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Table of Contents

List of abbreviations	5
List of Tables.....	6
List of Figures.....	7
Executive summary.....	11
1. Introduction	16
1.1 The PLATINA4Action project	16
1.2 Introduction to Work Package 4.....	16
1.3 Introduction to Task 4.2 of WP4.....	17
1.4 Structure of this report	18
2. Selected zero emission technologies	19
2.1 Scope and selection	19
2.2 Fixed batteries and charging from shore	20
2.3 Swappable batteries in pay-per-use scheme	20
2.4 Green hydrogen Fuel Cell.....	21
2.5 Green hydrogen combustion engines.....	22
2.6 Renewable methanol combustion engines	23
2.7 Renewable methane in combustion engines	23
3. Cost characteristics.....	25
3.1 Energy prices	25
3.2 Capital expenditures.....	34
3.3 Additional cost elements for the TCO	36
4. Total Cost of Ownership results	39

4.1	Case 1: 110m dry cargo vessel.....	40
4.2	Case 2: 105 metre dry cargo motor vessel	55
4.3	Case 3: 67 metre dry cargo vessel	69
4.4	Case 4: Pusher for large convoys on Rhine and Danube	79
4.5	Case 5: 135 metre tanker vessel.....	92
5.	Benefits and potential of break-through	101
5.1	Introduction and scenarios	101
5.2	Modal share potential	101
5.3	Potential to reduce external costs.....	110
6.	Scenarios for policy intervention.....	116
6.1	Energy policies.....	116
6.2	Grant funding to support investments	117
	Annex 1 applied external cost values in the Digital Twin.....	118
	Annex 2 applied technology shares in Road and IWT	119

List of abbreviations

APS	Announced Pledges Scenario
CAPEX	Capital Expenditures
ETD	Energy Taxation Directive
ETS	Emission Trading System
FAME	Fatty Acid Methyl Ester (a renewable diesel)
FC	Fuel Cell
H2	Hydrogen
H2FC	Hydrogen Fuel Cell
HVO	Hydrotreated vegetable oil (a renewable diesel)
ICE	Internal Combustion Engine
IWT	Inland Waterway Transport
MCS	Megawatt Charging System
MeOH	Methanol (CH ₃ -OH)
NRMM	Non Road Mobile Machinery
NZE	Net Zero Emissions Scenario
OPEX	Operational Expenditures
OPS	Onshore Power Supply
RED	Renewable Energy Directive
STEPS	Stated Policies Scenario
TCO	Total Cost of Ownership
TTW	Tank to Wake
WEO	World Energy Outlook
WP	Work Package
WTW	Well to Wake
ZES	Zero Emission Services

List of Tables

Table 1 Schematic view on the PLATINA4Action goal, method, impact and alignment	16
Table 2 Schematic view on the WP4 focus, aim, initiatives and role	17
Table 3 Assumed CO2e prices internalised in the energy prices for inland navigation in Europe.....	26
Table 4 Prices for fossil diesel fuel in inland navigation in Europe, in euro per m3 for the 3 WEO scenarios, minimum and maximum	27
Table 5 Energy prices in STEPS scenario per kg (fuels) or kWh (electricity)	28
Table 6 Energy prices in APS scenario per kg (fuels) or kWh (electricity)	29
Table 7 Energy prices in NZE scenario per kg (fuels) or kWh (electricity)	30
Table 8 Energy prices compared for the year 2025, considering the caloric value (lower heating value) and the efficiency of the energy conversion on board.	32
Table 9 Equipment cost for inland vessels	34
Table 10 Installation and integration cost for inland vessels	34
Table 11 Cost items per type of system to calculate the total capital costs	35
Table 12 Technology price development factors	35
Table 13 Maintenance cost per year as percentage of the investment in hardware components per technology.....	36
Table 14 Maintenance percentages per technology	37
Table 15 Estimated downtime days	38
Table 16 Initial capital expenditure for investment, 110 metre dry cargo vessel.....	40
Table 17 Average TCO per day for the year 2028 (STEPS).....	42
Table 18 Average TCO per day for STEPS scenario 2028-2047, 110 metre motor vessel	44
Table 19 Average TCO per day for STEPS scenario 2028-2047, 110 metre motor vessel and 60% CAPEX funding	48
Table 20 Average TCO per day for NZE scenario 2028-2047, 110 metre motor vessel	51
Table 21 Average TCO per day for NZE scenario 2028-2047, 110 metre dry cargo motor vessel and 60% CAPEX funding	53
Table 22 Initial capital expenditure for investment, 105 metre dry cargo vessel.....	55
Table 23 Average TCO per day for the year 2028 (STEPS).....	58
Table 24 Average TCO per day for STEPS scenario 2028-2047, 105 metre motor vessel	60
Table 25 Average TCO per day for STEPS scenario 2028-2047, 105 metre motor vessel and 60% CAPEX funding	62
Table 26 Average TCO per day for NZE scenario 2028-2047, 105 metre motor vessel	65
Table 27 Average TCO per day for NZE scenario 2028-2047, 105 metre motor vessel and 60% CAPEX funding	67
Table 28 Initial capital expenditure for investment, 67 metre dry cargo vessel	69
Table 29 Average TCO per day for STEPS scenario 2028-2047, 67 metre dry cargo vessel	71
Table 30 Average TCO per day for STEPS scenario 2028-2047, 67 metre dry cargo vessel and 60% CAPEX funding	74
Table 31 Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel	75

Table 32 Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel and 60% CAPEX funding	77
Table 33 Initial capital expenditure for investment, large pusher	80
Table 34 Average TCO per day for STEPS scenario 2028-2047, pusher	80
Table 35 Average TCO per day for STEPS scenario 2028-2047, pusher and 60% CAPEX funding for methanol and bio methane systems	84
Table 36 Average TCO per day for NZE scenario 2028-2047, pusher	87
Table 37 Average TCO per day for NZE scenario 2028-2047, pusher and 60% CAPEX funding	90
Table 38 Initial capital expenditure for investment, 135 metre tanker vessel	92
Table 39 Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel	94
Table 40 Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding	95
Table 41 Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel	97
Table 42 Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding	99
Table 43 Summarising table of the modal share results for the Digital Twin scenarios for 2050 compared to baseline 2025	108
Table 44 Comparison of NZE scenario with STEPS on average modal share of IWT	116
Table 44 Comparison of Impact of CAPEX support (60%)	117

List of Figures

Figure 1 Assumed CO2e prices internalised on the energy prices for inland navigation in Europe	26
Figure 2 Diesel fuel prices in euro per m3 for inland navigation in Europe at three scenarios	27
Figure 3 Energy price projections in euro per kg for fuels and euro per kWh for electricity for the STEPS scenario	29
Figure 4 Energy price projections in euro per kg for fuels and euro per kWh for electricity for the APS scenario	30
Figure 5 Energy price projections in euro per kg for fuels and euro per kWh for electricity for the NZE scenario	31
Figure 6 Energy cost comparison in different metrics for the year 2025	33
Figure 7 Volumetric energy density over gravimetric energy density	38
Figure 8 Initial capital expenditure for investment, 110 metre dry cargo vessel	41
Figure 9 Average TCO per day at 2028 energy prices (average) for the 110 metre dry cargo motor vessel	42
Figure 10 Cost breakdown of the average TCO per day at 2028 energy prices (average) for the 110 metre dry cargo motor vessel	43
Figure 11 Average TCO per day at 2028-2047 STEPS energy prices (average) for the 110 metre dry cargo motor vessel	45
Figure 12 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 105 metres dry cargo motor vessel	46

Figure 13 Average TCO per day at 2028-2047 STEPS energy prices (average) for the 110 metre dry cargo motor vessel and 60% CAPEX funding	48
Figure 14 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 110 metre dry cargo motor vessel and 60% CAPEX funding	49
Figure 15 Average TCO per day at 2028-2047 NZE energy prices (average) for the 110 metre dry cargo motor vessel	51
Figure 16 Cost breakdown of the average TCO per day for the NZE average price scenario for the 110 metre dry cargo motor vessel	52
Figure 17 Average TCO per day for NZE scenario 2028-2047, 110 metre dry cargo motor vessel and 60% CAPEX funding	54
Figure 18 Cost breakdown of the average TCO per day for the NZE average price scenario for the 110 metre dry cargo motor vessel and 60% CAPEX funding	54
Figure 19 Initial capital expenditure for investment, 105 metre dry cargo vessel	56
Figure 20 Average TCO per day at 2028 energy prices (average) for the 105 metre dry cargo motor vessel	58
Figure 21 Cost breakdown of the average TCO per day at 2028 energy prices (average) for the 105 metre dry cargo motor vessel	59
Figure 22 Average TCO per day at 2028-2047 STEPS energy prices (average) for the 105 metre dry cargo motor vessel	60
Figure 23 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 105 metre dry cargo motor vessel	61
Figure 24 Average TCO per day at 2028-2047 STEPS energy prices (average) for the 105 metre dry cargo motor vessel and 60% CAPEX funding	62
Figure 25 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 105 metre dry cargo motor vessel and 60% CAPEX funding	63
Figure 26 Average TCO per day at 2028-2047 NZE energy prices (average) for the 105 metre dry cargo motor vessel	65
Figure 27 Cost breakdown of the average TCO per day for the NZE average price scenario for the 105 metre dry cargo motor vessel	66
Figure 28 Average TCO per day for NZE scenario 2028-2047, 105 metre motor vessel and 60% CAPEX funding	67
Figure 29 Cost breakdown of the average TCO per day for the NZE average price scenario for the 105 metre dry cargo motor vessel and 60% CAPEX funding	68
Figure 30 Initial capital expenditure for investment, 67 metre dry cargo vessel	70
Figure 31 Average TCO per day for STEPS scenario 2028-2047, 67 metre dry cargo vessel	71
Figure 32 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 67 metre dry cargo vessel	72
Figure 33 Average TCO per day for STEPS scenario 2028-2047 and 650% CAPEX funding, 67 metre dry cargo vessel	74
Figure 34 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 67 metre dry cargo vessel and 60% CAPEX funding	75
Figure 35 Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel	76
Figure 36 Cost breakdown of the average TCO per day for the NZE average price scenario for the 67 metre dry cargo vessel	76

Figure 37 Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel and 60% CAPEX funding	78
Figure 38 Cost breakdown of the average TCO per day for the NZE average price scenario for the 67 metre dry cargo vessel and 60% CAPEX funding	78
Figure 39 Average TCO per day for STEPS scenario 2028-2047, pusher	81
Figure 40 Cost breakdown of the average TCO per day for the STEPS average price scenario for the pusher	82
Figure 41 Average TCO per day for STEPS scenario 2028-2047, pusher and 60% CAPEX funding for methanol and bio methane systems	84
Figure 42 Cost breakdown of the average TCO per day for the STEPS average price scenario for the pusher with 60% CAPEX funding for the Methanol and Bio-Methane solutions	85
Figure 43 Average TCO per day for NZE scenario 2028-2047, pusher	87
Figure 44 Cost breakdown of the average TCO per day for the NZE average price scenario for the pusher	88
Figure 45 Average TCO per day for NZE scenario 2028-2047, pusher and 60% CAPEX funding	90
Figure 46 Cost breakdown of the average TCO per day for the NZE average price scenario for the pusher and 60% CAPEX funding	91
Figure 47 Initial capital expenditure for investment, 135 metre tanker vessel	93
Figure 48 Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel	94
Figure 49 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 135 metre tanker vessel	95
Figure 50 Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding	96
Figure 51 Cost breakdown of the average TCO per day for the STEPS average price scenario for the 135 metre tanker vessel and 60% CAPEX funding	96
Figure 52 Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel	97
Figure 53 Cost breakdown of the average TCO per day for the NZE average price scenario for the 135 metre tanker vessel	98
Figure 54 Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding	99
Figure 55 Cost breakdown of the average TCO per day for the NZE average price scenario for the 135 metre tanker vessel and 60% CAPEX funding	100
Figure 56 Projections of Alternative Fuels prices / STEPS scenario (averaged prices) / CEMT Class: VI	103
Figure 57 Projections of alternative fuels prices / NZE scenario (averaged prices) – 60% CAPEX / CEMT Class: VI	103
Figure 58 Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: STEPS scenario (averaged prices)	104
Figure 59 Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: STEPS scenario (averaged prices)	104
Figure 60 Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: STEPS scenario (averaged prices) - 60% CAPEX	105

Figure 61 Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: STEPS scenario (averaged prices) - 60% CAPEX	105
Figure 62 Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: NZE scenario (averaged prices)	106
Figure 63 Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: NZE scenario (averaged prices)	106
Figure 64 Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: NZE scenario (averaged prices) - 60% CAPEX	107
Figure 65 Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: NZE scenario (averaged prices) - 60% CAPEX	107
Figure 66 Modal Share Results – scenarios compared	109
Figure 67 Modal Share Results – scenarios compared with current modal share (baseline)	109
Figure 68 Change in Total External Costs relative to the 2025 baseline, by price scenario [%]	111
Figure 69 External cost breakdown by price scenario – Containers - Road [%]	112
Figure 70 External cost breakdown by price scenario – Containers - Rail [%]	112
Figure 71 External cost breakdown by price scenario – Containers - IWT [%]	113
Figure 72 Total External Costs in mil EURO - Containers	113
Figure 73 Total External Costs in mil EURO – Dry Bulk	114
Figure 74 Total External Costs in mil EURO – Liquid Bulk	114
Figure 75 IWT External costs in mil EURO	115
Figure 76 Energy Transition Pathway – Conservative – IWT	120
Figure 77 Energy Transition Pathway – Conservative – Road	121
Figure 78 Energy Transition Pathway – Innovative – IWT	122
Figure 79 Energy Transition Pathway – Innovative – Road	123

Executive summary

Purpose and scope

This executive summary synthesises the findings of Deliverable D4.2 of the PLATINA4Action project. The report presents the analyses of the business economic feasibility of selected propulsion technologies which lead to a (near) zero-emission performance by inland waterway transport (IWT). Next, it presents the potential on macro level: impact on modal share of IWT and savings of external costs of transport. Using Total Cost of Ownership (TCO) modelling across multiple vessel types, operational profiles, energy price scenarios and policy contexts, the study assesses the conditions under which zero-emission solutions can become competitive with conventional diesel propulsion. Particular attention is given to sensitivity factors, critical cost drivers, benefits and potential of breakthrough and policy intervention scenarios and the scale of financial resources required to enable market uptake. For the approximate impact on modal share and external costs, the Digital Twin instrument is applied, which was developed in WP2 of PLATINA4Action. This part was updated in October 2026 to benefit from the latest results on model calculations with the Digital Twin.

A disclaimer needs to be mentioned here: A digital twin modelling instrument was applied, an approach to model complex systems. In combination with assumptions as well as scenarios, which sketch possible future development paths, e. g. on prices, availability or market readiness, the digital twin modelling instrument supports the analysis of possible future developments. Considering this it needs to be noted, that evaluations based on such modelling do have large uncertainties. In fact, the nature of the digital twin modelling rather is, to outline indications and approximations of possible developments. The models understandably assume a relatively stable macroeconomic environment for the technological transition and address uncertainty primarily through price sensitivity as well as technological, market, and financing uncertainties. However, when updating this report, the conflict between USA and Iran are still causing high energy prices and which may have impact on the scenarios. It therefore needs to be remarked that there can be significant positive or negative exogenous shocks which are inherently difficult to model but cannot be ignored and may materially influence transition pathways despite being outside the modelling scope.

Technologies and analytical framework

The analysis covers a representative set of zero-emission and low-emission technologies that are expected to be market-ready for deployment from 2027 onwards and compatible with EU policy frameworks and funding instruments (notably the Innovation Fund). These include battery-electric propulsion (fixed batteries and swappable batteries under pay-per-use models), hydrogen fuel cells as well as clean combustion engines running on renewable hydrogen, methanol and methane. A propulsion system with a Stage V diesel engine (with fossil diesel and HVO100) is used as the reference technology.

It is relevant to mention that for the short term, it is expected that the market will use blends of fossil fuels with renewable drop-in fuels. These can be blends with FAME (known as “B7” or “B20”) or HVO (for example “HVO30”). These fuels can be offered to the market to reduce the carbon intensity (grams CO₂e per MJ on well-to-wake basis) and to fulfil the requirements from RED-III legislation. However, although generally lower in price, the use of high blends of FAME is seen as unfeasible for the medium

and longer term, because of the limitations with the shelf life and the damage seen to after treatment systems (SCR) which are commonly used in modern Stage V engines to mitigate the emissions of nitrogen oxides (NOx). Therefore FAME is left out of scope as solution for the future. HVO100 however, is seen as the renewable drop-in fuel for Stage V engines. HVO100 has no problems with shelf life or damage to Stage V engines and can therefore be seen as a renewable drop-in fuel for modern Stage V engines, reducing both the climate change emissions and air pollutant emissions at the same time. And, in order to have HVO as a scalable option, the HVO molecules can also be made in a synthetic way using green hydrogen and carbon capture and the price bandwidth applied does include the possibility of e-diesel or e-HVO as drop-in solution.

TCO calculations are performed for newbuild vessels deployed from 2028 with a 20-year lifetime, across different vessel archetypes (dry cargo vessels, pushers and tankers). This includes also replacement/overhaul of battery cells and fuel cell components. These are covered as 'maintenance costs' in the TCO for these technologies.

Energy price assumptions are derived from the International Energy Agency's World Energy Outlook scenarios: the Stated Policies Scenario (STEPS) as baseline and the Net Zero Emissions Scenario (NZE) representing a much more stringent and ambitious policy package to limit the global warming to 1.5 degrees Celsius and to make renewable energy available at lower price levels. Policy options, take into account internalisation of CO₂ costs and the availability of public grant support for capital expenditures (CAPEX). Also in the baseline scenario (STEPS) assumed in this report, there is already a level of CO₂ costs internalisation included.

Sensitivity and critical factors

Energy prices and CO₂ cost internalisation

After analysing the cost structure and the results for different scenario settings, it turns out that the **most influential sensitivity factor is the evolution of energy prices**. In particular the fossil diesel price under increasing CO₂ cost internalisation can make a big difference to close the gap with using renewable energy solutions. Under STEPS, diesel prices already are expected to rise substantially over time due to impact of policies such as ETS, RED III and related measures. Here it needs to be noted that in this analyses **it is assumed that the implementation of ETS2 opt-in and RED-III will be successful and effective**, meaning that several (neighbouring) countries with substantial fuel supply to IWT will implement the RED III and apply the opt-in for ETS2.

As a result, the gap between operational costs of using fossil diesel costs compared with the operational costs for using renewable energy closes over time. Under NZE, this effect is significantly stronger, making several zero-emission solutions operationally competitive or even favourable within a shorter time frame.

Other conclusions are that zero-emission technologies with high energy efficiency, notably battery-electric propulsion, show strong sensitivity to electricity prices and recharging regimes. The pay-per-use option with swappable containers could be more competitive, but it depends also on the operational profile. If time needed for the recharging a fixed battery configuration leads to loss of productivity of the vessel, the fixed battery option will be less competitive. Moreover, the price of recharging from shore is a very important sensitive element. Furthermore, hydrogen-based solutions remain highly sensitive to hydrogen price assumptions regarding the pace at which large-

scale green hydrogen production reduces costs. It needs to be noted that the uncertainty of prices is quite large, especially for green hydrogen.

Capital expenditure (CAPEX)

When looking at the total costs of ownership, the operational costs (OPEX) have the largest share and importance. However, also the CAPEX is an important factor for zero-emission uptake, especially as the vast majority of vessel owners are micro-enterprises.

The initial investment costs for (near) zero-emission systems can be up to 6 times higher than for a conventional Stage V diesel system, depending on technology. Relatively modest capital costs are required for an electric propelled vessel using the swappable battery containers. Hydrogen fuel cell systems are consistently the most capital-intensive option.

Cost reduction trajectories for batteries, fuel cells and electric components materially affect long-term competitiveness. However, even with optimistic learning curves, high upfront investment remains a major barrier for the predominantly small and medium-sized companies active in inland navigation.

Operational impacts: downtime, payload and bunkering time

In some cases, such as the pusher of a large convoy, the required autonomy in combination with the power demand is too high to make it possible to store the required energy on board. This is in particular the case for application of battery-electric propulsion and also for using hydrogen as fuel. This is because of the relatively low energy density when storing the energy on board of vessels. Therefore, green methanol and methane with clean combustion engines are in-scope of zero-emission solutions for these types of vessels and operational profiles.

Beyond energy and CAPEX, operational factors can significantly affect TCO outcomes. Zero-emission solutions often entail longer bunkering or charging times, additional downtime during retrofit or installation, and loss of cargo capacity due to energy storage systems. These impacts are particularly relevant for fixed-battery systems and hydrogen storage. Swappable battery and tanktainer concepts mitigate some of these effects and therefore show more robust economic performance. An issue for the very short term is the reliability of innovative / experimental systems. However, in this report, it is assumed to start with using technologies in 2028 and the reliability is at the same level compared to using diesel as fuel.

Scenarios for policy intervention and investment support

STEPS as baseline

The calculations show that for the year 2028, zero-emission solutions are generally not cost-competitive with fossil diesel under STEPS assumptions. Even while the STEPS scenario already includes impacts of ETS2 and RED-III which is reflected in the planned implementation in The Netherlands. However, over the full 2028–2048 period, HVO100 is expected to become competitive or favourable due to rising diesel prices and phasing out sales of fossil diesel by 2044 (ETS2). It is however clear from the calculations that most zero-emission options retain a cost gap without additional support. It needs

to be noted however measures such as RED-III will require a minimum share of renewable energy to be used. This means that fuel suppliers will be obliged to sell a certain amount of renewable fuels in order to meet their targets by 2030. This is at least foreseen in The Netherlands which compared to other countries in Europe has a quite large share in the overall fuel bunkering market to inland vessels in Europe. It is likely that this will be achieved by blends of FAME and HVO with fossil diesel towards 2030.

CO₂-driven policy scenario with affordable renewably energy (NZE)

Under the NZE scenario, stringent climate policies and high internalised CO₂ costs substantially improve the relative economics of zero-emission solutions and reduce the prices of renewable energy compared to the STEPS scenario. As a result, battery-electric systems with swappable batteries and engines running on renewable methanol approach or achieve TCO parity with fossil diesel, while hydrogen combustion improves but remains borderline, much depending on the hydrogen price. Hydrogen fuel cells remain the least competitive option due to high CAPEX and maintenance costs. In NZE the prices of renewable energy solutions are expected to be lower than in the STEPS scenario. Under the NZE energy price assumptions, vessels using renewable energy will be more competitive in the NZE scenario compared to the STEPS scenario. This also explains the strong positive impact on modal share when selecting the NZE scenario instead of the STEPS scenario.

Investment support through grants

Next to internalising the CO₂ costs in the fossil fuel prices and promoting affordable renewable energy, providing grant support for CAPEX proves to be an effective policy lever. Simulations assuming **60% CAPEX funding**, consistent with the upper range of Innovation Fund support, show that:

- Renewable methanol single-fuel engines and battery-electric solutions with swappable batteries can reach TCO parity with fossil diesel even under STEPS scenario conditions for energy prices.
- Fixed-battery systems and hydrogen combustion engines see substantial improvement but may still face gaps depending on energy price assumptions at STEPS.
- Hydrogen fuel cell solutions, while improved, generally remain non-competitive without additional targeted support or further cost reductions.

The results indicate that combining CO₂ cost internalisation with targeted CAPEX grants is critical to accelerate early deployment and to create economies of scale. At the same time, it supports the competitiveness of IWT, resulting in a gain of modal share and lower external costs.

Potential for breakthrough and impact of policy interventions

The analyses and calculations on modal share impacts are based on the digital twin modelling instrument. In combination with assumptions as well as scenarios, future development paths are defined. Considering this it needs to be noted, that evaluations based on such modelling need to be seen as indications for impacts to be expected.

The indicative simulations with the Digital Twin show that modal share increase for IWT is depending significantly on the energy transition policies for IWT. A very positive response is seen when running scenarios which include strong policy measures in the EU to internalise the CO₂e emissions costs and to upscale renewable energy supply, a situation reflected by the NZE scenario leading to affordable

renewable energy prices. The modal share of IWT will be much higher when applying the NZE scenario compared to the STEPS scenario. This is in particular seen in the container transports market. For the container transport markets, the modal share would be around 80% higher in case of NZE energy prices compared to the STEPS energy prices for container transport (at 29% share compared to a 16% share of IWT in modal split) and for dry cargo it would be around 30% higher (a modal share of 35% compared to 28% in STEPS in dry cargo). The liquid bulk market seems less sensitive, with a limited increase of 6% of modal share at NZE compared to STEPS.

The underlying reason is that the **prices of renewable energy for IWT are lower in NZE scenario** compared to STEPS. The energy prices can be influenced directly by policy makers by means of internalising CO₂e costs and Renewable Energy Directive to set specific targets for renewable energy share or CO₂ reduction to achieve. This is illustrated by simulating the NZE scenario according to the International Energy Agency, internalising CO₂e costs up to 880 euro per ton CO₂e by 2050. At the same time, reduced prices for alternative and renewable fuels such as methanol and hydrogen are assumed, because of supporting mechanisms for production and supply of these renewable fuels.

The simulated policy measure to provide 60% CAPEX support would also give a significant impact on the competitiveness of IWT and thus on the modal share. The modal share gains are 24%, 9% and 2% respectively for the container market, dry bulk market and the liquid bulk markets. Again it reflects the sensitivity and effectiveness of policy interventions for the inland waterway container transport market.

The indicative calculations of the external costs also point towards a strong socio-economic benefit. The emission costs from IWT are currently relatively large. It makes sense from a socio-economic viewpoint to reduce these costs. In particular the air pollution costs of IWT are still significant today, because not many vessels are yet equipped with modern engines with aftertreatment systems to mitigate NO_x and PM emissions. These returning external cost savings from emissions provide a **solid argument to spend financial resources for CAPEX support**. Furthermore, required funds can be raised by means of CO₂e pricing, such as an ETS₂ applied for fuel sold to inland navigation in the EU.

By the year 2050 all modes are expected to have massively reduced the external costs from climate change and air pollution emissions. It is however clear that other type of external costs remain: the costs from noise, congestion and from accidents. **A modal shift from road to IWT in 2050 is still expected to bring a benefit to society due to less noise and congestion cost and higher safety levels.**

The analysis highlights the importance of EU-level instruments such as the ETS, RED and the Innovation Fund. It is important to combine these instrument complemented by national grant schemes, to de-risk investments and higher OPEX for early movers. Revenues from ETS-related mechanisms can be strategically reinvested in the competitiveness of the sector, aligning climate policy with industrial transition objectives. Without such coordinated financial support, uptake is likely to remain limited to niche cases and pilot projects. However, when assuming the implementation of RED-III with specific targets for energy supply to IWT, possibly complemented by ETS₂ for IWT fuel sales in the EU, there will be a steady growth in the use of renewable energy across the entire fleet. However, in the early years this will in most cases amount to relatively low percentages of blending FAME or HVO, gradually increasing to more than 14.5% renewable energy at fleet level by 2030. This is still far from fully zero-emission. When assuming the ETS₂ to be fully implemented for fuel supply to IWT in the EU, fossil fuel would be phased out by 2045. This corresponds with the STEPS scenario.

