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Needs

Dynamic Techno - Economical Scenario
Simulation Model for Sustainable
Waterborne Activities and Transport

D3.3 Scenarios for the inland region

Document information	
Short description	Building upon D3.1 and D3.2 and exploiting information from other key sources, this deliverable describes a number of sustainable fuel development scenarios which were analysed for the inland region. The simulation model was applied for these different scenarios with different assumptions on technology take-ups, fuel / energy prices and regulatory regimes. The main aim here was to develop and justify a stable simulation model that can be used for other scenarios and regions after the project.
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Executive summary

This deliverable provides the results of a set of NEEDS scenarios for the development of the fuel and energy mix between 2020 and 2050 for the execution of transport operations on 25 representative inland waterway journeys in the Rhine area. In total eight different scenarios have been developed and applied with the NEEDS model for the Rhine region. The model results show the differences between the scenarios and the sensitivity for cost input parameters and settings of the model.

By means of these scenarios, the boundary conditions and constraints across the different scenarios have been diversified properly. The results give insight on the sensitivity of input parameters. This concerns the assumptions on energy prices and required investments. Moreover, different assumptions were made for the decision making process of the vessel owner/operators at the occasion of a retrofit of a vessel regarding the choice for the energy carrier and technology. The assessment highlights critical parameters where priority should be given from the side of policy making.

The scenario runs with the NEEDS model show that the current behaviour of vessel owners/operators which choose for the technology with the lowest costs will result in a continuation of dominance of fossil diesel to be used. Such behaviour will not result in significant reductions of the CO2e emissions by inland waterway transport. This situation became obvious in the BAU scenario. However, this also was the result of two other scenarios using more favourable price assumptions towards transition to energy carriers and technologies with a lower carbon intensity. The price settings for energy costs and investment costs for these two scenarios were derived from the CCNR roadmap on energy transition for inland waterway transport. Scenario 2 was based on the price settings for the conservative pathway while scenario 3 was based on price settings for the innovative pathway.

The NEEDS model scenario results therefore lead to the conclusion that that much more interventions are needed to achieve reductions of CO2e emissions. The model indicates that without interventions, there is no return on investment for the vessel owner/operators to select more expensive energy carriers and technologies. In order to simulate such change in behaviour, the NEEDS model assumed revised conservative scenario (scenario 4) and a revised innovative scenario (scenario 5) in which a strong increase was modelled of the share of vessel owner/operators making socially and environmentally responsible choices. For the these revised scenarios (4 and 5), it is assumed that the technology/energy with the highest CO2 reduction per euro will be selected by a quickly growing share of the vessel owner/operators. A steady development was assumed towards a share of environmental responsible behaviour by 90% of the vessel owner/operators by the year 2049. With these settings the results indeed showed that CCNR emission reduction goals can be reached.
The scenario results for the revised conservative scenario (scenario 4) pointed towards high shares in using HVO fuel to replace the fossil diesel. For the revised innovative scenario (scenario 5), the usage of green methanol, renewable diesel and electricity charging become popular solutions to reach CO2e reduction.

Remarkably is that the uptake of compressed hydrogen as energy carrier using fuel cells didn’t appear significantly in these revised scenarios. The same was concluded for the use of full battery electric propulsion with swappable battery containers. This is contradictory to governmental policies and research and developments efforts to promote, develop and deploy these type of zero-emission tailpipe solutions with fully electrified vessels.

Therefore, in order to achieve a better understanding on the impacts and requirements of moving towards full electrified zero-emission tailpipe solutions, three more scenarios were developed. One scenario focussed solely on modelling the uptake and impact of battery electric solutions with swappable battery containers (scenario 6) while two other scenarios (7 and 8) focussed on the uptake of compressed hydrogen as energy and fuel cell technology using either swappable hydrogen tank containers (‘tanktainers’) or using fixed storage tanks on board and bunkering compressed hydrogen from shore.

In these three additional scenarios the assumed behaviour of vessel owners was changed. The list of available technologies at the occasion of a retrofit was therefore narrowed down and limited to:

- battery-electric with swappable battery containers (scenario 6)
- fuel cell conversion using compressed hydrogen from swappable tank containers (scenario 7)
- fuel cell conversion using compressed hydrogen from either swappable tank containers or from fixed tanks on board (scenario 8)

By means of limiting the available technologies and energy carriers at the occasion of a retrofit, a force was simulated for the transition to these CO2e zero emission tailpipe energy carriers.

These scenario runs and the analyses of the results points provided new conclusions and insights. Scenario 6 points towards a serious potential for battery electric sailing using swappable containers. For battery-electric sailing swappable containers with a pay-per-use business scheme, there are not that much additional investment and operational costs for the vessel owner/operator while the solution achieves full zero-emission performance as well as a strong energy saving.
From scenarios 7 and 8 it was learned that a similar zero-emission tailpipe performance can be reached with hydrogen solutions, but at much higher costs compared to any other alternative. Furthermore, the scenarios 7 and 8 for compressed hydrogen as energy carrier showed higher energy demand compared to the energy demand when using battery containers (scenario 6). The high levels of capital expenditure as well as high operational costs for solutions using compressed hydrogen result in concerns about the economic feasibility of this technology in comparison with other options.

This case study of the NEEDS model for the Rhine area also was used to test how the model performs and what further developments can be recommended. The work in NEEDS for the inland waterway Rhine region showed that the model is already providing useful results and insights. However, also some conclusions and recommendations were made on limitations and further developments to further increase the added value of the NEEDS model.

The main limitation of the current model is that the model does not take into account the involved costs for deploying additional vessels which are needed to compensate for the productivity loss which occurs with some energy carriers and technologies. For example, this limitation resulted in unrealistic outcomes for scenario 5, as it showed significant use of battery electricity charging from grid which is cost effective based on the required capital expenditures to retrofit the vessel and energy costs. However, this would require much more vessels and crew to be deployed due to the relatively much time required to recharge batteries of vessels in contrast to other solutions. The concept of swappable battery containers however, would allow much shorter time needed to take sufficient energy on board, but has higher direct costs and was therefore not selected by vessel owner/operators in the model run for scenario 5. The observed limitation was also one of the reasons to develop a separate scenario focussing on the solution using swappable battery containers (scenario 6).

Another recommendation for further development aims to make the retrofitting logic more advanced by taking into account the actual running hours of the drivetrain and its characteristic lifetime. For example fuel cell systems have a much lower lifetime in running hours compared to internal combustion engines. In the current version the model assumes a fixed 10 year lifetime for all technologies, which is not that realistic.

Furthermore, currently the model is fed with a set of 25 representative journeys for the Rhine area. This gives a good impression on the sensitivities and direction of evolution, but doesn’t allow a straightforward and reliable extrapolation towards the full fleet on the Rhine and the energy bunkering demand in terms of the geography in Europe. It is also recommended therefore to expand the journeys, to include more vessel types and to cover also other corridors on the Trans European Transport Network (TEN-T) in Europe such as for example the Danube river and the domestic markets in Germany, Belgium, France and The Netherlands.

With improvements the model can become even more valuable in terms of providing support for making policy decisions and investment decisions in clean energy infrastructure along the TEN-T waterway and in ports.

List of abbreviations

BAU	Business As Usual
C3L/B	Coupled Convoy with 3 barges in width or length
CAPEX	Capital Expenditures
CCNR	Central Commission for the Navigation of the Rhine
CH3OH	Methanol
CH4	Methane
CO2	Carbon Dioxide (a greenhouse gas)
CO2e	CO2 equivalent emissions (also known as CO2eq)
CSRD	Corporate Sustainability Reporting Directive
DPF	Diesel Particulate Filter
ETS	Emission Trading Scheme (setting a ceiling on CO2e emissions)
FC	Fuel Cell
H2	hydrogen
HVO	Hydrotreated Vegetable Oil
ICE	Internal combustion engine
IWT	Inland Waterway Transport
Kw	Kilowatt
kWh	Kilowatt-hour
LBM	Liquid biomethane
LNG	Liquified Natural Gas
LOHC	Liquid organic hydrogen carriers
MeOH	Methanol
MTS	Self propelled tanker vessel (motortankschip)
MVS	Self propelled freight vessel (motorvrachtschip)
MW	Megawatt
NEEDS	NEw sustainablE fuel Deployment Scenarios for the European waterborne community:
NOx	Nitrogen Oxides
OPEX	Operational Expenditures
PM	Particulate Matter
PushB4	Push convoy existing of a pusher and 4 freight barges
RED	Renewable Energy Directive
Ren Diesel	Renewable Diesel
Ren Methanol	Renewable Methanol
SCR	Selective Catalyst Reduction system
SPB	Stichting Projecten Binnenvaart
TCO	Total cost of ownership
TEN-T	Trans European Network for Transport
TRL	Technology readiness level
TTW	Tank-to-Wake
WP	Work Package
WTT	Well-to-Tank
WTW	Well-to-Wake

1. Introduction

This deliverable provides the description for a set of realistic sustainable fuel development scenarios which were analysed for the Rhine region. In total eight different scenarios have been applied with the NEEDS model for the Rhine region.

By means of these scenarios the boundary conditions and constraints across the different scenarios have been diversified properly. It also shows the sensitivity for input parameters such as the energy prices. This assessment highlights critical parameters where priority should be given.

1.1 Approach and methodology

The methodology and approach build on the macro model as developed in WP1 Deliverable 2 and the data sets for inland region developed in WP3 D9.

Therefore, without extensively repeating the work which was already done, in terms of the basis for the approach and methodology we refer to the following two NEEDS deliverables:

- Deliverable number 2 (D1.2) titled "*Overview of the final version of the generic model for application use*"
- Deliverable number 7 (D3.1) titled "*Regional inland application of the model*"

These two deliverables present the simulation logic and the data sets applied, such as the decision making on retrofitting, the vessel types and the journeys which have been modelled, the settings on the required time for bunkering and charging as well as prices of hardware and energy prices. This serves as basis for modelling the energy transition for selected representative journeys for the Rhine inland area.

However, as model results showed, the logic of the model and model settings were developed over time and iteratively adapted to get emission reduction results which match policy objectives and also to better capture the decision logic in the model, as explained below.

In this respect, the sensitivity analyses showed that the first scenario runs with the model acted rationally based on the economics (aiming on the lowest total cost of ownership) of different energy types and technical solutions. Therefore, also additional criteria were taken into account for the decision making and an "acceptance multiplier" was introduced based on the Technology Readiness Level as well as the Social Acceptance levels to express the environmental performance in the decision making. However, even after including these factors, still the model showed that the economics have quite a dominant role. Consequently, an additional scenario set (scenarios 4 and 5 as presented in chapter 3) were made by assuming a much higher level of 'early adopters' to select the more environmentally friendly energy and technology types, based on the best ratio between CO2e savings and the costs in euros.

In the end therefore, the following set of eight scenarios and model runs have been applied for which the results are presented in chapter 3 of this report:

1. BAU scenario
2. Conservative pathway scenario
3. Innovative pathway scenario
4. Conservative early adopter scenario
5. Innovative early adopter scenario
6. Full battery-electric scenario - swapping
7. Full hydrogen FC-electric swapping scenario
8. Full hydrogen FC-electric bunkering and swapping scenario

The work benefitted from an iterative approach which started by running and validating the first scenarios. However, the validated results for the conservative and innovative pathway scenarios clearly showed that there was not much response from the modelled ship owner/operators behaviour to drastically reduce emissions. Also, with adapted prices for these scenarios and by including acceptance multipliers, the sensitivity for the prices of hardware and energy turned out to be very high. This also led to the conclusion that energy transition needs to be forced by more significant interventions. Intervention measures one can think of are for example: introduction and increasing tax on fossil fuels, introduction of Emission Trading Scheme (ETS) with ceiling levels of the CO2e emission by IWT, forcing a mandatory high share of renewable fuel in the fuel mix for IWT, providing substantial grants to compensate for much higher capital costs and introducing obligations and rewards to clients of IWT (shippers) to choose for environmentally sound solutions.

Therefore, the ‘early adopter’ scenarios we added to arrive at scenarios to reach the emission reduction goals (aiming for 90% reduction of CO2e emissions by 2050) and boost the uptake of renewable energy. It can be remarked that in the situation of today, such strongly increased early adopter behaviour is not realistic terms of the social or economic modelling with the current market setting and legal framework. Much interventions and change of behaviour will thus be needed to arrive the emission reduction goals. Some impact may be expected from the implementation of the Fit for 55 package in this respect, depending on the further implementation. For example a full implementation of Corporate Sustainability Reporting Directive may trigger much more awareness and pressure to reduce emissions. Furthermore, also interventions such as ETS schemes in IWT, mandatory shares of renewable fuels in IWT (implementation of Renewable Energy Directive with specific targets for energy supply to IWT) or possibly even the banning of polluting vessels may be legal measures which may be needed and considered to achieve emission goals. These measures could be part of the scenario background for scenarios 4 and 5.
Moreover, in order to get further insight on the consequences of full zero-emission tailpipe technologies, separate scenarios were added on the application of full battery electric sailing and full hydrogen fuel cell. Here also the ‘swapping hydrogen container’ method was compared with the method of ‘bunkering fixed hydrogen tank on board’ which led to insights on the pros and cons of these applications.

The next and final step was the comparison of the scenario outputs and the conclusions on the gained emission reductions, the additional costs (CAPEX and OPEX) and the impact on transport capacity and bunkering/recharging.

Moreover, the comparisons made it possible to make conclusions on the policy interventions and possible requirements for the energy infrastructure along waterways and in ports.

1.2 Structure of the report

In the next chapter 2 the general assumptions are presented with a focus on the additional and modified elements compared to the model description as presented in WP1 D2 (D1.2) and the data sets in WP3 D7 (D3.1).

In chapter 3 the scenario results are presented and in chapter 4 the scenarios are compared. The report ends with the conclusions and recommendations in chapter 5.

2. General assumptions

As mentioned, the assumptions build on the work presented in Deliverable number 2 (D1.2) titled “Overview of the final version of the generic model for application use” and Deliverable number 7 (D3.1) titled “Regional inland application of the model”.

The assumptions will be summarized in this chapter and modifications made in Task 3.3 which deviate from Deliverables number 2 and 7 will be highlighted.

2.1 Considered fleet and transport network

The considered fleet and transport network does not deviate compared to D2 and D7. Therefore, the following summary can be provided:

Table 1 Rhine traffic database (source NEEDS D2, table 2)

					Speed between ports [kn]				
Ship Type	**Port A**	**Port B**	**#ships**	**Empty outbound**	**A-B**	**B-A**	**Port Waiting time [h]**	**Port cons. [kWh/day]**	**Operational hours / year**
PushB4	Rotterdam	Duisburg	9	TRUE	5.17	9.55	8	1	8064
C3L/B	Rotterdam	Antwerp	40	FALSE	5.40	5.40	48	1	8064
MTS 135m	Rotterdam	Karlsruhe	22	TRUE	5.65	6.03	10	1	7898
C3L/B	Amsterdam	Karlsruhe	17	TRUE	5.34	5.61	17	1	8064
C3L/B	Rotterdam	Basel	9	FALSE	5.32	5.35	64	1	8064
MVS 110m	Antwerp	Thionville	16	FALSE	4.79	4.81	9	1	4318
C3L/B	Amsterdam	Antwerp	9	FALSE	5.84	5.83	36	1	8064
C3L/B	Rotterdam	Krotzenburg	5	FALSE	5.15	5.13	27	1	8064
MTS 135m	Amsterdam	Rotterdam	6	TRUE	5.40	7.20	6	1	7898
MVS 135m	Antwerp	Mainz	7	FALSE	5.15	5.15	36	1	7898
MVS 110m	Breisach	Cuijk	12	FALSE	5.32	5.32	15	1	4318
C3L/B	Antwerp	Duisburg	4	FALSE	5.57	5.57	36	1	8064
MVS 110m	Rotterdam	Duisburg	15	FALSE	5.62	5.62	26	1	4318
MTS 86m	Rotterdam	Ludwigshafen	16	FALSE	5.54	5.54	8	1	3971
MTS 110m	Rotterdam	Kampen	4	FALSE	7.11	7.11	9	1	4318
MVS 110m	Rotterdam	Strassbourg	4	FALSE	5.47	5.47	15	1	4318
MVS 105m	Amsterdam	Heilbronn	4	FALSE	5.16	5.16	12	1	4013
MVS 110m	Duisburg	Antwerp	3	FALSE	5.67	5.67	12	1	4318
MVS 105m	Rotterdam	Alphen a/d Rijn	10	FALSE	5.11	5.11	18	1	4013
MTS 110m	Terneuzen	Rotterdam	3	FALSE	5.47	5.47	9	1	4318
MVS 67m	Wesel	Enkhuizen	1	FALSE	5.47	5.47	6	1	3778
MVS 86m	Rotterdam	Herne	2	FALSE	5.15	5.15	9	1	3971
MVS 110m	Dusseldorf	Antwerp	1	FALSE	5.63	5.63	12	1	4318
MVS 110m	Antwerp	Gent	2	FALSE	5.58	5.58	9	1	4318
MVS 86m	Rotterdam	Duisburg	1	FALSE	5.65	5.65	12	1	3971

2.2 Considered technologies and forms of energy

The considered technologies and forms of energy used on board of vessels are a key part of setting the scope of this deliverable. Based on the sustainable power database from MARIN[1] combined with the CCNR Roadmap[2], and two deliverables of the CCNR studies[3][4], a total set of 11 energy options were selected to be used in the model.

In its sustainable power database, MARIN has an overview of over 60 possible solutions for reducing the carbon footprint of shipping. SPB and several other partners have done extensive research on which technologies have the most potential to work in the IWT sector for the CCNR (see footnotes 1-4). A cross-check of these two sources has led to the selection of 11 energy options for the simulation runs and mainly the technologies and energy carriers as presented in the CCNR studies were used because they have been validated extensively already in previous project. This was also the result of a discussion with external experts and stakeholders which took place in autumn 2022 to develop the NEEDS Deliverable D3.1. These 11 options are presented in this sub-chapter. Of course, in the further development of the NEEDS model, other or emerging solutions can be taken into account as well, such as for example solutions which today have a low technology readiness level, for example LOHC (Liquid organic hydrogen carriers) and new types of batteries.

2.2.1 Considered Diesel (drop-in) options

Fossil Diesel

Fossil Diesel is the first energy carrier in the list. It is currently used by a very large majority of IWT vessels, both for propulsion and for usage in auxiliary combustion engines. IWT Diesel (EN590) is an ultra-low sulphur Diesel. Its availability is widespread and bunkering is done under known criteria and poses little challenges for IWT crew. Additionally, Diesel has a high energy intensity and is easy to store on board and can be bunkered quickly. It therefore offers a very large range of operation, so that vessels do not have to bunker very often and the bunkering time is rather limited. Bunkering Diesel fuel can even take place while the vessel is sailing and therefore doesn't have to cause any delay in the transport operations.

Diesel is the standard fuel for IWT and most cheaply available in big seaports like Rotterdam, Amsterdam and Antwerp. Since EN590 Diesel for IWT is (still) free of fuel taxation[5], it has an additional advantage over other energy carriers in inland waterway transport. However, there are attempts by the European Commission to introduce a mandatory minimum tax on fuels for IWT as well with their Fit for 55 proposal for revision of

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[1] For reference: https://sustainablepower.application.marin.nl/energy-carriers/table

[2] https://www.ccr-zkr.org/files/documents/Roadmap/Roadmap_en.pdf

[3] https://www.ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition1.pdf

[4] https://www.ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition2.pdf

[5] See for the Dutch regulations: https://www.belastingdienst.nl/bibliotheek/handboeken/html/boeken/HA/vrijstellingen-vrijstelling_bij_gebruik_minerale.html

the Energy Taxation Directive[6] (ETD) which results in a legal conflict with the CCNR and the Act of Mannheim. A decision is expected by end of 2023.

HVO

HVO, or Hydrotreated Vegetable Oil is a drop-in substitute for EN590 Diesel and is seen as quick-win solution to dramatically reduce the CO2e emissions from well-to-wake scope. HVO (EN15940) can be produced from a wide variety of feedstocks (from Used Cooking Oil to rapeseed and crop residues). It has very similar usability characteristics as Diesel and is therefore popular under vessel owners and operators as a substitute. However, HVO is much more expensive than Diesel[7]. In view of absence of direct measures to use high shares of renewable fuels the cost price prevails in the choice of fuel. This leads to the fact that only a small number of vessels are currently using it. In fact, they only use HVO in case there is a specific request from the client in view of their carbon footprint reduction.

Furthermore, not all engine manufacturers do guarantee the lifetime and quality of their engine for HVO in the engine manual[8]. Although HVO has been tested in IWT before and is currently also in use in a very small subset of vessels, the absence of manufacture guarantees for HVO are still a hurdle. However, for the Stage V NRE type engines and the marinized Euro VI truck engines, HVO application is guaranteed by these engine manufacturers.

HVO is, in line with IPCC assumptions, considered climate neutral in the tank-to-wake-cycle. This means that in practice, emissions are still coming from the tailpipe, but the carbon emissions can be assumed to be zero since the calculation of CO2 is done in different sectors. The Well-to-Wake emission depends on the feedstock of HVO, which currently is mainly Used Cooking Oil[9]. As a result, depending on the feedstock, the CO2e reduction of HVO can be up to 90%. Other emissions like air pollutants such as NOx and PM may still be an issue but can be greatly reduced (80-99%) by using after treatment solutions such as catalysts (SCR) and filters (DPF) which can be installed in the exhaust system and are currently part of modern IWT engines regulated under NRMM Stage V.

Currently, in the base model, HVO for the vessel owner/operator is assumed to be 30% more expensive (bunker prices per kWh) than EN590 Diesel which was based on the CCNR studies[10]. Further information on price assumptions is presented in Annex I. It can be expected that this difference will decrease over time, e.g., as result of fuel policy proposals such as the revision of the RED 2 directive and ETS-2. However, the latter depends on policy

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[6] See also: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0563

[7] The commodity price of HVO is around 2-3 times more expensive compared to EN590 diesel, not including incentives from implementation of RED, ETS or taxation which can be significant.

[8] Usually above a certain percentage of HVO blended in. Lower blends like 30% HVO added to EN590 diesel is usually o.k. for newer engines. 100% HVO usage is often not guaranteed.

[9] Currently, much HVO comes from Used Cooking Oil, which has been earmarked in the Renewable Energy Directive as a feedstock to be limited in use for biofuels. Therefore, other feedstocks may have to be used which might prove troublesome.

[10] See for more information: https://ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition2.pdf

decisions on national levels as there is no such direct measure for IWT on EU level as seen in maritime transport (FuelEU Maritime[11]) or road transport.

Biodiesel

Besides fossil diesel and HVO, there are also Bio Diesels on the market that do not fit EN590 or EN15940 standards. In the market they are perceived as being of lower quality and they are held responsible for problems with filters blockage in the fuel system of engines. An example of these Bio Diesels is FAME, which can be produced from the same feedstocks as HVO, but is usually less refined and is perceived to cause troubles with filter blockage in case it takes a longer time to consume the bunker on board. FAME shall be seen as a perishable product which requires to be consumed within a limited time and also needs temperature and humidity control. However, in particular for larger vessels with high frequent bunkering, FAME has been successfully tested in the IWT market. Also, smaller blends like B7 (7% share) are currently seen in the market, similar to the road specification of B7 diesel. Furthermore, quality specifications of FAME can be further tightened and good housekeeping can be further applied in parallel, which could result to much less or no significant risks in terms of filter blockage.

In the NEEDS model scenarios, it was assumed by MARIN that Biodiesel consists of a blend of 50% fossil diesel, 20% FAME made from UCO and 30% HVO made from rapeseed feedstocks. The idea behind this blend is that these lower quality biofuels have seen little serious uptake towards higher percentages of blending. Therefore, HVO and Fossil Diesel are added in the blend.

Renewable Diesel

Renewable Diesel, or E-Diesel, is a synthetic Diesel produced from carbon dioxide, water and electricity. If powered with renewable energy, and all upstream processes are done renewable, the outflowing E-Diesel is 100% renewable and 100% carbon neutral from WTW point of view.

E-Diesel would be a drop-in solution for all internal combustion engines currently active in IWT. It behaves similar to fossil Diesel or HVO. This brings an advantage for the vessel owner as the technology is known and can be applied in existing drivetrains. However, an extreme amount of energy is lost when converting electricity with carbon capture from atmosphere into an e-diesel. The latter will probably lead a very high price and thus a limited availability. Other fuel options such as methanol are however more cost-effective when it comes to the production costs as can be seen in Annex I. However, a Renewable Diesel has the big advantages that it can be applied in existing propulsion systems and thus requires less or no capital investments while for other fuels like methanol, biomethane of hydrogen more capital costs are needed. Moreover, renewable diesel is easy and quick to handle and bunker and can also utilise existing bunkering facilities.

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[11] See for more information: https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/fueleu-maritime-initiative-council-adopts-new-law-to-decarbonise-the-maritime-sector/

2.2.2 Considered types of liquified methane

Fossil LNG

Liquified Natural Gas (LNG), methane (CH_4) in liquid condition, is stored at very low temperatures in specially designed storage tanks. The use of LNG brings several safety requirements to the design of the vessel and the bunkering procedure. For instance, special requirements for the storage tank and the free space around it, the pipes used to transport LNG on board and the engine room apply. LNG consists largely of Methane, and LNG users must keep Methane slip under control since Methane is very climate-impacting.

In the last two decades, LNG use in the IWT sector has experienced significant fluctuations.. Before the financial crisis of 2008, LNG was cheaper to use than EN590 Diesel. This led to some very large vessels (with high levels of fuel consumption) to be retrofitted to LNG. A basic bunkering infrastructure was realized (mostly truck-to-ship and a single bunkering station) and LNG was expected to see more and more uptake. However, in the financial crisis, the price for diesel decreased so much that the investment of retrofitting a vessel to LNG was not worth it anymore. Coupled with increased concerns over Methane slip, attention for LNG as an option to reduce the carbon footprint of IWT decreased.

