.81	0.85	1.08	1.56	2.09	2.63	3.16
Bio-LNG	1.06	1.0	0.95	0.9	0.85	0.75	3.19	2.95	2.75	2.55	2.35	2.15
pay-per-use	0.35	0.33	0.3	0.28	0.27	0.265	0.5	0.45	0.4	0.37	0.35	0.34

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17 NZE Scenario , costs in €/kg

	min						max					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Methanol grey	0.65	1.42	1.81	2.21	2.55	2.89	0.85	1.71	2.1	2.49	2.84	3.18
Methanol green	0.85	0.7	0.6	0.5	0.4	0.3	2.15	1.2	1.1	1.0	0.9	0.8
Electricity	0.25	0.25	0.25	0.24	0.24	0.24	0.32	0.32	0.3	0.3	0.28	0.28
H2 grey	3.5	6.65	8.81	10.96	13.01	15.17	12	15.65	17.81	19.96	22.11	24.27
H2 green	5.5	6.0	4.5	4.5	4.0	4.0	21.0	9.0	8.5	8.5	8.0	8.0
Diesel	0.65	1.56	2.14	2.72	3.29	3.87	0.9	1.97	2.55	3.13	3.71	4.29
HVO	1.25	1.38	1.47	1.61	1.7	1.79	1.9	2.06	2.14	2.28	2.37	2.46
LNG	0.7	1.12	1.73	2.3	2.82	3.38	1.29	1.56	2.03	2.6	3.17	3.74
Bio-LNG	1.06	1.0	0.95	0.9	0.85	0.75	3.19	2.95	2.75	2.55	2.35	2.15
pay-per-use	0.35	0.33	0.3	0.28	0.27	0.265	0.5	0.45	0.4	0.37	0.35	0.34

The development of the prices for the marine fuels VLSFO and ULSF is assumed to be linked to that of fossil diesel. The 'starting values' for 2025 were determined from the data for the Rotterdam bunker location for the current year.

18 | Cost development assumptions for VLSFO and ULSFO in €/kg

	min						**max**					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
STEPS												
VLSFO	0.34	0.60	0.69	0.90	1.07	1.23	0.45	0.78	0.86	1.07	1.23	1.39
ULSFO	0.43	0.75	0.86	1.12	1.33	1.54	0.56	0.98	1.08	1.34	1.53	1.73
APS												
VLSFO	0.34	0.55	0.84	1.14	1.44	1.74	0.45	0.73	1.02	1.30	1.58	1.87
ULSFO	0.43	0.69	1.05	1.43	1.80	2.17	0.56	0.91	1.27	1.63	1.98	2.33
NZE												
VLSFO	0.34	0.82	1.12	1.42	1.72	2.02	0.45	0.99	1.28	1.57	1.86	2.15
ULSFO	0.43	1.02	1.40	1.78	2.15	2.53	0.56	1.23	1.59	1.96	2.32	2.68

5.2 Technologies

In order to compile the costs for the technologies, there was close communication with many manufacturers of the systems. The price development predicted in the CCNR study [27], namely a slight reduction that would have been expected with the increasing spread of the technologies, did not occur due to a variety of factors: the spread did not take off as quickly as expected, and costs increased due to crises and wars. The cost assumptions for unregulated, CCNR1 and CCNR2 engines are used in the tool to calculate additional costs for retrofits. They are not items to choose as retrofit option. For Dual fuel installations, the fixed values assumed for the share of energy are 30% diesel fuel / 70% methanol and 75% diesel fuel / 25% hydrogen. The current cost assumptions for the technologies are:

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19 | Equipment Cost for inland vessels

Equipment Cost	min	max
DPF&SCR,	82	115
Battery [€/kWh]	300	650
Electric engine [€/kW]	150	250
MEOH ICE [€/kW]	500	600
MEOH ICE Dual Fuel [€/kW]	500	600
H2 ICE [€/kW]	600	900
H2 ICE Dual Fuel [€/kW]	600	900
Stage V+, Euro VI ICEs [€/kW]	350	590
MEOH FC with reformer [€/kW]	2000	3000
H2 Fuel Cell [€/kW]	1500	2500
H2 Tank (350 and 500 bar) [€/kg]	500	800
Unregulated, CCNR1 and CCNR2 ICEs	150	200
Methane ICE	450	450