1. Introduction

1.1 The PLATINA4Action project

The PLATINA4Action project marks a major step forward in promoting environmentally friendly and integrated inland waterway transport (IWT) throughout Europe. This initiative strives to speed up the shift to waterborne transport solutions which are zero-emission regarding the greenhouse gas emissions and advanced in technology and innovations. It aims to combine state-of-the-art research and innovation with real-life use cases. By fostering synergies between parallel developments, estimating the impact of NAIADES III actions, and updating strategic agendas, PLATINA4Action serves as a cornerstone in supporting policy discussions that drive a modal shift towards sustainable inland navigation. The project not only highlights the potential for environmental improvements but also ensures alignment with broader EU goals for a sustainable and efficient transport sector.

Table 1 | Schematic view on the PLATINA4Action goal, method, impact and alignment

Goal of project	Method	Impact	Alignment
Promoting environmentally friendly and integrated inland waterway transport (IWT) throughout Europe	Combining state-of-the-art research and innovation with real-life use cases, fostering synergies, estimating impact, and updating strategic agendas	Speed up the shift to zero-emission and advanced technology waterborne transport solutions, support policy discussions for a modal shift towards sustainable inland navigation	Ensures alignment with broader EU goals for a sustainable and efficient transport sector

1.2 Introduction to Work Package 4

Work Package 4 (WP4) of the PLATINA4Action project focuses on **zero-emission innovations and their deployment across European inland waterways**. This WP aims to identify, validate, and facilitate the rollout of breakthrough technologies and business models that can thus drastically reduce emissions from existing or new inland waterway vessels.

WP4 tackles a variety of strategic initiatives ranging from stocktaking of best practices to economic modelling and the identification of financial and regulatory barriers to innovation. Through its comprehensive approach, WP4 plays a pivotal role in ensuring the scalability and economic viability of zero-emission technologies in the sector, thus propelling the industry towards a zero-emission future within a few decades. The challenge is to keep up with the pace of decarbonisation and innovation of road transport to safeguard the benefits of using inland navigation over road transport.

Table 2 | Schematic view on the WP4 focus, aim, initiatives and role

Focus	Aim	Initiatives	Role
Zero-emission innovations and deployment across European inland waterways	Identify, validate, and facilitate the rollout of breakthrough technologies and business models to reduce emissions	Stocktaking of best practices, economic modelling, identification of financial and regulatory barriers to innovation	Ensure scalability and economic viability of zero-emission technologies in the sector, propel the industry towards a zero-emission future

The journey towards sustainable IWT is marked by the necessity to integrate innovative technologies and operational paradigms that significantly reduce environmental footprints while enhancing efficiency. As part of the broader PLATINA4Action project, our approach in WP4 embodies **a comprehensive strategy aimed at accelerating the deployment of zero-emission innovations across Europe's inland waterways.**

We base our approach on a strategy that combines technological progress with economic and regulatory conditions. By focusing on the development, validation, and scalability of breakthrough innovations, we aim to ensure that emerging technologies not only meet current environmental and operational standards but also pave the way for future advancements. This next chapter outlines the structured methodology and analytical frameworks that guide the efforts in WP4 in identifying and promoting the most promising innovations in IWT.

1.3 Introduction to Task 4.2 of WP4

The WP4 started with Task 4.1 which resulted in an overview of good practices and innovative initiatives that can contribute to breakthroughs in zero-emission technologies for inland waterway transport. This report [D4.1 Stocktaking and good practices](#) provides a solid basis for further work. It serves as a longlist of technologies and innovations. Further investigations are being made in WP4 for the most promising and suitable ones, especially for those technologies and innovations which can be included in proposals to acquire co-funding from existing financial instruments for their deployment (Task 4.5).

Based on the findings from Task 4.1 and the report D4.1, the Task 4.2 dives into the economics. It presents the results of model calculation of the Total Cost of Ownership (TCO) for the solutions, taking into account different economic scenarios and policy backgrounds. TCO calculations have been made to conclude on the sensitivity and critical factors which make or break the economic feasibility. The digital twin developed in WP2 is used to support the assessment of the benefits and potential of breakthrough.

Scenarios are used to evaluate how energy policy and financial support (co-funding) for capital investments affect the viability of innovative business concepts. This was also relevant for the discussion about financial instruments and the possible resources from the next MFF (2028-2035) for supporting zero emission, digitalised and connected vessels, e.g. the EU Competitiveness Fund.

1.4 Structure of this report

The selected technologies are described in chapter two of this report.

Next, the chapter three presents the assumptions regarding the investments, the Capital expenditures which are required (CAPEX) and also presents the assumptions for the energy costs and other operational expenses (OPEX).

In chapter 4 the Total Costs of Ownership (TCO) results are presented with different economic scenarios for the energy prices and the internalisation of costs for GHG emissions. The scenarios are based on the research done in SYNERGETICS, aligned with the World Energy Outlook scenarios STEPS and NZE reflecting different commodity prices and CO2 costs which are internalised in the fossil energy prices. TCO results of various technical options to reduce emissions are compared with use fossil fuels.

The impact of grants is presented with respect to reducing the capital expenditures (60%) on technologies which reduce emissions. This is done to present the impact of such funding instruments on possible acceleration of investments. Again, the TCO results, including the grant for capital investments, was presented in different energy price scenarios and compared with the TCO of continuing the use of fossil diesel or HVO100.

Chapter 5 presents the results of the scenario run with the Digital Twin, presenting the potential and benefits of the breakthrough of zero-emission technology and renewable energy in inland navigation. Key elements are the impact on the modal share of inland waterway transport as well as savings on external costs because of reduced climate and air pollutant emissions and reductions of accident costs and noise (the latter resulting from the modal share impacts).

Finally, chapter 6 presents the main findings and conclusions from the execution of Task 4.2 regarding the policy intervention and financial support.

2. Selected zero emission technologies

2.1 Scope and selection

The Task 4.1 and Deliverable 4.1 present the scope for the breakthrough technologies and innovations for Zero-Emission Inland Waterway Transport. A clear reference here is the objective of the PLATINA4Action WP4 to support and promote a grant application for EU funding in the year 2026. As the CEF-AFIF instrument does not provide opportunities for 2026, the focus is on the preparation for a potential application in the Innovation Fund.

The eligibility criteria for [Innovation Fund](#) applications are therefore important to take into account. Another important reference is provided by the EU Taxonomy technical screening criteria for [inland passenger](#) and [freight vessels](#). PLATINA4Action aims for a proposal (Task 4.5) ultimately by the year 2026. Consequently, the choice of technologies is limited to those which are available to the market for larger scale deployment from 2027 onwards. This therefore brings requirements to the TRL level, to the maturity of the regulatory framework and also to the general acceptance level of the energy carriers and solutions.

The specific types of technologies and innovations included in the scope of PLATINA4Action WP4 activities are the following, because they are in scope of the Innovation Fund requirements:

- **Full electric propulsion systems**
 - Fixed batteries on board with charging from shore: Exploration of fully electric vessels with fixed batteries, taking advantage of advancements in battery technology, such as increased energy density and fast charging capabilities.
 - Swappable batteries on board with pay-per-use model for the battery containers: Exploration of fully electric vessels powered by swappable batteries provided by a third party. The battery containers are frequently transhipped and recharged and operated at a pay-per-use model.
 - Hydrogen Fuel Cells: Assessment of fuel cell technologies that convert hydrogen into electricity, providing high efficiency and zero tailpipe emissions at the point of use. This includes evaluating the infrastructure for hydrogen production, storage, and refuelling.
- **Clean combustion technologies**
 - Hydrogen as fuel for combustion: Assessment of the option to use hydrogen as fuel for clean combustion engines, in a single fuel option to reach high levels of emission reduction.
 - Methanol as fuel for combustion: Assessment of the option to use methanol as fuel for clean combustion engines, in a single fuel option to reach high levels of emission reduction.

Furthermore, although not fit for Innovation Fund, the renewable diesel option (HVO) combined with a modern and clean combustion engine is also considered, in order to have a reference and can be seen as an important transitional energy type.

While in the Deliverable 4.1 the option of methanol as fuel was not yet identified, recent developments indicate that that it may be an option to take into account. The reasons doing so are as follows:

- There has been a recent application in the Innovation Fund for a project for the river-cruise vessels focussing on battery electric propulsion and methanol direct drive propulsion
- Discussions within European Commission to lower the barriers for engine manufacturers to test methanol engines in inland vessels
- A new Dutch subsidy scheme is being launched in 2026 to promote and financially support the certification of methanol (and hydrogen) engines for inland vessels, with a total budget of 4 mln euro.

2.2 Fixed batteries and charging from shore

This option is based on a full-electric vessel, using fixed batteries on board. For example, the KOTUG E-Pusher operational in the Amsterdam/Zaan region is using this concept.

It is assumed that the batteries will be recharged by means of onshore power supply (OPS). The Megawatt Charging System (MCS) will allow charging power up to 3.75 MW. A critical issue is here the required grid capacity in ports or at mooring places to provide the electric power to the charging systems.

This solution may take advantage of the expectation that batteries will get cheaper over time while the storage capacity increases. A disadvantage is however the space and weight required to accommodate the batteries, seen also the relatively low energy density of batteries. This is a clear limitation for this option. Therefore, this concept is mainly interesting for vessels which can recharge the batteries frequently. A barrier for this option can be the relatively large investment in purchasing the batteries. Furthermore, the price of electricity is a key factor in the Total Cost of Ownership.

Moreover, seen the relatively low speed of energy transfer from shore to the vessel, this option will be interesting for vessels which do have significant idle time, for example during nighttime when the vessel is at a resting place. For example vessels operated in a day-time regime (14 hours per day for 5 days a week) can be potential candidates for fixed batteries on board and charging from shore. Furthermore, there will be a strong dependency on the infrastructure facilities available to recharge the vessel, particularly if the vehicle has to call and recharge at different locations. Safety regulations, especially when dangerous goods are handled, limit the possibility of simultaneous loading/unloading and charging. As a result, the option of fixed batteries will be most suitable for vessels which can plan their operations for a long term in advance, for example using fixed routes and in a stable operational profile, for which it is clear that the infrastructure to recharge the vessel is available.

2.3 Swappable batteries in pay-per-use scheme

A second option using batteries for a full-electric vessel is to use swappable batteries instead of fixed batteries on board and to use a pay-per-use scheme for the batteries. For example, the Alphenaar and Den Bosch Max Groen vessels are using this option for transporting containers.

These swappable batteries are then to be exchanged at specific locations, such as container terminals, which already have the crane infrastructure in place to tranship the battery containers and to recharge them. There are advantages for this option compared to using fixed batteries on board owned by the vessel owner. One clear advantage is that the investment barrier can be reduced by applying a “pay-per-use” scheme. With “pay-per-use” the capital and maintenance costs for the batteries are born by a third party which provide the pay-per-use service and not by the vessel owner/operator. The third party can provide such services to multiple vessels in parallel, the required amount of battery containers for the overall system can be reduced, resulting in lower costs. Moreover, also other services can be provided with the battery-containers, such as applications beyond inland vessels for off-grid power supply (e.g. festivals, construction sites) and also grid-stabilisation. Using swappable containers can help to increase the occupation rate of batteries and to create additional revenues, which may lead to lower prices for the pay-per-use services to inland vessels. Furthermore, such energy suppliers have more power and potential to acquire electricity at lower prices or to generate the electricity themselves (e.g. windmills, solar power). Therefore, such swappable batteries are an enabler for pay-per-use services.

Besides the broader commercial use of swappable containers, another big advantage of the swappable battery is the speed of the energy transfer. Instead of e.g. 1 MWh of charging power with a MCS connector, the swapping of two 3 MWh-battery packs within one hour would correspond to a speed of 6 MWh per hour. This can increase the productivity of the vessels, especially relevant for vessels which have a 24/7 operating scheme. However, a limitation can be the availability of such a pay-per-use service provider and the availability of infrastructure to swap the battery containers. Today only Zero Emission Services is operating this concept in specific regions in The Netherlands for inland waterway container transport services and there is no competition yet from other pay-per-use providers of battery containers.

2.4 Green hydrogen Fuel Cell

Another fully electric option is by means of using hydrogen fuel cells for providing the electric power for inland vessels combined with fixed batteries. For example, the vessels H2 Barge 1 and H2 Barge 2 are using this solution and the vessels Mannheim by Contargo and Laetitia by MTS in Germany are planning to start using this technology. For these vessels, the hydrogen is provided in specific hydrogen containers, called “tanktainers”. These tanktainers are swappable and can be owned by the energy provider which can generate economy of scales. In other cases they are owned by the shipping company themselves, but this can lead to higher costs as more tanktainers could be needed.

The hydrogen is not bunkered (e.g. truck to ship), but the tanktainers are being swapped with container cranes. Similar to battery-swapping, this raises also limitations for this concept because the infrastructure needs to be there to tranship the tanktainer. Next, the tanktainer can be refilled at another location using a truck for the transport between container terminal and refilling location. Obvioposly the distance between container terminal and refilling location brings additional logistics costs to be taken into account. Usually the energy/hydrogen providers need to offer such a logistic service in combination with a container terminal operator. The planning of management can be complex to ensure that the tanktainers are available at the right moment on the right location.

2.5 Green hydrogen combustion engines

Also, for this option the concept of the swappable tanktainer is used. However, the power conversion is a mechanical one, using hydrogen combustion engines as direct drive for the propulsion or using the mechanical power from the combustion for electricity generation on board (gensets) to propel electric engines, possibly combined with batteries. A factor deciding which propulsion system is applied is torque curve of the engine and the curve of the fuel economy. A hybrid setup, using electric motors, is more flexible to deal with hydrogen engines which possibly lack torque or are rather sensitive to load and speed in relation to the fuel economy. It needs to be noted that such engines using hydrogen as fuel are not yet available on the market for inland vessels. However, there are engine manufacturers working on making these engines available for the Non-Road Mobile Machinery market, including applications for inland vessels. The NRMM regulation is also expected to be adapted to make it easier to use hydrogen powered engines in inland vessels. It could be expected that from 2027/2028 onwards, such engines can be used in inland vessels. This is also being pushed and promoted by means of a subsidy scheme in The Netherlands for certification of hydrogen (or methanol) fuelled combustion engines.

In this report, the calculations of the TCO are based on single fuel hydrogen engines to make sure it is directly aligned with the EU Taxonomy and is at the same level as hydrogen fuel cell applications and full electric battery sailing. The EU Taxonomy states “(a) the vessels have zero direct (tailpipe) CO₂ emission”. For the calculations (see chapter 4) it is assumed that the vessel uses a mechanical drive system resulting in the lowest investment costs. Adding costs for generators, frequency convertors, electric motors and possibly also batteries would significantly increase investment costs while it is yet uncertain if there would be a saving of energy. On the other side, a vessel which is already using electric motors, can more easily be combined with usage of batteries on board, e.g. making use of opportunities to combine hydrogen with swappable batteries or charging from shore. Again, such flexibility and interoperability also come with a price tag because of higher investments to make the vessel ‘plug&play’ ready for multiple energy types which can be used. Attention is being paid in the MAGPIE project to demonstrate the interoperability between hydrogen fuel cell and usage of swappable batteries in the same vessel.

Moreover, it may well be possible to also see use dual fuel engines in the near future able to run on hydrogen. These dual fuelled engines can use a blend of fossil diesel or HVO100 combined with green hydrogen. Dual fuel engines increase the flexibility for the vessel owner: it makes it possible to use only HVO100 or fossil diesel in case hydrogen is too expensive or in case there are lack of options to swap the hydrogen tanktainers.

Such dual fuel engines do need after treatment systems (SCR and DPF) to ensure that emission limits for NO_x and particulate matter are achieved when operating the engine with diesel or HVO100. Furthermore, some CO₂ emissions would still be emitted at dual fuel application as these fuels have a carbon molecule. Therefore, they will not meet the ‘zero direct CO₂ emission tailpipe’ requirement which creates uncertainty if it aligns with the current EU Taxonomy technical screening criteria for inland vessels if it would be technologically and economically feasible to use also a single fuel hydrogen engine. Therefore, selecting dual fuel options may result in no possibilities to acquire low interest loans or grants from public authorities. As a result, in this report we focus on H₂ single fuel engines.

2.6 Renewable methanol combustion engines

This option is based on using renewable methanol as fuel for one or more internal combustion engines on board of the vessel. It is also based on a mechanical drive for the propulsion of the engine or usage of methanol combustion engines as generator set. In contrast to storage of hydrogen, for the storage of methanol, a fixed tank on board is assumed. ES-TRIN already provides all regulations for using and storing methanol as fuel for inland vessels.

Similar to the situation for hydrogen as fuel for combustion engines, there is no methanol combustion engine yet on the market for new vessels which is fully type approved. This is because the NRMM regulation does not have methanol as reference fuel for certification of new Stage V engines. Moreover, there are concerns about the formaldehyde emissions resulting from methanol combustion which need to be resolved before a wide scale application can be assumed for methanol as fuel for new Stage V engines. This is also being pushed and promoted by means of a subsidy scheme in The Netherlands for certification of methanol fuelled combustion engines. For the short and medium term, it is expected that green methanol will come from biological feedstocks. For this reason, we use bio-methanol in the report for indicating this fuel. For the medium and long term, it is also possible to produce synthetic renewable methanol (Renewable Fuels of Non-Biological Origin (RFNBO)). For example using green hydrogen produced from solar or wind generated electricity combined with CO₂ from Direct Air Capture (DAC).

It needs to be noted that using methanol as fuel is not immediately compliant with the EU Taxonomy. Burning methanol leads to CO₂ emissions from the exhaust. Therefore, it would need to be proven first that it is technologically and economically not feasible to equip and operate the vessel with a direct zero CO₂ emission power system (such as hydrogen fuel cell, monofuel hydrogen combustion engine or full battery sailing).

Single fuel methanol engines are assumed for this option, because dual fuel methanol engines may not be regarded as sufficiently innovative to qualify for grant funding to cover the capital costs while also the effectiveness in terms of emission reductions is at a lower performance for dual fuelled engines.

2.7 Renewable methane in combustion engines

This option is based on using renewable methane as fuel for one or more internal combustion engines on board of the vessel. It is based on a mechanical drive for the propulsion of the engine, either for direct shaft power or for generating electricity on board (genset).

For the storage of methane, a fixed cryogenic tank on board is assumed. In contrast to the situation for hydrogen and methanol, the NRMM regulation does acknowledge the use of methane for the certification of new Stage V internal combustion engines. Also ES-TRIN already provides all regulations for using and storing renewable liquified methane as fuel for inland vessels. For compressed natural gas (CNG), this is not yet allowed in the ES-TRIN technical regulations. However, because of the much lower energy density, a difference of a factor 2 at least, the use of CNG seems less suitable for application in IWT. For these reasons (missing regulations in ES-TRIN and lower energy density), in the report we limit the methane technology to liquified methane.

Already the methane engines are on the market for a longer time and inland vessels using LNG are operational. However, although liquid bio-methane is used by road trucks, the use of such renewable methane is not yet seen in inland navigation. Also here, for the effectiveness in terms of emission reductions it is assumed that single fuel methane engines are being applied.

For the short and medium term, it is expected that green methane will come from biological feedstocks, for example from processing wet manure or waste from agriculture. For this reason, we use bio-methane in the report for indicating this fuel type. For the medium and long term, it is also possible to produce synthetic renewable methane (Renewable Fuels of Non-Biological Origin (RFNBO)). For example using green hydrogen produced from solar or wind generated electricity combined with CO₂ from Direct Air Capture (DAC).

3. Cost characteristics

Cost characteristics are based on the extensive work done in the EU funded project [SYNERGETICS](#) (GA 101096809) to develop cost models for different solutions to reduce emissions by inland and coastal vessels. SYNERGETICS however does focus on retrofit solutions, while PLATINA4Action also considers the new build vessels.

3.1 Energy prices

A substantial part of the total cost of ownership of the propulsion system of an inland vessel consists of the energy costs. In the EU funded project SYNERGETICS a thorough research and analyses was made by SPB/EICB, DST and other partners on the energy prices and the possible evolution between 2025 and 2050. To anticipate to the different market prices seen across Europe, it was decided to work with a minimum and maximum price range per fuel / energy type. This bandwidth approach ensures broad applicability across most EU member states. It also covers the topic of limited feedstocks as the maximum price levels relate to the price of synthetic e-fuels which are scalable.

To ensure comparability, the following price components have been taken into account:

- Wholesale prices for each fuel / energy type reflecting the production price of energy/fuel
- Price impacts from regulations and directives, such as impacts from Renewable Energy Directive (RED), Energy Taxation Directive (ETD) and the EU Emissions Trading System (ETS)
- Distribution costs per fuel / energy type including handling costs, infrastructure and storage

Where possible, a distinction was made between fossil and renewable energy sources in order to enhance the quality and relevance of the comparison between the different energy types.

The scenario development was based on the International Energy Agency's 2024 World Energy Outlook (WEO) publication¹. It provides outlooks on the oil, gas and electricity prices. Moreover, further studies were done using these scenarios, for example about the hydrogen market. In the WEO 2024 there are three scenarios which are:

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

The Stated Policies Scenario (STEPS) reflects a business-as-usual scenario based on the planned and confirmed policy measures. The Announced Pledges Scenario (APS) takes it a step further and reflects the impact of measures which are required to reach the national climate targets of individual countries as basis for the forecasts of energy prices. The Net Zero Emissions Scenario (NZE) is the most ambitious scenario. The NZE scenario implies that more impactful measures are taken by governments for climate mitigation, based on actions needed to make sure that global warming will not exceed 1.5 degrees Celsius. This requires higher targets than assumed for the APS scenario. Therefore, the STEPS and NZE scenarios provide the bandwidth of the energy prices which can be expected in future, while for both scenarios also a minimum and maximum indication is being provided on the energy prices.

¹ Please find the publication here: <https://iea.blob.core.windows.net/assets/140a0470-5b90-4922-a0e9-838b3ac6918c/WorldEnergyOutlook2024.pdf>

Consequently, because of different CO₂e emission reduction targets, there are differentiated CO₂e cost levels which are taken into account for each scenario. Because of expected dropping demand for fossil fuel, the wholesale prices of crude fossil oil and natural gas is assumed to drop on the global wholesale market. However, as result of energy policies, pricing, taxation, caps on the emission levels (ETS) and mandatory targets for supply and use of renewable fuels (e.g. RED-III, FuelEU), the actual market prices of fossil energy for the customer increase significantly. This is reflected in the CO₂e prices. The following table presents the assumed CO₂ costs to be internalised in the energy prices.

Table 3 | Assumed CO₂e prices internalised in the energy prices for inland navigation in Europe

	Minimum price level					
STEPS	2025	2030	2035	2040	2045	2050
APS	€ 0	€ 96	€ 112	€ 189	€ 266	€ 343
NZE	€ 0	€ 104	€ 250	€ 396	€ 542	€ 688
	€ 0	€ 236	€ 392	€ 548	€ 704	€ 860
	Maximum price level					
STEPS	2025	2030	2035	2040	2045	2050
APS	€ 0	€ 136	€ 152	€ 229	€ 306	€ 383
NZE	€ 0	€ 144	€ 290	€ 436	€ 582	€ 728
	€ 0	€ 276	€ 432	€ 588	€ 744	€ 900

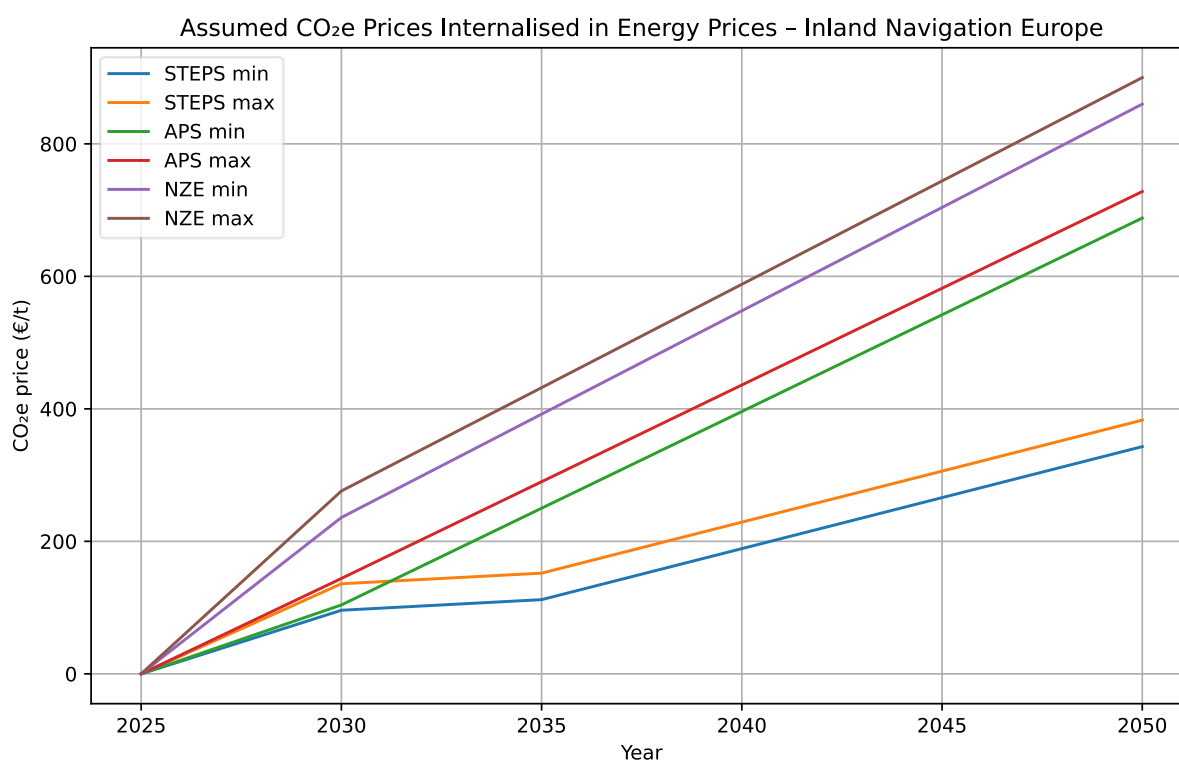


Figure 1 | Assumed CO₂e prices internalised on the energy prices for inland navigation in Europe

It can be seen that for 2025 there are no CO₂e costs yet internalised for the energy supply to inland navigation in Europe. However, because of RED-III implementation from 2026 and ETS2 opt-in (at least in The Netherlands) from 2028, it is assumed that CO₂e costs are being internalised under the STEPS scenario. For the NZE scenario, the CO₂e costs are much higher reaching 900 euro per ton of CO₂e in 2050 and already costs up to 276 euro per ton of emission in 2030. The NZE scenario reflects a strict policy to reduce CO₂e emissions already on the short term to stay below 1.5 degree global warming.