LNG is currently seen as a mature technology and has been used on board vessels for many years. Some parties[12] still invest in LNG vessels, but the majority of the sector has little interest. It is therefore expected that LNG will keep playing a very small role in the sector, especially on vessels with a high fuel consumption. Since there is also the option to apply a Bio-LNG in future the investments in LNG do not necessarily lead to stranded assets.

LNG is assumed to be less expensive than EN590 Diesel, but high capex costs combined with a low positive impact on the carbon footprint (up to 25% CO2 reduction[13]) make LNG not suitable to reach zero emission on the longer term, but it may be an option for reaching CO2e reduction on the short term. On the medium and long term, a blend or full replacement with Bio-LNG can be applied to meet the CO2e reduction goals for 2035 and 2050.

Bio LNG

Bio LNG is a form of LNG acquired by the liquification of methane biogas. It is also known in the market as LBM “Liquified Bio Methane”. The biogas could mostly be produced by anaerobic digestion of organic waste, which would boost the circular economy. Another option for feedstock is methane capture from wet manure which also prevents leakage of methane to the atmosphere and therefore can result in high rates of CO2e reduction. Even reduction levels above 100% are possible according to the default values as presented in the Renewable Energy Directive regulation Annex V[14].

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[12] Shell is still set to receive over 20 LNG IWT vessels. In Dutch: https://www.shell.nl/media/nieuwsberichten/2020/40-lng-binnenvaartschepen-voor-shell-vloot.html

[13] https://www.ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition1.pdf

[14] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02018L2001-20181221

At the tailpipe, Bio LNG has similar emission levels compare to fossil LNG. However, similar to HVO, one can discount the carbon emitted, depending on the feedstock. CAPEX and OPEX costs are assumed to be in the same line as LNG, but OPEX might be a little higher since Bio LNG is more expensive to produce.

Bio LNG would be a drop-in solution for LNG-fitted vessels to reach (near) zero emissions, but it is not expected that this has an uptake much beyond vessels already fitted with an LNG system.

2.2.3 Considered forms of Electricity

Grid electricity Swapping
Using electricity to propel a vessel is not a novel idea. Diesel electric propulsion, with a diesel engine generating electricity, has been used for many years in shipping. Using as electricity source a container filled with stacked lithium batteries is currently being applied in the IWT market. The idea is to fill a container with batteries that can contain 1, 2 or more MWh of electricity, and plug in this container on a cable that provides the electricity to the electric motor on the propellor shaft. Once the container is almost empty, it can be taken off board and replaced by a fully charged container while the empty container is being recharged on shore. Swapping at a quay with container handling facilities allows to reduce the idle time of the vessel: no long waiting times to be charged are needed as the charging of the battery is decoupled. As there is already a vast network of container handling terminals in the Rhine area, the existing infrastructures can largely be used. More challenging is the electricity grid which needs to have sufficient capacity for adding connections to recharge the battery containers.

Traditionally, electricity used by means of on shore power supply / cold ironing, is set to have much longer charging/bunkering time compared to bunkering diesel. Therefore, the swapping approach with exchangeable standardised battery containers, used for multiple purposes, solves a significant bottleneck in the business case.

For shorter trips between two container terminals that are fitted with the correct infrastructure to tranship and charge containers (this outfitting of container terminals with charging stations is a large infrastructural challenge in itself), this is already a workable solution[15]. However, a vast majority of vessels is not active in container transport, but transports bulk dry cargo, liquid cargo or passengers. Moreover, the vessels need to be ‘plug-and-play’ ready with electric motors to be able to operate with the battery containers. Furthermore, even container vessels do not always make the same trips over a longer period of time. This obviously limits the opportunity to apply swappable battery containers with electric propulsion of the vessel. There is a high dependency on the availability of infrastructure to tranship battery containers and to be able to recharge them in the vicinity.

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[15] See the Alphenaar by ZES. In Dutch: https://www.schuttevaer.nl/nieuws/actueel/2021/09/06/de-alphenaar-vaart-eerste-elektrische-schip-met-verwisselbare-accus/

The expectation is that the technology will still become more useable and at lower costs (e.g. more MWh per container), so that vessels with longer distance trips between container terminals can also use this option in the future. However, it does stand to reason that a very large group of vessels, that do not sail fixed trajectories, and do not service terminals with container handling capacity, will have a very hard time fitting swappable containers into their operations.

CAPEX costs for the retrofitting of a vessel to an electrical propulsion system are bearable for the vessel owner. The problem lies with the capital expenditure of the battery containers, as these are very high for a single vessel owner. Therefore, an energy-as-a-service concept / pay-per-use model is expected to be applied. In this concept the battery containers are rented to the vessel owner/operator and are paid on the basis of the duration of the renting combined with a price per kWh for the electricity use. The containers are standardised and can be applied to various vessel operators and servicing multiple vessels (and/or other consumers of electricity such as off-grid construction works or festivals).

This solution has zero emissions at the tank to wake level. The well-to-tank level however might very well have emissions, which depends on the type of electricity used. If grid electricity is used, this will in practice be a mix of grey and green electricity so emissions will apply. However, over time the electricity production is expected to increase the share of renewable energy from wind, solar and water power and thus also the grid electricity providers will reduce their CO2e footprint.

Currently, Grid Swapping is assumed to be more expensive than EN590 Diesel. Although not suitable for the majority of vessels, a significant group could benefit from this solution to reach zero emissions (at least tank to wake).

Renewable electricity Swapping
Renewable electricity Swapping does only differ from Grid Electricity swapping in the sense that instead of grid electricity, specifically renewable electricity is used to recharge the batteries. Price differences between Grid electricity and Renewable electricity fluctuate over the year and given weather conditions, but are expected to be not very large.

In sum, this would bring users of swappable battery containers to zero emissions on the well to wake level.

Grid Electricity Charging
Grid Electricity Charging is similar to the earlier described electricity swapping, but instead of a swappable container-battery, the vessel will be equipped with a fixed battery on board that needs to be charged from a shore-side charging station. Since there is no need to rent energy containers (and thus pay for them) operational costs (OPEX) are expected to be smaller than for container swapping. For CAPEX costs this will be the opposite since an expensive battery pack needs to be acquired by the vessel owner and installed on board.

Operationally, the dependency on a to-be-charged fixed battery on board will have a large impact. It is not clear what the operational range of such batteries will be, but it is expected that this will only be suitable for vessels that are not (semi) continually sailing (A1 & A2 sailing schemes, or “dagvaart” in Dutch). These would possibly have enough waiting time for the resting time of crew to charge a large battery pack. However, they will still only be able to operate where sufficient charging infrastructure along waterways or in ports is available. This is still a large infrastructural hurdle.

Vessels that fit these sailing schemes are often smaller vessels. This would be a benefit in the sense that they need less power, and thus smaller battery packs, which will allow for a shorter charging period. A clear negative would be the often limited space for a battery pack on board.

This way of electrical sailing could, if infrastructural challenges are overcome, offer a reasonable level of flexibility to an important subset of vessels. And again, electrical sailing offers zero emissions at the tank to wake level.

Currently, Grid Charging is assumed to be more expensive than EN590 Diesel (this excludes the significant CAPEX). Although not suitable for the majority of vessels, a significant group could benefit from this solution to reach zero emissions (at least tank to wake).

Renewable Electricity Charging
Renewable electricity Charging does only differ from Grid Electricity Charging in the sense that instead of grid electricity, specifically renewable electricity is used. Price differences between Grid electricity and Renewable electricity fluctuate over the year and given weather conditions, but are expected to be not very large.

In sum, this would bring users of fixed on-board batteries to zero emissions on the well to wake level.

2.2.4 Considered forms of Methanol

Bio Methanol
Methanol is an alcohol with molecular formula CH3OH, it is thus rich in hydrogen but has only one carbon bond. Methanol is a clear, colourless liquid. It can be produced from fossil sources, but also biomass (Bio Methanol), from captured CO2 and a reaction with renewable hydrogen and is a by-product of some industries (Renewable Methanol). Methanol can be used in an adapted Internal Combustion Engine[16] or as an energy carrier for hydrogen fuel cells. The development of new internal combustion engines running on methanol is however problematic as the Non-Road Mobile Machinery regulation (NRMM)[17] doesn’t list methanol as reference fuel. As a result, it is not foreseen that new combustion

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[16] Multiple seagoing vessels and some inland ones already use this technique.
[17] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32016R1628

engines running on methanol can be supplied to vessel owners within the next five years. First the NRMM regulation needs to be revised.

Although methanol is harmful for the environment and health, it is biodegradable. Further, it remains a liquid up to 60 degrees Celsius, which makes its handling similar to Diesel (e.g. simple storage tanks etc.). This makes methanol an attractive option for reducing the carbon footprint of a vessel. In the near future, work will be done to adapt an IWT engine to the use of methanol- first as a dual fuel option, but later options for 100% methanol use are foreseen.

Since Methanol can be handled with relatively slight deviations from how diesel is handled, it is currently assumed that methanol can offer almost as much freedom to its users as diesel is offering now. Here, we still have to take into account that methanol is not yet widely available for IWT at all and that significant investments in engines and infrastructure are still needed to achieve a workable network of bunkering options. Still, methanol might provide a pathway to zero emission for a large subset of vessels for the medium and longer term.

Similar to HVO, one can discount the carbon emitted since it is produced from biomass. Currently, Methanol is assumed to be more expensive than EN590 Diesel.

In the NEEDS model the methanol option is only applied in combination with an Internal Combustion Engine.

Renewable Methanol

Renewable Methanol is largely the same as Bio Methanol, described above. The only significant difference is that Renewable Methanol is produced from a different feedstock than biomass. It is produced from captured CO2 and a reaction with renewable hydrogen and is a by-product of some industries.

In this deliverable, the price levels and many other variables are kept constant between Bio- and Renewable Methanol because of lack of information on the specific price developments. In the NEEDS model the methanol option is only applied in combination with an Internal Combustion Engine. However, as mentioned, currently in IWT new internal combustion engines cannot yet be supplied as result of lacking recognition of methanol as reference fuel in the NRMM regulation. For the short term, only retrofitting existing engines (unregulated or CCNR stage 1 or 2 engines) could be an option.

2.2.5 Considered forms of Hydrogen

Fossil H2 Swapping
Sailing on electricity produced by a fuel cell, for which the hydrogen is made available in a swappable storage container is in many ways similar to swapping battery containers. The main difference is the need for a fuel cell and the need for more safety measures due to the nature of hydrogen. Fossil hydrogen offers zero emissions only on a tank-to-wake level.

Hydrogen is a gas under normal conditions and can be stored and transported in a compressed or liquid state. Hydrogen can be an industrious by-product, but the use of renewable electricity for electrolysis allows for the creation of renewable hydrogen. Hydrogen is not yet widely used or available for IWT, a lot of infrastructure will still have to be developed to achieve this. However, there is already one IWT vessel sailing on hydrogen, of which the owner is currently retrofitting more vessels.

As with swappable battery containers, swapping at a terminal with container handling facilities allows for fast charging of the vessel: no long waiting times to be bunkered are needed. Hydrogen is set to have slower bunkering times than diesel, so this is solving a significant problem. Again, as with swappable battery containers, an energy-as-a-service provider might offer containers to the IWT market.

Currently, fossil Hydrogen is assumed to be more expensive than EN590 Diesel (this excludes the significant capex). Although not suitable for the majority of vessels, a significant group could benefit from this solution to reach zero emissions (at least tank to wake).

Renewable H2 Swapping
Swapping with renewable hydrogen in the container is largely the same, only the hydrogen is produced trough electrolysis with renewable electricity.

Cost levels for renewable hydrogen are set to be higher in the earlier years of the scenarios, and availability might be an issue. However, later on (e.g. 2035, 2050) it is assumed in the NEEDS modelling that renewable hydrogen will become cheaper than fossil hydrogen as result of the economies of scale in green hydrogen production and policy measures.

Fossil H2 bunkering
When the choice for bunkering is made, the big differentiators are a fixed hydrogen tank on board. This will bring considerable safety requirements, but not that much more than a swappable container will. However, hydrogen will require long bunkering time, which can have a significant impact on productivity, transport capacity and thus costs.

It therefore stands to reason that this form of operation will only be advantageous for vessels that have (long) waiting times per 24 hours in which the vessels can bunker hydrogen. As with electricity charging, this will mostly be vessels in the “day-operation” which means that the vessel can be operational for 14h per day maximum. Usually vessels in day-operation concern smaller vessels operational on canals which need less power, and thus less hydrogen. This way of sailing could, if infrastructural challenges are overcome, offer a reasonable level of flexibility to an important subset of vessels. And again, fossil hydrogen sailing offers zero emissions at the tank to wake level. However, major CO2 emissions occur during the upstream process for the well to tank part as fossil hydrogen is mainly produced from fossil natural gas (CH4) from which the carbon molecule is separated from the hydrogen molecules.

Renewable H2 bunkering
Renewable Hydrogen bunkering does only differ from Fossil Hydrogen bunkering in the sense that instead of fossil hydrogen, specifically renewable H2 is used. Price differences between fossil and renewable hydrogen have been described above.

In sum, this would bring users of fixed on-board hydrogen tanks to zero emissions on the well to wake level.

To keep the model workable, the choice has been made to exclude dual fuel combinations. Most dual fuel technologies operate on a mix of a sustainable energy carrier and a fossil fuel, usually with the option of running 100% on the fossil fuel as a back-up. Currently, a significant part of dual fuel solutions cannot run on 100% sustainable fuels, but developments are being made to overcome this hurdle. It stands to reason that dual fuel solutions will play a role (of uncertain size) in the pathway to zero emission (e.g., current until 2050), however a zero-emission sector cannot use fossil fuels anymore in 2050 and will thus automatically lose many dual fuel options. Therefore, the impact of excluding dual fuel solutions from the model will have an impact on the period up to zero emission performance, but that impact will decline in the latter years of the scenarios, when zero emission solutions become the norm.

2.3 Assumed OPEX and CAPEX for different scenarios

The assumed OPEX and CAPEX for the simulated scenarios can be found in Annex I. The costs are divided into 4 categories:

- Table 16: Energy prices in €/kWh for the bunkered, charged and swapped fuel, electricity or energy containers containing hydrogen or batteries. Prices are illustrated for the BAU, conservative and innovative scenarios.

- Table 17: Price of storage (e.g., fuel tank, tank container, etc.) in €/kWh and considered multipliers for minimum, average and maximum price scenarios.
    - Average prices are assumed for the BAU scenario as well as for the forced zero-emission tailpipe scenarios (scenario 6, 7 and 8)
    - Minimum price levels are considered for storage hardware of fossil, bio and renewable diesel and gas. Maximum price levels are assumed for hardware related to all other forms of energy.

- Table 18: Prices of the ICE and FC's (excluding electric engines) in €/kW and considered multipliers for minimum, average and maximum price scenarios.
    - Average prices are assumed for the BAU scenario as well as for the forced zero-emission tailpipe scenarios (scenario 6, 7 and 8)
    - Minimum price levels are considered for hardware of fossil, bio and renewable diesel and gas. Maximum price levels are assumed for hardware related to all other forms of energy.

- Table 19: Prices of electric engines in €/kW and considered multipliers for minimum, average and maximum price scenarios.
    - Average prices are assumed for the BAU scenario as well as for the forced zero-emission tailpipe scenarios (scenario 6, 7 and 8)
    - Minimum price levels are considered for hardware of fossil, bio and renewable diesel and gas. Maximum price levels are assumed for hardware related to all other forms of energy.

The assumed prices are derived from the study "Assessment of technologies in view of zero-emission IWT"[18] and the internal MARIN database which contains indicative financial figures for investments in greening technologies. Both sources of information have been carefully assessed with expert opinion and combined into one dataset as illustrated in Annex 1.

In the MARIN Sustainable Power Database, the CAPEX are split out in three major contributors, namely Energy Carriers (tanks, batteries), Energy Distribution (piping, cables) and Energy Converter (electric motors, ICE). The CAPEX are presented in price per unit of energy (€/kWh) for the Energy Carriers and price per unit of power (€/kW) for the Energy Distribution and Energy Converter. The simulation model works with the same distribution. In order to combine both databases, the structure of the MARIN database has been used, but the missing data has been filled out from the IWT databases, where some of the CAPEX were presented as flat rates. These values have been converted to price per unit of energy/power.

The cost of the energy carriers not contained in the MARIN database have been calculated using the difference in prices (of the IWT database) between the cost of the energy carrier itself and the most similar energy carrier in the MARIN database. This difference has been applied to the cost of the energy carrier in the MARIN database. By doing so the costs are consistent between the two sources.

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[18] https://www.ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition2.pdf

2.4 Power system selection logic

The simulation model in its current state is capable of selecting a power system during a simulation run, based on a predefined and implemented so-called power system selection logic. This logic applies to the following scenarios:

- Business As Usual
- Conservative
- Innovative
- Innovative Early Adopter Increase
- Conservative Early Adopter Increase

It does not apply to the three forced scenarios, i.e., Forced Electric, Forced hydrogen swap and Forced hydrogen scenarios. Since these are scenarios in which the achievement of the defined objective is forced, the power system selection logic is disabled, since it might otherwise negatively impact the forced scenario objective.

The power system selection logic can be represented schematically in figure 1. Starting point of the representation is the blue box; the bunker port.

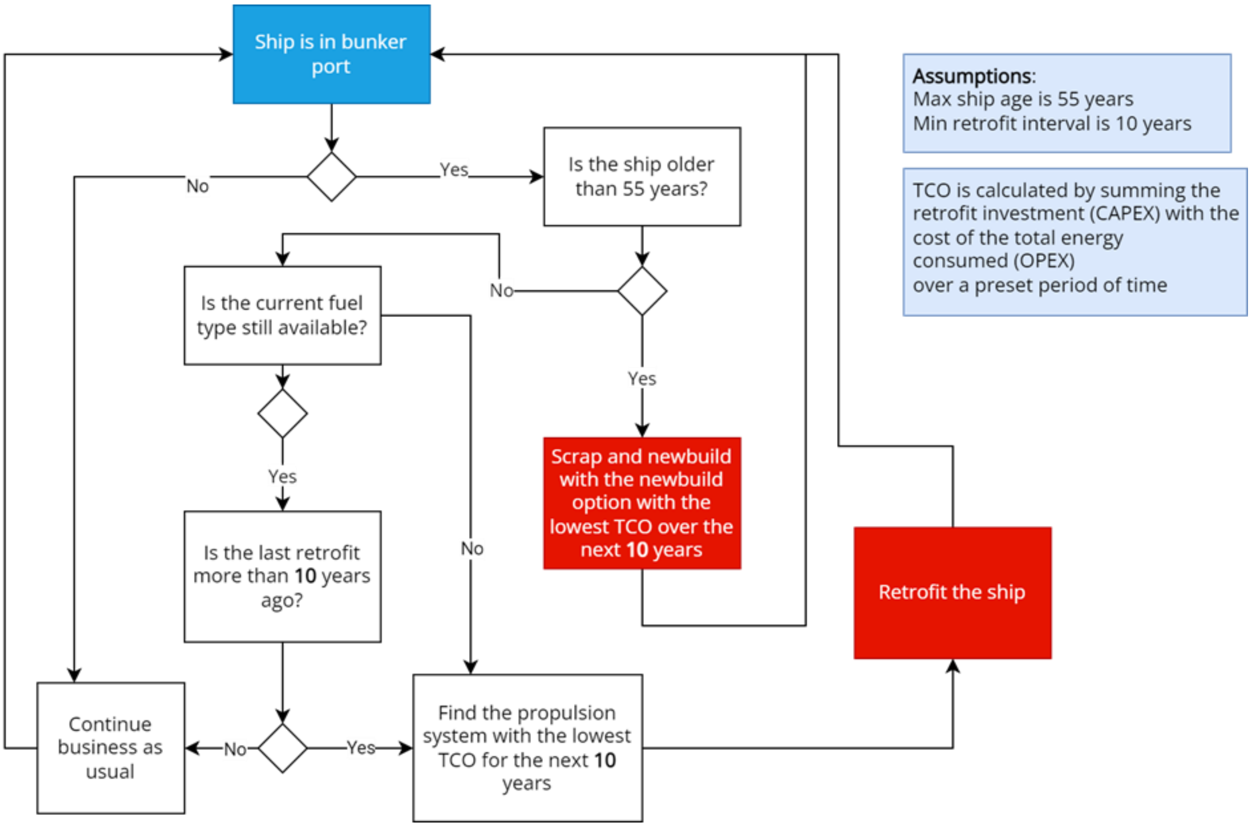

Figure 1: Power system selection logic

The step “Find the propulsion system with the lowest TCO for the next 10 years” is decided upon by the simulation model for each individual vessel in the considered scenario using the following reasoning:

- The historic fuel consumption for the vessel is used and extrapolated to 10 years. For each power system type, the expected 10 years fuel costs are calculated based on the current fuel prices.
- The historic transport capacity for the vessel is used and extrapolated to 10 years. For each power system type, the payload loss is calculated and the loss of income is calculated based on the operational costs per tonne-kilometre.
- The CAPEX are calculated based on the dimensions of the power system.
- For all the power systems, the total costs of ownership (TCO), which amounts to the sum of OPEX and CAPEX, is calculated and ordered. The costs are scaled between 9 and ~0 (9 being the cheapest) with the formula 9*lowest_tco/tco.
- Then for each other parameter (the TRL, port availability and social acceptance) the rating is fetched from predefined and implemented tables. Subsequently, the total rating is calculated as follows: TCOrating + PortAvailabilityRating + TRLRating + SocialAcceptanceRating. The latter three parameters together make up the Acceptance Multiplier. See paragraph 2.5 for an explanation of the Acceptance Multiplier.

Following the steps above, a rating is calculated and the power system with the highest rating becomes the best power system. In reality however, not all investment decisions made will be financially rational. Therefore, to introduce a level of scatter, vessels can randomly pick any power system from the top 5 power systems, where the best option has a 5 times higher chance to be picked than the 5th-best option.

Since trying to mimic reality in a simulation model introduces the necessary complexities and mimicking absolute reality is not possible, there are limitations to the model. A relevant limitation here concerns the imposed requirement to keep transport capacity more or less constant during any simulation run, which entails the introduction of new vessels. This specially creates a skewed view in simulations with the deployment of innovative techniques with low gravimetric and volumetric energy density, such as the forced scenarios. In the forced scenarios this limitation eventually results in underestimations of the CAPEX figures. While new vessels introduced in the simulations for the forced scenarios enter the simulation directly as newbuilds with a hydrogen (ICE or FC) or battery-electric power system. Since these ships already enter the simulation immediately with these power systems, their CAPEX is not included. Furthermore, for all scenarios, the CAPEX of newbuild ships that enter the simulation does not include the costs for the hull, fittings, etc. (all non power system related costs).

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2.5 Acceptance multiplier for different scenarios

To prevent the simulation model from modelling the transition solely on the basis of the listed OPEX and CAPEX figures, a so-called acceptance multiplier was set up that also allows other factors to factor into the shipowner's investment decision in the simulation. This acceptance multiplier contains figures for the TRL of each considered technology, the acceptance level of the vessel owner with regard to a particular technology and the energy availability in ports. This thus introduces more than just price factors into the model, which tries to better simulate reality.

Tables 2 to 4 show the acceptance multiplier for the various scenarios. For the forced scenarios, the acceptance multiplier does not apply, as the transition within these scenarios is forced top-down.

The variation in the figures for the BAU, conservative and innovative scenarios are driven by the share of technologies in these three scenarios as included in the study "Assessment of technologies in view of zero-emission IWT"[19] and adopted in the CCNR Roadmap[20]. As such, an attempt has been made to mimic this development in the energy mix within each scenario.

Practice also shows that there are always early adopters who, as frontrunners, invest in innovative technology earlier than the bulk. For example, because of their own corporate social responsibility programme, shippers and customers asking for it, etc. This was also the case with LNG in inland shipping, for example. Shell had been a big driver in this as a major customer and eventual supplier in the upstream chain. This can also be seen recently, for example with IWT clients such as corporate firms Nike and Nouryon which supported the deployment of the hydrogen fuel cell propelled innovative vessels “H2 Barge 1” and “Antonie”, respectively.

Therefore, for the BAU, conservative and innovative scenarios, a frontrunner share of 2% of the total fleet within each vessel trajectory was assumed. If this percentage were extrapolated to the total European fleet, the percentage of 2% frontrunners out of the total is indeed a close estimate of what actually happens in practice. In the simulation this means that early adopters choose the best value for money in terms of CO2 reduction per euro (e.g. cheapest means of reducing as much CO2 as possible). This scenario setting is defined in the modelling as “AVERAGE”

However, given the ambitious emission targets for the year 2050, the transition needs to strongly accelerate and in practice there will need to be more frontrunners investing in technologies and forms of energy that fit within the transition path. To simulate this acceleration, two scenarios were devised, the conservative early adopter scenario and innovative early adopter scenario. The last row of Tables 2 and 3 contain the percentages for the development of the share of early adopters/frontrunners in both scenarios.