20 | Installation and integration cost for inland vessels

Installation and integration cost	min [€/kW]	max [€/kW]
ICE high-speed	160	240
Methanol system	600	800
Hydrogen system	900	1100
Electric system for FC	370	450
Battery electric system (including electric switchboards, converters, etc.)	800	1200
DPF&SCR, engine < 300kW	70	90
DPF&SCR, engine > 300kW	50	70

LNG systems are not suitable for all types of inland waterway vessels. In addition, they have a different cost structure in the database with a base price for installation. The assumptions are therefore listed separately in the following table. To date, no European LNG projects involving cabin vessels or large push boats have been identified. However, it is assumed that retrofitting these two types of vessels would be very costly; therefore, the cost assumptions here are disproportionately high.

21 | LNG system and installation costs for inland vessels

	Large cabin vessels	Push boats (500 ≤ P < 2000 kW)	Push boats (P ≥ 2000 kW)	Motor vessels dry cargo (L ≥ 110 m)	Motor vessels liquid cargo (L ≥ 110 m)	Coupled convoys
LNG-system price min	2,000,000	1,900,000	3,100,000	1,800,000	1,800,000	2,300,000
LNG-system price max	2,300,000	2,100,000	3,300,000	2,000,000	2,200,000	2,500,000
Installation Gas engine	50,000	50,000	50,000	50,000	50,000	50,000

The systems are calculated using the following items:

22 | Cost items per system inland

System	Equipment	Installation and Integration
DPF&SCR	DPF&SCR	DPF&SCR
Battery-electric vessels	Electric engine, Batteries	Battery-electric system
MEOH ICE SF	MEOH ICE SF	Methanol System, Installation ICE high-speed
MEOH ICE DF	MEOH ICE DF, DPF&SCR	Methanol System, Installation ICE high-speed
H2 ICE SF	H2 ICE SF	Hydrogen System, Installation ICE high-speed
H2 ICE DF	H2 ICE DF, DPF&SCR	Hydrogen System, Installation ICE high-speed
Stage V+, Euro VI	Stage V+, Euro VI [€/kW]	ICE with SCR and DPF (Stage V)
H2 FC	H2 Fuel Cell, Electric Engine, Battery, Tank	Hydrogen System, Electric system for FC,
MeOH FC	MeOH Fuel Cell, Electric Engine, Battery,	Methanol System, Electric system for FC,
Liquified (Bio)Methane (also known as LNG /Bio-LNG)	Methane gas ICE	ICE high-speed, cryogenic fuel storage system

23 | Equipment Cost for coastal vessels

Equipment Cost	min	max
DPF&SCR [€/kW]	150	300
Battery [€/kWh]	300	650
Electric engine [€/kW]	150	250
MEOH ICE [€/kW]	500	600
MEOH ICE Dual Fuel [€/kW]	500	600
H2 ICE [€/kW]	600	900
H2 ICE Dual Fuel [€/kW]	600	900
Stage V+, Euro VI ICEs [€/kW]	350	590
Medium speed Tier II ICE, excl. SCR for Tier III **[28]**, **[29]**	244	350
Medium speed Tier III ICE **[28]**, **[29]**	344	450
MEOH FC with reformer [€/kW]	2000	3000
H2 Fuel Cell [€/kW]	1500	2500
H2 Tank (350 and 500 bar) [€/kg]	500	800
Retrofit kit for methane gas ICE	650	750

24 | Installation and integration cost for coastal vessels

Installation and integration cost	min [€/kW]	max [€/kW]
ICE high-speed	200	300
Methanol system	700	900
Hydrogen system	1000	1200
Electric system for FC	470	550
Battery electric system (including electric switchboards, converters, etc.)	800	1200

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DPF&SCR, engine < 300kW	70	90
DPF&SCR, engine > 300kW	50	70
Medium speed Tier II, Tier III ICE	400	500
Cryogenic methane system below 5MW	700	900
Cryogenic methane system above 5MW	500	600

The systems are calculated using the following items:

25 | Cost items per system coastal

System	Equipment	Installation and Integration
DPF&SCR	DPF&SCR	DPF&SCR
Battery-electric vessels	Electric engine, Batteries	Battery-electric system
MEOH ICE SF	MEOH ICE SF	Methanol System, Installation cost for ICE (highspeed or medium speed)
MEOH ICE DF	MEOH ICE SF, DPF&SCR	Methanol System, Installation cost for ICE (highspeed or medium speed)
H2 ICE SF	H2 ICE SF	Hydrogen System, Installation cost for ICE (highspeed or medium speed)
H2 ICE DF	H2 ICE DF , DPF&SCR	Hydrogen System, Installation cost for ICE (highspeed or medium speed)
Stage V+, Euro VI ICEs	Stage V+, Euro VI [€/kW]	ICE with SCR and DPF (Stage V)
Medium speed Tier II ICE	Medium speed Tier II ICE, excl. SCR for Tier III	Medium speed Tier II, Tier III ICE
Medium speed Tier III ICE	Medium speed Tier III ICE	Medium speed Tier II, Tier III ICE
H2 FC	H2 Fuel Cell, Electric Engine, Battery, Tank	Hydrogen System, Electric system for FC
MeOH FC	MeOH Fuel Cell, Electric Engine, Battery	Methanol System, Electric system for FC
Methane ICE	Retrofit kit for methane ICE	Cryogenic fuel system below/above 5MW

Inflation is not included in the anticipated price development until 2050. It could even be between 2% and 3%. However, this assumption is very uncertain. The price development of batteries can be extrapolated somewhat better based on past price declines and could follow the trend shown in the table [30], [31], [32], [33], [34], [35], [36], [37]. However, this is also uncertain. Therefore, the development of costs is modelled with significantly more moderate developments:

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26 | Current price development factors. For most technologies, there are no min and max price scenario developments.

Systems	Factors [%]				
	2030	2035	2040	2045	2050
Installation and Integration Retrofit System	1.00	0.95	0.80	0.75	0.70
MEOH ICE (Single and Dual-Fuel)	1.00	0.95	0.80	0.75	0.70
Battery [€/kWh] min	0.70	0.49	0.34	0.24	0.17
Battery [€/kWh] max	0.80	0.64	0.51	0.41	0.33
Electric engine	1.00	0.95	0.80	0.75	0.70
H2-Tank	1.00	0.95	0.80	0.75	0.70
H2 ICE (Single and Dual-Fuel)	1.00	0.95	0.80	0.75	0.70
H2 Fuel Cell	1.00	0.95	0.80	0.75	0.70
Methanol Fuel Cell with reformer	1.00	0.95	0.80	0.75	0.70
Stage V+, Euro VI ICEs [€/kW]	1.00	0.95	0.80	0.75	0.70
Medium Speed IMO Tier II ICE	1.00	0.95	0.80	0.75	0.70
Medium Speed IMO Tier III ICE	1.00	0.95	0.80	0.75	0.70
DPF and SCR cost per kW installed	1.00	0.95	0.80	0.75	0.70
Methane engine/cryogenic retrofit kit	1.00	0.95	0.80	0.75	0.70
Hydrodynamic measures equipment cost	1.00	0.95	0.80	0.75	0.70

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5.3 Losses due to cargo space loss or bunker times

As mentioned in deliverable D4.4 of SYNERGETICS chapter 2.4.4.1 there will be a difference in bunker time for the different fuel types. In the project NEEDS deliverable D3.1 extensive research has been done to determine the different bunker speeds for the alternative fuel types, which are used in the SYNERGETICS database. In the database differentiation has been made between the swapping of containers, for batteries and hydrogen, and direct bunkering for all fuel types, as shown in table 25.

As shown in table 25 there are two different bunker speed values are included for electricity. The slow charging value represents the charging speed that is currently used for shore power. However, when calculating the amount of time, most vessels need to charge their batteries with this speed and there is not enough time in a year to do so. This charging speed is still suitable for charging small batteries or powering hotel functions, so that is the way it is included in the database. For EVs, charging stations of 1000 kW exist, which is currently the maximum charging speed available for logistic vehicles. There are ambitions with the new SAE MCS standard to install charging points with up to 3.75 MW[38]. These charging speeds offer a more realistic bunker time for larger batteries and is therefore used in the WP5 as the charging speed for battery electric vessels.