The CO₂e costs presented in the table have been included in the forecasted prices of fossil fuels. The following table presents the prices of fossil diesel for the scenarios at minimum and maximum price levels.

Table 4 | Prices for fossil diesel fuel in inland navigation in Europe, in euro per m3 for the 3 WEO scenarios, minimum and maximum

	Minimum price level					
	2025	2030	2035	2040	2045	2050
STEPS	€ 546	€ 960	€ 1099	€ 1449	€ 1714	€ 1979
APS	€ 546	€ 879	€ 1356	€ 1834	€ 2311	€ 2788
NZE	€ 546	€ 1308	€ 1795	€ 2281	€ 2768	€ 3254
	Maximum price level					
	2025	2030	2035	2040	2045	2050
STEPS	€ 756	€ 1308	€ 1447	€ 1796	€ 2061	€ 2326
APS	€ 756	€ 1226	€ 1704	€ 2181	€ 2659	€ 3136
NZE	€ 756	€ 1656	€ 2142	€ 2629	€ 3115	€ 3602

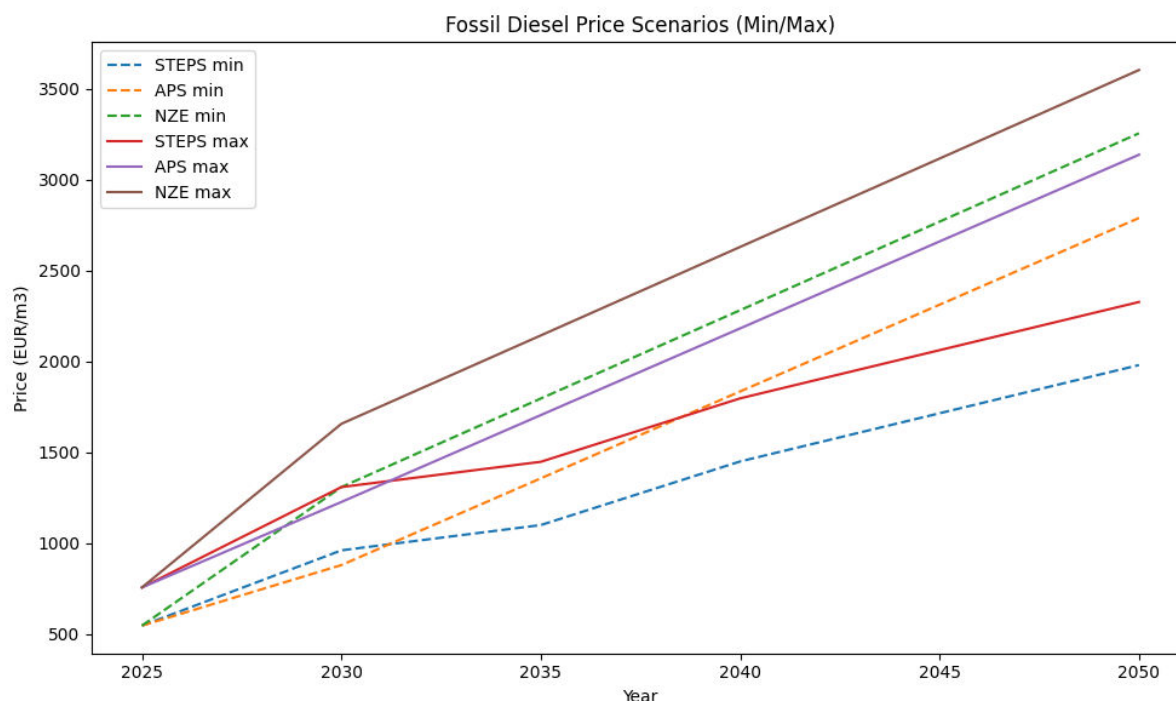


Figure 2 | Diesel fuel prices in euro per m3 for inland navigation in Europe at three scenarios

It can be seen that, according to these scenarios, the costs of diesel will rapidly increase. Already in 2030, the costs will be much higher compared to 2025.

As a result of the cost increase of diesel, the cost difference with renewable energy options will reduce or turn around into a cost advantage for use of renewable energy options compared to diesel. For example, the price of HVO is expected to become competitive with the price of fossil diesel, providing a clear commercial incentive to abandon fossil diesel fuel and to use HVO instead to save on operational costs.

It needs to be noted that the price level of HVO will also depend on the availability of HVO and the required feedstocks to produce HVO. This is affected by the demand for HVO and related feedstocks from other modes of transport (e.g. road haulage, aviation, maritime shipping) and also from other industry sectors (e.g. construction and chemical industry). The maximum price level of HVO therefore presents the price of synthetic HVO, which is scalable.

Furthermore, it shall be remarked that the costs for hydrogen (H2 green) in the tables includes the costs of the swappable tanktainer and includes the logistics handling of this container. For hydrogen it is assumed that this swappable tanktainer will be owned and exploited by a third party, similar as for the pay-per-use model for battery containers.

Table 5 until Table 7 present the price ranges per kg in case of fuels and per kWh for the two electricity options for the STEPS, APS and NZE scenarios.

Table 5 | Energy prices in STEPS scenario per kg (fuels) or kWh (electricity)

	year	Minimum price level						Maximum price level					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Fossil diesel		0.65	1.14	1.31	1.72	2.04	2.36	0.9	1.56	1.72	2.14	2.45	2.77
HVO		1.25	1.4	1.41	1.41	1.4	1.24	1.9	2.08	2.09	2.08	2.07	1.92
Electricity from shore		0.25	0.25	0.26	0.27	0.28	0.29	0.32	0.32	0.33	0.34	0.35	0.36
Pay-per-use batteries		0.35	0.33	0.3	0.28	0.27	0.265	0.5	0.45	0.4	0.37	0.35	0.34
Bio-methane		1.06	1.0	0.94	0.88	0.82	0.76	3.19	3.01	2.82	2.64	2.45	2.27
Methanol green		0.85	0.65	0.4	0.4	0.4	0.4	2.15	1.65	1.02	1.02	1.02	1.02
H2 green		5.5	5.5	5.5	5.5	5.5	5.5	21.0	21.0	18.0	14.0	12.0	10.0

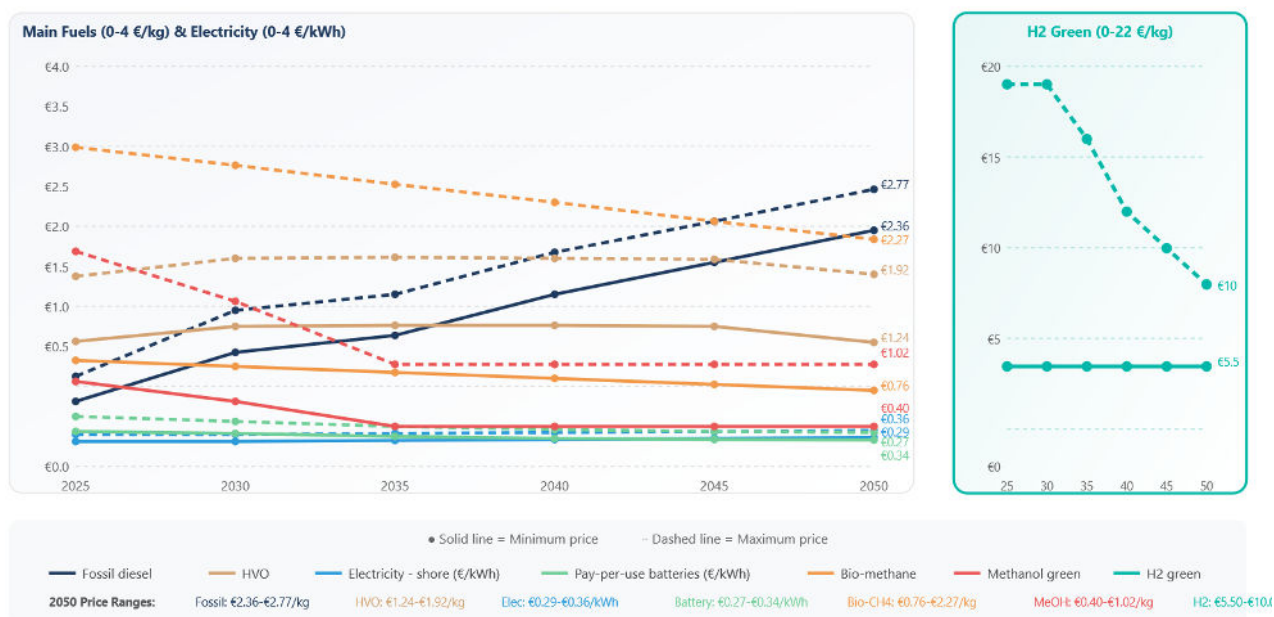


Figure 3 | Energy price projections in euro per kg for fuels and euro per kWh for electricity for the STEPS scenario

Table 6 | Energy prices in APS scenario per kg (fuels) or kWh (electricity)

	year	Minimum price level						Maximum price level					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Fossil diesel		0.65	1.05	1.61	2.18	2.75	3.32	0.9	1.46	2.03	2.6	3.16	3.73
HVO		1.25	1.36	1.44	1.57	1.66	1.84	1.9	2.03	2.11	2.25	2.33	2.46
Electricity from shore		0.25	0.25	0.25	0.25	0.25	0.25	0.32	0.32	0.31	0.31	0.3	0.3
Pay-per-use batteries		0.35	0.33	0.3	0.28	0.27	0.265	0.5	0.45	0.4	0.37	0.35	0.34
Bio-methane		1.06	1.0	0.95	0.9	0.85	0.75	3.19	2.95	2.75	2.55	2.35	2.15
Methanol green		0.85	0.7	0.6	0.5	0.4	0.3	2.15	1.2	1.1	1.0	0.9	0.8
H2 green		5.5	5.5	5.5	5.0	5.0	5.0	21.0	9.0	9.0	8.5	8.5	8.5

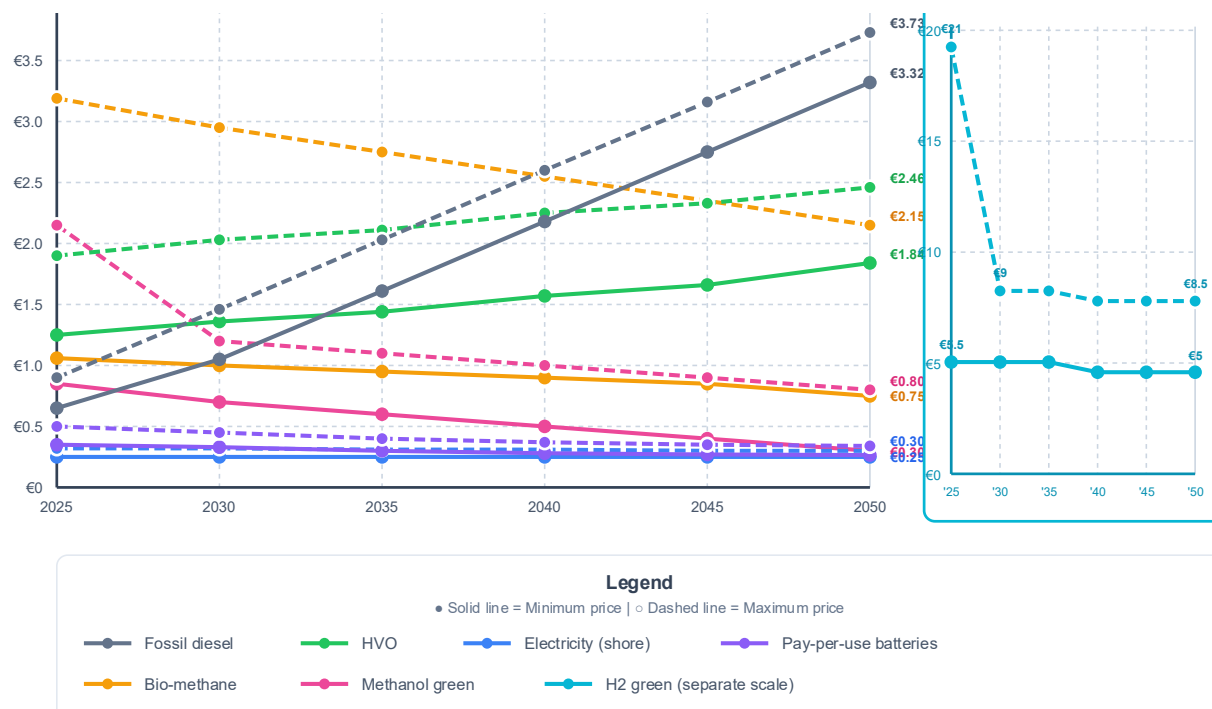


Figure 4 | Energy price projections in euro per kg for fuels and euro per kWh for electricity for the APS scenario

Table 7 | Energy prices in NZE scenario per kg (fuels) or kWh (electricity)

	year	Minimum price level						Maximum price level					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Fossil diesel		0.65	1.56	2.14	2.72	3.29	3.87	0.9	1.97	2.55	3.13	3.71	4.29
HVO		1.25	1.38	1.47	1.61	1.7	1.79	1.9	2.06	2.14	2.28	2.37	2.46
Electricity from shore		0.25	0.25	0.25	0.24	0.24	0.24	0.32	0.32	0.3	0.3	0.28	0.28
Pay-per-use batteries		0.35	0.33	0.3	0.28	0.27	0.265	0.5	0.45	0.4	0.37	0.35	0.34
Bio-methane		1.06	1.0	0.95	0.9	0.85	0.75	3.19	2.95	2.75	2.55	2.35	2.15
Methanol green		0.85	0.7	0.6	0.5	0.4	0.3	2.15	1.2	1.1	1.0	0.9	0.8
H2 green		5.5	6.0	4.5	4.5	4.0	4.0	21.0	9.0	8.5	8.5	8.0	8.0

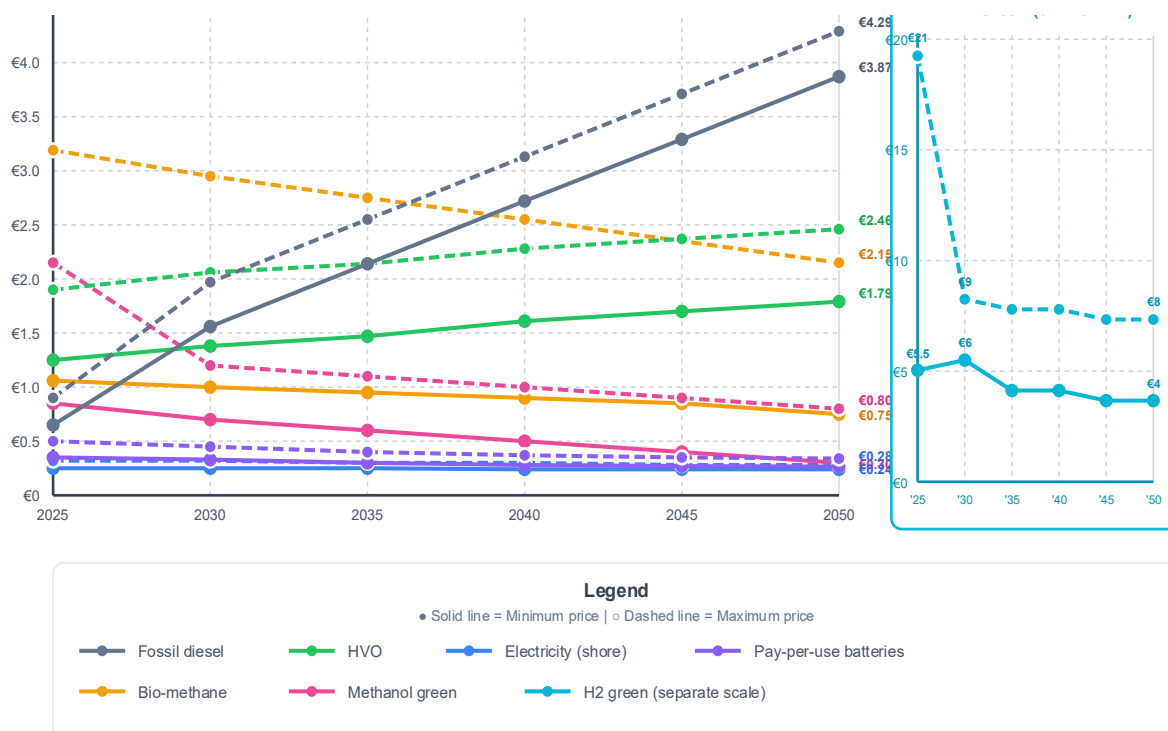


Figure 5 | Energy price projections in euro per kg for fuels and euro per kWh for electricity for the NZE scenario

It needs to be noted that there are differences in the energy contents and the efficiency of the energy conversion on board. For example, methanol has a lower gravimetric energy density compared to diesel, but compressed hydrogen has a much higher gravimetric but low volumetric energy density, even more when the storage tank is taken into account. Battery-electric propulsion presents a considerable advantage, as its powertrain efficiency is approximately double that of combustion engines. Consequently, vessels equipped with battery-electric systems require only half the energy (measured in kWh on board) to operate compared to those powered by traditional combustion engines. Consequently, the costs can also be expressed in euro per GJ mechanical output. This is presented in the next table.

Table 8 | Energy prices compared for the year 2025, considering the caloric value (lower heating value) and the efficiency of the energy conversion on board.

Energy type	Euro per kg		Lower Heating Value MJ/kg	Euro per GJ caloric value		Euro per GJ mechanical output (incl. efficiency)	
	Minimum	Maximum		Minimum	Maximum	Minimum	Maximum
Fossil Diesel	0.65 (= € 54.60 per 100 litres)	0.90 (=€ 75.60 per 100 litres)	43	15.1	20.9	35.9	49.7
HVO	1.25	1.90	44	28.4	43.2	67.7	102.8
Bio-Methane	1.06	3.19	53	20	60.2	50.0	150.5
Bio-Methanol	0.85	2.15	20	42.5	107.5	111.8	282.9
Green H2	3.50	12.00	120	45.8	175	91.7	350
Energy type	Euro per kWh	Euro per kWh	MJ/kg	Minimum	Maximum	Minimum	Maximum
	Minimum	Maximum					
Electricity	0.25	0.32	3.6	69.4	88.9	77.2	98.8
Pay-per-use battery packs	0.35	0.50	3.6	111.1	144.4	123.6	160.7



Figure 6 | Energy cost comparison in different metrics for the year 2025

Currently, without the internalisation of CO₂e emission costs, there is a clear price advantage for the fossil diesel. The low costs seen in the market (e.g. in The Netherlands) is 35.9 euro per GJ mechanical output while electric or renewable energy options are at least 50% more expensive. For example, using onshore power supply while at berth is costing at least 77 euro per GJ power output. This is roughly twice the costs of using a diesel generator set to provide electricity for the vessel at berth (hotel use).

However, when diesel prices will increase due to internalisation of CO₂e costs, the situation will change. Electricity from shore will become a cost-effective solution from the year 2036 in the STEPS scenario. Under the STEPS minimum scenario, bio-methanol and bio-methane could become cost-competitive even sooner. However, both options require significant capital expenditure.

Furthermore, besides the direct energy cost and the capital costs, there are also other aspects which play a role. This is for example the impact on productivity of the vessel. Other option can lead to more bunker-time needed and also to a possible loss of payload to accommodate the energy storage on board (e.g. batteries, liquid bio-methane tank, hydrogen ‘tanktainer’). For this reason, next to the direct energy costs, also the capital costs and other operational impacts need to be taken into account. Only with this holistic approach for the ‘total cost of ownership’ (TCO) a full and fair comparison is possible. In the next section, the capital expenditures are presented.

3.2 Capital expenditures

The capital expenditures concern the costs required for purchasing the hardware components and the work and installation of propulsion systems. The capital costs are estimated for conventional systems to have a reference. For new vessels the reference is a propulsion system using a Stage V internal combustion engine with mechanical direct drive (no electric engines). To develop accurate cost estimates for the various technologies, manufacturers were consulted extensively. The cost assumptions for the technologies, for the year 2025, are the following:

Table 9 | Equipment cost for inland vessels

Equipment type	min	max
Battery [€/kWh]	300	650
Electric engine [€/kW]	150	250
Stage V methanol ICE [€/kW]	500	600
Stage V H2 ICE [€/kW]	600	900
Stage V diesel/HVO ICE [€/kW]	350	590
H2 Fuel Cell [€/kW]	1500	2500
Stage V methane ICE	450	450

It needs to be noted here that costs for methanol and hydrogen engines are ballpark estimates provided by manufactures and engine experts (e.g. TNO). These engines are not yet on the market due to the bottleneck in the NRMM regulation.

Table 10 | Installation and integration cost for inland vessels

Installation and integration type	min [€/kW]	max [€/kW]
Stage V ICE	160	240
Methanol system (including storage)	600	800
Hydrogen system	900	1100
Electric system for FC (including convertors)	370	450
Battery electric system (including electric switchboards, converters, etc.)	800	1200
Methane system (including storage)	873	1042

The following components are taken into account when calculating the total capital investment costs for different systems:

Table 11 | Cost items per type of system to calculate the total capital costs

System type	Equipment	Installation and Integration
Battery-electric vessels	Electric engine, Batteries	Battery-electric system
MEOH ICE SF	MEOH ICE SF	Methanol System, Installation ICE high-speed
H2 ICE SF	H2 ICE SF	Hydrogen System, Installation ICE high-speed
Stage V diesel/HVO ICE	Stage V ICE [€/kW]	ICE with SCR and DPF (Stage V)
H2 FC	H2 Fuel Cell, Electric Engine, Battery, Tank	Hydrogen System, Electric system for FC,
Methane ICE	Methane ICE SF	Methane system, installation ICE SF

The actual costs of a complete energy storage and conversion system for a vessel will mainly depend on the overall power of the installation, expressed in kilowatts. In addition, it also depends on the required energy storage on board. Especially for full battery-electric sailing, the costs for energy storage can be significant. The required energy storage is defined by the energy demand and the required operational autonomy of the vessel.

Another element is the timing of investments. Costs evolutions are being taken into account when investments take place in the future, taking advantage of expected technological developments and economies of scale in production and deployment expected over the next years. This is particularly relevant for the battery industry, as it is expected that costs will come down significantly while the storage capacity and the possible speed of recharging and deployment will increase. For this reason, a bandwidth, presenting a minimum and maximum range was applied for the battery technology. The following table presents the evolution factors which are taken into account to estimate the capital expenses in future years.

Table 12 | Technology price development factors

Systems	Factors [%]					
	Year of installation	2030	2035	2040	2045	2050
Stage V methanol ICE		1.00	0.95	0.80	0.75	0.70
Battery min		0.70	0.49	0.34	0.24	0.17
Battery max		0.80	0.64	0.51	0.41	0.33
Electric engine		1.00	0.95	0.80	0.75	0.70
Stage V hydrogen ICE		1.00	0.95	0.80	0.75	0.70
Hydrogen Fuel Cell		1.00	0.95	0.80	0.75	0.70
Stage V diesel/HVO ICE		1.00	0.95	0.80	0.75	0.70
Stage V methane ICE		1.00	0.95	0.80	0.75	0.70

Another factor related to the capital expenditure is the annual maintenance costs. These are calculated as a percentage of hardware costs and cover activities such as overhauling and replacing components, such as battery cell, fuel cells, filters and engine parts.

The following table presents the percentages applied based on the capital expenses for the hardware (excluding the installation and integration costs).

Table 13 | Maintenance cost per year as percentage of the investment in hardware components per technology

Maintenance	[%]
Stage V methanol ICE	7
Battery electric system	7
Stage V hydrogen ICE	7
Stage V methane ICE	10
Fuel Cell hydrogen	10
Stage V diesel/HVO ICE	10

3.3 Additional cost elements for the TCO

Other elements which need to be included to get to the overall Total Costs of Ownership are the following:

- Costs due to loss of cargo space or passenger seats or cabins
- Costs due to (additional) time required for bunkering energy and/or swapping tanktainers or battery-containers
- Costs due to downtime of the vessel for the installation of technologies, when retrofitting existing vessels.

3.3.1 Bunkering time impacts

All renewable energy/fuel types do take longer to take on board bunker compared to diesel by means of bunkering or swapping. In some cases, this can have a significant impact on the productivity of the vessel. By monetising the loss of productivity, the time loss is taken into account in the Total Costs of Ownership calculations.

There can be a big difference in bunker time for the different fuel/energy types. In order to reduce the time an option is also to use energy storage containers which can be swapped. This is for example done for hydrogen in so called “tanktainers” and for electricity by means of swappable battery containers. In the projects NEEDS² and SYNERGETICS extensive research was done to determine the different bunker speeds for the renewable energy types. The next table presents the characteristics based on the current situation.

² Salih Karaarslan, Martin Quispel, and Niels Kreukniet, ‘D3.1 Regional inland application of the model’, NEEDS Project, Mar. 2023. Accessed: Dec. 10, 2025. [Online]. Available: https://www.waterborne.eu/images/D07_NEEDS_WP3-D3.1_Regional_inland_application_of_the_model.pdf

Table 14 | Maintenance percentages per technology

Fuel type	Swapping speed	Transfer/bunker speed
Methanol	-	550 L/min
Electricity	3000 kWh per 30 min	188 kW 1000 kW (fast charging)
Hydrogen	400 kg per 30 min	3.6 kg/min
Fossil diesel	-	550 L/min
HVO	-	550 L/min
Methane	-	250 kg/min

There are two different bunker speed values included for electricity which are considered in the calculation. The lower value represents the charging power that is currently used for onshore power supply in inland ports. This charging speed can still be suitable for charging small batteries or powering hotel functions. For full battery electric trucks charging stations of 1000 kW exist, which is currently the maximum charging power available. There are ambitions with the new SAE MCS standard³ to install charging points with up to 3.75 MW. Such charging powers will significantly reduce charging time for larger batteries. It may therefore become an alternative for swapping containers for vessels which require a lot of electric energy.

Moreover, the bunker time is also affected by the volumetric energy density. Diesel has a high energy density and can be stored in a regular tank. Although, for example, hydrogen has a higher gravimetric energy content (per kg) than diesel, the volumetric energy density is much lower. Additionally, the tanks in which the compressed hydrogen gas is stored are very bulky, while diesel tanks are relatively narrow and do not take up a lot of extra space. When calculating the actual amount of space required on board for the fuel system not only the fuel input should be taken into account but also the fuel tank itself. As can be seen in the next figure⁴ taking into account the storage system can make a big difference.