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[19] https://www.ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition2.pdf

[20] https://www.ccr-zkr.org/files/documents/Roadmap/Roadmap_en.pdf

Table 1 Acceptance multiplier BAU scenario (also known as scenario setting "AVERAGE")

	Estimated value (1-9 scale)								
	2023			2035			2050		
Technology	**TRL**	**Acceptance level**	**Availability in ports**	**TRL**	**Acceptance level**	**Availability in ports**	**TRL**	**Acceptance level**	**Availability in ports**
Fossil diesel + Stage V ICE	9	9	9	9	8	9	9	7	9
Hydrotreated Vegetable Oil (HVO) + Stage V ICE	9	9	7	9	9	9	9	9	9
Liquefied Natural Gas (LNG) + Stage V ICE	9	3	4	9	2	4	9	1	4
Liquid Biomethane (LBM)+ Stage V ICE	9	6	4	9	7	4	9	8	5
Battery/electricity	8	7	2	9	8	6	9	9	8
Hydrogen Fuel Cell (H2 FC)	7	6	1	9	7	5	9	8	7
Hydrogen Internal Combustion Engine (H2 ICE)	5	5	1	9	6	5	9	7	7
Methanol Fuel Cell (MeOH FC)	7	5	1	9	6	4	9	7	6
Methanol Internal Combustion Engine (MeOH ICE)	5	4	1	9	5	4	9	6	6

Table 2 Acceptance multiplier conservative scenario (also known as scenario setting "CONSERVATIVE")

	Estimated value (1-9 scale)								
	2023			2035			2050		
Technology/energy	**TRL**	**Acceptance level**	**Availability in ports**	**TRL**	**Acceptance level**	**Availability in ports**	**TRL**	**Acceptance level**	**Availability in ports**
Fossil diesel + Stage V ICE	9	9	9	9	8	8	9	7	7
Hydrotreated Vegetable Oil (HVO) + Stage V ICE	9	9	7	9	9	9	9	9	9
Liquefied Natural Gas (LNG) + Stage V ICE	9	3	4	9	2	4	9	1	4
Liquid Biomethane (LBM)+ Stage V ICE	9	6	4	9	8	6	9	9	7
Battery/electricity	8	7	2	9	8	6	9	8	6
Hydrogen Fuel Cell (H2 FC)	7	6	1	9	7	5	9	7	5
Hydrogen Internal Combustion Engine (H2 ICE)	5	5	1	9	6	5	9	6	5
Methanol Fuel Cell (MeOH FC)	7	5	1	9	6	4	9	6	4
Methanol Internal Combustion Engine (MeOH ICE)	5	4	1	9	5	4	9	5	4
Share of frontrunners/share of social responsible operators	2%			35%			90%		

Note: the last row only applies in the conservative early adopter scenario

Table 3 Acceptance multiplier innovative scenario (also known as scenario setting "INNOVATIVE")

	Estimated value (1-9 scale)								
	2023			**2035**			**2050**		
Technology/energy	**TRL**	**Acceptance level**	**Availability in ports**	**TRL**	**Acceptance level**	**Availability in ports**	**TRL**	**Acceptance level**	**Availability in ports**
Fossil diesel + Stage V ICE	9	9	9	9	7	8	9	6	7
Hydrotreated Vegetable Oil (HVO) + Stage V ICE	9	9	7	9	8	8	9	7	7
Liquefied Natural Gas (LNG) + Stage V ICE	9	3	4	9	2	3	9	1	2
Liquid Biomethane (LBM)+ Stage V ICE	9	6	4	9	6	3	9	5	2
Battery/electricity	8	7	2	9	8	8	9	9	9
Hydrogen Fuel Cell (H2 FC)	7	6	1	9	7	7	9	8	8
Hydrogen Internal Combustion Engine (H2 ICE)	5	5	1	9	7	7	9	8	8
Methanol Fuel Cell (MeOH FC)	7	5	1	9	6	6	9	7	7
Methanol Internal Combustion Engine (MeOH ICE)	5	4	1	9	6	6	9	7	7
Share of frontrunners/share of social responsible operators	2%			35%			90%		

Note: the last row only applies in the innovative early adopter scenario

3. Scenario results

The scenario results have largely been downloaded from the online dashboard: https://needs.application.marin.nl/dashboard

In this dashboard also the bunkering data for each port can be seen by means of graphics per month presenting the volume per port per type of energy (see Annex 2). As can be seen in Annex 2, for specific scenarios such as the forced battery-electric one, the spread in charging/swapping ports is more equal compared to the status-quo. However, since this information is based on a selection of 25 representative journeys in the Rhine region, it does not provide the necessary results to make a reasonable extrapolation to the whole European bunkering situation for IWT. Hence, this would a require a more extensive simulation to include more journeys and vessels in order to provide a better and more representative geographic coverage.

3.1 Business As Usual scenario

The following settings have been used for this simulation:

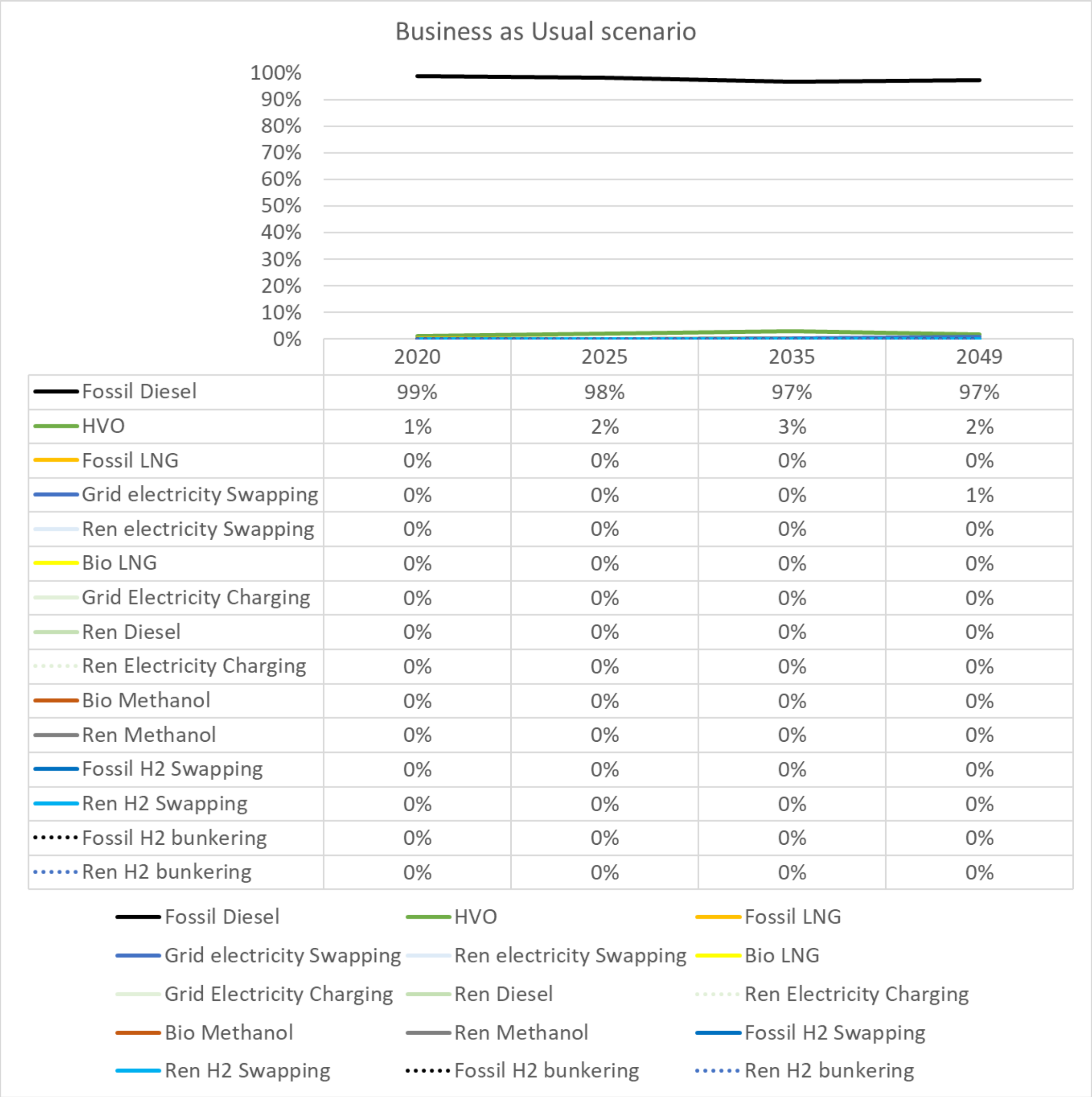
- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have followed the power system selection logic: every 10 year a ship reassessed the applicability of the ships' power system
- The innovation level was set to **AVERAGE**. This influences the prices and availability of energy carriers, the capex for refits, the TRL and social acceptance of technology solutions.
- The energy carrier types available in the simulation where: Fossil Diesel, Bio Diesel, HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Charging, Grid Electricity Swapping, Ren Electricity Charging, Ren Electricity Swapping, fossil hydrogen, renewable hydrogen, Bio Methanol, Ren Methanol

The Business As Usual (BAU) scenario provides the following results on the development of the type of fuels and technical solutions as well as the CO2e emissions and the development of the OPEX and CAPEX. In total 671 retrofits take place in the BAU scenario.

The able 4 presents the summarizing overview of results:

Table 4 summarising results performance indicators BAU scenario

	2020	**2025**	**2035**	**2049**
CO2 WTW, kTon	387	393	355	360
Index compared to 2020	100	102	92	93
Total number of refits (2020-2050)	671			
Average investment (CAPEX) per refit	€ 681,135			
CAPEX total (2020-2050)	€ 457,041,849			
OPEX Total (2020-2050)	€ 2,514,770,836			
Number of vessels in model in 2049	230			



	2020	2025	2035	2049
Fossil Diesel	99%	98%	97%	97%
HVO	1%	2%	3%	2%
Fossil LNG	0%	0%	0%	0%
Grid electricity Swapping	0%	0%	0%	1%
Ren electricity Swapping	0%	0%	0%	0%
Bio LNG	0%	0%	0%	0%
Grid Electricity Charging	0%	0%	0%	0%
Ren Diesel	0%	0%	0%	0%
Ren Electricity Charging	0%	0%	0%	0%
Bio Methanol	0%	0%	0%	0%
Ren Methanol	0%	0%	0%	0%
Fossil H2 Swapping	0%	0%	0%	0%
Ren H2 Swapping	0%	0%	0%	0%
Fossil H2 bunkering	0%	0%	0%	0%
Ren H2 bunkering	0%	0%	0%	0%

Figure 2: Energy mix distribution BAU scenario

In figures 2 and 3 it can be seen that also in the BAU scenario the share of fossil diesel fuel remains very high at 97% in 2049. Only usage of HVO and some grid electricity swapping have a small share. The latter can be explained by a few early adopters which didn't choose the energy carrier and technology with the lowest TCO but a solution with a lower carbon footprint. The vast majority of the retrofit operations therefore concerns the replacement of the 10 year old diesel engine for a new diesel engine. Consequently, the CO2e reduction does not take place either as can be seen in the following figure.

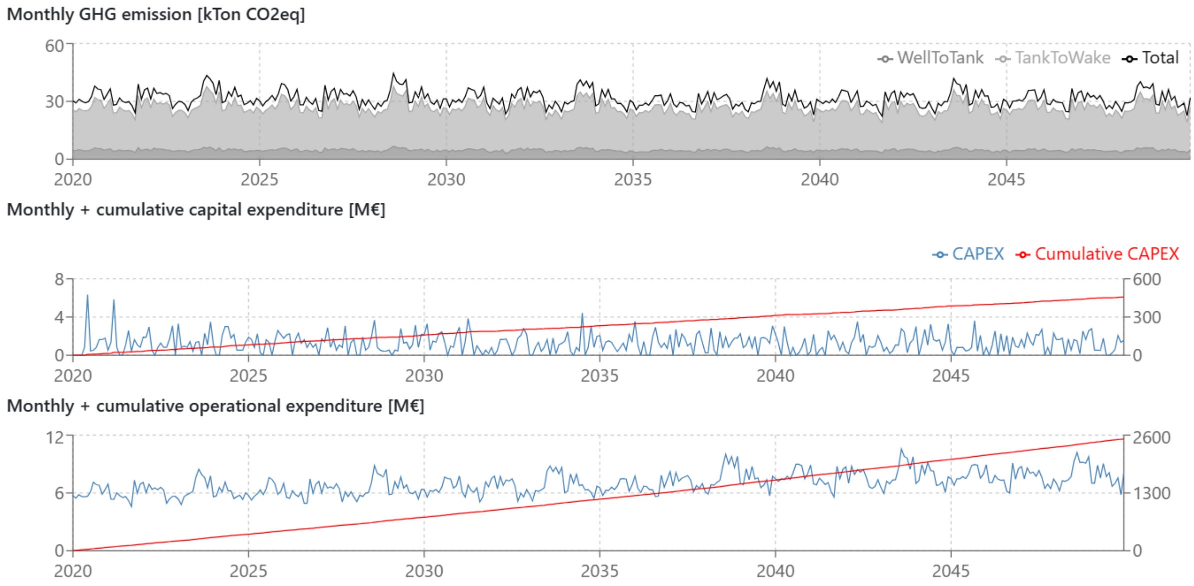


Figure 3: Development GHG emissions and CAPEX and OPEX for BAU scenario

3.2 Conservative pathway scenario

The following settings have been used for this simulation:

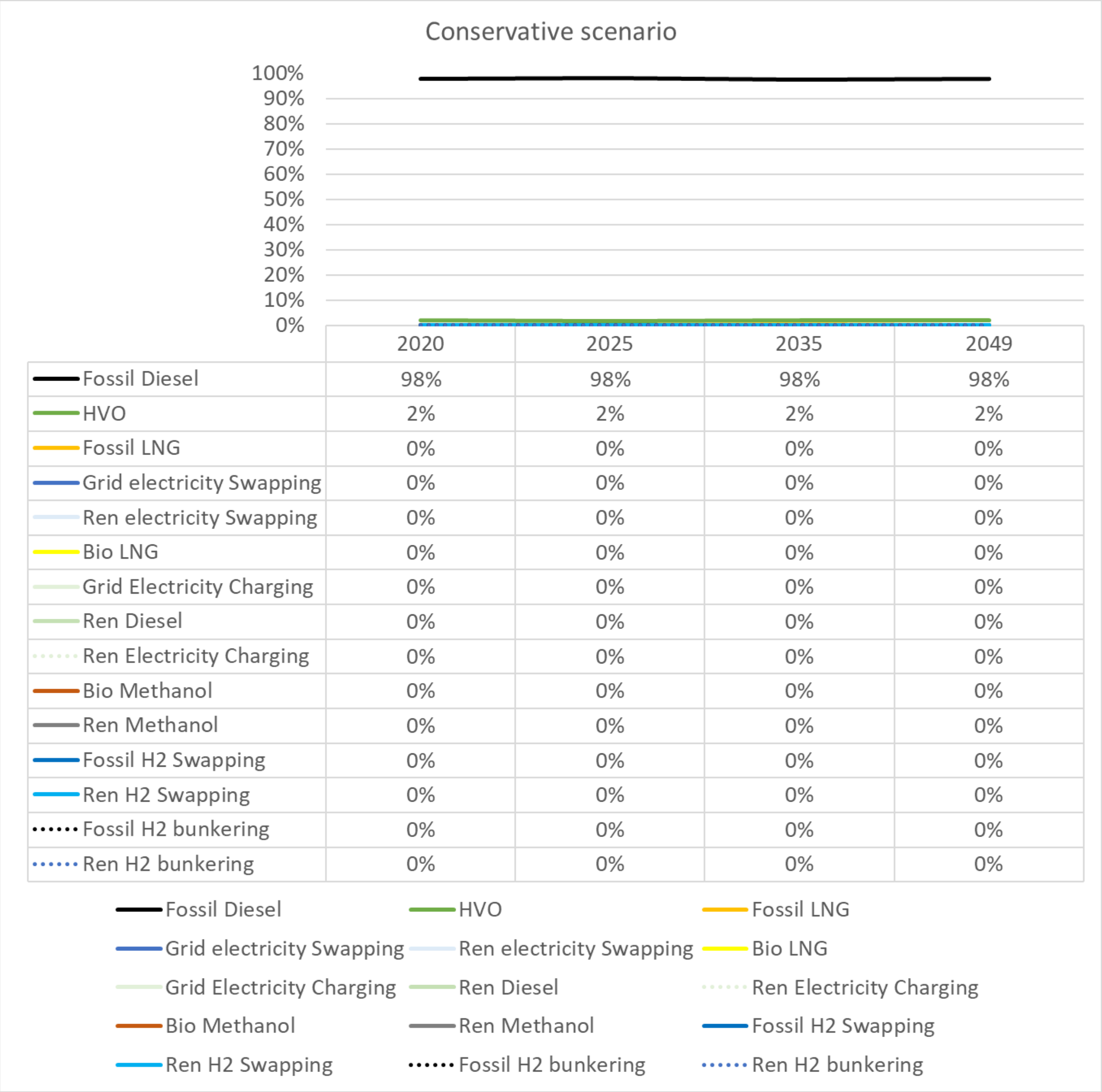
- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have followed the power system selection logic: every 10 year a ship reassessed the applicability of the ships' power system
- The innovation level was set to **CONSERVATIVE**. This influences the prices and availability of energy carriers, the capex for refits, the TRL and social acceptance of technology solutions.
- The energy carrier types available in the simulation were: Fossil Diesel, Bio Diesel, HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Charging, Grid Electricity Swapping, Ren Electricity Charging, Ren Electricity Swapping, H2 Fossil Bunkering, H2 Renewable Bunkering, Bio Methanol, Ren Methanol.

The conservative scenario provides the following results on the development of the type of fuels and technical solutions as well as the CO2e emissions and the development of the OPEX and CAPEX. In total 670 retrofits take place in the conservative scenario.

The table 5 presents the summarizing overview of results:

Table 5 summarising results performance indicators Conservative scenario

	2020	**2025**	**2035**	**2049**
CO2 WTW, kTon	380	393	402	400
Index compared to 2020	100	103	106	105
Total number of refits (2020-2050)	670			
Average investment (CAPEX) per refit	€ 699,978			
CAPEX total (2020-2050)	€ 468,984,938			
OPEX Total (2020-2050)	€ 3,079,602,311			
Number of vessels in model in 2049	235			



	2020	2025	2035	2049
Fossil Diesel	98%	98%	98%	98%
HVO	2%	2%	2%	2%
Fossil LNG	0%	0%	0%	0%
Grid electricity Swapping	0%	0%	0%	0%
Ren electricity Swapping	0%	0%	0%	0%
Bio LNG	0%	0%	0%	0%
Grid Electricity Charging	0%	0%	0%	0%
Ren Diesel	0%	0%	0%	0%
Ren Electricity Charging	0%	0%	0%	0%
Bio Methanol	0%	0%	0%	0%
Ren Methanol	0%	0%	0%	0%
Fossil H2 Swapping	0%	0%	0%	0%
Ren H2 Swapping	0%	0%	0%	0%
Fossil H2 bunkering	0%	0%	0%	0%
Ren H2 bunkering	0%	0%	0%	0%

Figure 4: Energy mix distribution Conservative scenario

It can be seen in figures 4 and 5 that the fossil diesel remains the dominant fuel in this conservative scenario. In fact, there is hardly a significant difference compared to the BAU scenario. Small differences can be seen in de detailed data which point towards a higher share of renewable electricity compared and a higher share of bioLNG. The vast majority of the retrofit operations therefore concerns the replacement of the 10 year old diesel engine for a new diesel engine. Consequently, the CO2e reduction does not take place either as can be seen in the following figure.

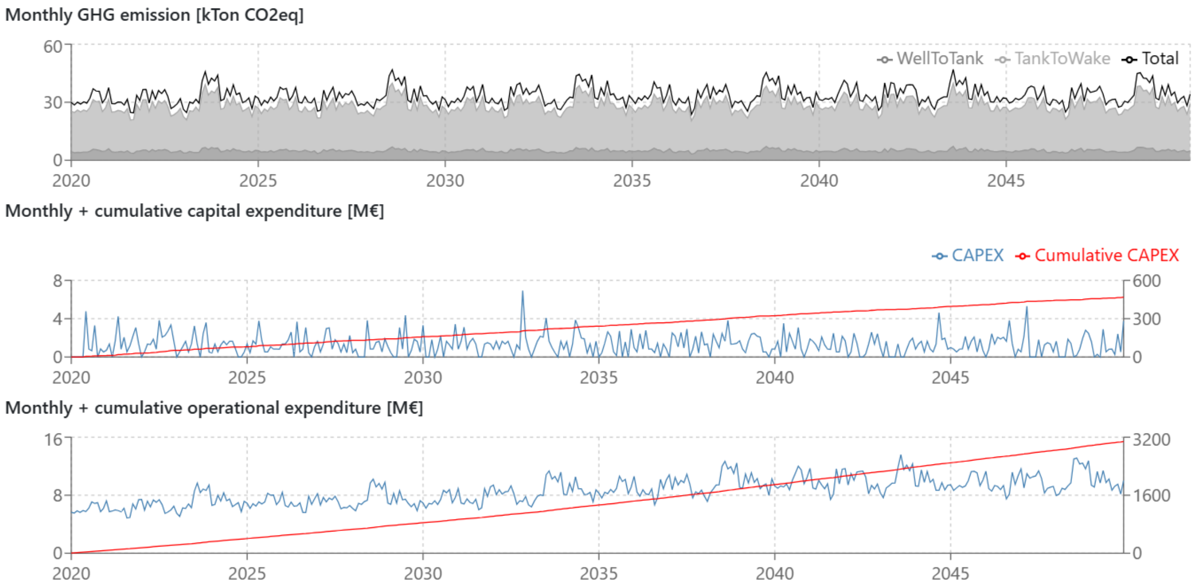


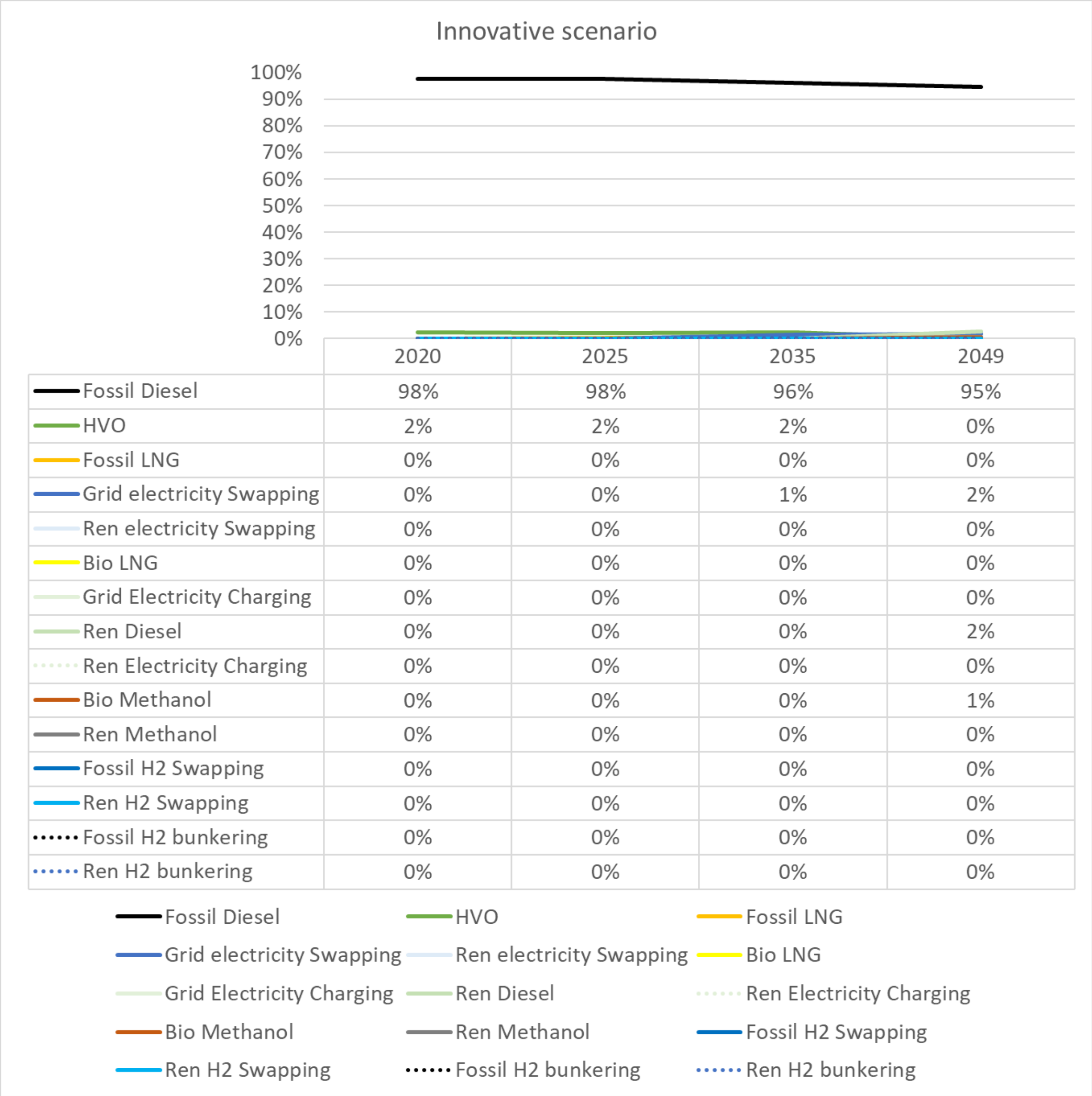
Figure 5: Development GHG emissions and CAPEX and OPEX for Conservative scenario

3.3 Innovative pathway scenario

The following settings have been used for this simulation:

- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have followed the power system selection logic: every 10 year a ship reassessed the applicability of the ships' power system
- The innovation level was set to **INNOVATIVE**. This influences the prices and availability of energy carriers, the capex for refits, the TRL and social acceptance of technology solutions.
- The energy carrier types available in the simulation were: Fossil Diesel, Bio Diesel, HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Charging, Grid Electricity Swapping, Ren Electricity Charging, Ren Electricity Swapping, H2 Fossil Bunkering, H2 Renewable Bunkering, Bio Methanol, Ren Methanol

The Innovative scenario provides the following results on the development of the type of fuels and technical solutions as well as the CO2e emissions and the development of the OPEX and CAPEX. In total 706 retrofits take place in the conservative scenario.