27 | Fuel supply speeds [39]

Fuel type	Swapping speed	Bunker speed
Methanol green	-	550 L/min
Methanol grey	-	550 L/min
Electricity	3000 kWh per 30 min	188 kW (slow charging) 1000 kW (fast charging)
H2 grey	400 kg per 30 min	3.6 kg/min
H2 green	400 kg per 30 min	3.6 kg/min
Diesel	-	550 L/min
HVO	-	550 L/min
LNG	-	250 kg/min

The bunker time is not only depended on the bunker speed but also on how much energy input is needed to reach the same energy input compared to diesel. To calculate how much energy input is needed, the ratio between the energy density (the LHV is shown in chapter 4.2 and 4.3) is used and in the case of fuels with a volumetric bunker speed also the density ratio is used, where the densities are shown in table 27.

The bunker time is not the only parameter that is affected by the difference in fuel properties of the alternative fuel. Often these differences result in an increase of the weight or volume of the energy storage systems for the alternative fuels compared to diesel. Although, for example, even though hydrogen has a higher gravimetric energy content than diesel, the volumetric energy density is much lower. Additionally, the tanks in which the high pressurised hydrogen gas is stored are very bulky, while diesel tanks are relatively narrow and do not take up a lot of extra space. So, for the actual amount of space required on board for the fuel system not only the fuel input should be taken into account but also the fuel tank itself. As part of the NEEDS project MARIN calculated how much MJ actually can be stored per volumetric and weight unit which are shown in table 27. By multiplying these values with the energy input the actual size of the fuel storage system can be determined.

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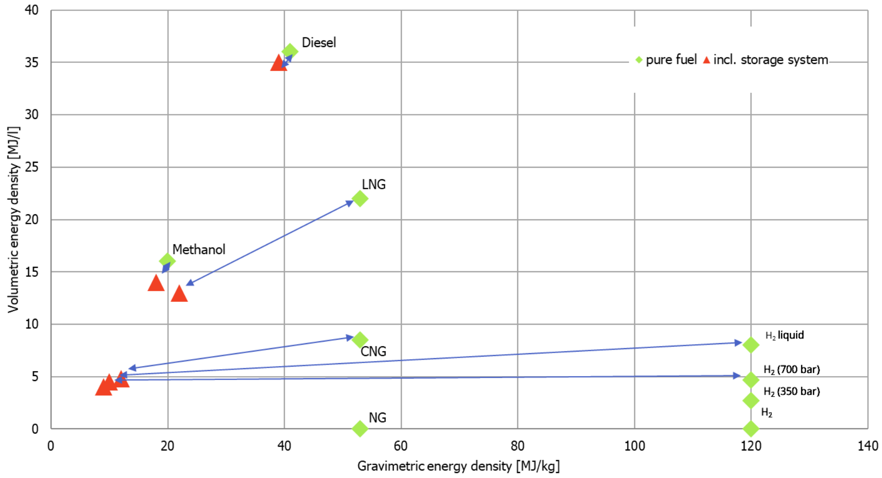
28 | Fuel properties including tank system [39]

Fuel type	**Density [kg/m³]**	**Energy Content [MJ/L]**	**Energy Content [MJ/kg]**
Methanol green	791 [40]	13.6	14.5
Methanol grey	791 [40]	13.6	14.5
Electricity	-	0.22	0.36
H2 grey	31.2 [40]	3.92	1.4
H2 green	31.2 [40]	3.92	1.4
Diesel	832 [6]	33.2	29.65
HVO	770 [6]	31.06	31.9
LNG	420 [41]	13.17	28.37

Regarding the energy densities with tank system, there are also quite similar values from the CCNR studies [42] available:



14 | Volumetric energy density over gravimetric energy density for different fuels and storage conditions and at ambient pressure [42].

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5.4 Other costs

Other costs are maintenance, downtime days opportunity costs for the installation of the new systems, financing costs as well as a set of vessel economics default values per vessel type. The maintenance cost assumptions can be found in table 29. The financing costs are set to an interest rate of 6% and a depreciation time of 20 years.

29 | Maintenance

Maintenance	[%]
MeOH System	7
Battery System	7
H2 ICE	7
Fuel Cell	10
New Diesel ICE	10
DPF and SCR	10
Hydrodynamic measures	10

The downtime days for the calculation are currently hard to estimate since there is little experience with most of the systems in the sector: a few dozens of alternative systems vs. thousands of conventional diesel systems. Therefore, the numbers are order of magnitude estimates that could easily have an uncertainty of factor two. Also, the option to install a new technology along with a whole aft-ship replacement is not considered in the assumptions.