³ https://www.sae.org/standards/j3271_202503-sae-megawatt-charging-system-electric-vehicles

⁴ Source: Friederike Dahlke-Wallat, Benjamin Friedhoff, and Sophie Martens, 'Study "Assessment of technologies in view of zero-emission IWT, Edition 1", Part of the overarching study "Financing the energy transition towards a zero-emission European IWT sector"', DST – Development Centre for Ship Technology and Transport Systems, 2020.

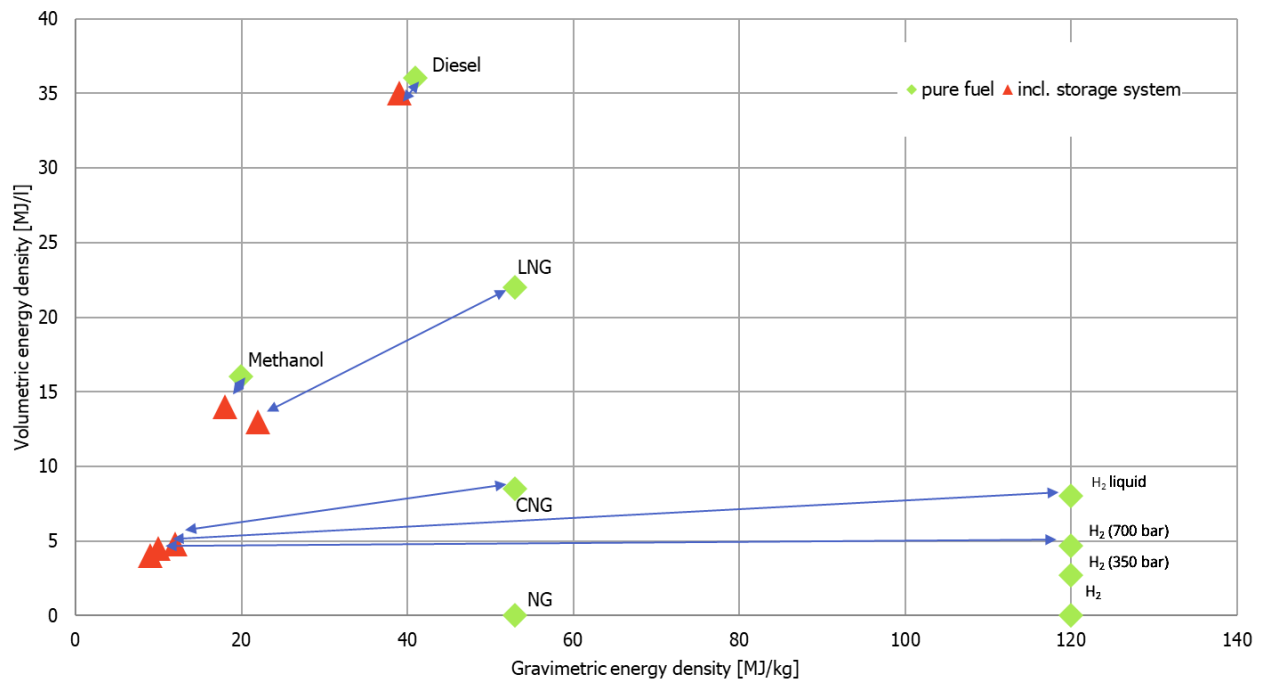


Figure 7 | Volumetric energy density over gravimetric energy density for different fuels and storage conditions and at ambient pressure.

The additional weight and space required for the storage of energy on board and the energy conversion system itself is monetised as well. The Dutch waterway authority Rijkswaterstaat made a publication⁵ presenting the average costs for various vessel types and operations. This publication was used to derive the economic value of a ton of cargo transported or a cubic meter of cargo space.

3.3.2 Downtime days

The downtime days for the installation of the equipment are expected to be higher compared to installing a conventional diesel engine. This may lead to the situation that the vessel is later in service which causes a loss of revenues. The estimation is presented in the next table. For the monetisation of lost days, the Rijkswaterstaat publication was used to assess the fixed cost per day related to the invested capital and the estimated profit loss.

Table 15 | Estimated downtime days

Technology	Estimated downtime days
Stage V diesel/HVO ICE	20
H ₂ , methanol and methane ICE	40
Fuel cells and full electric battery systems	60

⁵ Kostenkengetallen voor het goederenvervoer | Kennisinstituut voor Mobiliteitsbeleid'. Accessed: Dec. 10, 2025. [Online]. Available: <https://www.kimnet.nl/documenten/2023/03/30/kostenkengetallen-voor-het-goederenvervoer>

4. Total Cost of Ownership results

The TCO analysis was conducted for different vessel types, assuming new builds deployed from 2028 for a 20-year time period (2028-2047).

Five cases are elaborated:

- 110 * 11.40 metre dry cargo motor vessel
- 105 * 9.5 metre dry cargo motor vessel
- 67 metre dry cargo motor vessel
- Large pusher
- 135 metre tanker barge for liquid cargo

The Stage V diesel engine is the primary reference, with a second case added for the same engine operating on HVO100.

Next, if applicable, the following technology options have been simulated and compared with the two references:

- Bio-Methane combustion system using cryogenic (liquified) storage on board
- Green methanol single fuel combustion system with fixed storage tank on board
- Green hydrogen single fuel combustion system using 40 foot tanktainers
- Green hydrogen fuel cell system using 40 foot tanktainers
- Full battery electric with fixed batteries and charging from shore
- Full battery electric with swappable 20 foot battery containers (pay-per-use)

However, because of space limitations on board, some technologies may not be physically possible to used (e.g. batteries, cryogenic bio methane tank). Moreover, for methanol single fuel it is yet uncertain if the engines will indeed be on the market in 2028. This is yet to be seen. Into lesser extent, this is also the case for hydrogen single fuel systems as currently such engines are not available yet but the NRMM regulation will be adapted soon to allow the certification with hydrogen as reference fuel.

Two energy price scenarios have been applied on the cases: the STEPS scenario and the NZE scenario. By means of applying these two scenarios the bandwidth is provided for the operational expenditures (OPEX) which mainly consist of energy costs.

Furthermore, as it concerns innovative zero-emission technologies, the cases have also been calculated including a grant on the initial investment. Here a 60% share of the initial capital expense (CAPEX) was taken into account, which is the maximum percentage applied in the Innovation Fund. By means of adding the calculation taking into account public grant support for capital investment, the possible impact of such instrument is also made clear to see if the gaps are closed.

4.1 Case 1: 110m dry cargo vessel

This vessel is seen as the ‘working horse’ for inland waterway transportation in Europe. It is therefore an important reference case for the assessment of the Total Cost of Ownership for different options to drastically reduce the climate change and air pollutant emissions of inland navigation.

4.1.1 Case characteristics

This case concerns the following vessel:

- Vessel dimensions: 110m * 11.40m* 3.5m
- 3043 tons payload
- 1527 kW installed power
- Consumption: 311 tons of diesel per year
- Required autonomy: at least 1 day

Compared technologies:

- Stage V with fossil diesel (= first reference)
- Stage V with HVO100 (= second reference)
- Stage V Methanol ICE, single fuel
- Full battery electric sailing Swappable batteries in pay-per-use service
- Full battery electric sailing: Fixed batteries on board
- Stage V Hydrogen ICE, single fuel
- Hydrogen Fuel cell system

TCO scenarios simulated:

- Energy prices for the year 2028
- STEPS for the energy prices and no grant support
- STEPS and 60% initial CAPEX support
- NZE for the energy prices, reflecting stringent energy policies
- NZE and 60% initial CAPEX support

The following capital investments are applicable for these technologies

Table 16 | Initial capital expenditure for investment, 110 metre dry cargo vessel

	Initial capital expenditure for investment minimum	Initial capital expenditure for investment maximum	Index compared to CAPEX for Stage V diesel/HVO, average
Stage V diesel/HVO ICE (reference)	€ 638,354	€ 1,056,786	100
Stage V methanol single fuel ICE	€ 1,581,744	€ 1,825,360	201
Battery system swapping	€ 714,213	€ 1,103,768	107
Battery system charging	€ 1,885,286	€ 3,826,752	337
Stage V hydrogen ICE	€ 1,604,564	€ 2,244,496	227
Hydrogen Fuel Cell	€ 3,130,732	€ 5,312,610	498

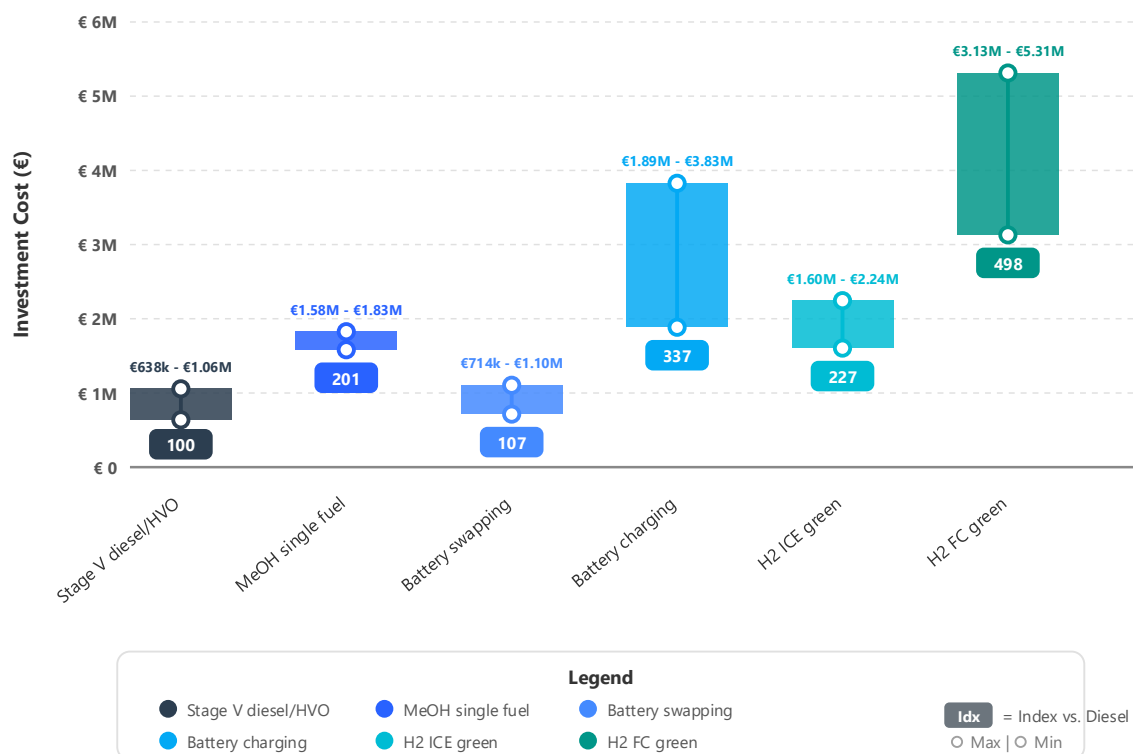


Figure 8 | Initial capital expenditure for investment, 110 metre dry cargo vessel

As it can be seen from Table 16 and Figure 8, there is a quite big additional investment which needs to be done in a zero-emission system.

These initial capital expenses have been included in the calculation of the Total Costs of Ownership, using assumptions on the interest rate (6%) and the depreciation time (20 years). This calculation converts the initial investments into figures for the annual capital costs to be taken into account in the total cost of ownership calculation. Other elements for the TCO are the annual energy costs, the annual maintenance costs and, if relevant, the costs because of loss of bunkering time and possible payload loss. The results of the TCO calculations are presented in the next sections for the different scenarios and assumptions.

4.1.2 TCO per day for 2028

First the calculation of the TCO is presented reflecting the situation in 2028 according to STEPS prices for this year, as it is assumed that the vessels of current initiated projects can be operational from January 2028, benefitting from a certain impact of CO₂e costs internalisation by 2028. The following table presents the overview of the TCO per day.

Table 17 | Average TCO per day for the year 2028 (STEPS)

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 1,079	€ 1,579	€ 1,329	100
Stage V HVO ICE (reference 2)	€ 1,379	€ 2,124	€ 1,751	132
Stage V methanol single fuel ICE	€ 1,784	€ 3,830	€ 2,807	211
Battery system swapping	€ 1,877	€ 2,617	€ 2,247	169
Battery system charging	€ 2,181	€ 3,302	€ 2,742	206
Stage V hydrogen ICE	€ 2,171	€ 6,929	€ 4,550	342
Hydrogen Fuel Cell	€ 2,683	€ 7,344	€ 5,014	377

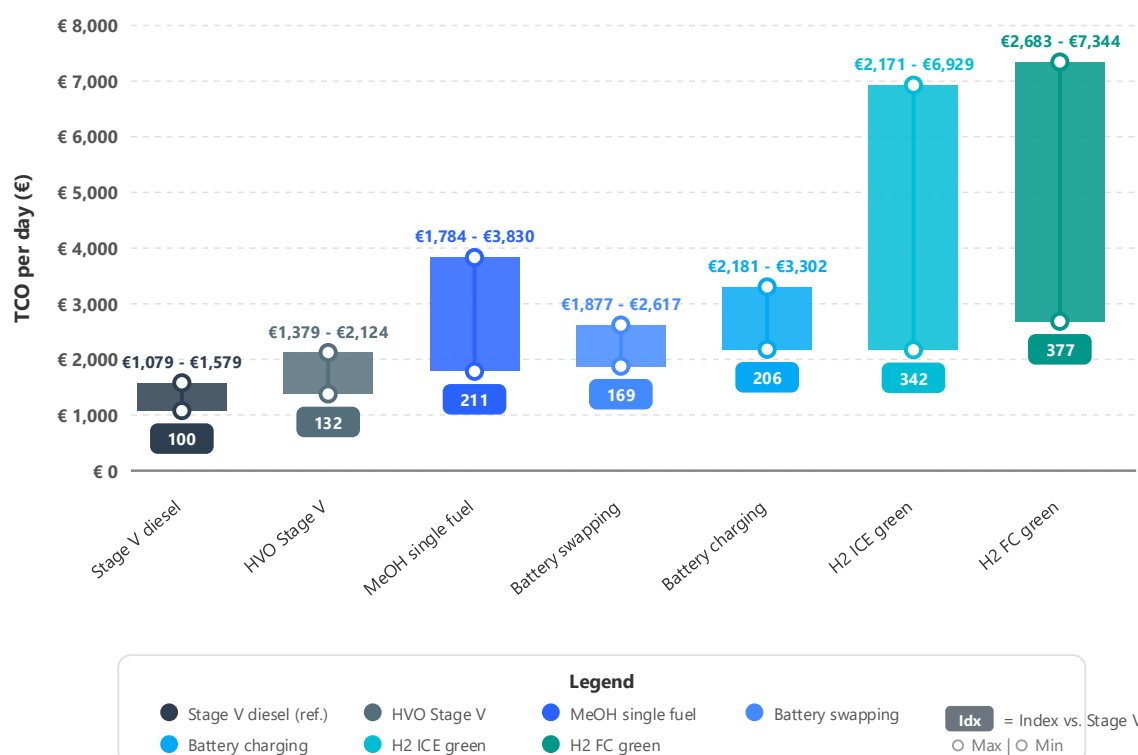


Figure 9 | Average TCO per day at 2028 energy prices (average) for the 110 metre dry cargo motor vessel

As shown in

Table 17, looking at the average TCO cost levels per day for the year 2028, the fossil diesel has a cost advantage of at least 30% compared to the most cost-effective renewable solution (HVO). However, it is to be remarked that these averaged values are used to indicate the policy impacts. It shall be kept in mind that there is a bandwidth applicable. For example, there may be an option that HVO100 could already be competitive, if fossil diesel will be at the maximum price range and HVO100 will be at the minimum price range. However, when looking at the average price difference, running on HVO100 is expected to be 32% more expensive. For the other alternative options the cost gap is much higher and more costly than HVO100. Hydrogen solutions show the highest TCO, particularly the hydrogen fuel cell option. The following graph presents the breakdown of cost for the TCO per technology for the year 2028.

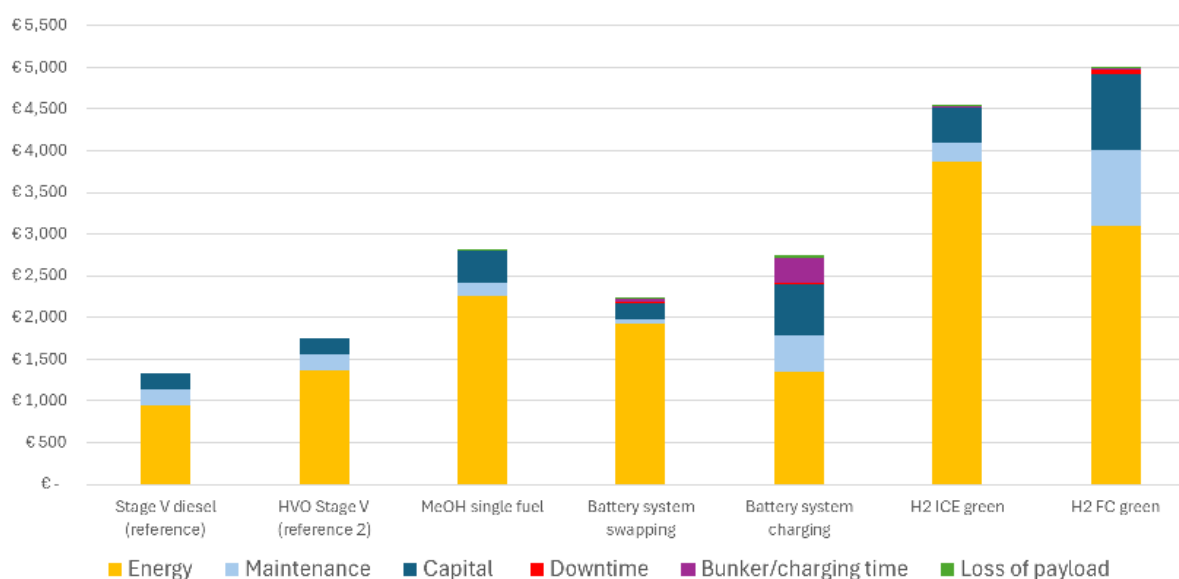


Figure 10 | Cost breakdown of the average TCO per day at 2028 energy prices (average) for the 110 metre dry cargo motor vessel

The share of the energy costs (yellow coloured areas in Figure 10) is in general significant in the TCO for the propulsion of the vessel. For the option of fixed batteries on board (with recharging from shore) the energy costs are relatively low but there is a significant time loss for recharging of the batteries. However, when the battery can be recharged during idle time of the vessel, these time loss costs are not occurring and thus irrelevant. As can be seen in the 'battery system swapping', the yellow part is larger compared to 'battery system, charging' but the capital costs (blue) are much lower. This which reflects the operational costs from the pay-per-use of the battery which are included in the yellow part. The battery costs are not included in the capital expenditure by the vessel owner.

Furthermore, there are high capital costs involved and maintenance costs for the zero-emission solutions. The option of hydrogen fuel cell is most costly, both from the side of operational costs (high energy costs) and also high capital and maintenance costs. Although the energy costs for the hydrogen combustion are higher, the capital and maintenance costs are significantly lower compared to the fuel cell electric option, which results overall in a lower TCO per day for the averaged prices expected for the year 2028.

Clearly in 2028 there is not yet a business case for zero-emission technologies as the costs are significantly higher compared to diesel. However, it is expected that CO₂e emission costs are being internalised in the fossil fuel prices, for example by means of ETS2 opt-in and by means of the Renewable Energy Directive (RED III). Consequently, the gap between using renewable energy versus fossil diesel will get smaller over time. The next section therefore presents this outlook, taking into account the impact of expected energy policy implementation.

4.1.3 TCO per day for the STEPS scenario

Table 18 presents the overview of the TCO per day averaged for the whole period 2028-2047 for the STEPS scenario.

Table 18 | Average TCO per day for STEPS scenario 2028-2047, 110 metre motor vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 1,570	€ 2,117	€ 1,844	100
Stage V HVO ICE (reference 2)	€ 1,423	€ 2,174	€ 1,798	98
Stage V methanol single fuel ICE	€ 1,326	€ 2,677	€ 2,001	109
Battery system swapping	€ 1,675	€ 2,254	€ 1,964	107
Battery system charging	€ 2,254	€ 3,375	€ 2,815	153
Stage V hydrogen ICE	€ 2,171	€ 5,523	€ 3,847	209
Hydrogen Fuel Cell	€ 2,683	€ 6,220	€ 4,451	241

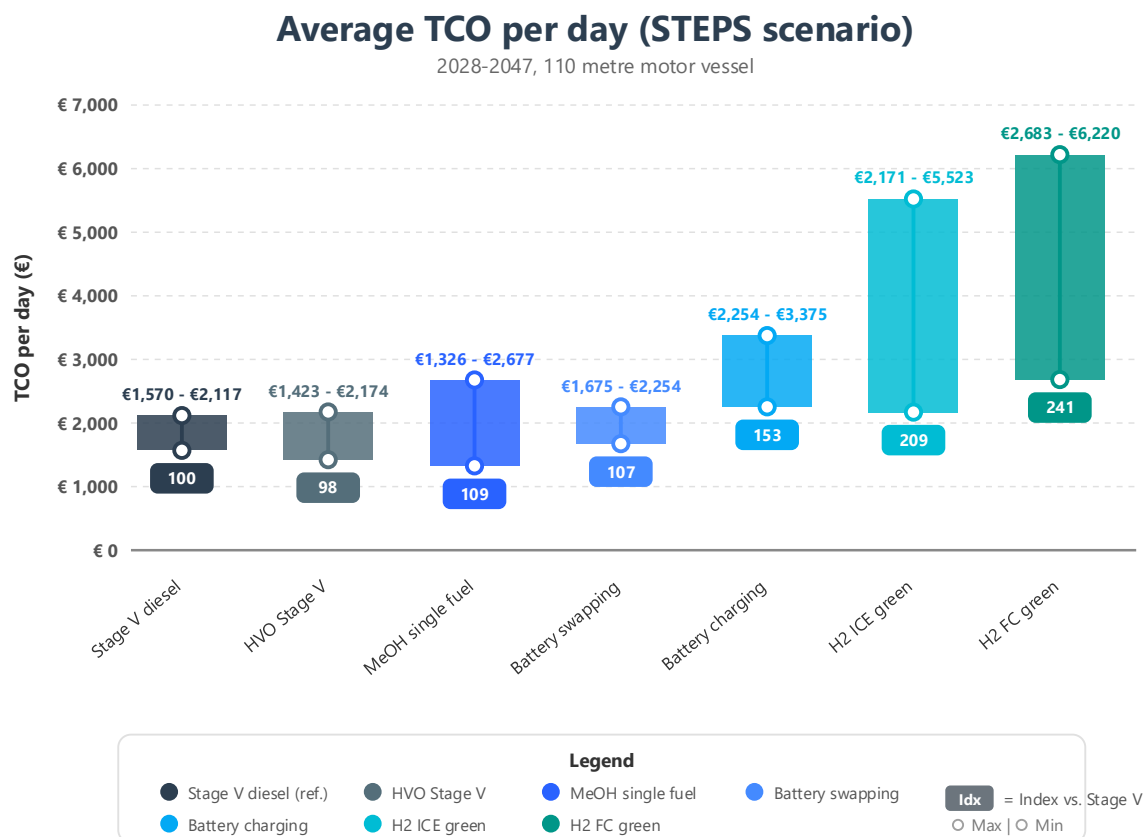


Figure 11 | Average TCO per day at 2028-2047 STEPS energy prices (average) for the 110 metre dry cargo motor vessel

It may be expected, in the STEPS scenario, that HVO will already be competitive with fossil diesel during the period 2028-2044. However, the zero-emission options using methanol, hydrogen or batteries do have a significant gap compared to the Stage V diesel.

Hydrogen, methanol, and fixed battery solutions show a wide cost bandwidth, reflecting uncertainty in both energy and investment prices. Under favourable conditions, at minimum methanol and battery swapping prices (pay-per-use), zero-emission solutions could already be competitive. On average, however, a cost gap remains.

Figure 12 presents the breakdown of cost for the average TCO per technology for the period 2028-2047.

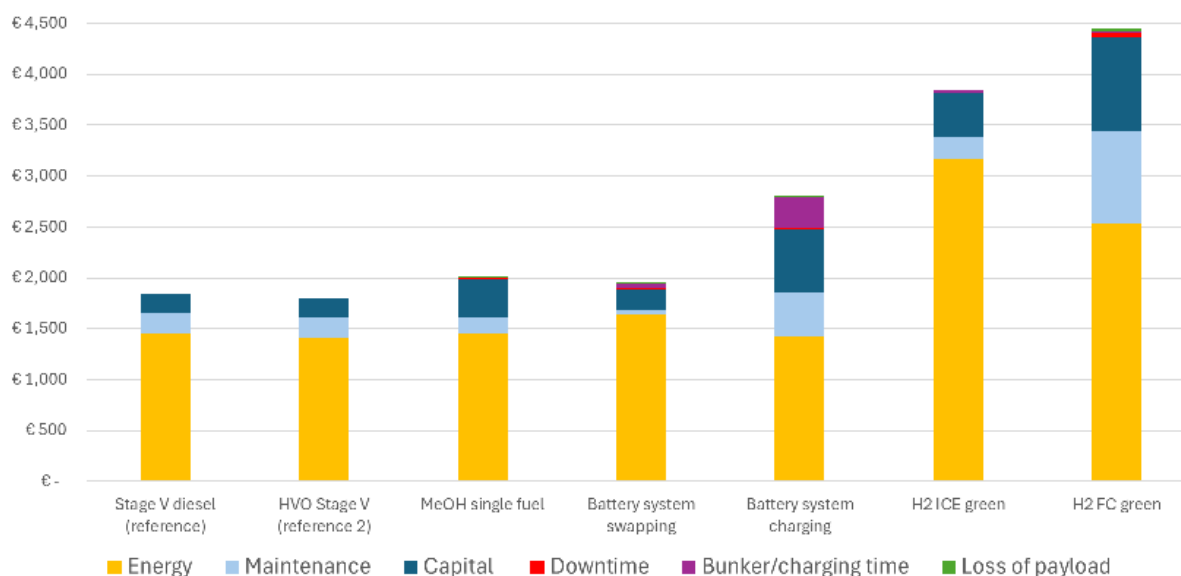


Figure 12 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 105 metres dry cargo motor vessel

4.1.4 TCO per day for the STEPS scenario and 60% CAPEX funding

Already in the STEPS scenario there is internalisation of CO₂e costs in the fuel prices. This can be done by means of an ETS system, like the ETS2 opt-in as decided by the Dutch government. This ETS system generates revenues which can be used to stimulate the uptake of innovative zero-emission technologies by means of providing grants to the early movers to create economies of scale and a breakthrough of technology. Such funding instruments can be effective in the first period of the energy transition, as in this period there may still be a significant gap between the energy costs of fossil diesel and alternative renewable options.