	2020	2025	2035	2049
Fossil Diesel	98%	98%	96%	95%
HVO	2%	2%	2%	0%
Fossil LNG	0%	0%	0%	0%
Grid electricity Swapping	0%	0%	1%	2%
Ren electricity Swapping	0%	0%	0%	0%
Bio LNG	0%	0%	0%	0%
Grid Electricity Charging	0%	0%	0%	0%
Ren Diesel	0%	0%	0%	2%
Ren Electricity Charging	0%	0%	0%	0%
Bio Methanol	0%	0%	0%	1%
Ren Methanol	0%	0%	0%	0%
Fossil H2 Swapping	0%	0%	0%	0%
Ren H2 Swapping	0%	0%	0%	0%
Fossil H2 bunkering	0%	0%	0%	0%
Ren H2 bunkering	0%	0%	0%	0%

Figure 6: Energy mix distribution Innovative scenario

It can be seen in figures 6 and 7 that also in the innovative scenario, the fossil diesel remains the dominant fuel with a share in total energy consumption of 95% in 2049. Still the vast majority of the retrofit operations therefore concerns the replacement of the 10 year old diesel engine for a new diesel engine. In the year 2049 the innovative scenario shows some share as well for swapping batteries charged from grid, usage of renewable diesel and usage of bio methanol to complete the remaining 5% of the energy consumption.

Resulting from the dominance of fossil diesel, the CO2e reduction does not take place in this scenario, which can be seen in the following figure.

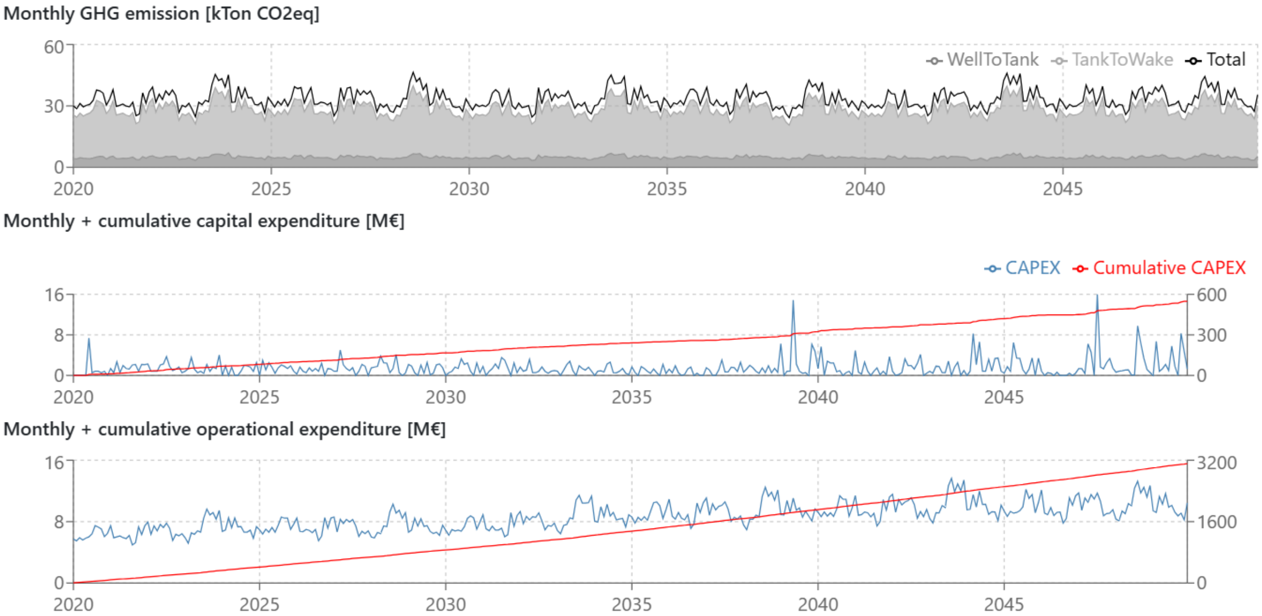


Figure 7: Development GHG emissions and CAPEX and OPEX for Innovative scenario

Table 6 presents the summarizing overview of results:

Table 6 summarising results performance indicators Innovative scenario

	2020	**2025**	**2035**	**2049**
CO2 WTW, kTon	388	404	400	391
Index compared to 2020	100	104	103	101
Total number of refits (2020-2050)	706			
Average investment (CAPEX) per refit	€ 777,507			
CAPEX total (2020-2050)	€ 548,919,874			
OPEX Total (2020-2050)	€ 3,108,559,519			
Number of vessels in model in 2049	243			

3.4 Conservative early adopter scenario

The following settings have been used for this simulation:

- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have followed the power system selection logic: every 10 year a ship reassessed the applicability of the ships' power system
- The early adopter increase was switched on. This means that in 2020 2% of the bunker actions is performed with the energy carrier that has the best ratio between price and CO2 emission (instead of the lowest price). This percentage is increasing to 35% in 2035 and 90% in 2050.
- The innovation level was set to **CONSERVATIVE**. This influences the prices and availability of energy carriers, the capex for refits, the TRL and social acceptance of technology solutions.
- The energy carrier types available in the simulation were: Fossil Diesel, Bio Diesel, HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Charging, Grid Electricity Swapping, Ren Electricity Charging, Ren Electricity Swapping, H2 Fossil Bunkering, H2 Renewable Bunkering, Bio Methanol, Ren Methanol

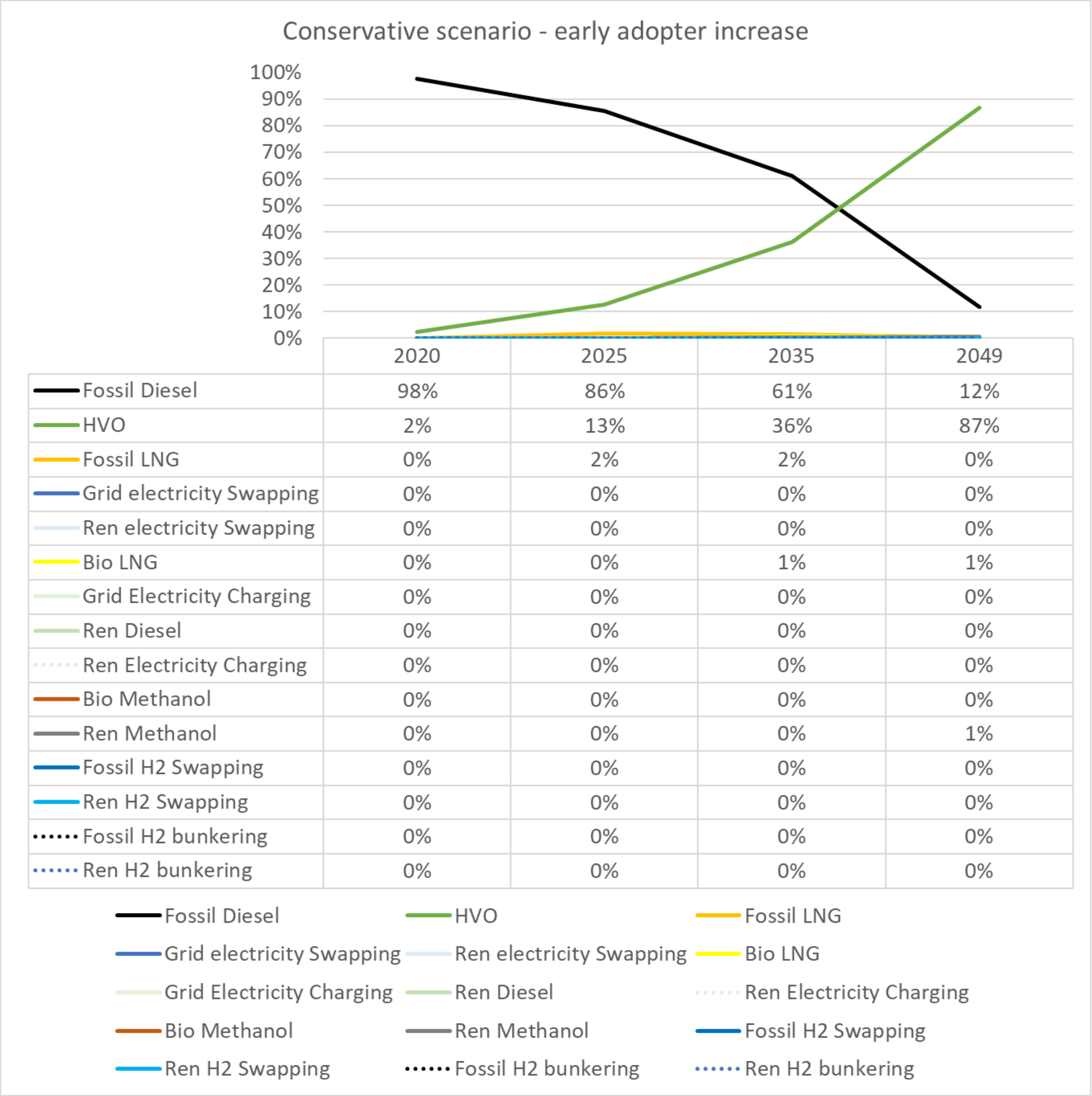
Since both the conservative and innovative scenario didn’t result in the desired emission reduction of CO2e, the settings of the model were adjusted. Two additional scenarios were made based on the price settings and acceptance factors for the conservative and innovative scenario but with a much more optimistic assumption on the share of ‘early adopters’ of technologies and energy types with a higher CO2e reduction. It was now assumed that between 2020 and 2049 there is a gradual increase from 2% to 90% of the vessel owners/operators which choose for the socially responsible energy carrier and technology, aiming for the highest CO2e reduction per euro in the TCO. However, this obviously requires additional policy measures, which are not yet included in regular scenarios. For this conservative scenario with optimistic early adopter setting, the following result was produced with the model run for the technology and energy mix.

Table 7 presents the summarising overview of results:

Table 7 summarising results performance indicators Conservative early adopter increase scenario

	2020	**2025**	**2035**	**2049**
CO2 WTW, kTon	384	356	262	112
Index compared to 2020	100	93	68	29
Total number of refits (2020-2050)	661			
Average investment (CAPEX) per refit	€ 732,357			
CAPEX total (2020-2050)	€ 484,088,119			
OPEX Total (2020-2050)	€ 3,028,952,306			

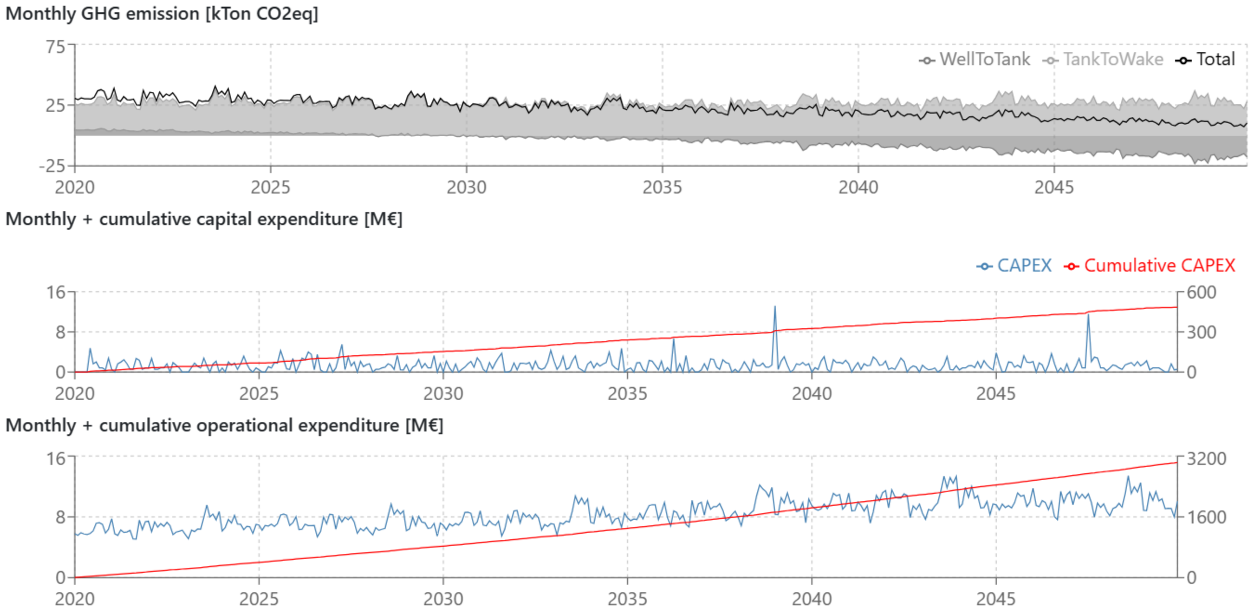
Number of vessels in model in 2049	292



	2020	2025	2035	2049
Fossil Diesel	98%	86%	61%	12%
HVO	2%	13%	36%	87%
Fossil LNG	0%	2%	2%	0%
Grid electricity Swapping	0%	0%	0%	0%
Ren electricity Swapping	0%	0%	0%	0%
Bio LNG	0%	0%	1%	1%
Grid Electricity Charging	0%	0%	0%	0%
Ren Diesel	0%	0%	0%	0%
Ren Electricity Charging	0%	0%	0%	0%
Bio Methanol	0%	0%	0%	0%
Ren Methanol	0%	0%	0%	1%
Fossil H2 Swapping	0%	0%	0%	0%
Ren H2 Swapping	0%	0%	0%	0%
Fossil H2 bunkering	0%	0%	0%	0%
Ren H2 bunkering	0%	0%	0%	0%

Figure 8: Energy mix distribution Conservative early adopter increase scenario

In this scenario it becomes clear that HVO / biodiesel becomes the most dominant fuel type with a share of 87% in 2049, see figure 8. Still 12% remains using fossil diesel in 2049 while 1% uses BioLNG. As result of the usage of HVO/biodiesel and BioLNG the GHG emissions do have a significant reduction. Compared to 2020 there is a reduction of 81% reached in 2049 on Well-to-Wake basis. This is shown in figure 9.


Monthly GHG emission [kTon CO2eq]

Monthly + cumulative capital expenditure [M€]

Monthly + cumulative operational expenditure [M€]

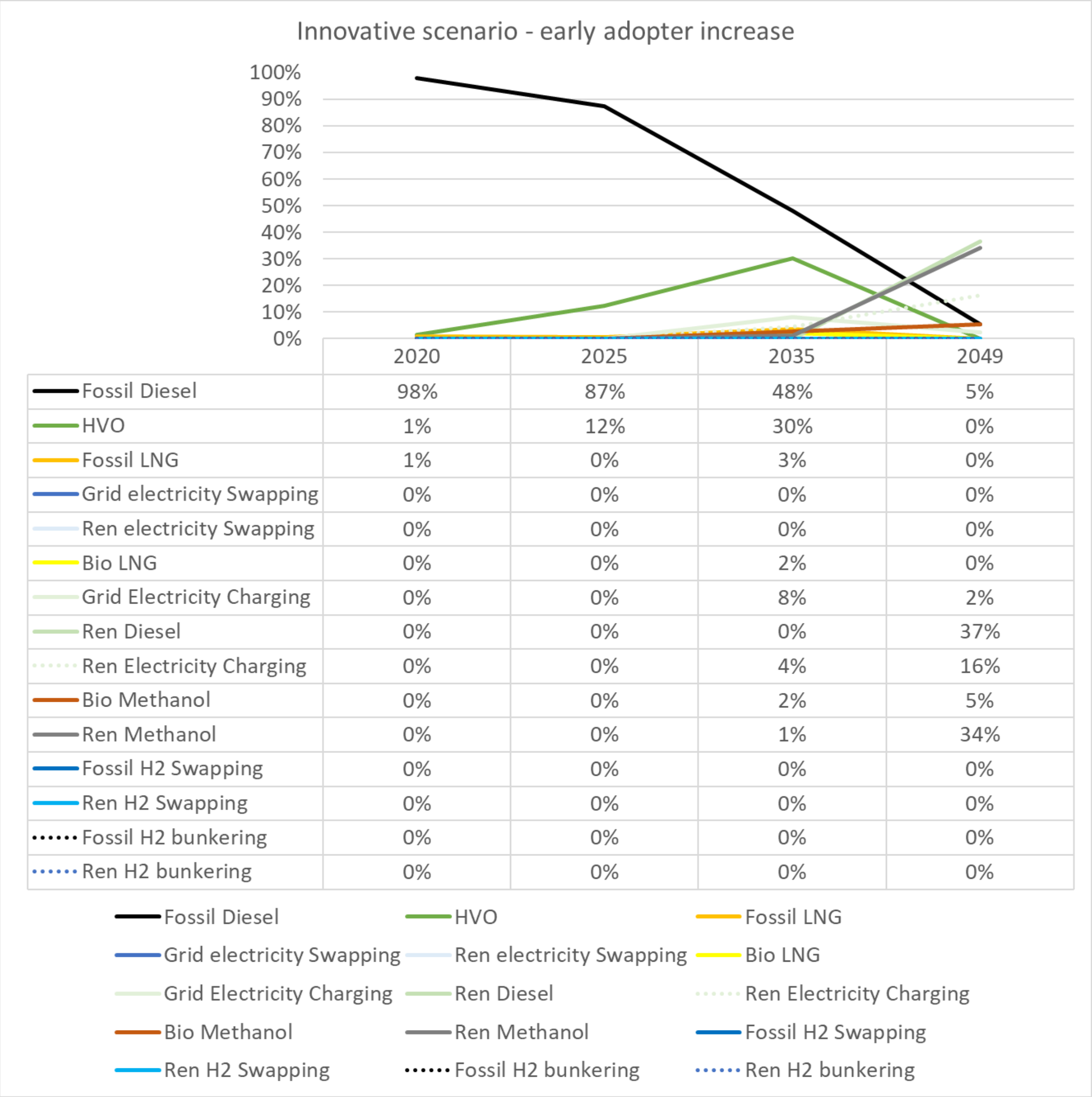
Figure 9: Development GHG emissions and CAPEX and OPEX for Conservative early adopter scenario

3.5 Innovative early adopter scenario

Also, the innovative scenario was applied but with a much more optimistic assumption on the share of socially responsible vessel owner/operators (an assumed gradual increase from 20% in 2020 to 90% in 2049). The following settings have been used for this simulation:

- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have followed the power system selection logic: every 10 year a ship reassessed the applicability of the ships' power system
- The early adopter increase was switched on. This means that in 2020, 2% of the bunker actions is performed with the energy carrier that has the best ratio between price and CO2 emission (instead of the lowest price). This percentage is increasing to 35% in 2035 and 90% in 2050.
- The innovation level was set to INNOVATIVE. This influences the prices and availability of energy carriers, the CAPEX for refits, the TRL and social acceptance of technology solutions.
- The energy carrier types available in the simulation were: Fossil Diesel, Bio Diesel , HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Charging, Grid Electricity Swapping, Ren Electricity Charging, Ren Electricity Swapping, H2 Fossil Bunkering, H2 Renewable Bunkering, Bio Methanol, Ren Methanol

The following results were found while running the innovative scenario with more optimistic assumptions on the share of early adopter.



	2020	2025	2035	2049
Fossil Diesel	98%	87%	48%	5%
HVO	1%	12%	30%	0%
Fossil LNG	1%	0%	3%	0%
Grid electricity Swapping	0%	0%	0%	0%
Ren electricity Swapping	0%	0%	0%	0%
Bio LNG	0%	0%	2%	0%
Grid Electricity Charging	0%	0%	8%	2%
Ren Diesel	0%	0%	0%	37%
Ren Electricity Charging	0%	0%	4%	16%
Bio Methanol	0%	0%	2%	5%
Ren Methanol	0%	0%	1%	34%
Fossil H2 Swapping	0%	0%	0%	0%
Ren H2 Swapping	0%	0%	0%	0%
Fossil H2 bunkering	0%	0%	0%	0%
Ren H2 bunkering	0%	0%	0%	0%

Figure 10: Energy mix distribution Innovative early adopter increase scenario

As shown in figure 10 this scenario the share of renewable (synthetic) diesel becomes dominant in 2049 in combination with the usage of renewable methanol. Both technologies assume the usage of internal combustion engines. In addition, the battery-electric solution with charging from shore with renewable electricity is selected by ship owners and counts for 16% of the total energy consumption. Other energy types seen in the mix for 2049 are bio methanol, charging from electricity grid. Also, fossil diesel is still used in 2049 and counts for 5% of the energy used.

As a result of the major usage of energy carriers with zero or low carbon intensity, the CO2e emissions reduce dramatically in this scenario. This can be seen in figure 11. The reduction of CO2e emissions in 2049 is 88% compared to the 2020 emission level.

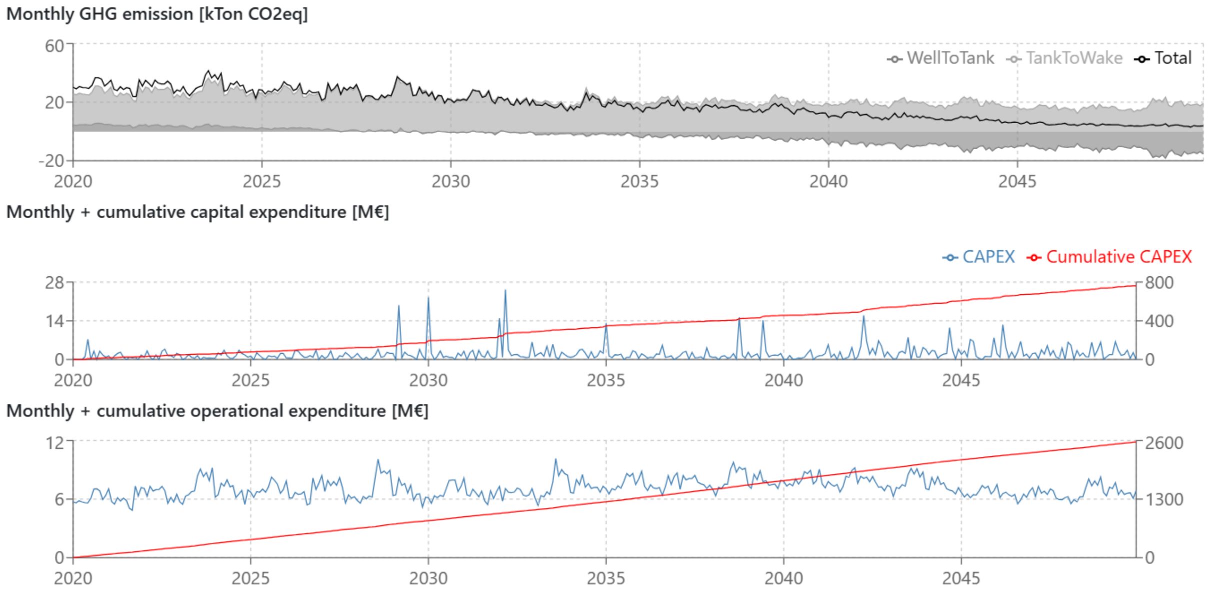


Figure 11: Development GHG emissions and CAPEX and OPEX for Innovative early adopter scenario

Table 8 presents the summarizing overview of results:

Table 8 summarising results performance indicators Innovative early adopter increase scenario

	2020	2025	2035	2049
CO2 WTW, kTon	384	349	206	46
Index compared to 2020	100	91	54	12
Total number of refits (2020-2050)	887			
Average investment (CAPEX) per refit	€ 857,716			
CAPEX total (2020-2050)	€ 760,794,004			
OPEX Total (2020-2050)	€ 2,566,714,423			
Number of vessels in model in 2049	356			

It can be seen that in this scenario the number of refits is significantly higher compared to the previous scenarios. Furthermore, the investment per retrofit is much higher compared to previous ones. On the other hand, the OPEX is lower compared to the conservative early adopter scenario. However, the number of vessels to keep the transport capacity stable needs to be extended drastically to 356 vessels in total in 2049 compared to 230 vessels in the BAU scenario. Although the OPEX and CAPEX for the propulsion systems of the vessels have been taken into account, these 126 vessels in addition obviously result in additional costs, such as costs for the crew as well as costs for the hull of the vessel.