30 | Estimated downtime days for installation at shipyard

Technology	Estimated downtime days
Conventional diesel engine ICE	20
H2 and methanol ICE	40
Fuel cells and full electric battery systems	60
Cryogenic methane ICE system	28

The time loss is being monetarised into figures in euros which can be taken into account in the cost calculations for the different technological solutions. Therefore, cost data is required. The default cost values regarding the vessel economics are mainly based on Dutch cost values. In 2023 a report was developed by Panteia and published by the Dutch Ministry of Infrastructure and Water management. In this report their research to the cost values for the Dutch fleet sorted by vessel type over the period 2015 and 2021 was outlined [43]. This detailed study was used to obtain the personnel cost default values.

In the European project PROMINENT also research has been done to obtain cost default values. From this project the yearly insurance cost where used. There are more fleet families included in SYNERGETICS than there were in PROMINENT. The remaining cost default values of the fleet families that are not in PROMINENT, were estimated based on a fleet family with somewhat similar properties. Then by summing all the cost parameters in PROMINENT and using an estimated profit margin of 3 % the yearly profit default values where estimated.

In 2019 the Dutch waterway authority Rijkswaterstaat made a cost model using cost data from 2017 [44]. This model included the depreciation cost and interest cost which were summed to obtain the capital cost of the vessel. This model also distinguishes between different exploitation types and sailing route. As an assumption an average exploitation type was selected and the Rhine was used as sailing route.

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The model made by Rijkswaterstaat included all cost for a vessel owner. By summing these values together with the obtained profit, the yearly revenue default values where determined.

31 | Default cost values regarding the vessel economics, including the yearly revenue, the yearly profit, the yearly total capital cost of the vessel, the personnel cost and the yearly insurance cost.

Vessel type	Yearly profit	Yearly personnel costs	Yearly insurance costs	Yearly revenue	Yearly capital cost of vessel
Large cabin vessels	210000	1850000	210000	3360000	837000
Push boats (P < 500 kW)	9000	130000	10000	240000	14000
Push boats (500 ≤ P < 2000 kW)	27000	400000	40000	525000	54000
Push boats (P ≥ 2000 kW)	173000	900000	140000	2320000	470000
Motor vessels dry cargo (L ≥ 110 m)	47000	600000	95000	1110000	310000
Motor vessels liquid cargo (L ≥ 110 m)	65000	610000	140000	1560000	600000
Motor vessels dry cargo (80 m ≤ L < 110 m)	14000	170000	30000	366000	62000
Motor vessels liquid cargo (80 m ≤ L < 110 m)	22000	185000	60000	564000	192000
Motor vessels (L < 80 m)	9000	125000	12000	200000	19000
Coupled convoys	53000	620000	90000	1170000	243000
Ferries	32500	325000	65000	575000	195000
Day trip and small cabin vessels	16000	165000	20000	257000	39000

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6. Conclusion

The SYNERGETICS database represents a significant step forward in providing a transparent, centralised, and sustainable resource for evaluating greening options in inland and coastal shipping. It is designed for easy maintenance and future updating to avoid the experience from previous projects, where tools were outdated and/or disappeared shortly after the projects finished.

By compiling and comparing diverse data sources, this report does not only highlight the current challenges in standardising emission calculations but also underlines the importance of flexibility and adaptability in a rapidly evolving technological landscape. Therefore, not only data used for this report and the SYNERGETICS tool today but also strategies for future updates were developed. For the costs, future projects and activities of the SYNERGETICS partners EICB/SPB and DST will feed into revisions of the data and calculation methodology. For the Well-to-Tank emission factors, it was decided to implement future editions of the well-documented EcoTransIT World model.

While the assumptions and data presented here are the result of efforts by the SYNERGETICS consortium, the unique nature of each vessel and the current early stage of many onboard technologies underscore the need for continuous review and updating. As such, the database and linked tools like the Decision Support Tool for Vessel Owners (see SYNERGETICS Deliverable D5.1) are designed to evolve alongside advancements in technology, regulation, and market conditions, ensuring access to reliable, up-to-date information.

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