Therefore, one may assume that revenues generated via schemes such as ETS can be used to feed a fund to support the early adopters. A common principle in grant schemes is to fund the initial investment. Possible combinations may also be possible between national grant schemes and European instruments, such as Innovation Fund or the European Competitiveness Fund. In order to have a good view on possible impact of grants support, this scenario assumes 60% of the investment to be covered by means of funding by public bodies. This amount seems reasonable especially for smaller companies which are dominating the ship owners of inland vessels in Europe. Innovation Fund also can support the capital expenses with a share of 60%.

Table 19 presents the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario including the assumption that a strong funding would be provided by means of grants to cover 60% of the costs of the initial investment. This gives an indication what the impact is of such policy instruments, to close the gap with a Stage V engine running on diesel or HVO100.

Table 19 | Average TCO per day for STEPS scenario 2028-2047, 110 metre motor vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 1,570	€ 2,117	€ 1,844	100
Stage V HVO ICE (reference 2)	€ 1,423	€ 2,174	€ 1,798	98
Stage V methanol single fuel ICE	€ 1,117	€ 2,437	€ 1,777	96
Battery system swapping	€ 1,581	€ 2,109	€ 1,845	99
Battery system charging	€ 2,006	€ 2,872	€ 2,439	132
Stage V hydrogen ICE	€ 1,960	€ 5,228	€ 3,594	195
Hydrogen Fuel Cell	€ 2,272	€ 5,521	€ 3,896	211

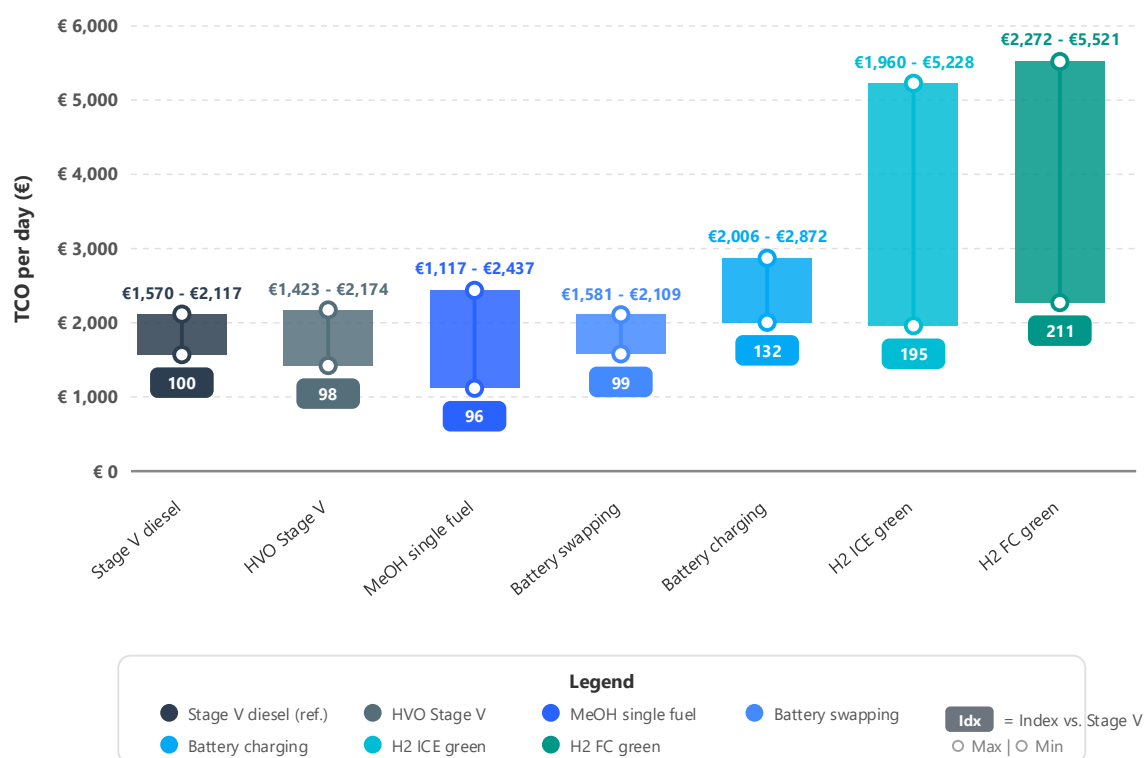


Figure 13 | Average TCO per day at 2028-2047 STEPS energy prices (average) for the 110 metre dry cargo motor vessel and 60% CAPEX funding

Assuming the CAPEX funding of 60%, it is expected that the methanol single fuel and full battery electric navigation (using swappable containers) will be competitive. At average and maximum price levels, however, hydrogen technologies and fixed battery systems still show a significant cost gap.

Figure 14 presents the breakdown of cost for the average TCO per technology, which now shows the reduced share of capital costs (the dark blue areas).

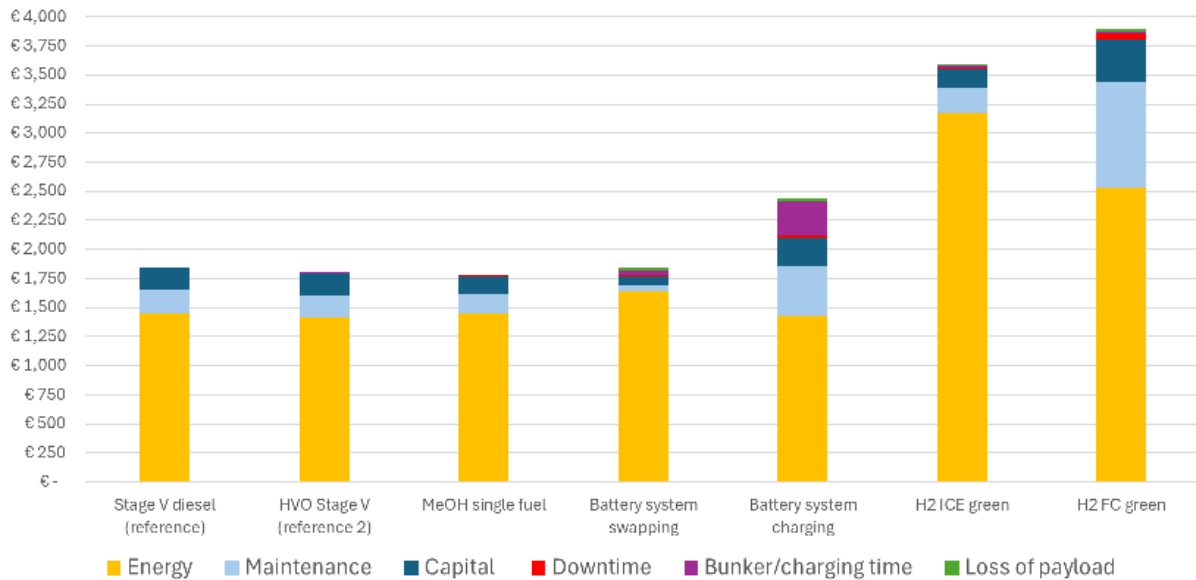


Figure 14 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 110 metre dry cargo motor vessel and 60% CAPEX funding

4.1.5 TCO per day for the NZE scenario

Another option for policy makers to reduce the TCO gap with diesel is to take more measures focussing on the energy supply. This is reflected in the Net Zero Emissions (NZE) scenario, developed by the International Energy Agency.

To better understand the potential impact of stricter climate policies, the TCO was also calculated using NZE CO₂ prices, averaged over the 2028–2047 period. The NZE prices assume much higher prices for the CO₂e costs to be internalised in the fossil diesel fuel. Furthermore, the spread between minimum and maximum prices for renewable energy types like hydrogen is reduced, because of expectations for this NZE scenario that hydrogen will be produced on large scale and the production will receive support resulting in lower costs for hydrogen. Therefore, the gaps in the STEPS scenario are expected to reduce.

Table 20 presents the outcome of the TCO per day when applying the NZE prices (2028-2047).

Table 20 | Average TCO per day for NZE scenario 2028-2047, 110 metre motor vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 2,278	€ 2,823	€ 2,550	100
Stage V HVO ICE (reference 2)	€ 1,537	€ 2,285	€ 1,911	75
Stage V methanol single fuel ICE	€ 1,471	€ 2,472	€ 1,972	77
Battery system swapping	€ 1,675	€ 2,254	€ 1,964	77
Battery system charging	€ 2,157	€ 3,207	€ 2,682	105
Stage V hydrogen ICE	€ 1,947	€ 3,382	€ 2,665	104
Hydrogen Fuel Cell	€ 2,504	€ 4,507	€ 3,506	137

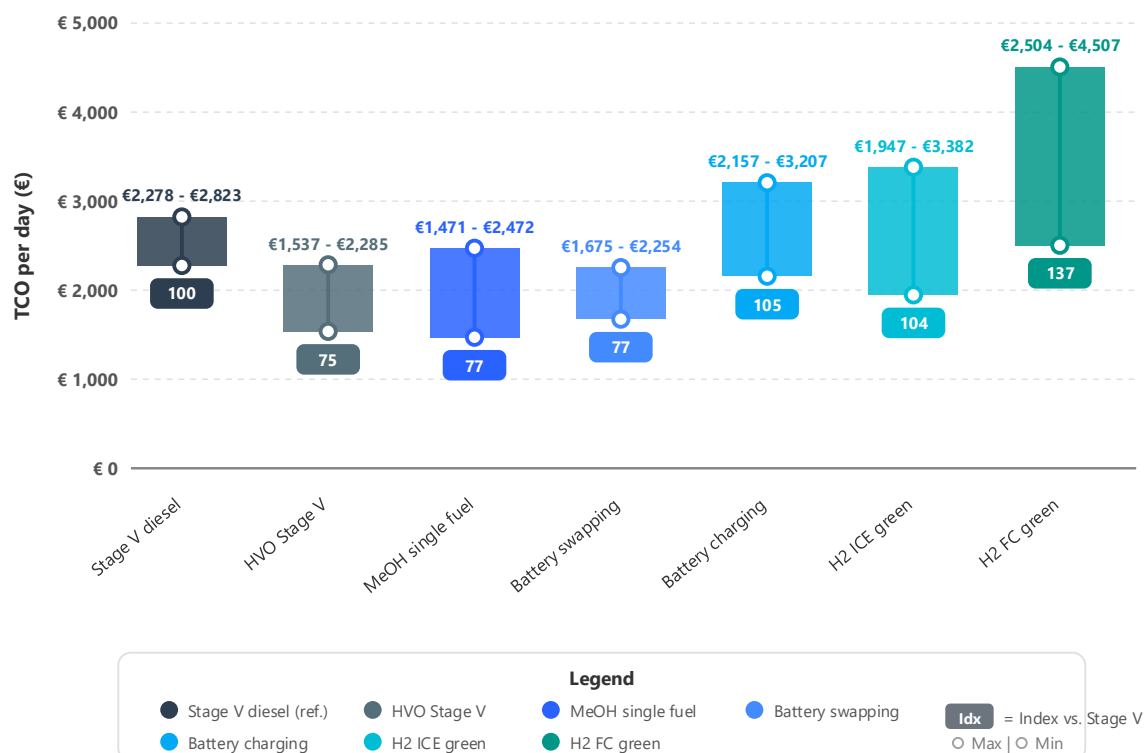


Figure 15 | Average TCO per day at 2028-2047 NZE energy prices (average) for the 110 metre dry cargo motor vessel

It can be concluded by comparing

Table 20 with Table 18 presenting the outcome with the STEPS prices that there is a significant improvement of the economic feasibility of zero-emission solutions under the NZE energy prices scenario. The HVO100 application is becoming favourable if compared with the fossil diesel. Also methanol single fuel internal combustion engines and swappable battery solutions show positive economic feasibility under the NZE scenario.

The hydrogen fuel cell solution remains the least competitive option, with a cost index of 137 relative to fossil diesel and the gap widens further when compared to HVO100.

As can be concluded from the figure presenting the cost breakdown there are quite significant capital and maintenance costs involved in the hydrogen fuel cell solution. These high costs are not sufficiently compensated by lower prices for the hydrogen energy in this scenario.

Also for the battery-electric solution with fixed batteries on board there is a gap when looking at the averaged cost levels for the TCO per day. The energy costs itself are much lower but also here the high capital costs and the time loss for bunkering result in a gap in the comparison with fossil diesel. The costs of productivity loss can be considerable for the solution with fixed batteries and fast charging from shore. These costs are estimated at 300 euro per day, which is at average prices, 11% of the total costs per day.

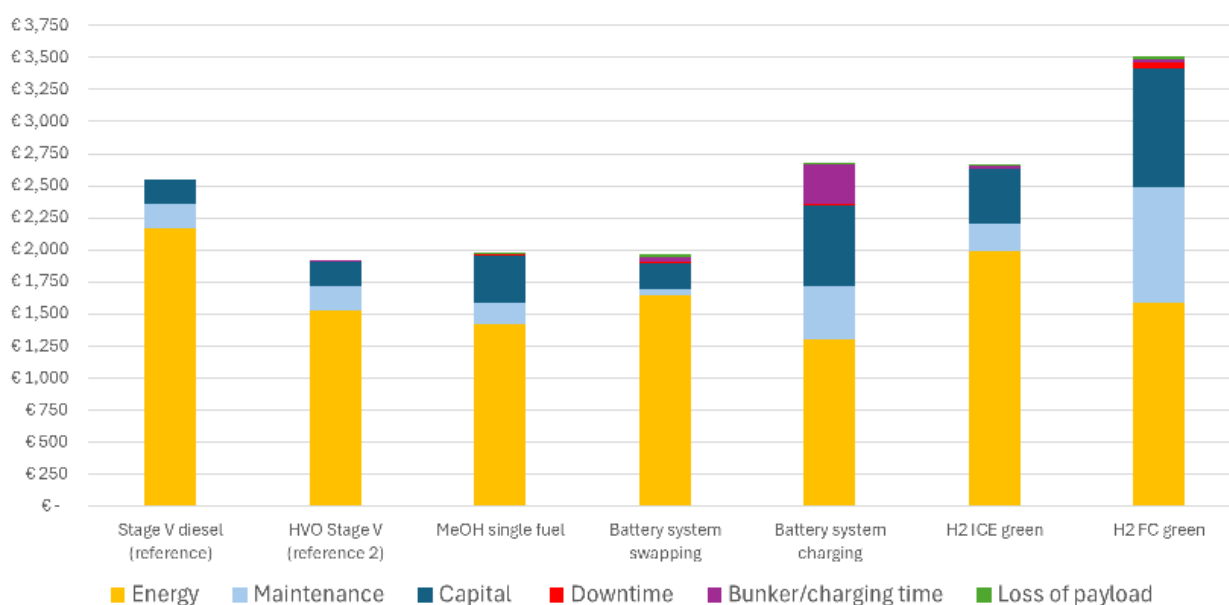


Figure 16 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 110 metre dry cargo motor vessel

4.1.6 TCO per day for the NZE scenario and 60% CAPEX funding

Especially in the NZE scenario there are most likely significant revenues generated for public bodies by means of taxation and Emission Trading Systems. Therefore, one may assume that a viable option could be to spend the revenues on giving a further boost to the uptake of the clean technologies.

This section therefore presents the TCO levels per day when applying the NZE scenario for the energy prices combined with 60% funding of the initial capital expenditure (CAPEX) for zero-emission technologies.

Table 21 presents the outcome of the TCO per day when applying the NZE prices in combination with the 60% funding on the initial capital expense for a methanol single fuel, battery-electric or hydrogen system.

Table 21 | Average TCO per day for NZE scenario 2028-2047, 110 metre dry cargo motor vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 2,278	€ 2,823	€ 2,550	100
Stage V HVO ICE (reference 2)	€ 1,537	€ 2,285	€ 1,911	75
Stage V methanol single fuel ICE	€ 1,263	€ 2,232	€ 1,748	69
Battery system swapping	€ 1,581	€ 2,109	€ 1,845	72
Battery system charging	€ 1,909	€ 2,704	€ 2,307	90
Stage V hydrogen ICE	€ 1,736	€ 3,087	€ 2,412	95
Hydrogen Fuel Cell	€ 2,093	€ 3,808	€ 2,950	116

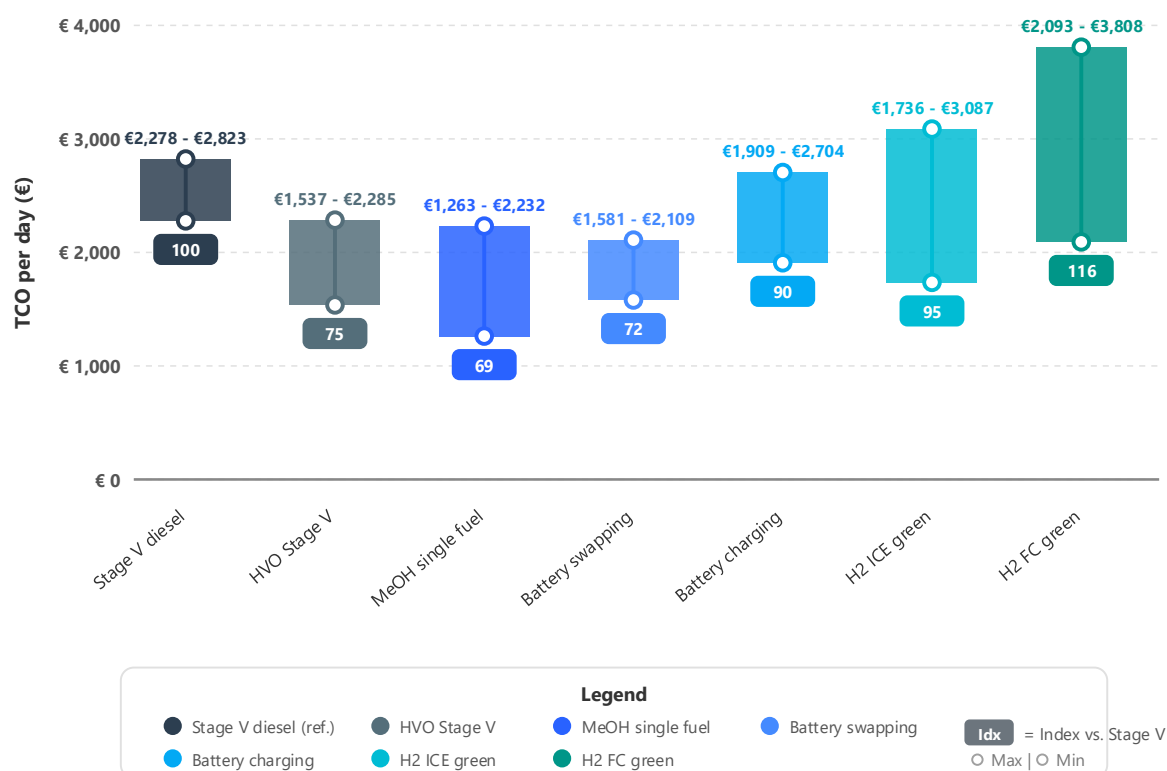


Figure 17 | Average TCO per day for NZE scenario 2028-2047, 110 metre dry cargo motor vessel and 60% CAPEX funding

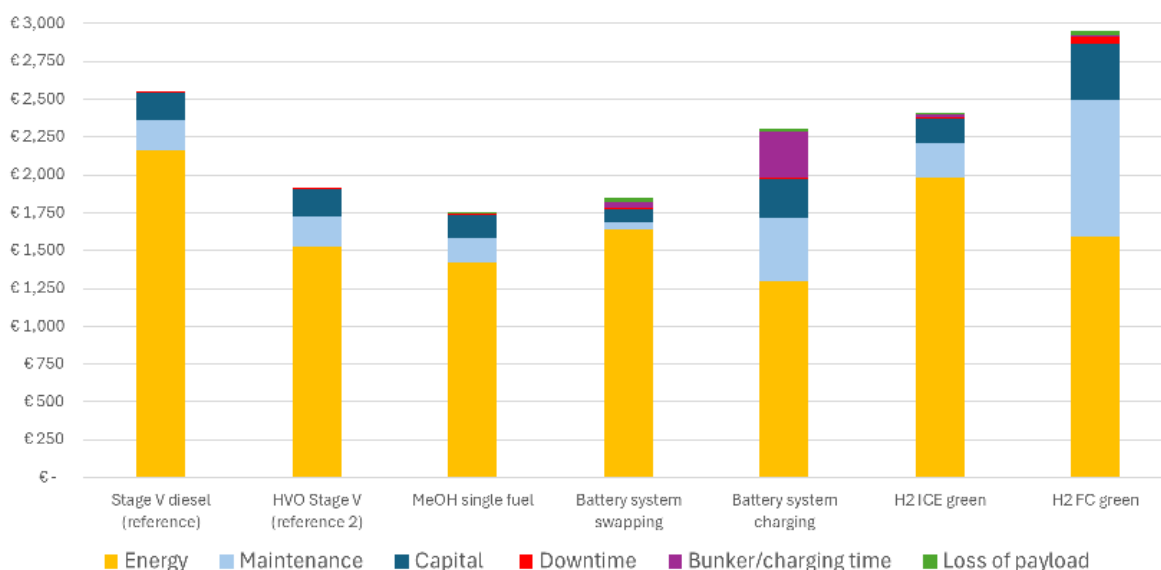


Figure 18 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 110 metre dry cargo motor vessel and 60% CAPEX funding

It can be concluded that the methanol option and the battery swapping option are getting a strong business case in this scenario for this vessel type. These solutions can compete with a Stage V engine using HVO100. Also, vessels using fixed batteries and recharging during idle hours, not resulting in productivity loss, can be competitive. When looking at the minimum and averaged costs levels for the TCO per day, also the hydrogen (ICE) option is now competitive. However, when comparing the maximum cost levels of hydrogen with the cost levels for diesel, there may still be a gap. Clearly the relatively high uncertainty on the price of hydrogen as fuel explains this.

Furthermore, as can be seen in Figure 18, the maintenance costs for the hydrogen fuel cell system are quite significant. Longer lifetime of fuel cells and cost reductions to replace the equipment can possibly lead to reduced maintenance costs. Further research and development work in the field of hydrogen fuel cells seems therefore a logical recommendation to reduce the gap between hydrogen fuel cell technologies with diesel and other zero-emission technologies.

For the solution using fixed batteries and charging from shore the maintenance costs are also relatively large. Here also further research and development may lead to battery systems with a longer lifetime and thus lower cost. Furthermore, the estimated costs for productivity losses are also substantial. Faster recharging systems, with higher capacities than 1 MWh per vessel may be developed in future, which can reduce the recharging times to improve the competitiveness of this option.

4.2 Case 2: 105 metre dry cargo motor vessel

This vessel of 105 metre is not much smaller in length, but the beam and draught are also smaller, resulting into a payload of 2/3 of the 110 metre vessel. Furthermore, this vessel typically has a lower fuel consumption compared to the 110 metre vessel and also much less installed power (about half the installed power of a 110 metre vessel). Because of the smaller engine size and also the much smaller energy consumption it is relevant to see the differences with the 110 metre and to analyse how the solutions perform for this vessel type and operational profile.

4.2.1 Case characteristics

This case concerns the following vessel:

- Vessel dimensions: 105m * 9.5m* 3m
- 2000 tons payload
- 750 kW installed power
- Consumption: 135 tons of diesel per year
- Required autonomy: at least 1 day

Compared technologies:

- Stage V with fossil diesel (= first reference)
- Stage V with HVO100 (= second reference)
- Stage V methanol ICE, single fuel
- Full battery electric sailing Swappable batteries in pay-per-use service
- Full battery electric sailing: Fixed batteries on board
- Stage V hydrogen ICE, single fuel
- Hydrogen Fuel cell system

TCO scenarios simulated:

- Energy prices for the year 2028
- STEPS for the energy prices and no grant support
- STEPS and 60% initial CAPEX support
- NZE for the energy prices, reflecting stringent energy policies
- NZE and 60% initial CAPEX support

The following capital investments are applicable for these technologies

Table 22 | Initial capital expenditure for investment, 105 metre dry cargo vessel

	Initial capital expenditure for investment minimum	Initial capital expenditure for investment maximum	Index compared to CAPEX for Stage V diesel/HVO, average
Stage V diesel/HVO ICE (reference)	€ 366,404	€ 598,356	100
Stage V methanol single fuel ICE	€ 1,193,244	€ 1,359,160	265
Battery system swapping	€ 615,145	€ 938,655	161
Battery system charging	€ 1,123,489	€ 2,120,658	336
Stage V hydrogen ICE	€ 1,138,364	€ 1,545,196	278
Hydrogen Fuel Cell	€ 1,917,244	€ 3,028,272	513

As it can be seen from the table, there is a quite big additional investment which needs to be done in a zero-emission system.

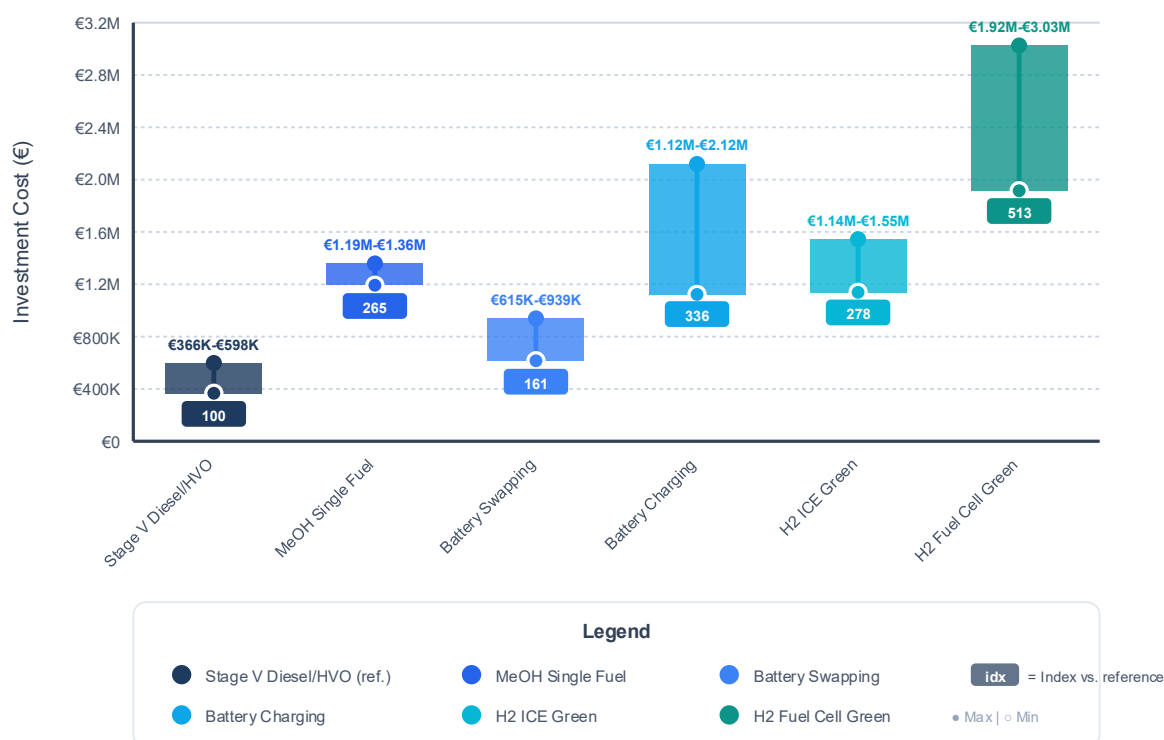


Figure 19 | Initial capital expenditure for investment, 105 metre dry cargo vessel

These initial capital expenses have been included in the calculation of the Total Costs of Ownership, using assumptions on the interest rate (6%) and the depreciation time (20 years). This calculation converts the initial investments into figures for the annual capital costs to be taken into account in the total cost of ownership calculation. Other elements for the TCO are the annual energy costs, the annual maintenance costs and, if relevant, the costs because of loss of bunkering time and possible payload loss. The results of the TCO calculations are presented in the next sections for the different scenarios and assumptions.