In this scenario we see that more options are being selected in the energy mix. It is therefore interesting to further analyse the technology per vessel and route

Motorvessel 67 metre, Enkhuizen – Wezel

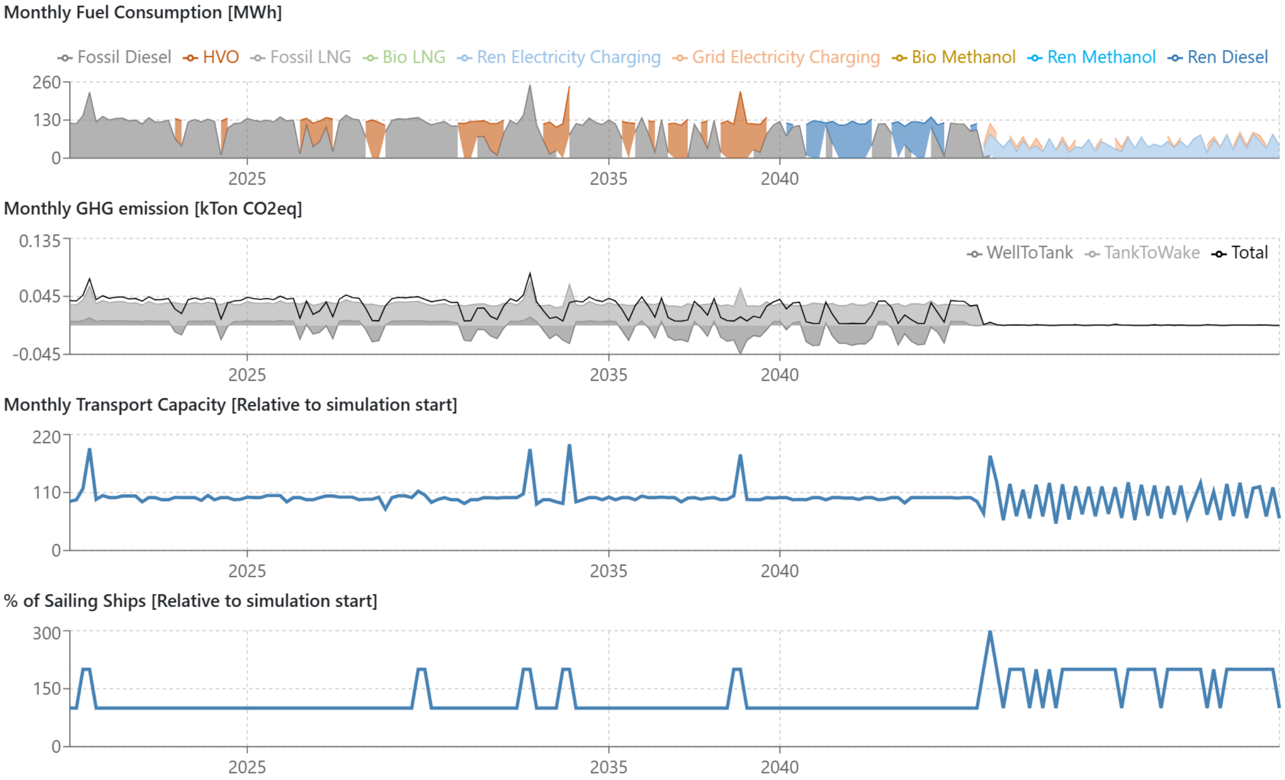


Figure 12: Development energy mix, GHG emissions, transport capacity and sailing vessels for motorvessels of 67metres on relation Wesel – Enkhuizen at Innovative early adopter scenario

The 67 meter motor vessels carrying sand and gravel on this route switch to fixed batteries from 2046 onwards. It can be seen in figure 12 that the energy consumption drops due to the higher energy efficiency and also that the GHG emissions become zero. Also, it can be seen that there is an impact on the capacity as additional vessels are needed to meet the transport demand. This is because of the loss of payload due to the batteries which need to be on board as well as caused by the additional time required for recharging the batteries.

Coupled convoy, Rotterdam – Basel

On the other end of the spectrum we can take a look at a long distance trip between Rotterdam and Basel with a large coupled convoy transporting containers.

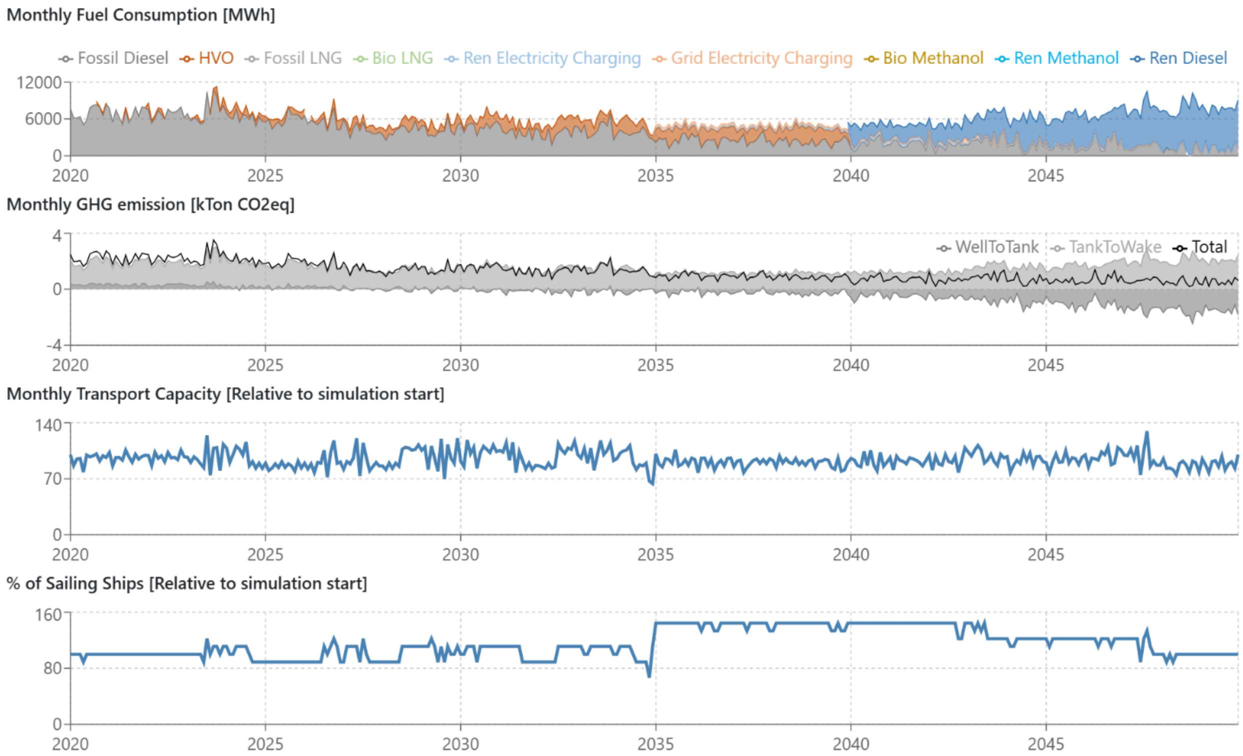


Figure 13: Development energy mix, GHG emissions, transport capacity and sailing vessels for coupled convoy on journeys between Rotterdam – Basel at Innovative early adopter scenario

As can be seen in figure 13 up to year 2035 there is a mix of HVO and diesel fuel. After 2035 there is a vessel using also grid electricity charging, which requires additional vessels to be deployed on this route. From 2040 onwards the HVO is being replaced by renewable diesel.

Motortankvessel 135 metres Antwerp – Rotterdam

Another example is are the journeys on the route between Antwerp and Rotterdam for liquid cargo in large motortankers. Here it can be seen in figure 14 that up to 2040 there is a usage of HVO next to fossil diesel. After 2040 the HVO is being replaced by renewable diesel and from 2043 onwards also some vessels use bio-renewable methanol. Gradually fossil diesel us phased out and in the last year of the model run (2049) there is also some electricity charging which causes a small decrease of transport capacity.

Figure 14: Development energy mix, GHG emissions, transport capacity and sailing 135 metre motortanker vessels on route Antwerp - Rotterdam at Innovative early adopter scenario

Large push convoy, Rotterdam – Duisburg

Also interesting is the push barge convoy (4 barges) operational on the route Rotterdam – Duisburg to carry ores for the steel production. In this output presented in figure 15 we see many changes happening during the 2020-2050 time period.

In the simulation results we see till 2030 a small share of HVO, which increases towards 2040. Surprisingly from 2032 onwards, we see that grid electricity charging is applied, which causes a big need to deploy additional push barges (3.5 times). Here we need to remark that the model does not take into account the economic costs of deployment of additional push barges. If the model would actually do that, the battery charging from shore option would not be selected.

From 2040 the renewable diesel takes over the HVO while usage of fossil diesel is phased out by 2045. After 2045 we see and increasing share of renewable electricity charged from shore but also renewable methanol and bio-methanol being selected as energy carriers.

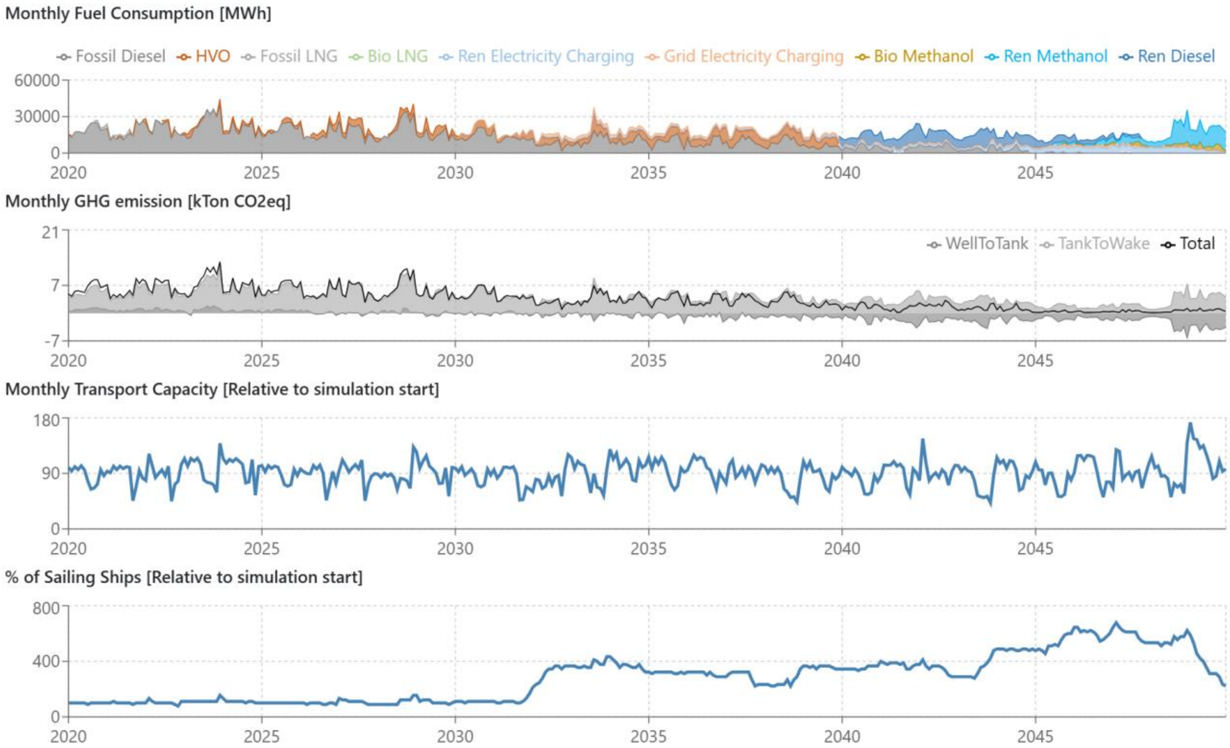


Figure 15: Development energy mix, GHG emissions, transport capacity and sailing push barge convoys on route Rotterdam – Duisburg at Innovative early adopter scenario

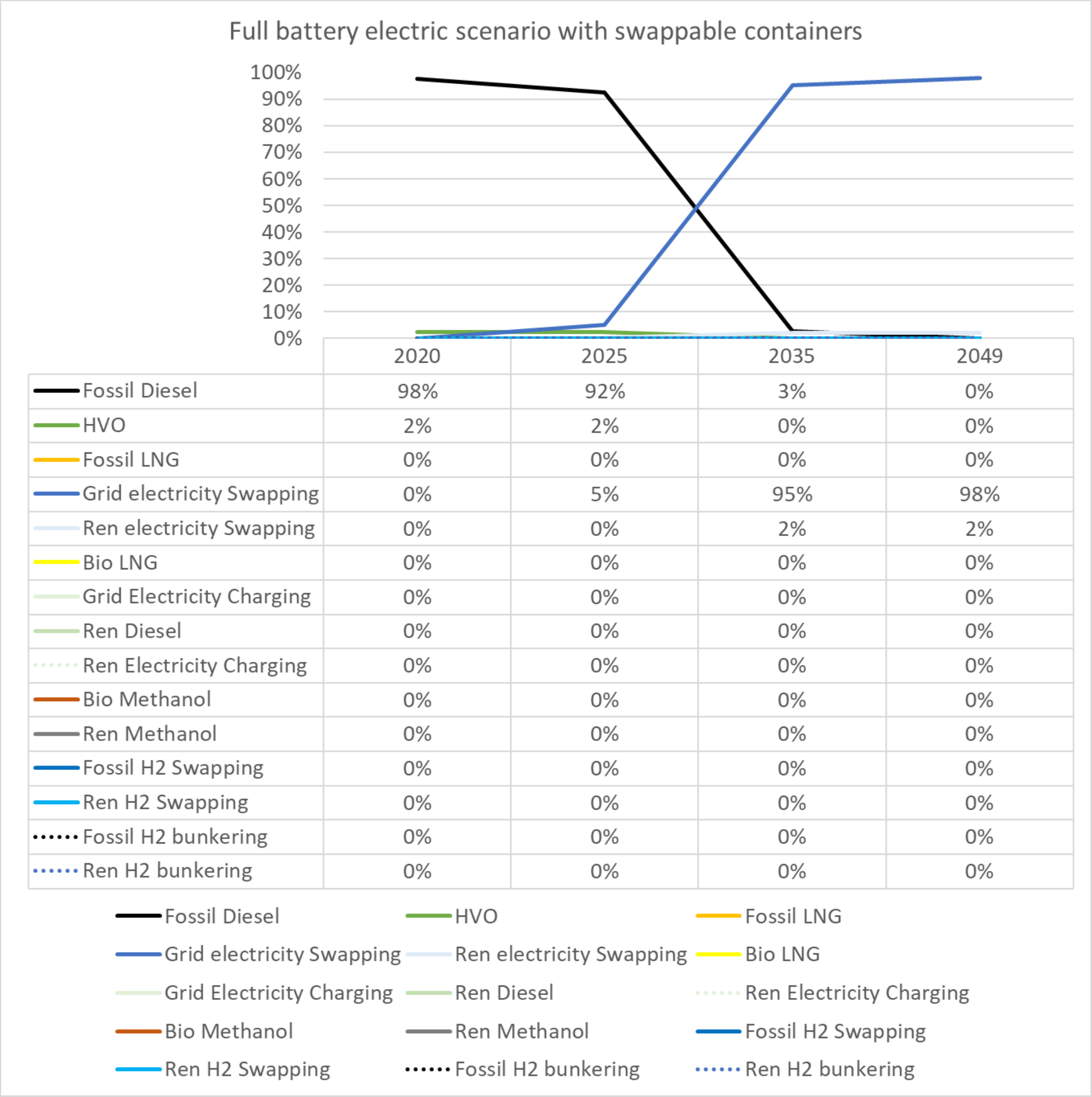
3.6 Full battery-electric scenario – swapping

This scenario was developed to see the impact of a full transition to the usage of battery - electric solutions with swappable battery containers providing a full zero-emission tailpipe solution while also the electricity itself is expected to reduce the carbon emissions quickly by means of using more green electricity, e.g. from wind and solar power.

The following settings have been used for this simulation:

- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have retained their power system throughout the simulation, unless enforced from the outside
- The innovation level was set to **AVERAGE.** This influences the prices and availability of energy carriers, the capex for refits, the TRL and social acceptance of technology solutions.

- At the start, the energy carrier types available in the simulation where: Fossil Diesel, Bio Diesel, HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Swapping, Ren Electricity Swapping, Fossil Hydrogen, Ren Hydrogen, Fossil Hydrogen Swap, Ren Hydrogen Swap, Bio Methanol, Ren Methanol
- When making a retrofit decision, only the choice could be made by vessels for Grid Electricity Swapping or Renewable Electricity swapping.



	2020	2025	2035	2049
Fossil Diesel	98%	92%	3%	0%
HVO	2%	2%	0%	0%
Fossil LNG	0%	0%	0%	0%
Grid electricity Swapping	0%	5%	95%	98%
Ren electricity Swapping	0%	0%	2%	2%
Bio LNG	0%	0%	0%	0%
Grid Electricity Charging	0%	0%	0%	0%
Ren Diesel	0%	0%	0%	0%
Ren Electricity Charging	0%	0%	0%	0%
Bio Methanol	0%	0%	0%	0%
Ren Methanol	0%	0%	0%	0%
Fossil H2 Swapping	0%	0%	0%	0%
Ren H2 Swapping	0%	0%	0%	0%
Fossil H2 bunkering	0%	0%	0%	0%
Ren H2 bunkering	0%	0%	0%	0%

Figure 16: Energy mix distribution forced battery electric with swapping scenario

Moreover, this scenario assumes a 'pay-per-use' model to be applied for the usage of the battery containers which avoids heavy investments to be made by the ship owner. The ship owner only needs to invest in the electrification of the vessel, meaning that the vessel has electric motors and energy management systems and a 'plug and play' connection for exchangeable battery containers. This is therefore a forced scenario where all vessels will choose for the battery electric swappable option. It can be seen in figure 16 that there is a rather rapid transition taking place between years 2025 and 2030. As a result also the GHG emissions reduce rapidly as can be seen in the figure 17. It also becomes clear from figure 17 that there is a big impact on the number of bunker events, meaning that much more often a container needs to be transhipped compared to the frequency of a traditional bunker operation of diesel. This is due to the much lower energy amount which can be stored on board, even though battery electric propulsion only requires half of the energy compared with the energy input for other technologies. In this scenario the total volume of energy sums up to 557 GWh in the year 2049 while the BAU scenario requires 1144 GWh of energy in 2049.

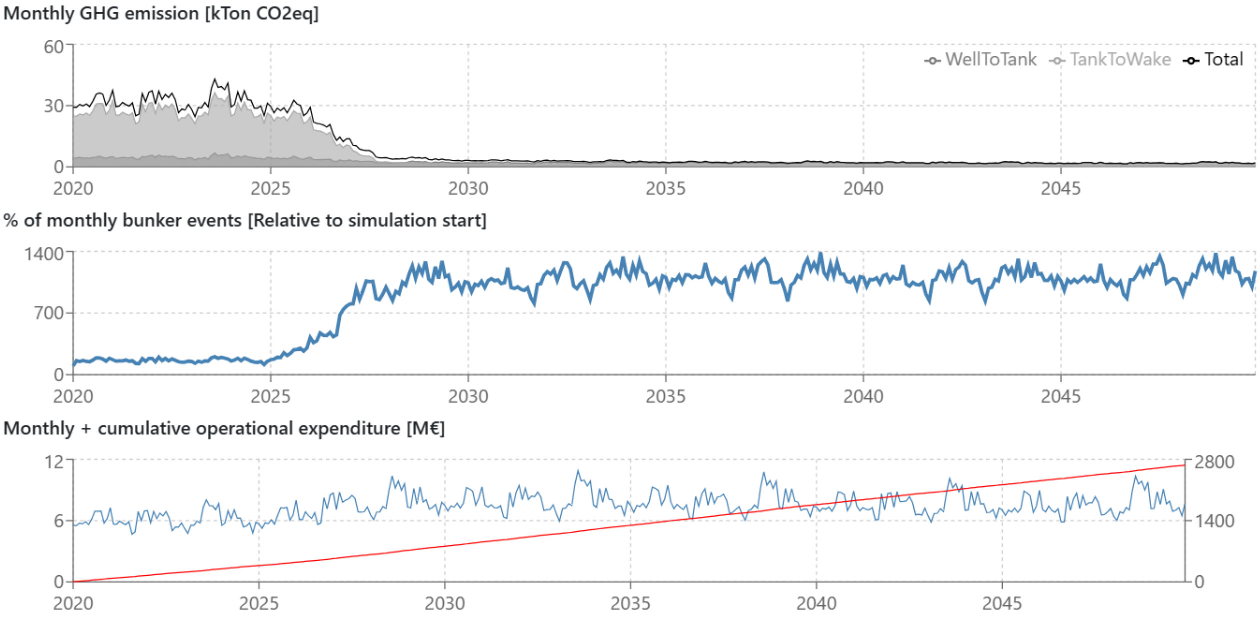


Figure 17: Development GHG emissions, bunker events and OPEX for forced battery electric scenario with swapping containers

This scenario however requires also significant infrastructure investments in battery charging facilities and transshipment facilities.

The figures 18 and 19 show the development of the bunkering per port over time, starting with December 2020 and showing the situation also in December 2035. It can be seen that the inland ports along the Rhine will have an increase of energy demand for providing the (charged) swappable containers while a more dense network of transhipment terminals and recharging points develops. Obviously, this requires the development of recharging facilities in that area and also sufficient transhipment facilities for handling the swappable battery containers. The share of Rotterdam in the energy supply clearly reduces.

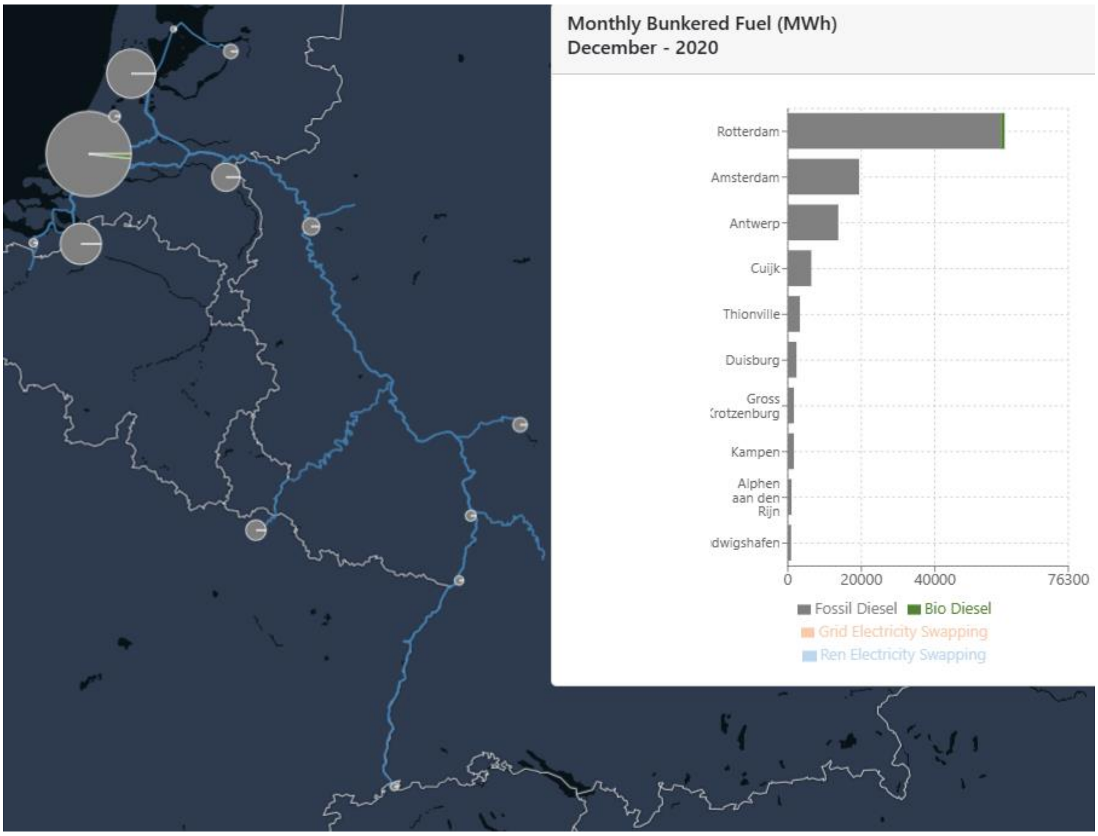


Figure 18: Map of energy supply demand for the forced swappable battery container scenario in December 2020

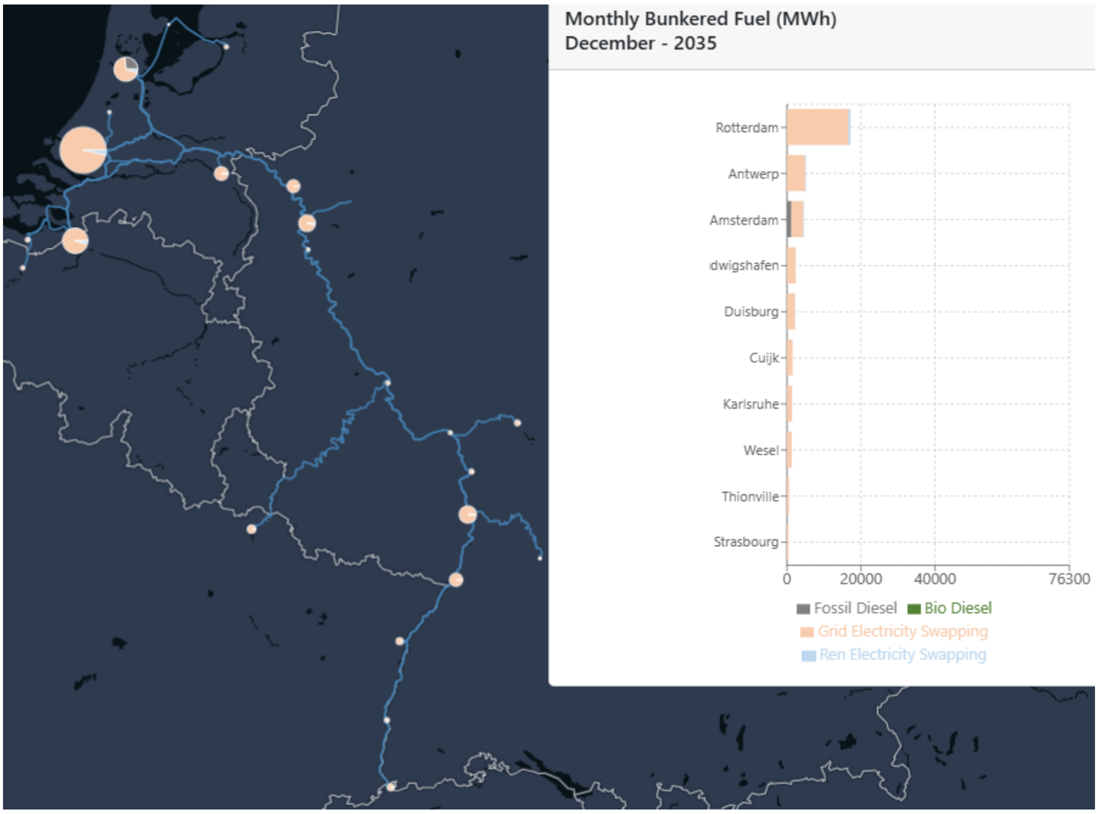


Figure 19: Map of energy supply demand for the forced swappable battery container scenario in December 2035