4.2.2 TCO per day for 2028

First the calculation of the TCO is presented reflecting the situation in 2028 according to STEPS prices for this year, as it is assumed that the vessels of current initiated projects can be operational from January 2028, possibly also using financial instruments for support of CAPEX and benefitting from a certain impact of CO2e costs internalisation by 2028.

Table 23 presents the overview of the TCO per day when applying the energy prices expected for the year 2028 at the STEPS scenario.

Table 23 | Average TCO per day for the year 2028 (STEPS)

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 496	€ 730	€ 613	100
Stage V HVO ICE (reference 2)	€ 626	€ 967	€ 797	130
Stage V methanol single fuel ICE	€ 894	€ 1,798	€ 1,346	219
Battery system swapping	€ 892	€ 1,249	€ 1,071	175
Battery system charging	€ 1,011	€ 1,536	€ 1,273	208
Stage V hydrogen ICE	€ 1,054	€ 3,153	€ 2,104	343
Hydrogen Fuel Cell	€ 1,325	€ 3,402	€ 2,363	385

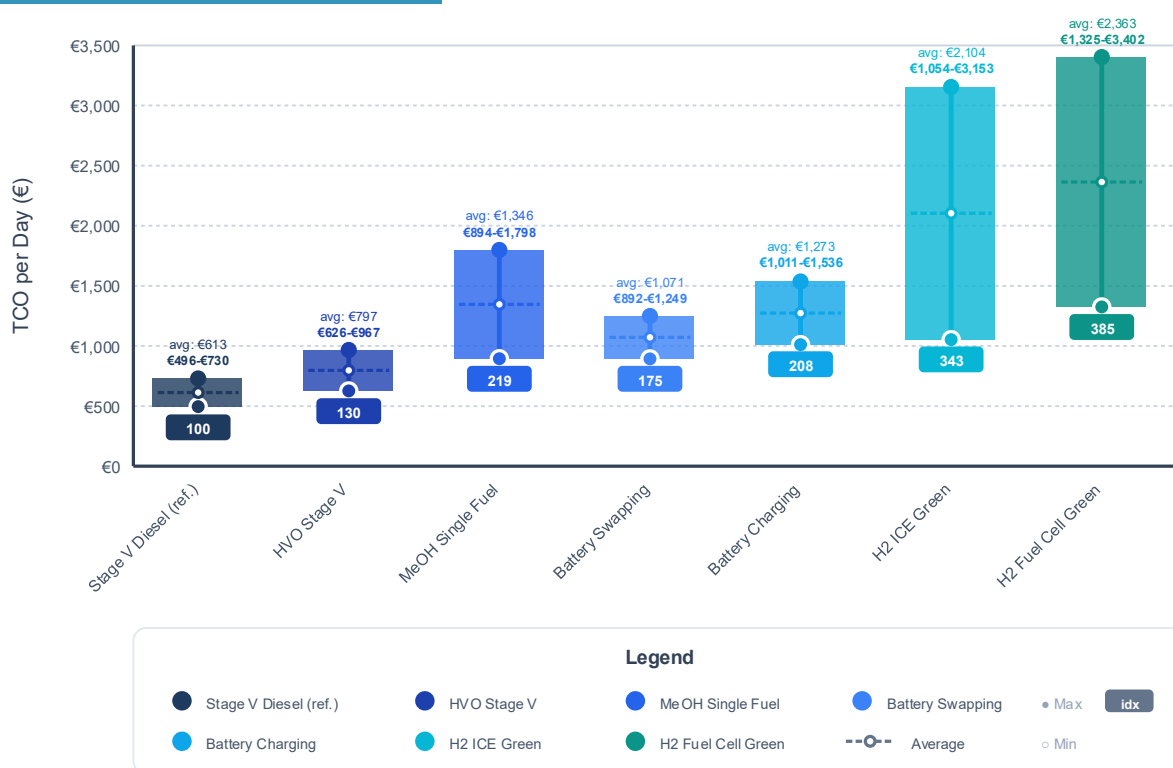


Figure 20 | Average TCO per day at 2028 energy prices (average) for the 105 metre dry cargo motor vessel

As shown, looking at the average TCO cost levels per day, the fossil diesel has a cost advantage of 30% compared to the alternatives. There may be an option that HVO100 could already be competitive, if fossil diesel will be at the maximum price range and HVO100 will be at the minimum price range.

When looking at the average price difference, running on HVO100 is expected to be 30% more expensive and for the other alternative options the cost gap is much higher and more costly than HVO100, though battery swapping could be competitive. Hydrogen solutions show the highest TCO, particularly the hydrogen fuel cell option. The following graph presents the breakdown of cost for the TCO per technology for the year 2028.

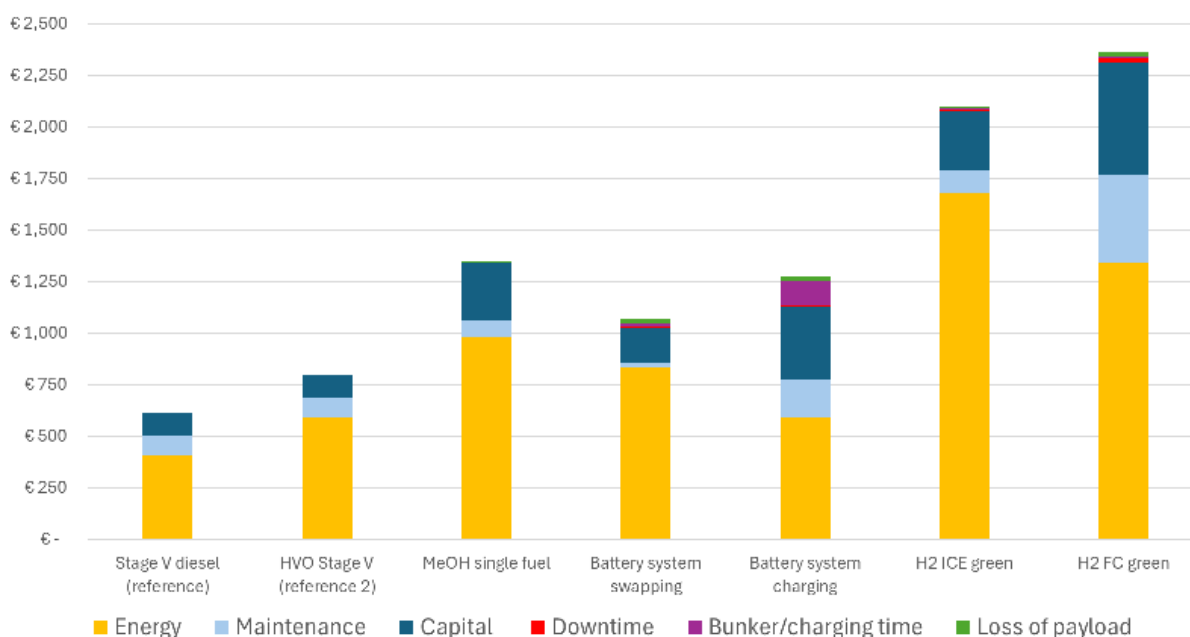


Figure 21 | Cost breakdown of the average TCO per day at 2028 energy prices (average) for the 105 metre dry cargo motor vessel

Figure 21 shows that the share of the energy costs is in general significant in the TCO for the propulsion of the vessel, also with the lower fuel consumption compared to a 110 metre vessel. For the option of fixed batteries on board (with recharging from shore) the energy costs are relatively low but there is a significant time loss for recharging of the batteries. However, when the battery can be recharged during idle time of the vessel, these time loss costs are not occurring and thus irrelevant. This can occur when the vessel operates in a daytime regime (5 days at 14 hours per day) and can recharge during the night.

Furthermore, there are high capital costs involved and maintenance costs for the zero-emission solutions. The option of hydrogen fuel cell is most costly, both from the side of operational costs (high energy costs) and also high capital and maintenance costs. Although the energy costs for the hydrogen combustion are higher, the capital and maintenance costs are significantly lower compared to the fuel cell electric option, which results overall in a lower TCO per day for the averaged prices expected for the year 2028.

Clearly in 2028 there is not yet a business case for zero-emission technologies as the costs are significantly higher compared to diesel. However, it is expected that CO₂e emission costs are being internalised in the fossil fuel prices, for example by means of ETS2 opt-in and by means of the Renewable Energy Directive (RED III). Consequently, the gap between using renewable energy versus fossil diesel will get smaller over time. The next section therefore presents this outlook, taking into account the impact of expected energy policy implementation.

4.2.3 TCO per day for the STEPS scenario

The following table presents the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario.

Table 24 | Average TCO per day for STEPS scenario 2028-2047, 105 metre motor vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 709	€ 964	€ 709	100
Stage V HVO ICE (reference 2)	€ 646	€ 988	€ 646	98
Stage V methanol single fuel ICE	€ 696	€ 1,297	€ 696	119
Battery system swapping	€ 804	€ 1,092	€ 804	113
Battery system charging	€ 1,042	€ 1,568	€ 1,042	156
Stage V hydrogen ICE	€ 1,054	€ 2,543	€ 1,054	215
Hydrogen Fuel Cell	€ 1,325	€ 2,914	€ 1,325	253

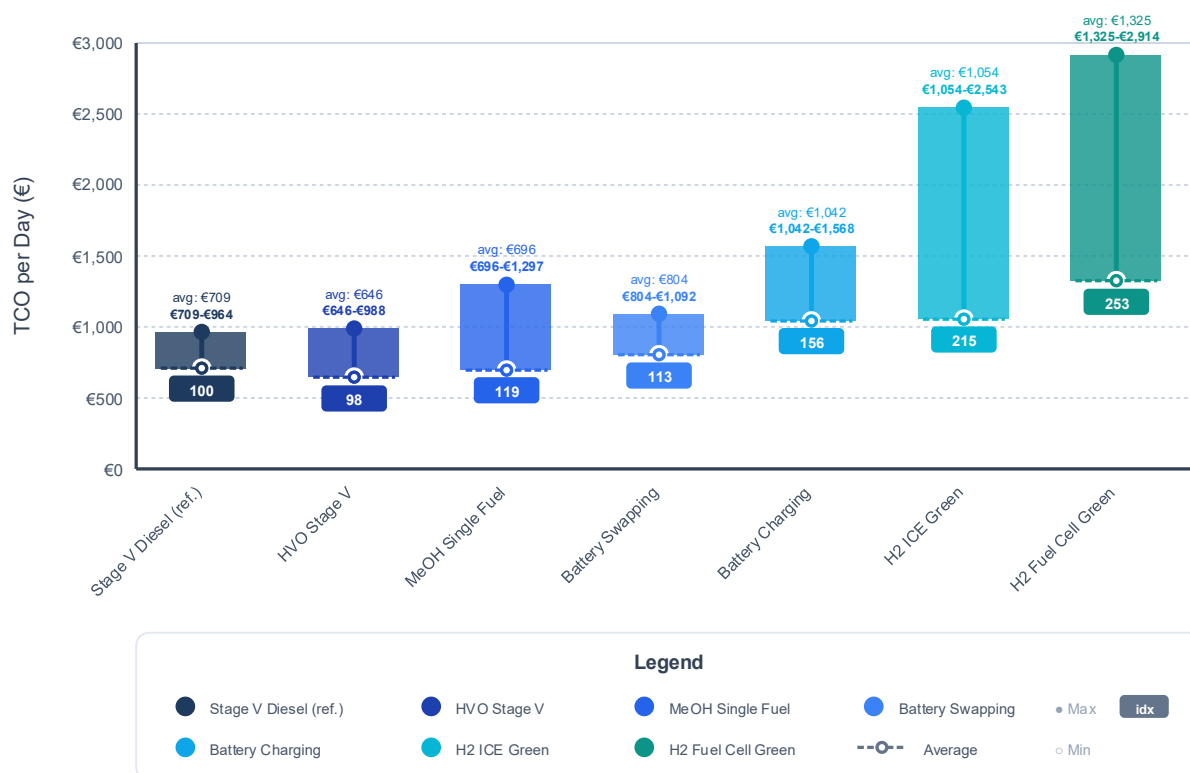


Figure 22 | Average TCO per day at 2028-2047 STEPS energy prices (average) for the 105 metre dry cargo motor vessel

It may be expected, in the STEPS scenario, that HVO will already be competitive with fossil diesel during the period 2028-2044. However, the zero-emission options using methanol, hydrogen or batteries do have a significant gap compared to the Stage V diesel.

Hydrogen, methanol, and fixed battery solutions show a wide cost bandwidth, reflecting uncertainty in both energy and investment prices. Under favourable conditions, with low methanol and electricity prices, zero-emission solutions could already be competitive. On average, however, a cost gap remains.

Figure 23 presents the breakdown of cost for the average TCO per technology. (2028-2047).

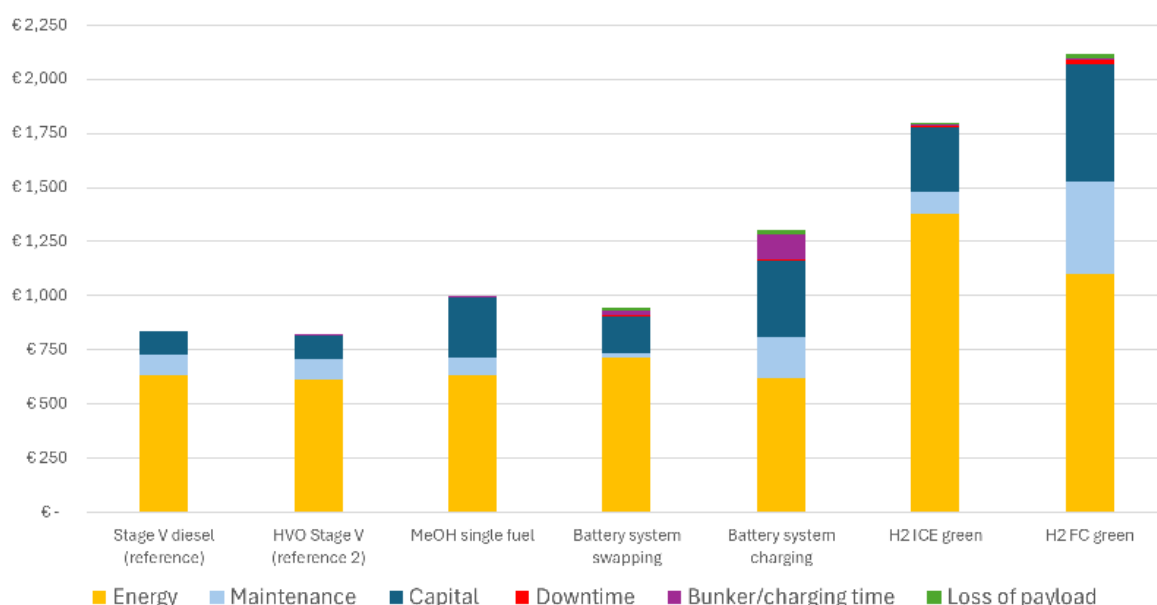


Figure 23 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 105 metre dry cargo motor vessel

4.2.4 TCO per day for the STEPS scenario and 60% CAPEX funding

Already in the STEPS scenario there is internalisation of CO₂e costs in the fuel prices. This can be done by means of an ETS system, like the ETS2 opt-in as decided by the Dutch government. This ETS system generates revenues which can be used to stimulate the uptake of innovative zero-emission technologies by means of providing grants to the early movers to create economies of scale and a breakthrough of technology. Such funding instruments can be effective in the first period of the energy transition, as in this period there may still be a significant gap between the energy costs of fossil diesel and alternative renewable options.

Therefore, one may assume that revenues generated via schemes such as ETS can be used to feed a fund to support the early adopters. A common principle in grant schemes is to fund the initial investment. Possible combinations may also be possible between national grant schemes and European instruments, such as Innovation Fund or the European Competitiveness Fund. In order to have a good view on possible impact of grants support, this scenario assumes 60% of the investment to be covered by means of funding by public bodies. This amount seems reasonable especially for smaller companies which are dominating the ship owners of inland vessels in Europe. Innovation Fund also can support the capital expenses with a share of 60%.

Table 25 presents the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario including the assumption that a strong funding would be provided by means of grants to cover 60% of the costs of the initial investment. This gives an indication what the impact is of such policy instruments, to close the gap with a Stage V engine running on diesel or HVO100.

Table 25 | Average TCO per day for STEPS scenario 2028-2047, 105 metre motor vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 709	€ 964	€ 837	100
Stage V HVO ICE (reference 2)	€ 646	€ 988	€ 817	98
Stage V methanol single fuel ICE	€ 539	€ 1,119	€ 829	99
Battery system swapping	€ 724	€ 968	€ 846	101
Battery system charging	€ 895	€ 1,289	€ 1,092	130
Stage V hydrogen ICE	€ 905	€ 2,340	€ 1,622	194
Hydrogen Fuel Cell	€ 1,073	€ 2,515	€ 1,794	214

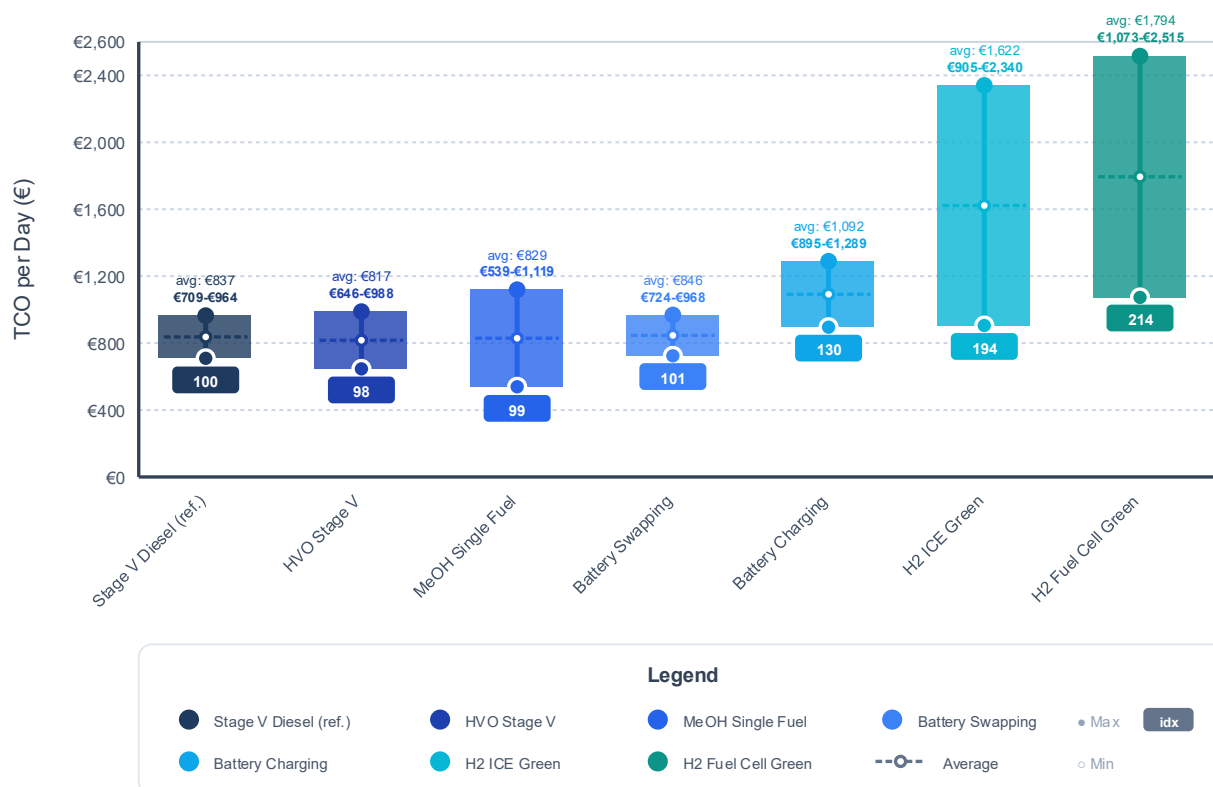


Figure 24 | Average TCO per day at 2028-2047 STEPS energy prices (average) for the 105 metre dry cargo motor vessel and 60% CAPEX funding

Assuming the CAPEX funding of 60%, it is expected that the methanol single fuel and full battery electric navigation (using swappable containers) will be competitive. At average and maximum price levels, however, hydrogen technologies and fixed battery systems still show a significant cost gap.

Figure 25 graph presents the breakdown of cost for the average TCO per technology, which now shows the reduced share of capital costs.

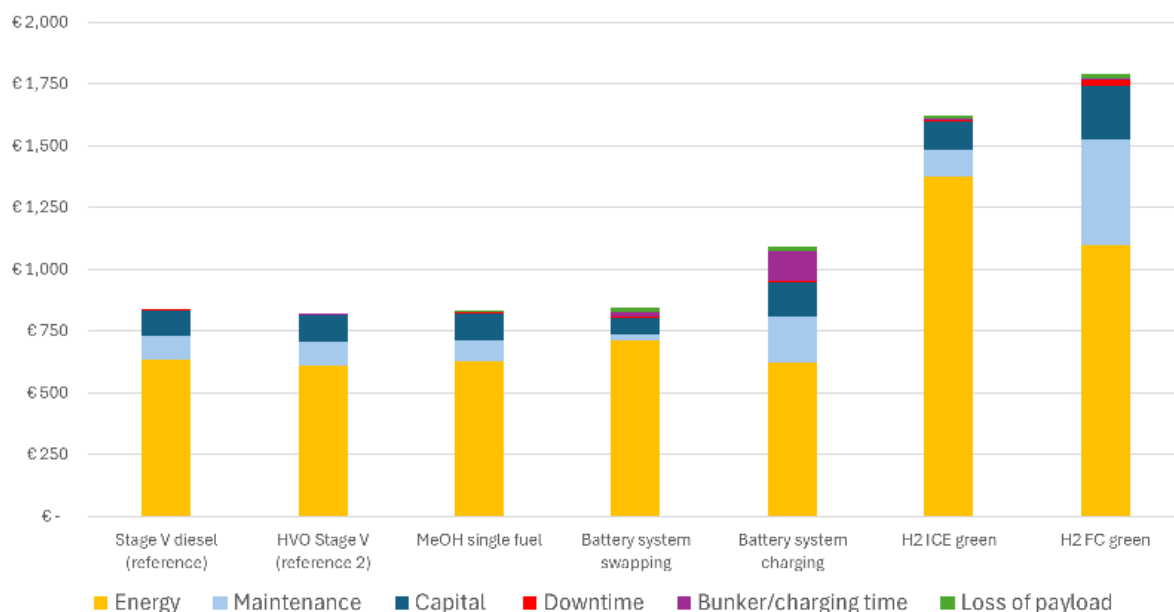


Figure 25 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 105 metre dry cargo motor vessel and 60% CAPEX funding

4.2.5 TCO per day for the NZE scenario

Another option for policy makers to reduce the TCO gap with diesel is to take more measures focussing on the energy supply. This is reflected in the Net Zero Emissions (NZE) scenario, developed by the International Energy Agency.

To better understand the potential impact of stricter climate policies, the TCO was also calculated using NZE CO₂ prices, averaged over the 2028–2047 period. The NZE prices assume much higher prices for the CO₂e costs to be internalised in the fossil diesel fuel. Furthermore, the spread between minimum and maximum prices for renewable energy types like hydrogen is reduced, because of expectations for this NZE scenario that hydrogen will be produced on large scale and the production will receive support resulting in lower costs for hydrogen. Therefore, the gaps in the STEPS scenario are expected to reduce.

Table 26 presents the outcome of the TCO per day when applying the NZE prices (2028-2047).

Table 26 | Average TCO per day for NZE scenario 2028-2047, 105 metre motor vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 1,017	€ 1,270	€ 1,143	100
Stage V HVO ICE (reference 2)	€ 695	€ 1,037	€ 866	76
Stage V methanol single fuel ICE	€ 759	€ 1,208	€ 984	86
Battery system swapping	€ 804	€ 1,092	€ 948	83
Battery system charging	€ 1,000	€ 1,495	€ 1,247	109
Stage V hydrogen ICE	€ 957	€ 1,614	€ 1,285	112
Hydrogen Fuel Cell	€ 1,247	€ 2,170	€ 1,709	149

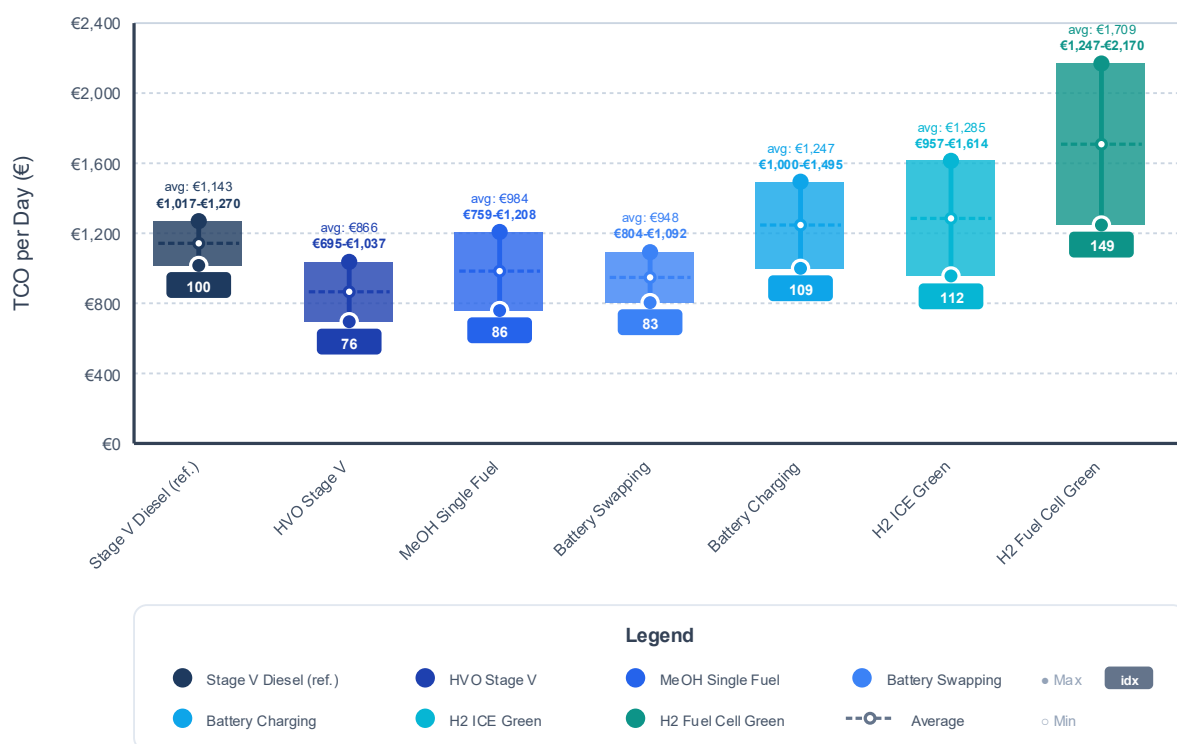


Figure 26 | Average TCO per day at 2028-2047 NZE energy prices (average) for the 105 metre dry cargo motor vessel

It can be concluded by comparing

Table 26 with Table 24 presenting the outcome with the STEPS prices that there is a significant improvement of the economic feasibility of zero-emission solutions under the NZE energy prices scenario. This is mainly because the costs of fossil diesel are much higher in the NZE scenario. The HVO100 application is becoming favourable if compared with the fossil diesel. Also, methanol single fuel internal combustion engines and swappable battery solutions show positive economic feasibility under the NZE scenario. The hydrogen fuel cell solution remains the least competitive option, with a cost index of 149 relative to fossil diesel and the gap widens further when compared to HVO100.

As can be concluded from Figure 27 presenting the cost breakdown, there are quite significant capital and maintenance costs involved in the hydrogen fuel cell solution. These high costs are not sufficiently compensated by lower prices for the hydrogen energy in this scenario.

Also for the battery-electric solution with fixed batteries on board there is a gap when looking at the averaged cost levels for the TCO per day. The energy costs itself are much lower but also here the high capital costs and the time loss for bunkering result in a gap in the comparison with fossil diesel.

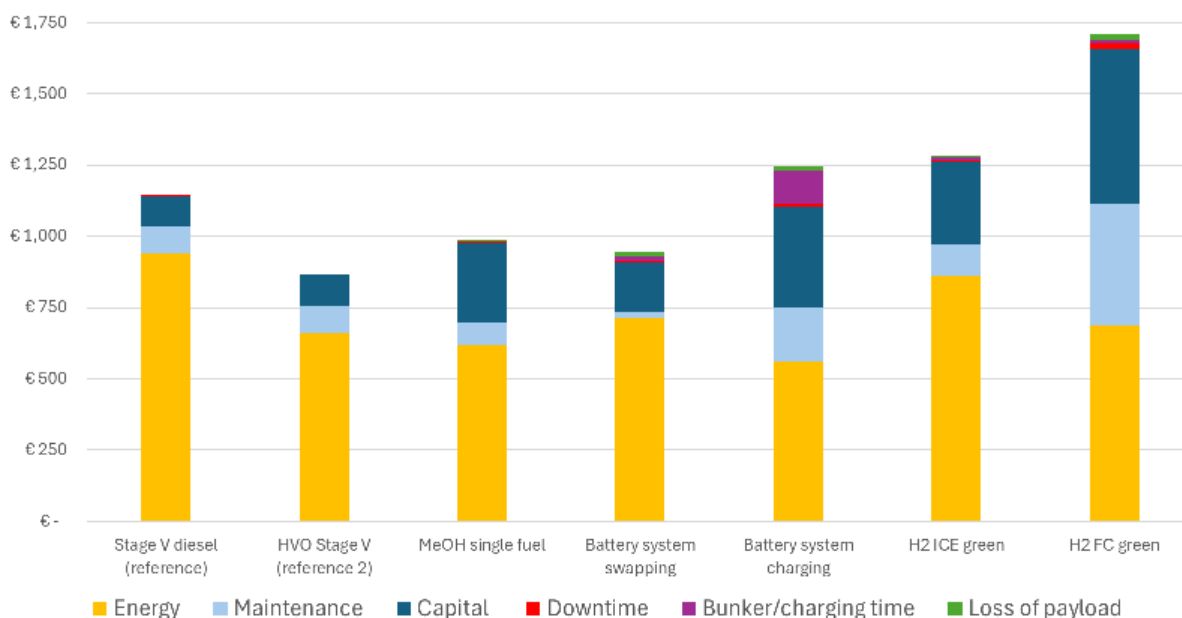


Figure 27 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 105 metre dry cargo motor vessel

4.2.6 TCO per day for the NZE scenario and 60% CAPEX funding

Especially in the NZE scenario there are most likely significant revenues generated for public bodies by means of taxation and Emission Trading Systems. Therefore, one may assume that a viable option could be to spend the revenues on giving a further boost to the uptake of the clean technologies in inland waterway transport and thus to mitigate the costs impact for owners and operators in inland navigation.

This section therefore presents the TCO levels per day when applying the NZE scenario for the energy prices combined with 60% funding of the initial capital expenditure (CAPEX) for zero-emission technologies.

Table 27 and Figure 28 present the outcome of the TCO per day when applying the NZE prices in combination with the 60% funding on the initial capital expense for a methanol single fuel, battery-electric or hydrogen system.

Table 27 | Average TCO per day for NZE scenario 2028-2047, 105 metre motor vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 1,017	€ 1,270	€ 1,143	100
Stage V HVO ICE (reference 2)	€ 695	€ 1,037	€ 866	76
Stage V methanol single fuel ICE	€ 602	€ 1,030	€ 816	71
Battery system swapping	€ 724	€ 968	€ 846	74
Battery system charging	€ 853	€ 1,216	€ 1,034	90
Stage V hydrogen ICE	€ 808	€ 1,410	€ 1,109	97
Hydrogen Fuel Cell	€ 995	€ 1,772	€ 1,383	121



Figure 28 | Average TCO per day for NZE scenario 2028-2047, 105 metre motor vessel and 60% CAPEX funding

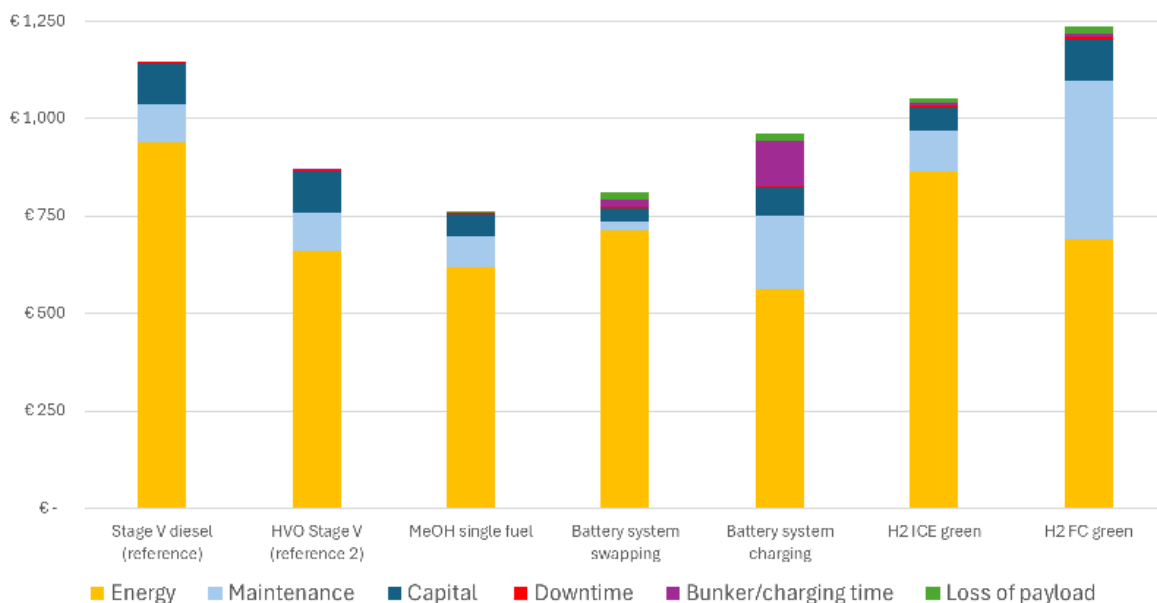


Figure 29 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 105 metre dry cargo motor vessel and 60% CAPEX funding

It can be concluded that the methanol option and the battery swapping option are getting a strong business case in this scenario for this vessel type. These solutions can compete with a Stage V engine using HVO100. Also vessels using fixed batteries and recharging during idle hours, not resulting in productivity loss, can be competitive. When looking at the minimum and averaged costs levels for the TCO per day, also the hydrogen (ICE) option is now competitive. However, when comparing the maximum cost levels of hydrogen with the cost levels for diesel, there may still be a gap. Clearly the relatively high uncertainty on the price of hydrogen as fuel explains this.

Furthermore, Figure 46 shows that the maintenance costs for the hydrogen fuel cell system are quite significant. Longer lifetime of fuel cells and cost reductions to replace the equipment can possibly lead to reduced maintenance costs. Further research and development work in the field of hydrogen fuel cells seems therefore a logical recommendation to reduce the gap between hydrogen fuel cell technologies with diesel and other zero-emission technologies.

For the solution using fixed batteries and fast charging from shore, the competitiveness can also increase by research and development to reach higher recharging speeds and usage of battery cells which have a longer lifetime.

4.3 Case 3: 67 metre dry cargo vessel

This case presents the situation for a relatively small new build vessel which is used for transporting dry cargo. They usually operate usually in day-time regime (5 days per week, 14 hours per day) on canals at relative low speeds. This explains the relatively low fuel consumption of this vessel.

4.3.1 Case characteristics

This case concerns the following vessel:

- 400 kW installed power on the vessel
- Consumption: 68 tons of diesel per year
- Required autonomy: 1 day

The following technologies are in scope and are being compared:

- Stage V with fossil diesel (= first reference)
- Stage V with HVO100 (= second reference)
- Methanol ICE, single fuel
- Full battery electric sailing Swappable batteries in pay-per-use service
- Full battery electric sailing: Fixed batteries on board
- Hydrogen ICE, single fuel
- Hydrogen Fuel cell system

TCO scenarios simulated:

- STEPS for the energy prices and no grant support
- STEPS and 60% CAPEX support
- NZE for the energy prices, reflecting stringent energy policies
- NZE and 60% CAPEX support

The following capital investments are applicable for these technologies as presented in Table 28.

Table 28 | Initial capital expenditure for investment, 67 metre dry cargo vessel

	Initial capital expenditure for investment minimum	Initial capital expenditure for investment maximum	Index compared to CAPEX for Stage V diesel/HVO, average
Stage V diesel/HVO ICE (reference)	€ 181,072	€ 297,608	100
Stage V methanol single fuel ICE	€ 523,442	€ 599,380	235
Battery system swapping	€ 256,360	€ 393,040	136
Battery system charging	€ 512,565	€ 988,769	314
Stage V hydrogen ICE	€ 512,102	€ 703,978	254
Hydrogen Fuel Cell	€ 899,732	€ 1,455,323	492

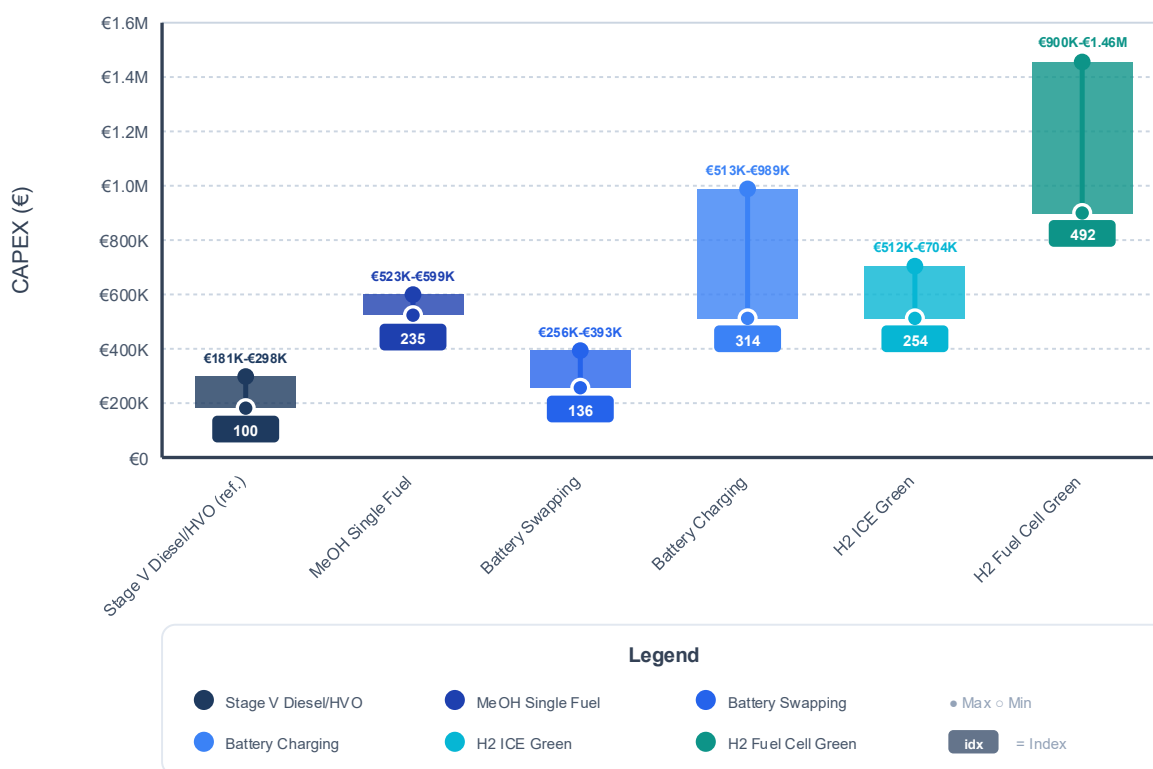


Figure 30 | Initial capital expenditure for investment, 67 metre dry cargo vessel

Again, there is a big gap in the required investment when comparing the capital costs for a Stage V engine able to use fossil diesel or HVO100 with the other options. The additional investment required for making the vessel able to use the battery swapping concept is relatively limited, at 36% (index 136) higher costs. However, the costs for the batteries are not included here, as a pay-per-use model for the swappable battery containers is assumed. If battery costs are included, the capital costs are more than doubled (index 314). For the methanol and hydrogen combustion systems the initial capital investment is around 2.5 times higher compared to a Stage V diesel engine. Capital costs for a fuel cell system are estimated to be close to 5 times the costs of a Stage V diesel engine system.

These capital expenses have been included in the calculation of the Total Costs of Ownership. Other elements are the energy costs, maintenance costs and the costs because of downtime, bunkering time and possible payload loss. The results of the TCO calculations are presented in the next sections for the different scenarios and assumptions.

4.3.2 TCO per day for the STEPS scenario

Table 29 presents the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario.

Table 29 | Average TCO per day for STEPS scenario 2028-2047, 67 metre dry cargo vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 358	€ 488	€ 423	100
Stage V HVO ICE (reference 2)	€ 326	€ 500	€ 413	98
Stage V methanol single fuel ICE	€ 334	€ 636	€ 485	115
Battery system swapping	€ 383	€ 522	€ 452	107
Battery system charging	€ 476	€ 730	€ 603	142
Stage V hydrogen ICE	€ 515	€ 1,264	€ 889	210
Hydrogen Fuel Cell	€ 645	€ 1,447	€ 1,046	247

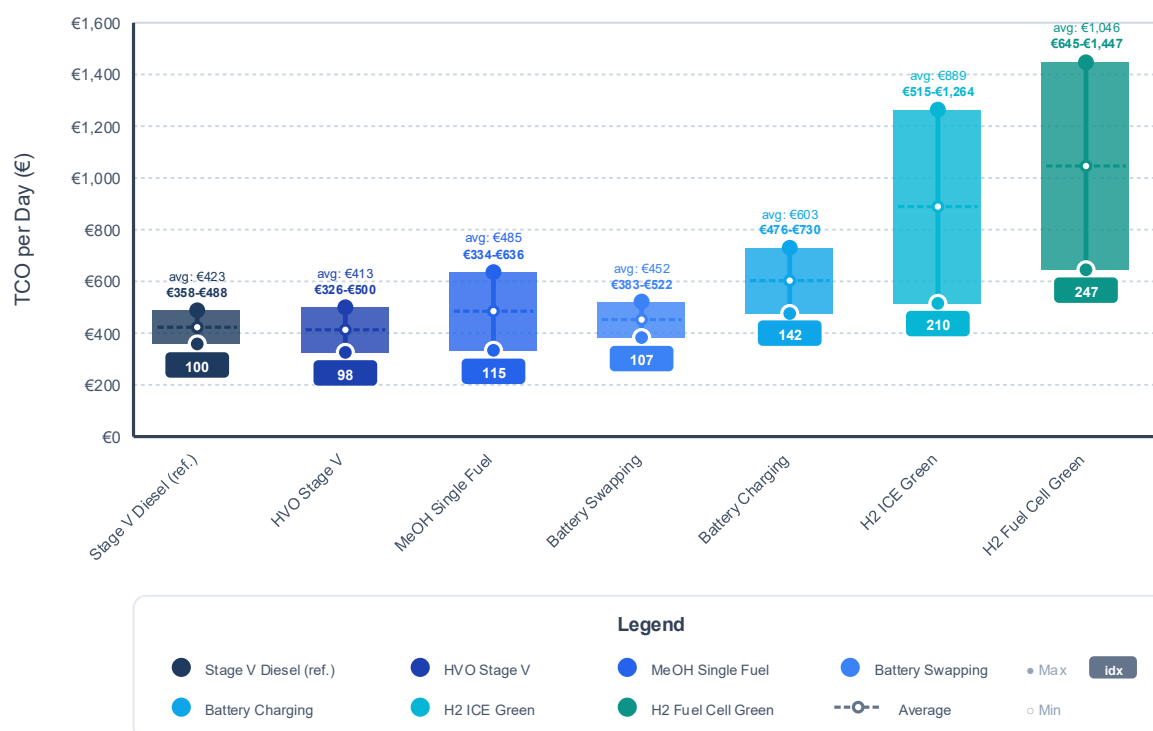


Figure 31 | Average TCO per day for STEPS scenario 2028-2047, 67 metre dry cargo vessel

It can be concluded that using HVO100 instead of fossil diesel during the 20 years period (2028-20247) will result in a 2% saving at the average energy prices in the STEPS scenario. The other technologies are expected to result in higher costs when comparing the averaged energy cost levels. The gap with swappable batteries, assuming 1 day of autonomy, is however relatively limited with a cost increase

of 7% compared to fossil diesel. Again, the hydrogen solutions are expected to have the highest total cost of ownership.

Figure 32 presents the breakdown of cost for the average TCO per technology. It can also be seen that the energy costs for the hydrogen solutions are expected to be high, while also there are high capital and maintenance costs.

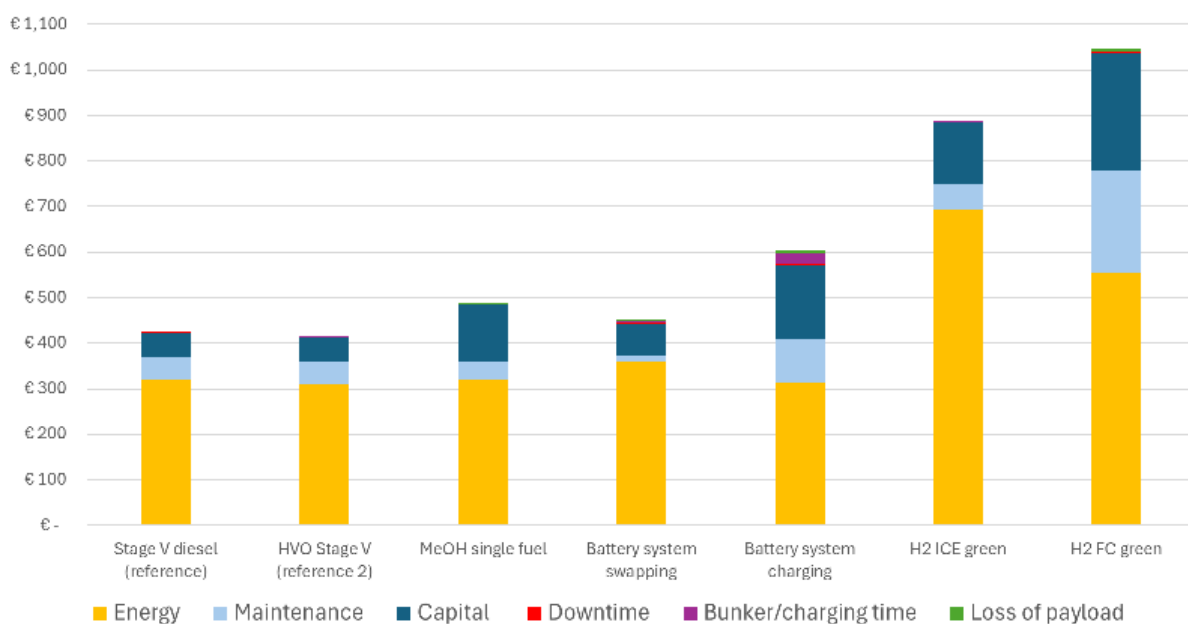


Figure 32 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 67 metre dry cargo vessel

4.3.3 TCO per day for the STEPS scenario and 60% CAPEX funding

Table 30 and *Figure 33* present the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario including the assumption that a strong funding would be provided by means of grants to cover 60% of the costs of the initial investment for the Methanol, Battery, Hydrogen options. This gives an indication what the impact is of such policy instruments, to close the gap with a Stage V engine running on diesel or HVO100.

Table 30 | Average TCO per day for STEPS scenario 2028-2047, 67 metre dry cargo vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 358	€ 488	€ 423	100
Stage V HVO ICE (reference 2)	€ 326	€ 500	€ 413	98
Stage V methanol single fuel ICE	€ 265	€ 558	€ 412	97
Battery system swapping	€ 349	€ 470	€ 410	97
Battery system charging	€ 408	€ 600	€ 504	119
Stage V hydrogen ICE	€ 448	€ 1,171	€ 809	191
Hydrogen Fuel Cell	€ 526	€ 1,255	€ 891	210

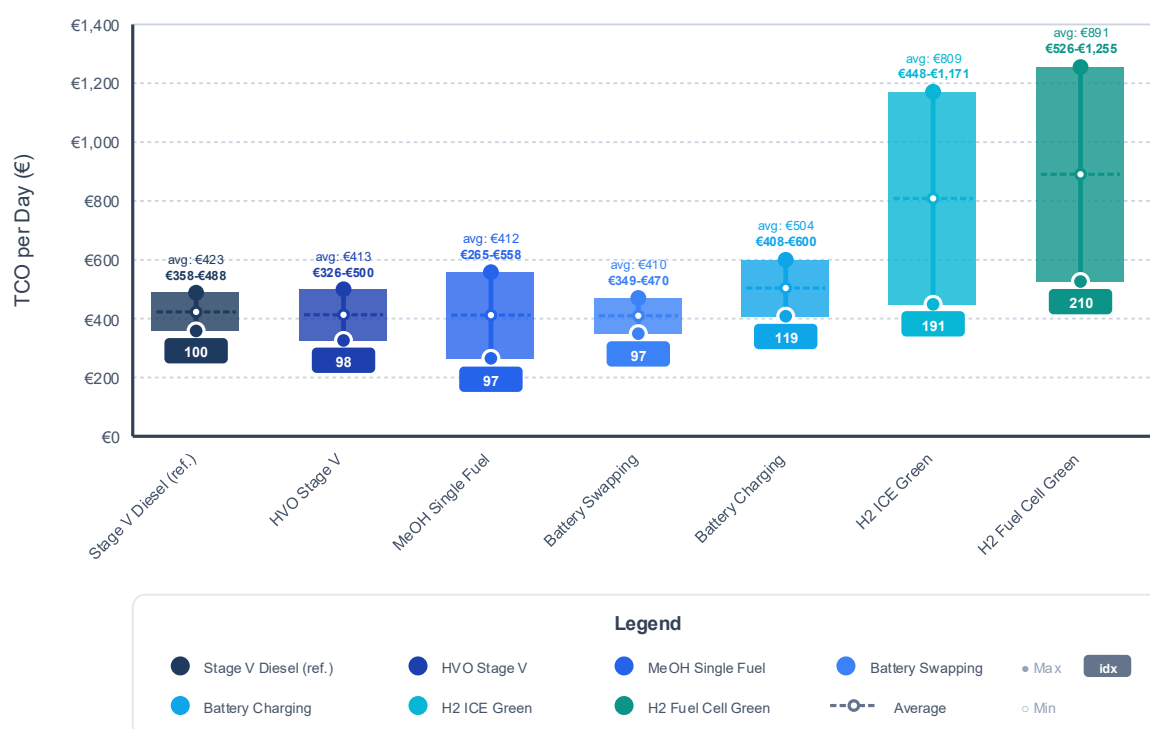


Figure 33 | Average TCO per day for STEPS scenario 2028-2047 and 650% CAPEX funding, 67 metre dry cargo vessel

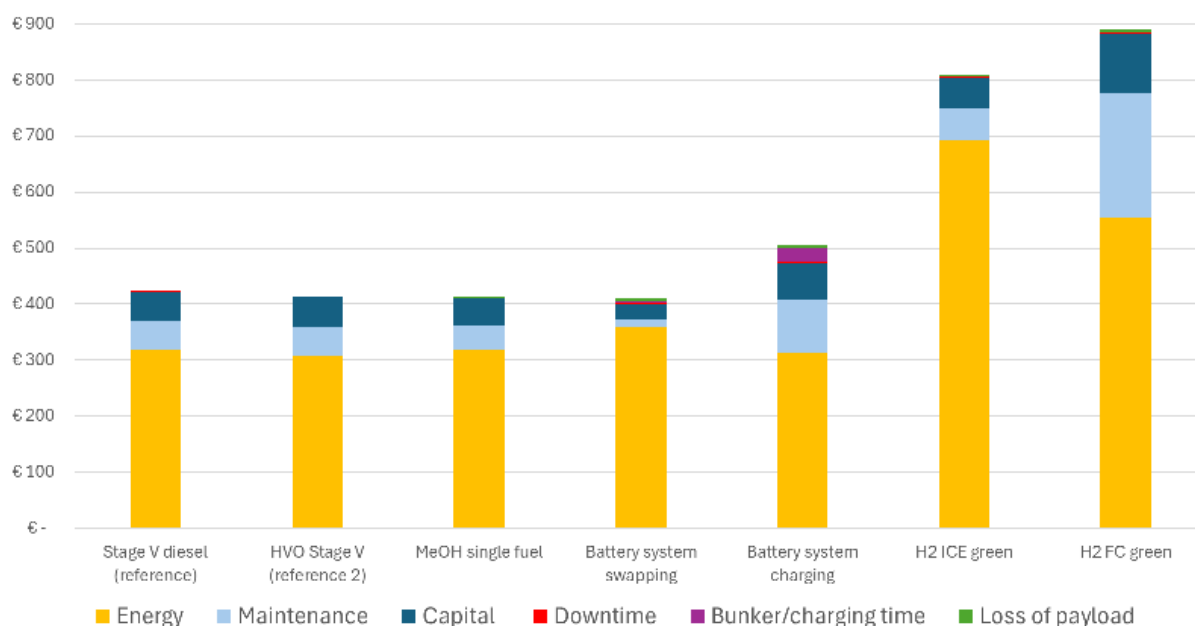


Figure 34 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 67 metre dry cargo vessel and 60% CAPEX funding

It can be concluded that a grant support of 60% results in the situation that methanol and battery swapping become competitive with fossil diesel, assuming the average cost levels for the energy in the STEPS scenario. For the solution with fixed batteries and charging from shore, the situation can improve if charging of fixed batteries on board can be done during the idle time of the vessel. This vessel type is usually operated in day-time operation, e.g. 14 hours per day, which makes it an option to recharge during the night. As can be seen the hydrogen systems still present significant cost gaps in the TCO compared to Stage V fossil diesel or HVO100.