Table 9 presents the summarizing overview of results:

Table 9 summarising results performance indicators for forced battery electric scenario with swapping containers

	2020	2025	2035	2049
CO2 WTW, kTon	382	342	29	23
Index compared to 2020	100	90	8	6
Total number of refits (2020-2050)	671			
Average investment (CAPEX) per refit	€ 224,965			
CAPEX total (2020-2050)	€ 150,951,623			
OPEX Total (2020-2050)	€ 2,667,753,703			
Number of vessels in model in 2049	281			

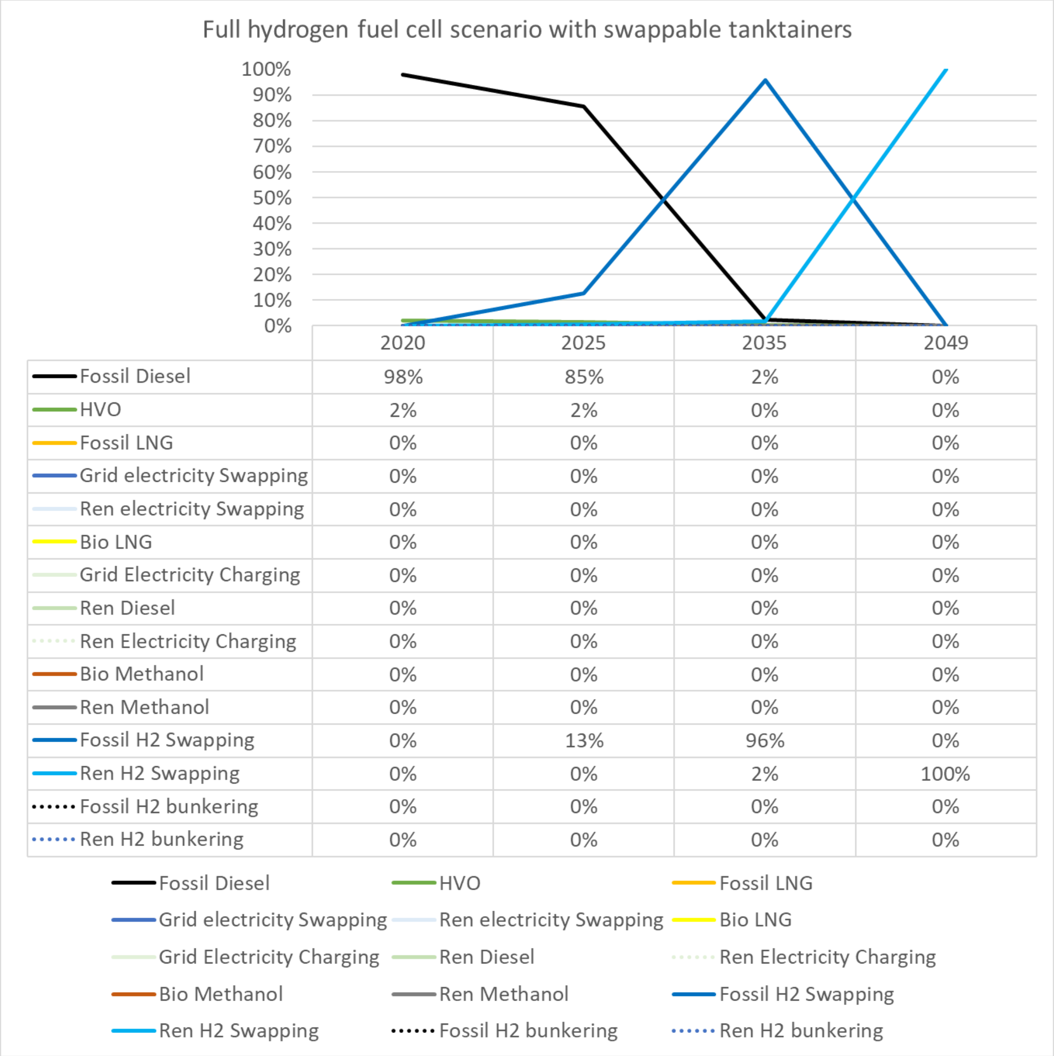
It can be seen that in this scenario the CO2e reduction target of 90% is already achieved by 2035. It decreases even further with more usage of fully renewable electricity instead of the average electricity mix on the grid. It can also be seen that the average CAPEX per vessel is rather low, while there is no dramatic increase in OPEX. At first glance, looking at the costs for the vessels, the swappable battery containers with electric vessels seems therefore a cost-effective technology and energy carrier approach to reduce emissions. However, the number of vessels to keep the transport capacity stable needs to be extended to 281 vessels in total in 2049 compared to 230 vessels in the BAU scenario. Although the OPEX and CAPEX for the propulsion systems of the vessels have been taken into account, these 51 vessels in addition obviously result in additional costs, such as costs for the crew as well as costs for the hull of the vessel.

3.7 Full hydrogen FC-electric swapping scenario

The following settings have been used for this simulation:

- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have retained their power system throughout the simulation, unless enforced from the outside
- The innovation level was set to **AVERAGE**. This influences the prices and availability of energy carriers, the capex for refits, the TRL and social acceptance of technology solutions.
- At start of the simulation the energy carrier types available were: Fossil Diesel, Bio Diesel, HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Charging, Grid Electricity Swapping, Ren Electricity Charging, Ren Electricity Swapping, Fossil Hydrogen Swap, Ren Hydrogen Swap, Bio Methanol, Ren Methanol
- When making a retrofit decision, only the choice could be made by vessels for Fossil Hydrogen Swapping or Ren Hydrogen Swapping

This scenario was developed to see the impact of a full transition to the usage of fuel cell hydrogen solutions with swappable hydrogen containers (tanktainers) providing a full zero-emission tailpipe solution. Here it is expected that renewable hydrogen will become available over the next decades to provide a zero-emission solution both from tank to wake but also from well to wake point of view. This scenario however requires also significant infrastructure investments in (green) hydrogen production facilities and transshipment facilities for the tanktainers. The ship owner however needs to invest heavily in the fuel cell and hydrogen storage and management systems on board. Moreover, the vessel needs to be electrified, meaning that the vessels require electric motors, energy management systems, and a 'plug and play' connection for fuel cell system. This is therefore a forced scenario where all vessels will choose the hydrogen fuel cell option with swappable containers to minimize the time loss for bunkering.



	2020	2025	2035	2049
Fossil Diesel	98%	85%	2%	0%
HVO	2%	2%	0%	0%
Fossil LNG	0%	0%	0%	0%
Grid electricity Swapping	0%	0%	0%	0%
Ren electricity Swapping	0%	0%	0%	0%
Bio LNG	0%	0%	0%	0%
Grid Electricity Charging	0%	0%	0%	0%
Ren Diesel	0%	0%	0%	0%
Ren Electricity Charging	0%	0%	0%	0%
Bio Methanol	0%	0%	0%	0%
Ren Methanol	0%	0%	0%	0%
Fossil H2 Swapping	0%	13%	96%	0%
Ren H2 Swapping	0%	0%	2%	100%
Fossil H2 bunkering	0%	0%	0%	0%
Ren H2 bunkering	0%	0%	0%	0%

Figure 20: Energy mix distribution forced hydrogen fuel cell with swapping scenario

In this scenario the transition to hydrogen as fuel is also going very rapid as can be seen in figure 20. However, it can be seen in figure 21 that until 2038 fossil hydrogen is used which is being replaced by renewable hydrogen. Therefore, from year 2038 onwards there is a full zero-emission performance seen in this scenario.

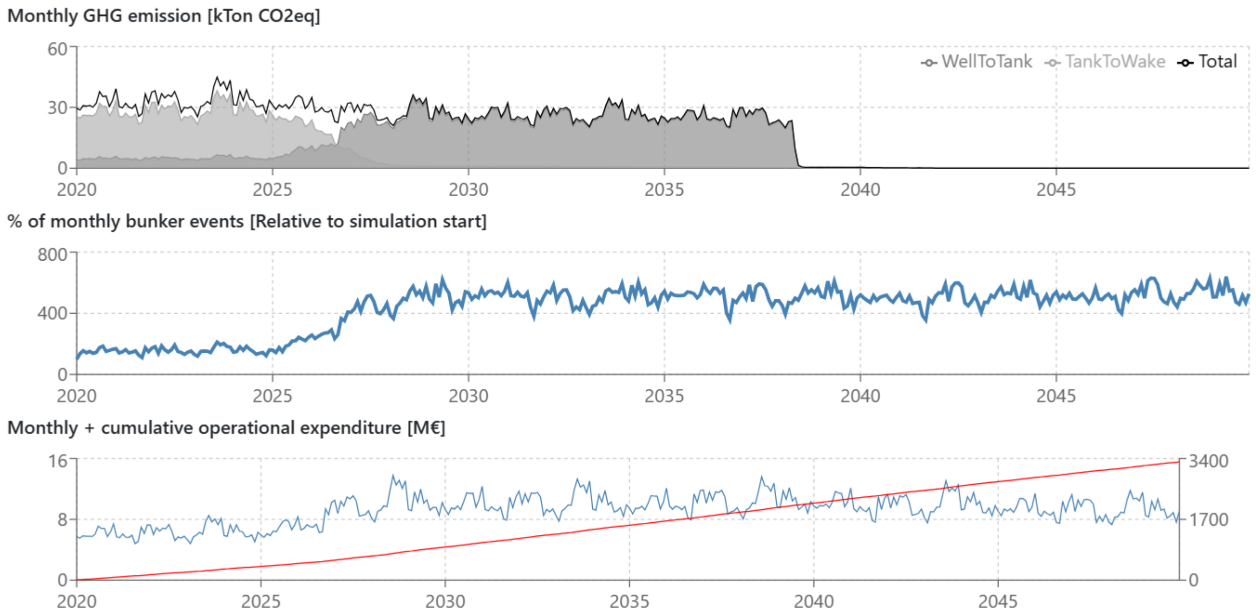


Figure 21: Development GHG emissions, bunker events and OPEX for forced hydrogen fuel-cell electric scenario with swapping containers

Table 10 presents the summarizing overview of results:

Table 10 summarising results performance indicators for forced hydrogen fuel-cell electric scenario with swapping containers

	2020	**2025**	**2035**	**2049**
CO2 WTW, kTon	385	380	308	0
Index compared to 2020	100	98	80	0
Total number of refits (2020-2050)	671			
Average investment (CAPEX) per refit	€ 10,804,107			
CAPEX total (2020-2050)	€ 7,249,555,673			
OPEX Total (2020-2050)	€ 3,303,803,050			
Number of vessels in model in 2049	259			

Although full zero-emission performance is reached in this scenario, it can be seen that there are big costs implications. The average CAPEX per vessel is extremely high at 10.8 million euro per vessel. Furthermore, also the OPEX is significantly higher. Also the number of vessels to keep the transport capacity stable needs to be extended a bit to 259 vessels in total in 2049 compared to 230 vessels in the BAU scenario. Although the OPEX and CAPEX for the propulsion systems of the vessels have been taken into account, these 29 vessels in addition obviously result in additional costs, such as costs for the crew as well as costs for the hull of the vessel.

3.8 Full hydrogen FC-electric bunkering and swapping scenario

In order to get a view on the difference between swappable only and a mix with bunkering hydrogen (in fixed compressed hydrogen storage on board), a separate scenario run was made. Here there was a random pick for the technology between fixed hydrogen tanks on board or swappable hydrogen 'tanktainers'.

The following settings have been used for this simulation:

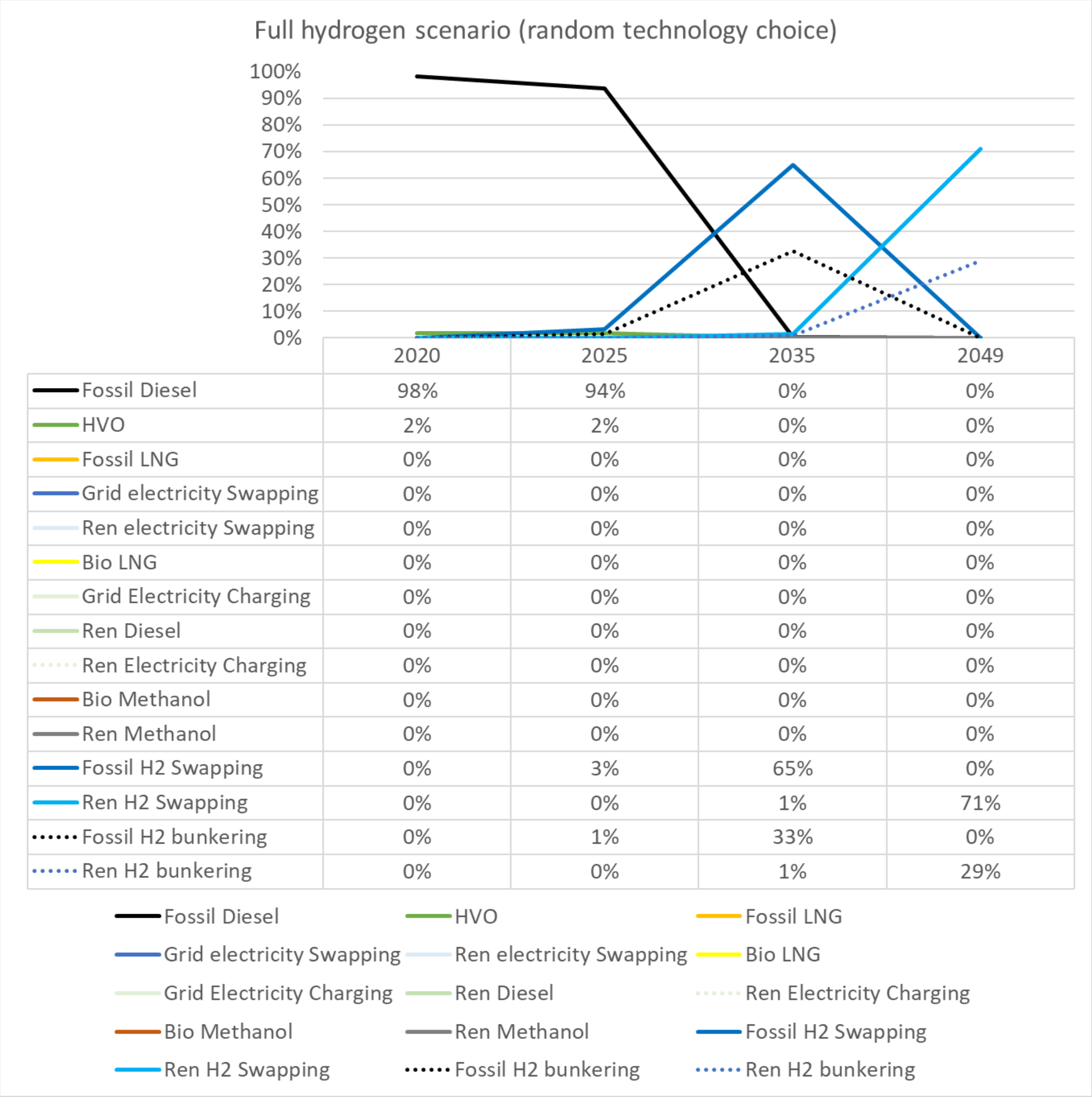
- The simulation has run from January 1st 2020 to January 1st 2050
- Ships have automatically been added and deleted to the fleet to keep the transport capacity as constant as possible.
- The ships have retained their power system throughout the simulation, unless enforced from the outside
- The innovation level was set to **AVERAGE**. This influences the prices and availability of energy carriers, the capex for refits, the TRL and social acceptance of technology solutions.
- At start of the simulation the energy carrier types available were: Fossil Diesel, Bio Diesel, HVO, Ren Diesel, Fossil LNG, Bio LNG, Grid Electricity Charging, Grid Electricity Swapping, Ren Electricity Charging, Ren Electricity Swapping, Fossil Hydrogen, Ren Hydrogen, Fossil Hydrogen Swap, Ren Hydrogen Swap, Bio Methanol, Ren Methanol
- When making a retrofit decision, only the choice could be made by vessels for:
  - Swapping exchangeable tanktainers: fossil or renewable hydrogen
  - Bunkering options (fixed hydrogen storage on board): fossil or renewable hydrogen

Table 11 presents the summarizing overview of results:

Table 11 summarising results performance indicators for forced hydrogen electric scenario with swapping and bunkering

	2020	**2025**	**2035**	**2049**
CO2 WTW, kTon	391	379	215	0
Index compared to 2020	100	97	55	0
Total number of refits (2020-2050)	671			
Average investment (CAPEX) per refit	€ 11,995,544			
CAPEX total (2020-2050)	€ 8,049,010,076			
OPEX Total (2020-2050)	€ 2,526,895,271			
Number of vessels in model in 2049	314			

The model run for this scenario resulted in the energy mix distribution as shown in figure 22.



	2020	2025	2035	2049
Fossil Diesel	98%	94%	0%	0%
HVO	2%	2%	0%	0%
Fossil LNG	0%	0%	0%	0%
Grid electricity Swapping	0%	0%	0%	0%
Ren electricity Swapping	0%	0%	0%	0%
Bio LNG	0%	0%	0%	0%
Grid Electricity Charging	0%	0%	0%	0%
Ren Diesel	0%	0%	0%	0%
Ren Electricity Charging	0%	0%	0%	0%
Bio Methanol	0%	0%	0%	0%
Ren Methanol	0%	0%	0%	0%
Fossil H2 Swapping	0%	3%	65%	0%
Ren H2 Swapping	0%	0%	1%	71%
Fossil H2 bunkering	0%	1%	33%	0%
Ren H2 bunkering	0%	0%	1%	29%

Figure 22: Energy mix distribution forced hydrogen scenario, combination swapping and bunkering

It can be seen from the results shown in figure 22 that the swappable option is more selected with a share of 71% in 2049 compared to bunkering at 29% in 2049. Moreover, similar to the full swappable scenario, the transition can be seen from fossil hydrogen to renewable hydrogen, resulting in zero well-to-tank CO2e emissions from the year 2038 onwards.

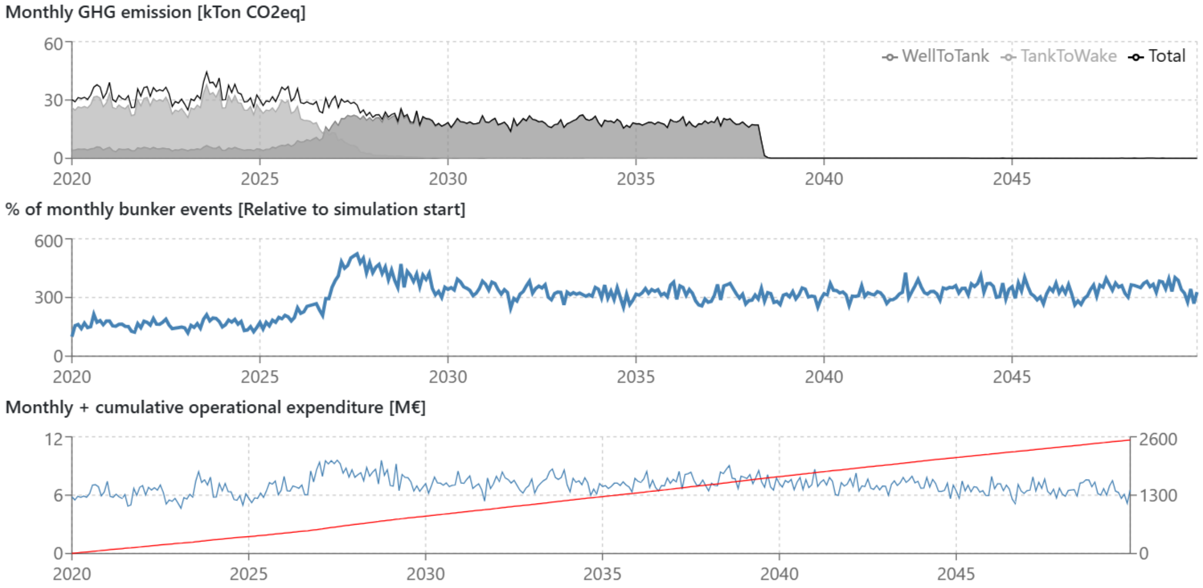


Figure 23: Development GHG emissions, bunker events and OPEX for forced hydrogen electric scenario with swapping and bunkering

Obviously there is a full zero-emission performance in this scenario as well. Figure 23 illustrates a zero well-to-wake performance from the year 2038 onwards.

It can be seen that this scenario has big costs implications, especially in the CAPEX. The average CAPEX per vessel is extremely high at 12 million euro per vessel. The OPEX is however more modest at levels of the BAU scenario. However, the number of vessels to keep the transport capacity stable needs to be extended drastically to 314 vessels in total in 2049 compared to 230 vessels in the BAU scenario. Although the OPEX and CAPEX for the propulsion systems of the vessels have been taken into account, these 84 vessels in addition obviously result in additional costs, costs for the crew as well as costs for the hull of the vessel.

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4. Scenario result comparison

4.1 Comparison of key performance indicators

Tables 12 and 13 present the summary of key performance indicators for the scenarios, both in absolute figures and subsequently in Indexes compared to BAU scenario:

Table 12 comparing performance indicators for scenarios: GHG emissions, total OPEX and CAPEX and required vessels to meet transport demand, absolute values

	GHG emissions CO2 WTW 2049, kTon	OPEX Total (2020-2050) million euro	CAPEX total (2020-2050) million euro	Vessels total in 2050
1. Business As Usual	360	2515	457	230
2. Conservative	360	3080	469	235
3. Innovative	391	3109	549	243
4. Conservative early adopter	112	3029	484	292
5. Innovative early adopter	46	2567	761	356
6. Full battery electric sailing – swapping	23	2668	151	281
7. Full H2 FC – swapping	0	3304	7249	259
8. Full H2 FC – bunkering and swapping	0	2529	8049	314

Table 13 comparing performance indicators for scenarios: GHG emissions, total OPEX and CAPEX and required vessels to meet transport demand, relative to BAU scenario

Relative compared to BAU (index, BAU = 100)				
	CO2 WTW 2049, kTon	OPEX Total (2020-2050)	CAPEX total (2020-2050)	Vessels total in 2050
1. Business As Usual	100	100	100	100
2. Conservative	111	122	103	102
3. Innovative	109	124	120	106
4. Conservative early adopter	31	120	106	127
5. Innovative early adopter	13	102	166	154
6. Full battery electric sailing – swapping	6	106	33	122
7. Full H2 FC – swapping	0	131	1586	112
8. Full H2 FC – bunkering and swapping	0	100	1761	136

It can be seen that scenarios 1,2 and 3 clearly do not meet the emission reduction ambitions as written in the policy documents (e.g. CCNR Roadmap, NAIADES III). Furthermore, the conservative scenario early adopter also seems to have a limited impact with a well-to-wake emission reduction of 69%. However, this may also depend on the specific assumption on the well-to-wake CO2e emission of HVO, which has a bandwidth, depending on the type of feedstock and the production process. Hence, also the conservative could reach the policy target of 90% reduction according to IPCC methodology followed by CCNR where biofuels in transport are set on zero-emission.

Regarding the information on CAPEX and OPEX, it needs to be remarked that the provided quantitative figures in euro do not cover all costs. Significant costs will also be needed to deploy additional vessels to maintain the transport capacity to perform the work. As a result, the transport price per ton carried cargo will (further) increase. The model however doesn’t account for the costs of additional vessels and therefore this is considered as a ‘pro memorie’ item. Additional vessels may be the result of:

- loss of transport capacity due to increased weight for energy storage and propulsion systems, such as for example the storage of battery containers or hydrogen containers
- loss of time due to more time needed for taking energy on board (e.g. in case of using bioLNG, electricity or hydrogen fuel without swappable containers)
- loss of time due to time needed to adapt the vessel to install new propulsion systems

It can be derived from tables 12 and 13 however that these costs in particular occur for scenarios 4 to 8.

Furthermore, it is interesting to compare the CAPEX costs per refit. Table 14 presents the overview:

Table 14 comparing CAPEX per refit for the scenarios

Scenario	CAPEX per refit (k euro)	Index BAU
1. Business As Usual	681	100
2. Conservative	700	103
3. Innovative	778	114
4. Conservative early adopter	732	108
5. Innovative early adopter	858	126
6. Full battery electric sailing - swapping	225	33
7. Full H2 FC - swapping	10804	1586
8. Full H2 FC - bunkering and swapping	11996	1761

Remarkable is the low CAPEX per vessel for the full battery electric application as this only accounts for one third of the CAPEX of installing a new diesel propulsion system. However, it needs to be kept in mind here that the CAPEX costs for the swappable batteries are assumed to be covered by the energy provider which offers a ‘pay-per-use’ contact to the vessel operator for the use of the battery container. These costs for the pay-per-use are covered in the OPEX of the vessel owner.

Also remarkable is the extremely high CAPEX for scenarios 7 and 8. The CAPEX is around 16 times higher compared to the BAU scenario. This is due to the very high costs for hydrogen storage and related fuel facilities on board (note: no pay-per-use scheme assumed for the tanktainers) and the high investment costs for the fuel cell system. However, it needs to be remarked here that with a pay-per-use model for the hydrogen tanktainer the CAPEX for the vessel owner would be drastically reduced. Moreover, there is also development foreseen in the fuel cell technology which is expected to lead to reduced costs for fuel cells and longer lifetimes.

Consequently, it is recommended to make further assessments taking into account such developments to see what the impact would be on the CAPEX and OPEX for the solutions based on (compressed) hydrogen as energy carrier.

Moreover, also work is being done on possibly more effective energy carriers for hydrogen such as LOHC (Liquid organic hydrogen carriers) and Sodium borohydride (NaBH4), which needs to be followed as well as this may improve the business case on medium and longer term for hydrogen as energy carrier for IWT vessels.

4.2 Comparison energy mix in 2049 per scenario

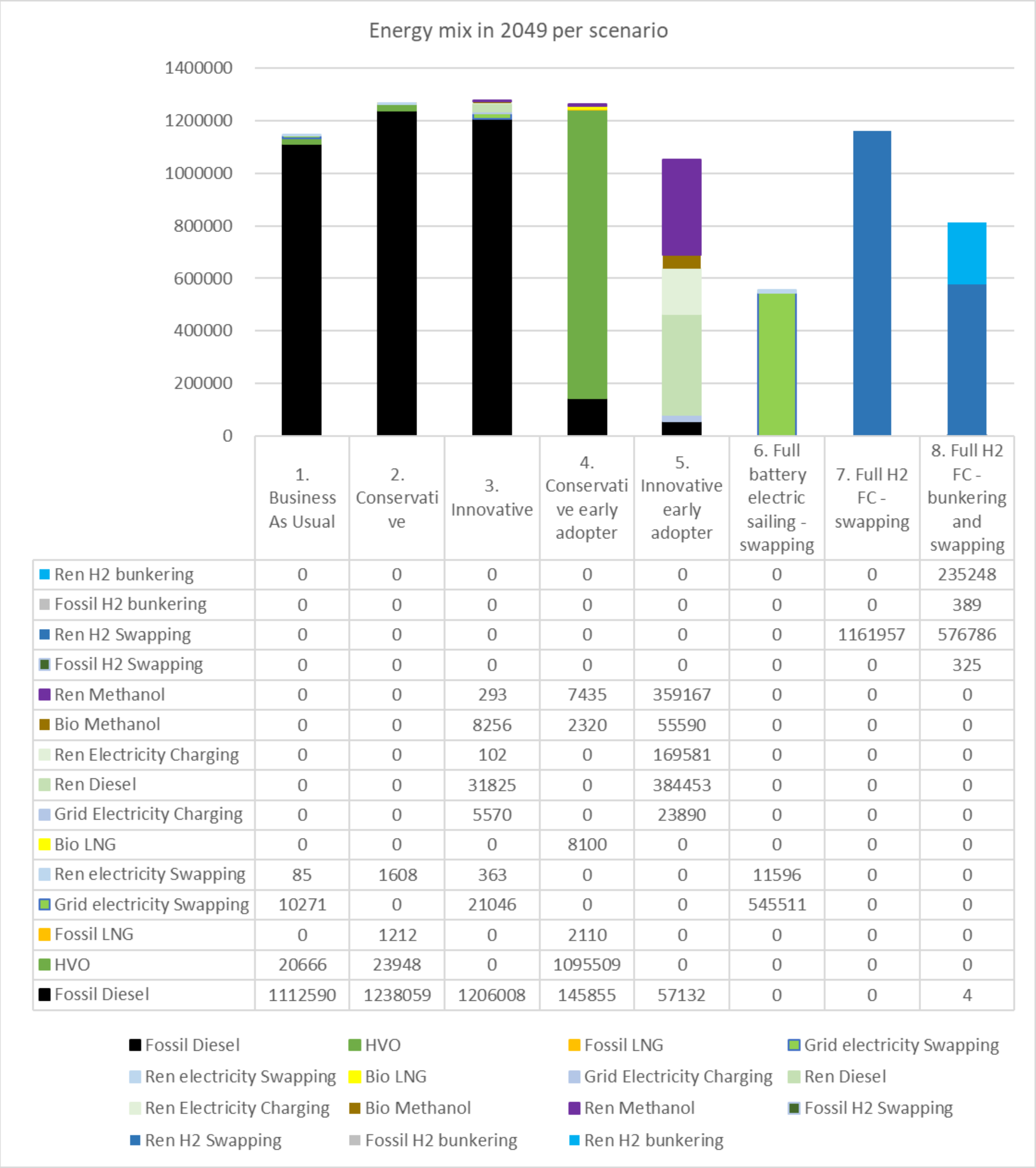
Another element to highlight is the energy demand and the energy mix. Table 15 presents the comparison between the required energy (caloric value) for the different scenarios.

Table 15 comparing energy demand per scenario in 2048

Scenario	Energy demand (GWh)	Index BAU
1. Business As Usual	1144	100
2. Conservative	1265	111
3. Innovative	1273	111
4. Conservative early adopter	1261	110
5. Innovative early adopter	1050	92
6. Full battery electric sailing - swapping	557	49
7. Full H2 FC - swapping	1162	102
8. Full H2 FC - bunkering and swapping	813	71

It can be seen that the scenario 6 with the battery electric sailing only requires 49% of the energy compared to the BAU scenario. This is because of the high energy efficiency of electric propulsion where much less thermal loss occurs in the drivetrain compared to drivetrains using combustion engines or fuel cells.

Figure 24 presents the energy mix for the 8 scenarios in the year 2049.



	1. Business As Usual	2. Conservative	3. Innovative	4. Conservative early adopter	5. Innovative early adopter	6. Full battery electric sailing - swapping	7. Full H2 FC - swapping	8. Full H2 FC - bunkering and swapping
Ren H2 bunkering	0	0	0	0	0	0	0	235248
Fossil H2 bunkering	0	0	0	0	0	0	0	389
Ren H2 Swapping	0	0	0	0	0	0	1161957	576786
Fossil H2 Swapping	0	0	0	0	0	0	0	325
Ren Methanol	0	0	293	7435	359167	0	0	0
Bio Methanol	0	0	8256	2320	55590	0	0	0
Ren Electricity Charging	0	0	102	0	169581	0	0	0
Ren Diesel	0	0	31825	0	384453	0	0	0
Grid Electricity Charging	0	0	5570	0	23890	0	0	0
Bio LNG	0	0	0	8100	0	0	0	0
Ren electricity Swapping	85	1608	363	0	0	11596	0	0
Grid electricity Swapping	10271	0	21046	0	0	545511	0	0
Fossil LNG	0	1212	0	2110	0	0	0	0
HVO	20666	23948	0	1095509	0	0	0	0
Fossil Diesel	1112590	1238059	1206008	145855	57132	0	0	4

Figure 24: Energy mix per scenario for the year 2049 (MWh)

5. Conclusion and recommendations

5.1 Conclusions and recommendations for the model

The model runs show that indeed good insight can be gained on the energy transition behaviour of vessel owners / operators based on the cost characteristics of energy carriers and the required investments. At the same time, the impact on CO2e emissions is made clear as well. This combination allows for an optimisation of the cost effectiveness to reach certain emission reductions at the lowest economic impact for the transport operator.

Moreover, the model makes clear which solutions are selected and why. The model showed the big relevance of speed of bunkering processes and the prices of fuel which have a decisive factor. This also led to the need for more manipulated scenarios with more optimistic assumptions on the 'early adaptor' behaviour and forced scenarios to see the specific impact for choosing particular zero-emission tailpipe technologies like battery electric drive and hydrogen fuel cell drive systems.

Nonetheless, there are also recommendations for further development. We can distinguish the following:

- **Taking into account the costs of deployment of additional vessels** to keep the transport capacity sufficient to meet the demand. We see now in the model that unrealistic situations occur, such as push convoys in 24/7 operation choosing battery electric sailing with charging from shore which require 4 times more vessels. This impact needs to be included in the retrofit logic to include also the costs in the TCO calculation for the additional vessels which are needed in case of (severe) loss of productivity of the vessel after the retrofit.

- **Adaptation of the rule to add new vessels to the model to keep the transport performance sufficient to meet demand**. The current rule assumes a completely new vessel is deployed, which causes an unrealistic boost in the fleet renewal as oldest vessels are taken out of the model in case transport capacity is superfluous. In reality there is a certain overcapacity in the overall fleet which should be modelled. It can be seen as a centralised pool of vessels available for all journeys in Europe to mitigate short term capacity shortage on specific journey level as result of vessels being out-of-service due to assumed retrofitting work. Moreover, the model assumes a fixed contract and stable transport services for long term, but in reality there is a high share of spot market contracts for short term with different journeys. Therefore, there are in reality much less long-term dedicated transport assignments to specific vessels on one journey.

- **More advanced retrofitting logic, taking into account the actual running hours** of propulsion systems parts, instead of a 'one-size-fits-all' assumption of 10 year lifetime for all technologies and components.

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- **Expansion of the journeys and vessel types**: not only the top 25 journeys on the wider Rhine area but also less important journeys in this area as well as expansion to other waterway areas in Europe such as for example the Danube and smaller /domestic networks in France.

- **Expansion of energy carriers and updating assumptions**: currently 11 energy/technology options have been included in the model based on currently available and validated information. However, there is a wider range possible, for example also including pay-per-use for tanktainers for (compressed hydrogen) as well as LOHC or NaBH4 as hydrogen carriers. Furthermore, also adapted scenarios can be applied assuming higher storage capacity of batteries (e.g., up to 5 MWh for a 20-foot container) and more advanced fuel cell systems. It is recommended to include such options as well as soon as there is validated information available. The model can thus also be applied to indicate the added value of these new options which may emerge in the near future. Furthermore, price predictions are changing, also influenced by policy such as the implementation of the Fit-for-55. Future runs may use updated assumptions on the prices of energy carriers and hardware components.

- **Reduction of model running time** which allows more iterations and optimisation of model settings. At the moment it takes 11 hours of computer time to make one scenario run. This long waiting time is limiting the speed of further development of the model and makes this development more time consuming and thus more expensive.

5.2 Conclusions and recommendations for the energy transition policy

From the modelling results it becomes clear that major interventions are needed to reach the emission reduction goals of 90% GHG emission reduction in 2050 compared to the year 2015 as envisaged in the CCNR roadmap.

Based on the economic rationale, the costs of energy carriers and technologies with a lower carbon footprint need to either become competitive or become the only remaining option by banning the use of fossil fuels.

The conservative and innovative pathways require early adoption to reach targets. This may be achieved by additional policy interventions and by means of pressure from the market.

From the model results it became clear that energy prices have a big impact with the assumption in the model that vessel owner/operators will select the solutions with the lowest costs of ownership. Therefore, it could make sense to make fossil diesel more expensive than low/neutral carbon intensity energy types. Future runs with the model may also be used to determine the required taxation level on CO2e emissions to reach the CO2e emission targets. It can also be considered to model the setting of a CO2e ceiling in IWT, as result of a possible Emission Trading Scheme specifically for IWT.

As was made clear in the chapter 2 and in the Deliverable D3.2, for the short term there is a big potential for drop-in solutions such as biodiesel and HVO which can be seen as ‘quick wins’ since they do not require significant CAPEX investments, as can be seen in the Conservative early adopter scenario (scenario 4).

The model results of scenarios 7 and 8 also highlight the out very high CAPEX for hydrogen technology. Therefore, if hydrogen would need to get a significant market share in inland waterway transport, not only the energy costs of hydrogen need to become competitive but also major support is required to offset the additional CAPEX. Moreover, options can be explored to enable pay-per-use concepts for hydrogen equipment as well, such as swappable hydrogen tankcontainers. This can bring down the CAPEX for the vessel owner which seems to be a big barrier. The CAPEX for swappable hydrogen tankcontainers will however be part of the fee for the energy provider. An advantage here is that the energy provider may realize economies of scale and has easier access to financial resources.

Remarkable in this respect is the low CAPEX for the battery electric solution using swappable containers. Also, the OPEX seems to be competitive in comparison to BAU. However, this requires a dense network of terminals where battery containers can be transhipped and recharged. This can be a major topic for the development of the energy infrastructure along the TEN-T waterways in Europe, where financial resources from Connecting Europe Facility can play a role.

Moreover, there may be some time loss and loss of payload involved, which may lead to some additional vessels needed to provide required capacity. The model results (scenario 6) indicated a 20% increase in the number of vessels. It needs to be kept in mind that these costs for additional vessels have not been taken into account in the total costs of ownership calculations. Seeing the low OPEX and CAPEX for vessel owner as well as the strong energy efficiency gains and the strong impact of GHG reduction, the battery electric sailing with swappable containers seems very promising. It is therefore strongly recommended to further explore, investigate and support from the side of policy.

Annex I CAPEX and OPEX assumptions applied for the scenarios

Tables 16-19 below provide an overview of the assumed cost components, both capital and operational costs, for the simulation runs.

Table 16 Energy Price in €/kWh

	Energy Price in €/kWh																				
Technology	bau_2020	bau_2025	bau_2030	bau_2035	bau_2040	bau_2045	bau_2050	cons_2020	cons_2025	cons_2030	cons_2035	cons_2040	cons_2045	cons_2050	inno_2020	inno_2025	inno_2030	inno_2035	inno_2040	inno_2045	inno_2050
Fossil Diesel	0,06	0,06	0,06	0,07	0,08	0,08	0,08	0,06	0,07	0,07	0,08	0,09	0,09	0,09	0,06	0,07	0,07	0,08	0,09	0,09	0,09
HVO	0,08	0,08	0,08	0,08	0,09	0,09	0,09	0,08	0,08	0,08	0,09	0,10	0,10	0,09	0,08	0,08	0,08	0,09	0,10	0,10	0,09
Fossil LNG	0,05	0,05	0,05	0,06	0,07	0,07	0,07	0,05	0,06	0,06	0,07	0,08	0,08	0,08	0,05	0,06	0,06	0,07	0,08	0,08	0,08
Ren Diesel	0,19	0,19	0,19	0,17	0,16	0,15	0,13	0,19	0,19	0,19	0,17	0,16	0,15	0,13	0,19	0,18	0,12	0,12	0,11	0,10	0,09
Bio LNG	0,11	0,11	0,11	0,11	0,12	0,12	0,12	0,11	0,10	0,09	0,09	0,09	0,08	0,08	0,11	0,10	0,09	0,09	0,09	0,08	0,08
Grid Electricity Charging	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,10	0,10	0,10	0,10	0,10	0,10	0,08	0,07	0,07	0,07	0,07	0,07	0,07
Grid Electricity Swapping	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,16	0,18	0,18	0,18	0,18	0,18	0,18	0,16	0,13	0,13	0,13	0,13	0,13	0,13

Ren Electricity Charging	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,12	0,12	0,12	0,12	0,12	0,12	0,10	0,09	0,09	0,09	0,09	0,09	0,09
Ren Electricity Swapping	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,23	0,23	0,23	0,23	0,23	0,23	0,21	0,16	0,16	0,16	0,16	0,16	0,16
Fossil H2 bunkering	0,10	0,10	0,10	0,10	0,11	0,11	0,12	0,10	0,13	0,13	0,13	0,13	0,13	0,13	0,10	0,13	0,13	0,13	0,13	0,13	0,13
Fossil H2 Swapping	0,10	0,10	0,10	0,10	0,11	0,11	0,12	0,10	0,13	0,13	0,13	0,13	0,13	0,13	0,10	0,13	0,13	0,13	0,13	0,13	0,13
Ren H2 bunkering	0,13	0,13	0,12	0,11	0,11	0,10	0,09	0,10	0,10	0,10	0,09	0,08	0,08	0,07	0,10	0,09	0,08	0,07	0,07	0,06	0,05
Ren H2 Swapping	0,13	0,13	0,12	0,11	0,11	0,10	0,09	0,10	0,10	0,10	0,09	0,08	0,08	0,07	0,10	0,09	0,08	0,07	0,07	0,06	0,05
Bio methanol	0,12	0,12	0,09	0,09	0,08	0,08	0,08	0,12	0,10	0,07	0,06	0,06	0,06	0,06	0,12	0,10	0,07	0,06	0,06	0,05	0,05
Ren Methanol	0,13	0,13	0,09	0,09	0,08	0,08	0,08	0,13	0,10	0,08	0,07	0,07	0,06	0,06	0,13	0,10	0,08	0,07	0,06	0,06	0,06

Table 17 Price of storage (e.g. fuel tank, batteries, etc.) in €/kWh and factors for min, avg and max prices

	Price of storage (e.g. fuel tank, batteries, etc.) in €/kWh and factors for min, avg and max prices																				
Form of energy	2020	2025	2030	2035	2040	2045	2050	min_2020	min_2025	min_2030	min_2035	min_2040	min_2045	min_2050	max_2020	max_2025	max_2030	max_2035	max_2040	max_2045	max_2050
Fossil Diesel	0,11	0,11	0,11	0,11	0,11	0,11	0,11	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
HVO	0,11	0,11	0,11	0,11	0,11	0,11	0,11	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Fossil LNG	0,40	0,40	0,40	0,40	0,40	0,40	0,40	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren Diesel	0,11	0,11	0,11	0,11	0,11	0,11	0,11	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Bio LNG	0,40	0,40	0,40	0,40	0,40	0,40	0,40	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Grid Electricity Charging	700,00	496,22	333,16	216,27	145,56	121,03	142,68	0,67	0,67	0,67	0,67	0,62	0,50	0,43	1,33	1,33	1,33	1,33	1,38	1,50	1,57
Grid Electricity Swapping	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ren Electricity Charging	700,00	496,22	333,16	216,27	145,56	121,03	142,68	0,67	0,67	0,67	0,67	0,62	0,50	0,43	1,33	1,33	1,33	1,33	1,38	1,50	1,57
Ren Electricity Swapping	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Fossil H2 bunkering	30,00	30,00	30,00	30,00	30,00	30,00	30,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Fossil H2 Swapping	30,00	30,00	30,00	30,00	30,00	30,00	30,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren H2 bunkering	30,00	30,00	30,00	30,00	30,00	30,00	30,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren H2 Swapping	30,00	30,00	30,00	30,00	30,00	30,00	30,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Bio methanol	0,18	0,18	0,18	0,18	0,18	0,18	0,18	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren Methanol	0,18	0,18	0,18	0,18	0,18	0,18	0,18	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Table 18 ICE/FC price excluding electric engine in €/kW and factors for min, avg and max prices

	ICE/FC price excluding electric engine in €/kW and factors for min, avg and max prices																			
fuel_adjusted_name	2020	2025	2030	2035	2040	2045	2050	min2020	min2025	min2030	min2035	min2040	min2045	min2050	max2020	max2025	max2030	max2035	max2040	max2045
Fossil Diesel	350,00	350,00	350,00	350,00	350,00	350,00	350,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
HVO	350,00	350,00	350,00	350,00	350,00	350,00	350,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Fossil LNG	450,00	450,00	450,00	450,00	450,00	450,00	450,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren Diesel	350,00	350,00	350,00	350,00	350,00	350,00	350,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Bio LNG	450,00	450,00	450,00	450,00	450,00	450,00	450,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Grid Electricity Charging	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Grid Electricity Swapping	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren Electricity Charging	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren Electricity Swapping	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Fossil H2 bunkering	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	0,75	0,75	0,75	0,75	0,75	0,75	0,75	1,25	1,25	1,25	1,25	1,25	1,25
Fossil H2 Swapping	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	0,75	0,75	0,75	0,75	0,75	0,75	0,75	1,25	1,25	1,25	1,25	1,25	1,25
Ren H2 bunkering	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	0,75	0,75	0,75	0,75	0,75	0,75	0,75	1,25	1,25	1,25	1,25	1,25	1,25
Ren H2 Swapping	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	2500,00	0,75	0,75	0,75	0,75	0,75	0,75	0,75	1,25	1,25	1,25	1,25	1,25	1,25
Bio methanol	475,00	475,00	475,00	475,00	475,00	475,00	475,00	0,95	0,95	0,95	0,95	0,95	0,95	0,95	1,05	1,05	1,05	1,05	1,05	1,05
Ren Methanol	475,00	475,00	475,00	475,00	475,00	475,00	475,00	0,95	0,95	0,95	0,95	0,95	0,95	0,95	1,05	1,05	1,05	1,05	1,05	1,05

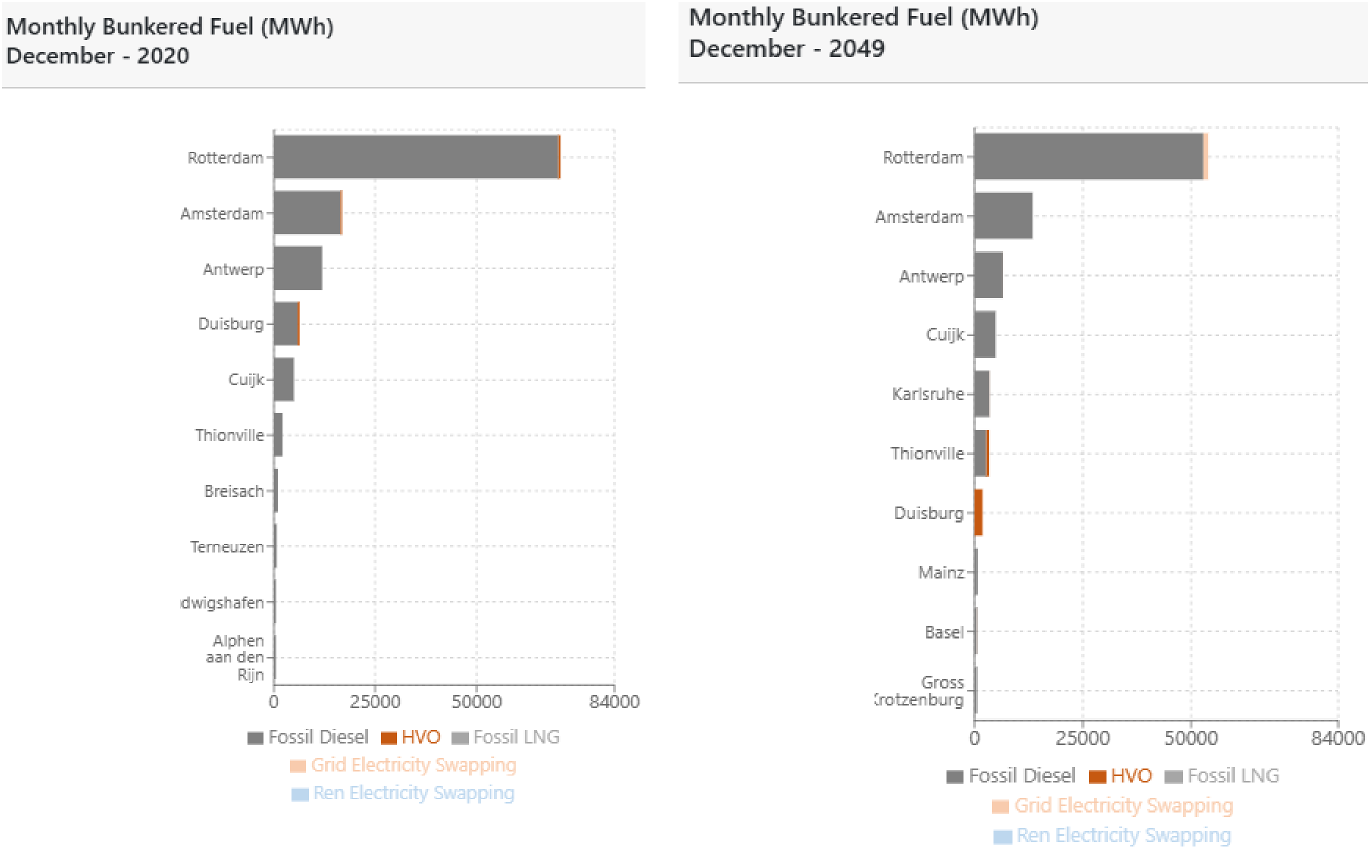
Table 19 Price of electric engine in €/kW and factors for min, avg and max prices

	Price of electric engine in €/kW and factors for min, avg and max prices																				
fuel_adjusted_name	2020	2025	2030	2035	2040	2045	2050	min_2020	min_2025	min_2030	min_2035	min_2040	min_2045	min_2050	max_2020	max_2025	max_2030	max_2035	max_2040	max_2045	max_2050
Fossil Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
HVO	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Fossil LNG	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Bio LNG	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Grid Electricity Charging	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Grid Electricity Swapping	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Ren Electricity Charging	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Ren Electricity Swapping	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Fossil H2 bunkering	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Fossil H2 Swapping	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Ren H2 bunkering	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Ren H2 Swapping	180,00	180,00	180,00	180,00	180,00	180,00	170,00	0,67	0,67	0,67	0,67	0,67	0,56	0,59	1,33	1,33	1,33	1,33	1,33	1,33	1,41
Bio methanol	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Ren Methanol	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Annex II Bunker figures per port

This Annex presents the bunker graphs (figures 25– 32) as presented on the online dashboard for the 8 different scenarios. It however needs to be remarked that the energy bunkering/charging volumes fluctuate over time. Therefore, only specific results are presented for a specific month. It was not possible to export the full dataset to provide figures on the bandwidth or average volume per year.

Business As Usual scenario


Monthly Bunkered Fuel (MWh)
December - 2020

Monthly Bunkered Fuel (MWh)
December - 2049

Figure 25: Monthly bunkering volume per port, December 2020 and December 2049 for BAU scenario

Conservative scenario

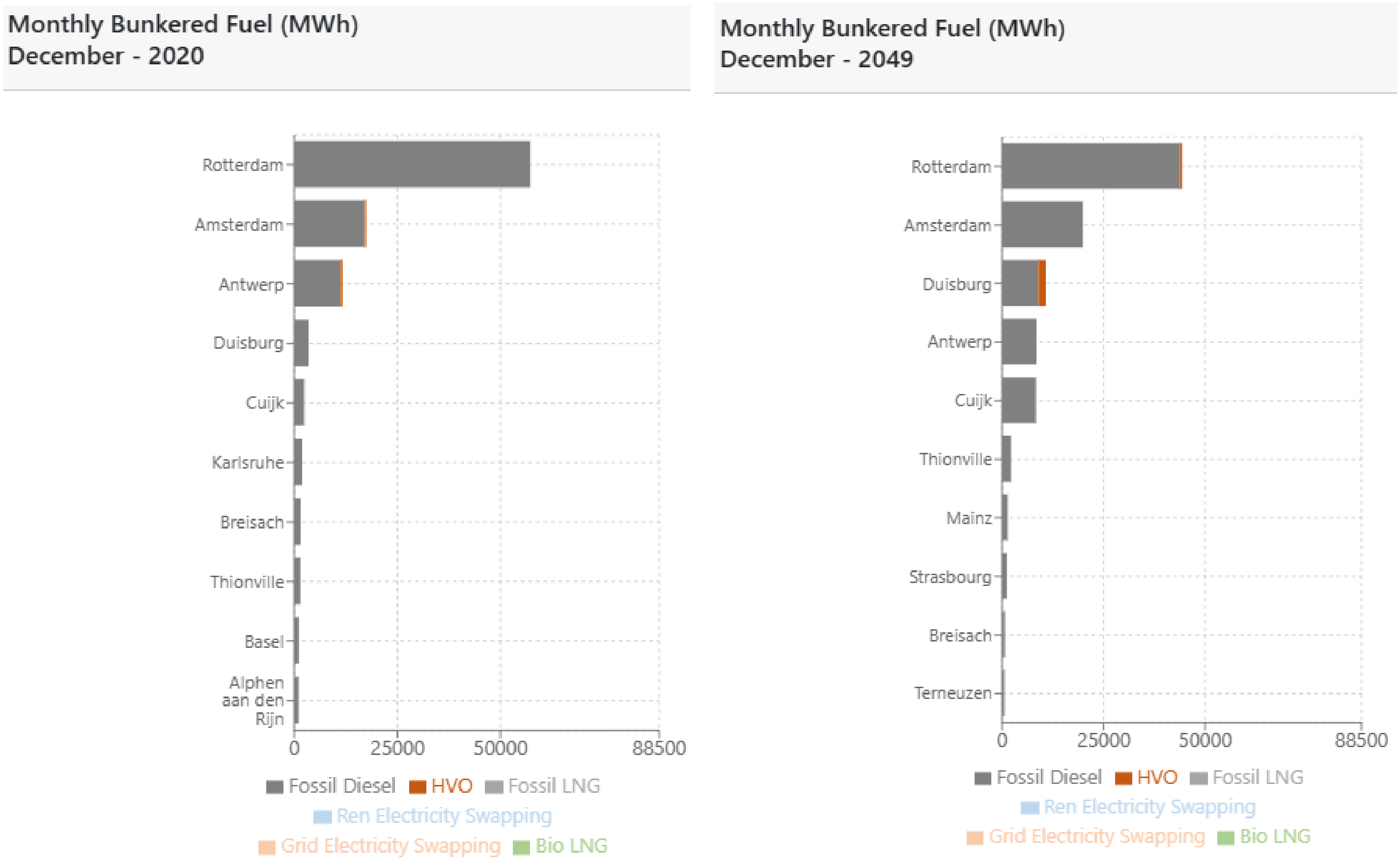


Figure 26: Monthly bunkering volume per port, December 2020 and December 2049 for conservative scenario

Innovative scenario

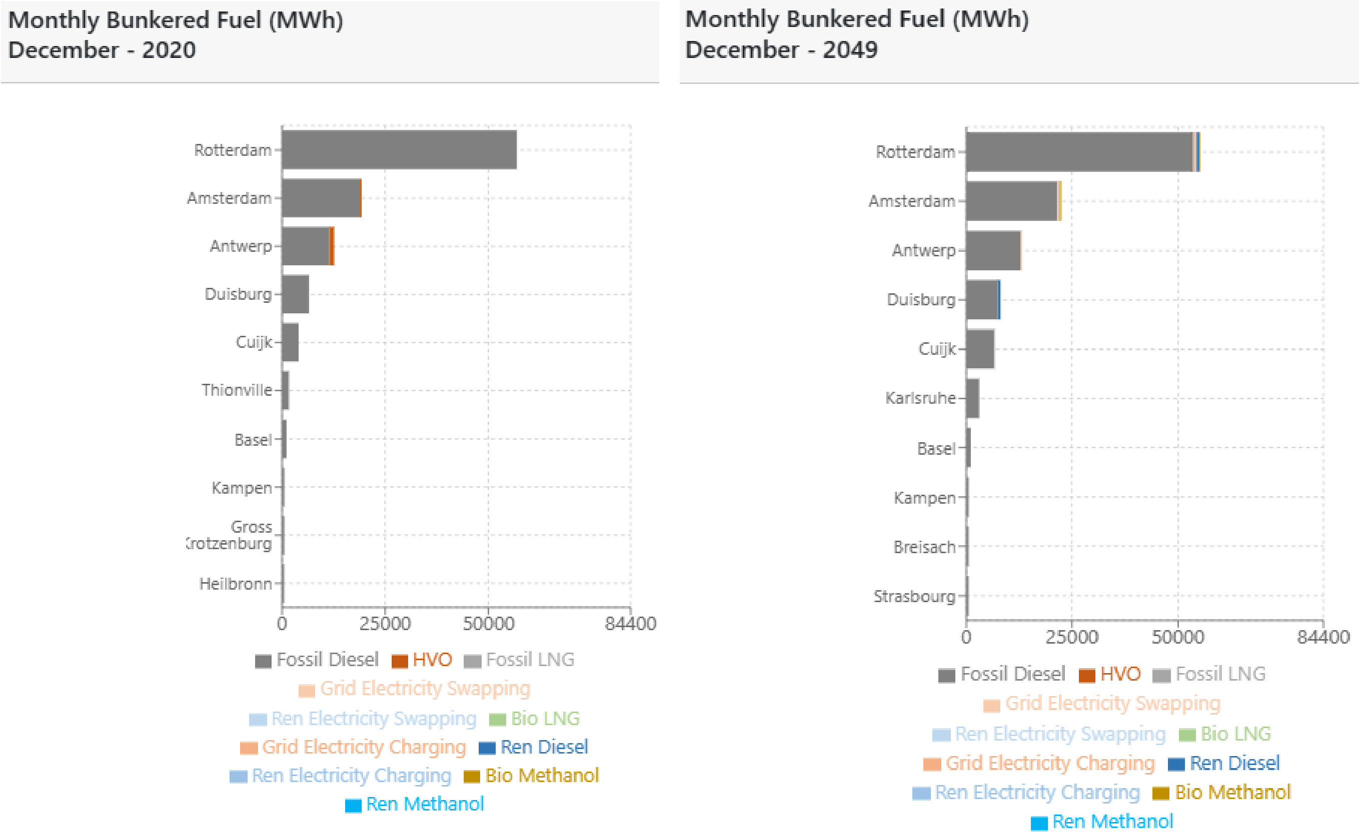


Figure 27: Monthly bunkering volume per port, December 2020 and December 2049 for innovative scenario

Conservative early adopter increase scenario

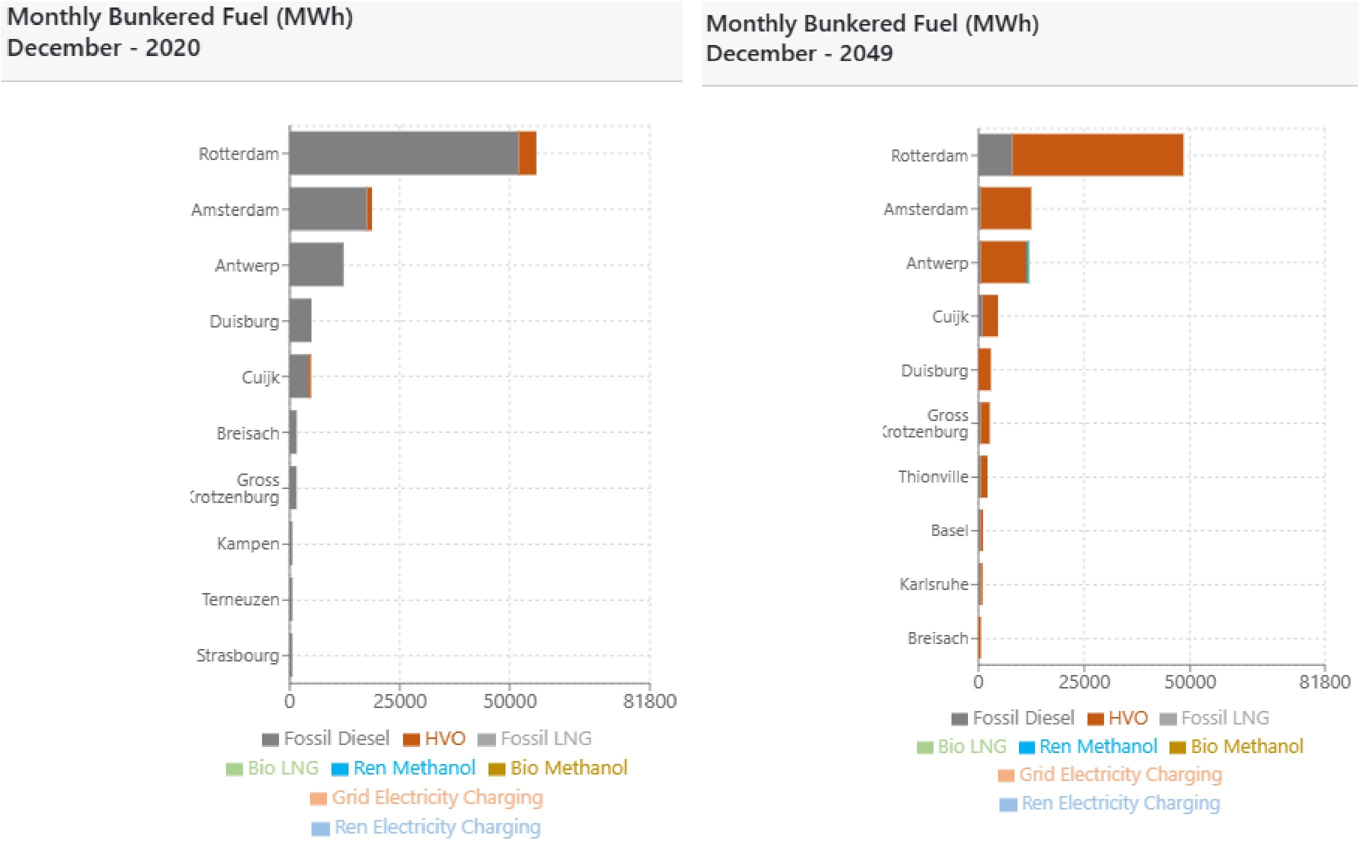
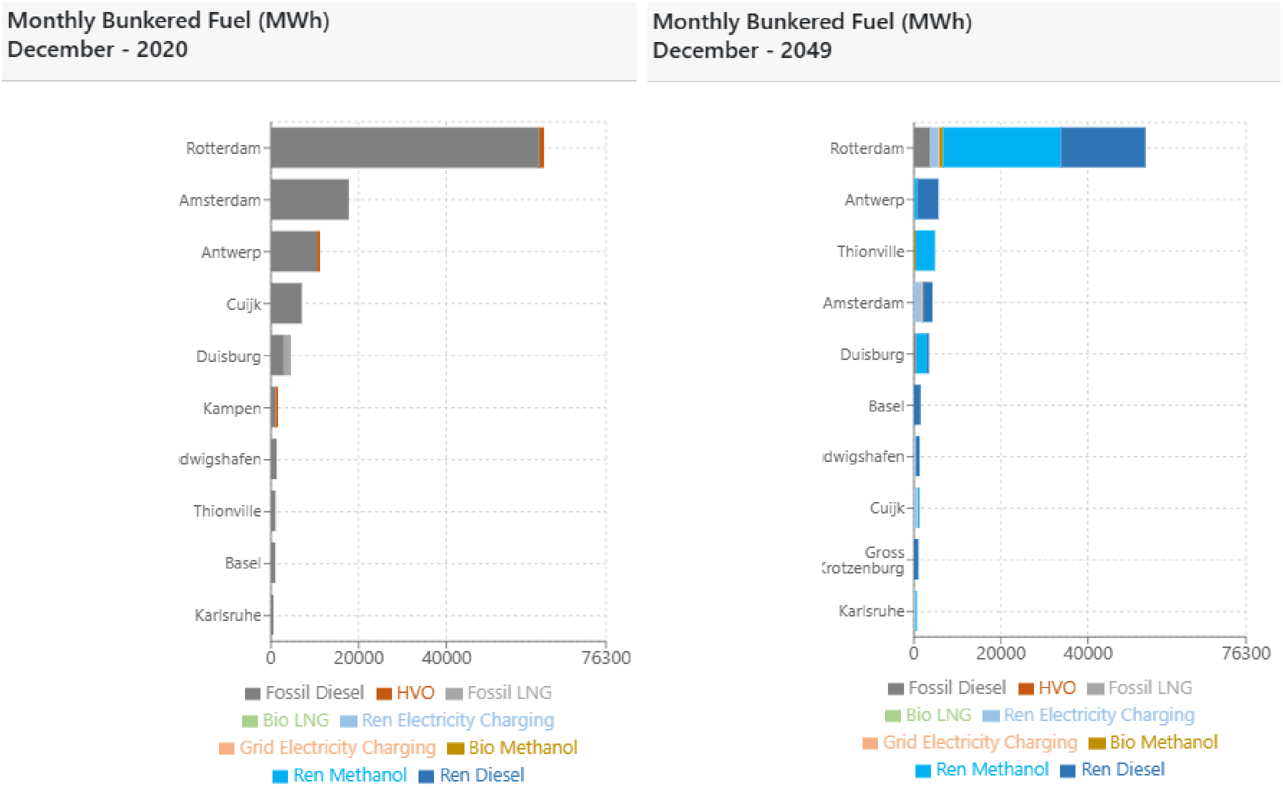


Figure 28: Monthly bunkering volume per port, December 2020 and December 2049 for conservative early adopter scenario

Innovative early adopter increase scenario

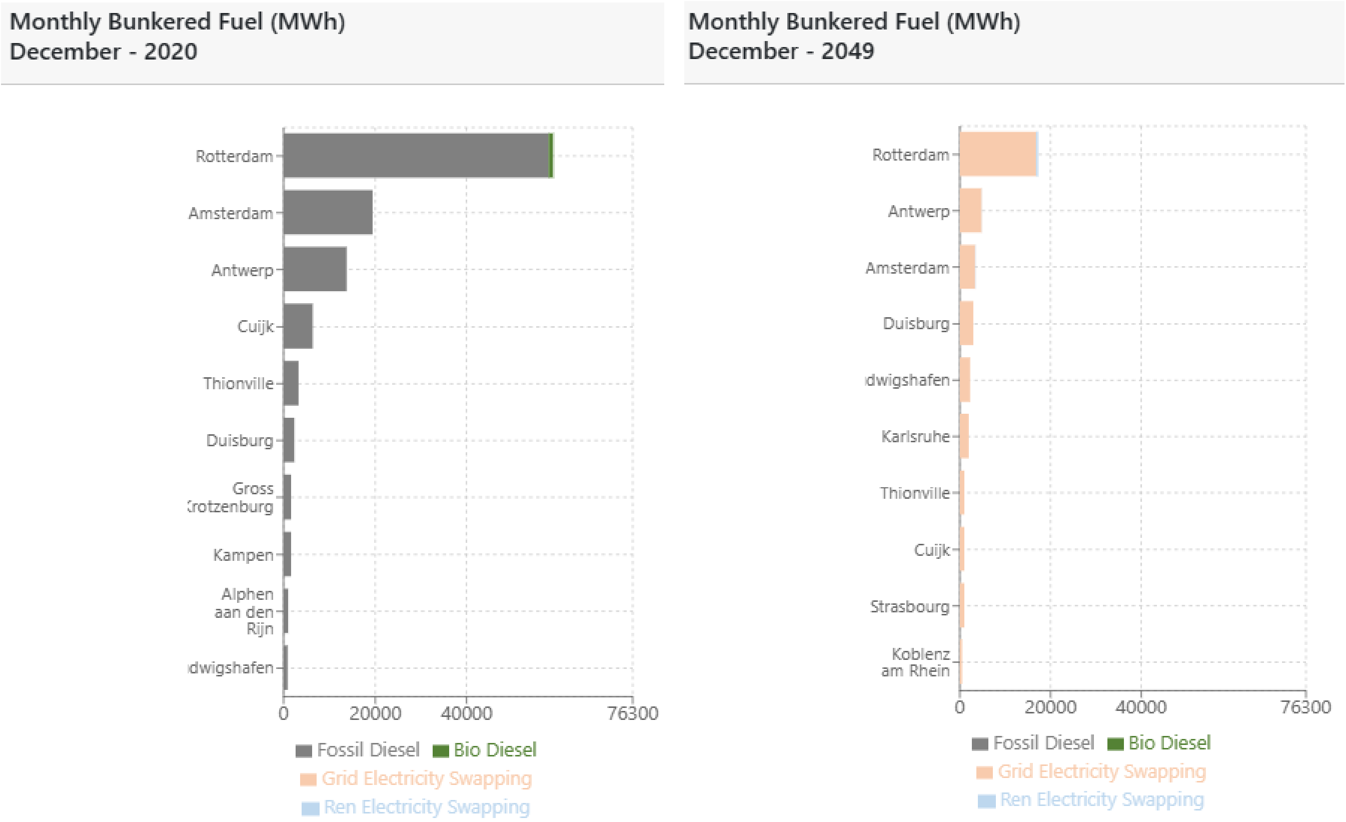


Monthly Bunkered Fuel (MWh)
December - 2020

Monthly Bunkered Fuel (MWh)
December - 2049

Figure 29: Monthly bunkering volume per port, December 2020 and December 2049 for innovative early adopter scenario

Forced battery electric sailing with swapping scenario



Monthly Bunkered Fuel (MWh)
December - 2020

Monthly Bunkered Fuel (MWh)
December - 2049

Figure 30: Monthly bunkering volume per port, December 2020 and December 2049 for forced battery electric sailing with swapping scenario

Forced fuel cell hydrogen with swapping hydrogen containers scenario

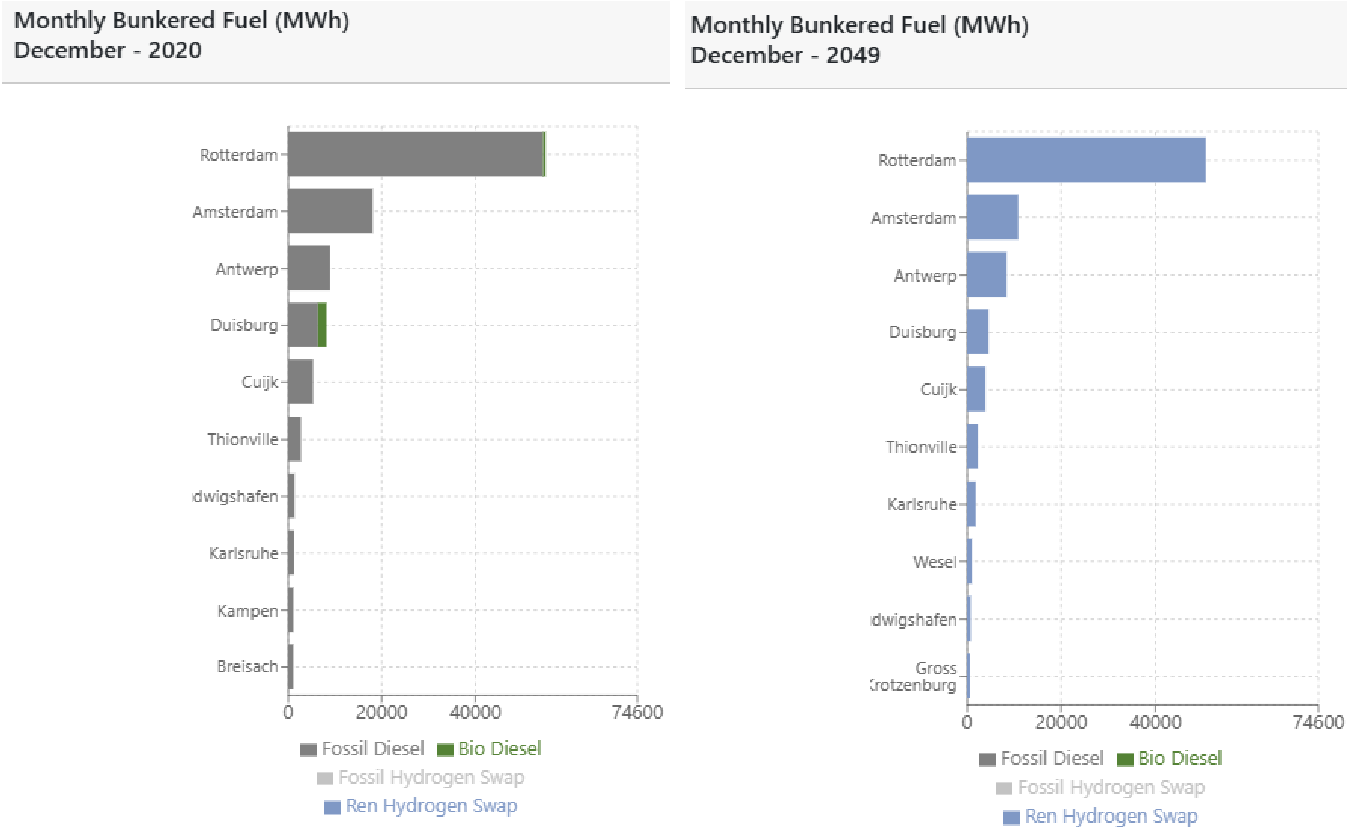


Figure 31: Monthly bunkering volume per port, December 2020 and December 2049 for forced fuel cell hydrogen with swapping hydrogen containers scenario

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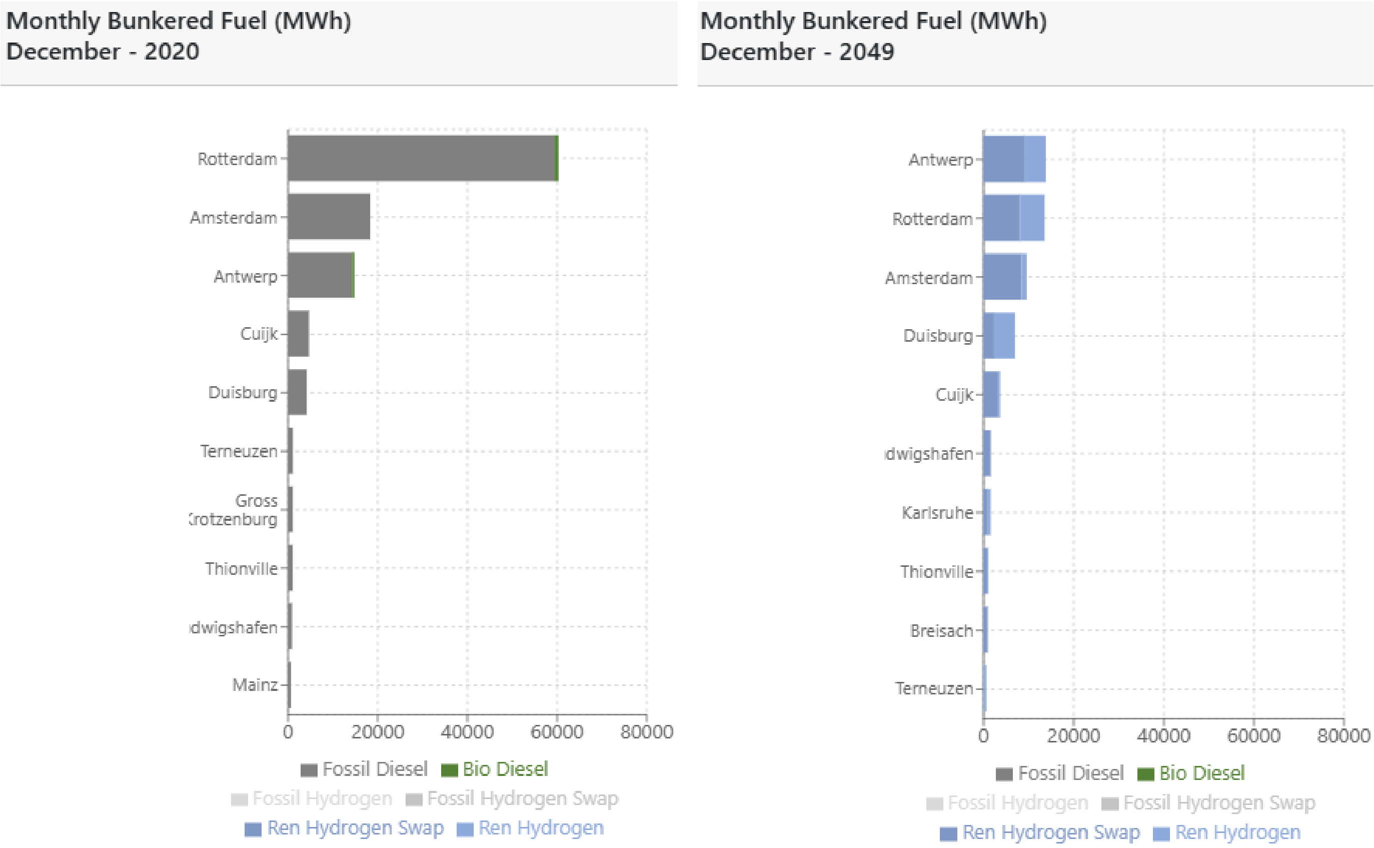
Forced fuel cell hydrogen with swapping hydrogen containers and bunkering scenario



Monthly Bunkered Fuel (MWh)
December - 2020

Monthly Bunkered Fuel (MWh)
December - 2049

Figure 32: Monthly bunkering volume per port, December 2020 and December 2049 for forced fuel cell hydrogen with swapping hydrogen containers and bunkering scenario