4.3.4 TCO per day for the NZE scenario

Table 31 presents the outcome of the TCO per day and the breakdown to cost components when applying the NZE prices.

Table 31 | Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 513	€ 642	€ 578	100
Stage V HVO ICE (reference 2)	€ 351	€ 525	€ 438	76
Stage V methanol single fuel ICE	€ 366	€ 591	€ 479	83
Battery system swapping	€ 383	€ 522	€ 452	78
Battery system charging	€ 455	€ 693	€ 574	99
Stage V hydrogen ICE	€ 466	€ 795	€ 631	109
Hydrogen Fuel Cell	€ 605	€ 1,072	€ 839	145



Figure 35 | Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel

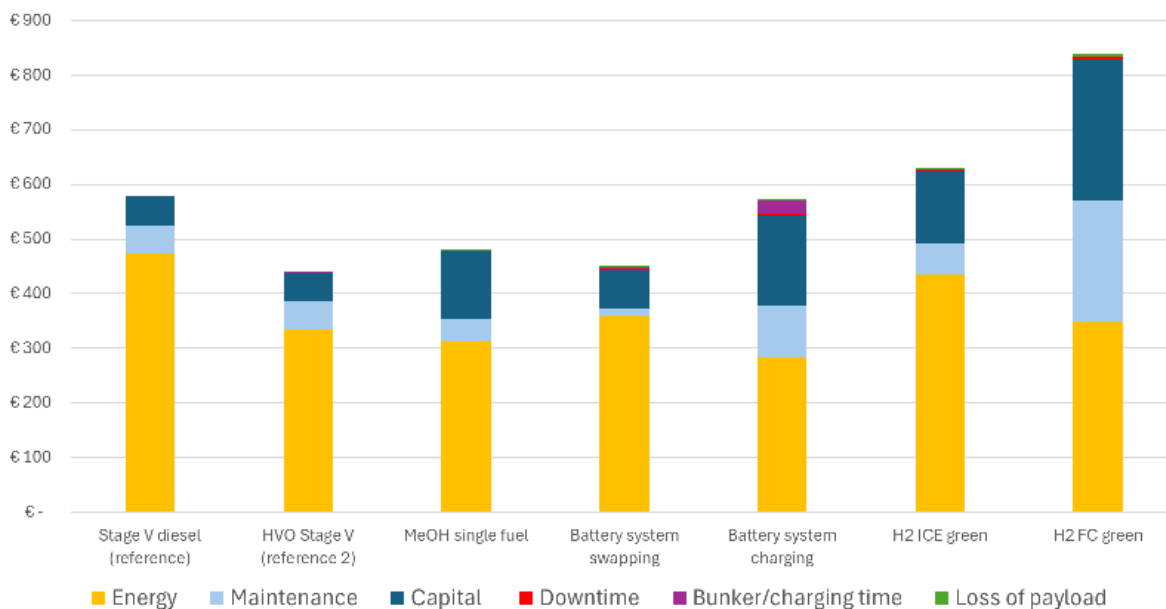


Figure 36 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 67 metre dry cargo vessel

As result of the higher energy price in the NZE for the fossil diesel, there is a clear economic advantage for using HVO100. Furthermore, assuming the averaged energy prices for NZE also methanol and

battery swapping are more competitive compared to fossil diesel. The fixed batteries on board can become competitive with fossil diesel, especially if recharging the battery can be done during idle time of the vessel. The hydrogen technologies are still more expensive, despite the high CO₂e costs which are internalised and lower prices for hydrogen in the maximum scenario compared to the STEPS scenario.

4.3.5 TCO per day for the NZE scenario and 60% CAPEX funding

Also for this vessel type, another TCO calculation is made assuming the 60% funding of the initial capital expenditure (CAPEX) for zero-emission technologies. This is expected to close the gap for capital intensive investments for technologies, such as methanol, fix batteries and the hydrogen solutions. Table 32 and Figure 37 present the TCO per day when applying the NZE prices in combination with the 60% funding on the initial capital expense for a methanol single fuel, battery-electric or hydrogen system.

Table 32 | Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V fossil diesel ICE (reference 1)	€ 513	€ 642	€ 578	100
Stage V HVO ICE (reference 2)	€ 351	€ 525	€ 438	76
Stage V methanol single fuel ICE	€ 297	€ 513	€ 405	70
Battery system swapping	€ 349	€ 470	€ 410	71
Battery system charging	€ 387	€ 563	€ 475	82
Stage V hydrogen ICE	€ 399	€ 703	€ 551	95
Hydrogen Fuel Cell	€ 487	€ 881	€ 684	118

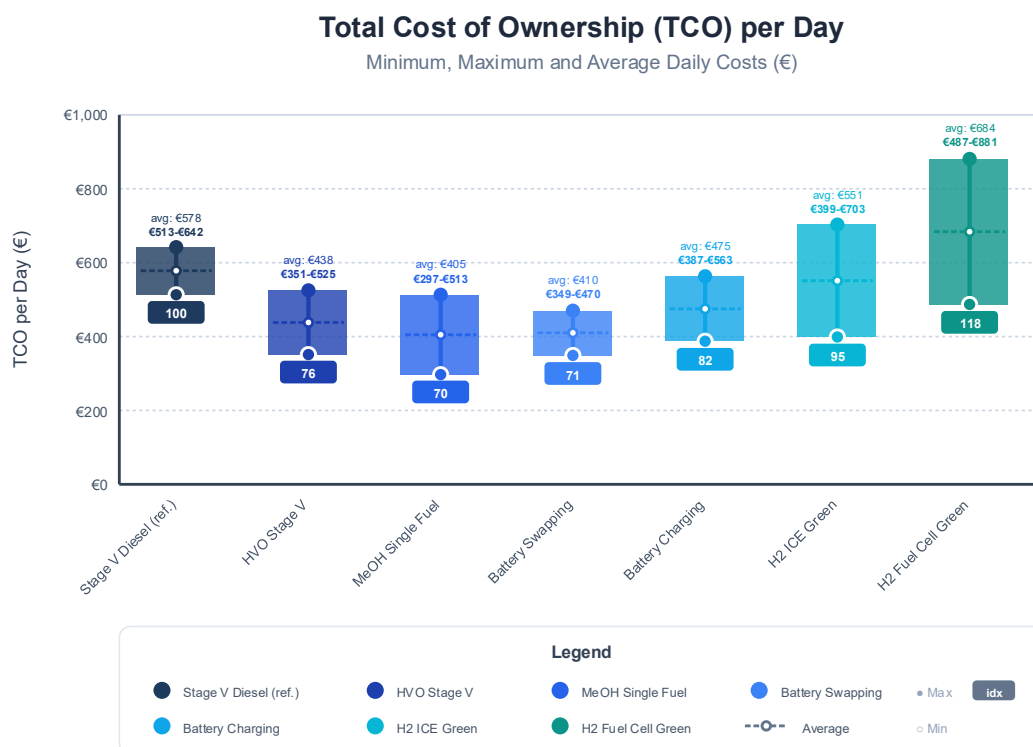


Figure 37 | Average TCO per day for NZE scenario 2028-2047, 67 metre dry cargo vessel and 60% CAPEX funding

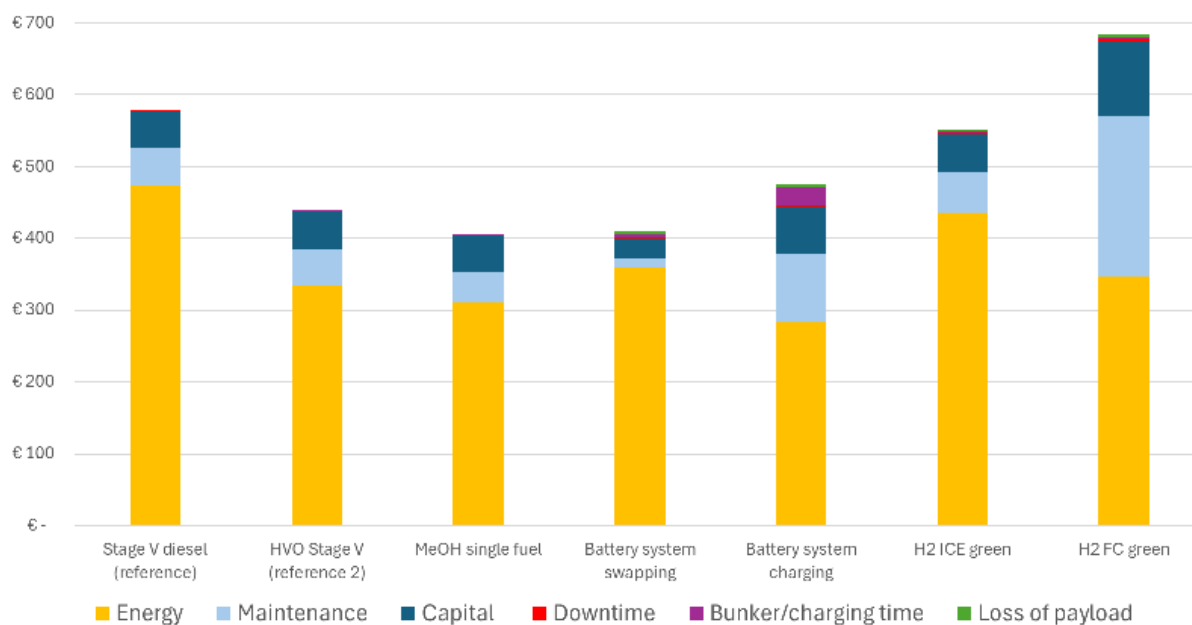


Figure 38 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 67 metre dry cargo vessel and 60% CAPEX funding

As can be seen, the reduction of CAPEX results in a quite competitive situation for methanol single fuel and battery swapping as they are expected at lower total cost of ownership compared to using HVO100. Furthermore, the fixed battery option still has a competitive advantage compared to fossil

diesel and potentially also with HVO100 if recharging can be done during idle time of the vessel (e.g. during the night). There is a chance that hydrogen combustion solution can be competitive with fossil diesel and possibly also with HVO100. This depends on the prices of the energy.

The minimum TCO for green hydrogen in combustion engines and also for application in fuel cell electric solutions is for example lower than the maximum price range for HVO100. However, when comparing on average, the costs for the hydrogen fuel cell solutions are relatively high. It gives therefore severe risks to invest in hydrogen, even at high CO₂e costs being internalised and with 60% of public funding support on the initial capital expenditures.

4.4 Case 4: Pusher for large convoys on Rhine and Danube

The pusher vessel is used for the large push convoys transported on the Danube and Rhine, for example transporting iron ore, coal and agricultural products with payloads well over 10,000 tons of cargo. The data for this vessel type for making the case calculations are provided by a large shipping line active on the Danube.

4.4.1 Case characteristics

This case concerns the following vessel:

- 2800 kW installed power on the vessel
- Consumption: 2490 tons of diesel per year
- Required autonomy: 7 days

Because of the required autonomy of 7 days, it is not a realistic option to use batteries as primary energy source. The pusher consumes 47 tons of diesel per week. This would be equivalent to 285 MWh electrical energy per week with a battery electric propulsion. This would be equivalent to 100 containers of 20 foot, which clearly does not fit in terms of weight and size. The same limitation applies to the case of hydrogen. The storage of hydrogen (17 tons) to be able to sail for 7 days in a row would require too much space. At 300 bar only 350 kg of hydrogen can be stored on board in a 40 foot container, up to 900 kg per 40 foot container at 500 bar and in case of cryogenic storage up to 3040 kg could be carried. Therefore, even when storing the hydrogen in cryogenic tank containers, it requires six 40 foot containers to be accommodated by the pusher, which is not realistic. Furthermore, the cryogenic storage of hydrogen as fuel is not yet seen today in inland navigation.

Concluding, the following technologies are in scope and are being compared:

- Stage V diesel (= reference)
- Stage V HVO100 (= reference 2)
- Methanol ICE, single fuel
- Liquid Bio Methane (LBM), single fuel

TCO scenarios simulated:

- STEPS for the energy prices and no grant support
- STEPS and 60% CAPEX support
- NZE for the energy prices, reflecting stringent energy policies
- NZE and 60% CAPEX support

The following capital investments are applicable for these technologies as presented in Table 33.

Table 33 | Initial capital expenditure for investment, large pusher

	Initial capital expenditure for investment minimum	Initial capital expenditure for investment maximum	Index compared to CAPEX for Stage V diesel/HVO, average
Stage V diesel/HVO (reference) ICE	€ 1,450,288	€ 2,357,432	100
Stage V methanol single fuel ICE	€ 5,103,518	€ 5,795,020	286
Stage V methane single fuel ICE	€ 4,410,000	€ 4,630,000	237

There is a quite big additional investment which needs to be done in methanol or liquid(bio)-methane systems. This is because of the additional costs for the storage on board and the additional safety requirements which need to be met.

4.4.2 TCO per day for the STEPS scenario

Table 34 and Figure 39 present the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario.

Table 34 | Average TCO per day for STEPS scenario 2028-2047, pusher

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference 1)	€ 10,839	€ 14,063	€ 12,451	100
Stage V HVO ICE (reference 2)	€ 9,662	€ 14,515	€ 12,088	97
Stage V bio-methanol ICE single fuel	€ 7,983	€ 18,349	€ 13,166	106
Stage V bio-methane ICE single fuel	€ 7,466	€ 20,017	€ 13,741	110

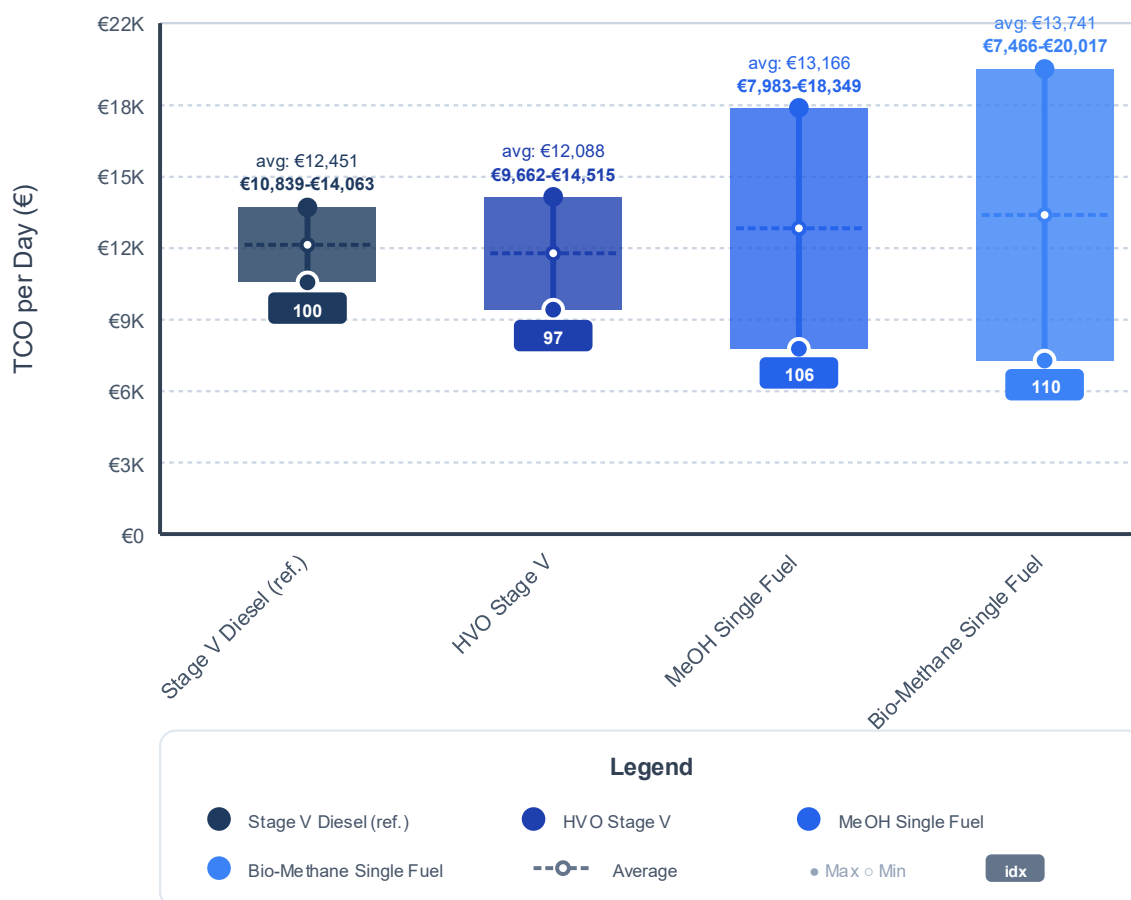


Figure 39 | Average TCO per day for STEPS scenario 2028-2047, pusher

As can be seen in Table 34 It is expected that HVO will be competitive with fossil diesel during the period 2028-2047. Furthermore, the minimum range of energy costs for Methanol and Bio-Methane are pointing towards a favourable business case. But on the other side, the maximum ranges are showing higher costs compared to the maximum ranges for HVO and diesel. Therefore, there are large uncertainties and risks for selecting the methanol or Bio-Methane options. Because of the high maximum range for Methanol and Bio-Methane the average costs level for these technologies is also higher compared to the average TCO per day when using fossil diesel or HVO.

Figure 40 presents the breakdown of cost for the average TCO per technology.

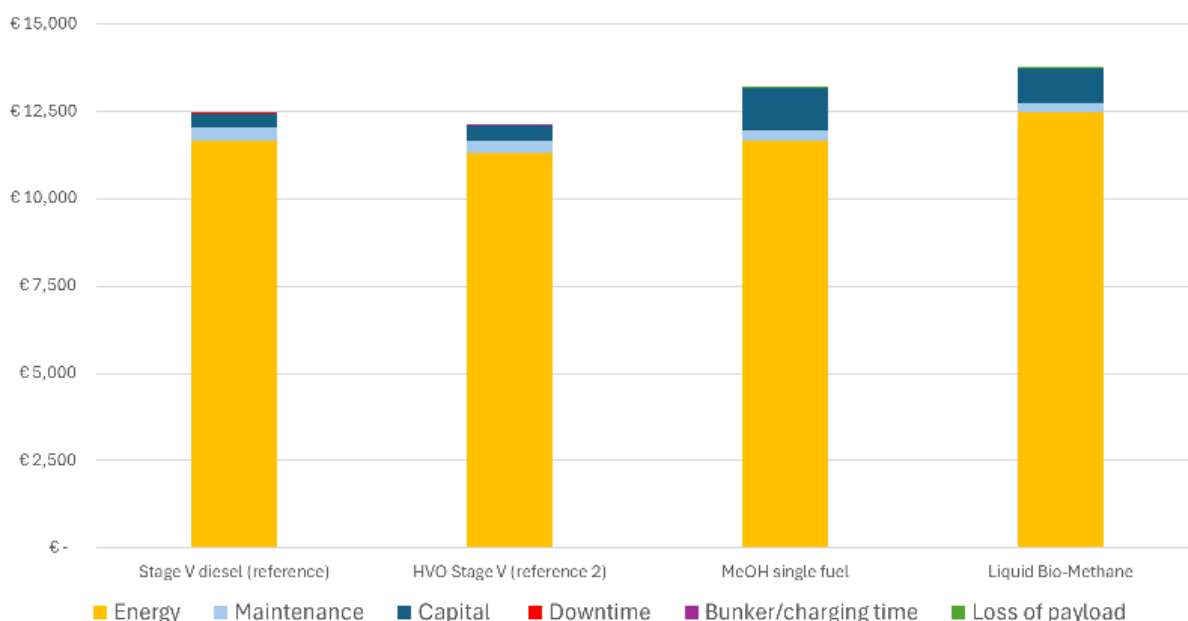


Figure 40 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the pusher

The TCO depends mainly on the energy costs as can be seen in Figure 40. Capital intensive solutions such as using batteries or hydrogen fuel cells are not feasible for this type of vessels and operational profile due to their energy demand and space limitations. Therefore, in this case, the gap in the TCO is most sensitive for the energy prices and policy measures which can have an influence.

4.4.3 TCO per day for the STEPS scenario and 60% CAPEX funding

Although the share of capital costs in the TCO is relatively limited in the case of the pusher, the additional investment costs for a methanol or the cryogenic Bio-Methane system are still very high, while there is a big uncertainty in the market prices of methanol and Bio-Methane compared to diesel and HVO100.

Table 35 and Figure 41 present the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario including the assumption that a strong funding would be provided by means of grants to cover 60% of the costs of the initial investment for the methanol and methane options. This gives an indication what the impact is of such policy instruments, to close the gap with a Stage V engine running on diesel or HVO100.

Table 35 | Average TCO per day for STEPS scenario 2028-2047, pusher and 60% CAPEX funding for methanol and bio methane systems

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference 1)	€ 10,839	€ 14,063	€ 12,451	100
Stage V HVO ICE (reference 2)	€ 9,662	€ 14,515	€ 12,088	97
Stage V bio-methanol ICE single fuel	€ 7,312	€ 17,587	€ 12,449	100
Stage V bio-methane ICE single fuel	€ 6,890	€ 19,455	€ 13,172	106

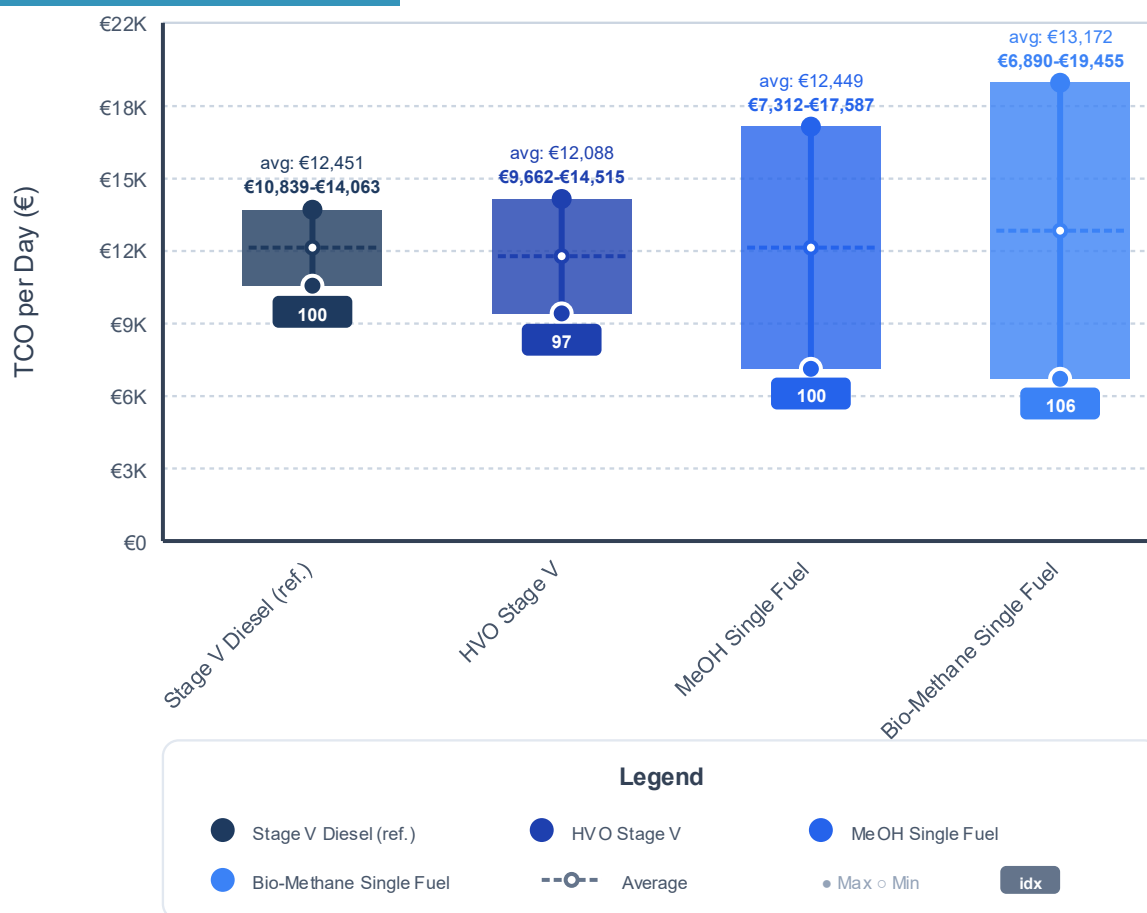


Figure 41 | Average TCO per day for STEPS scenario 2028-2047, pusher and 60% CAPEX funding for methanol and bio methane systems

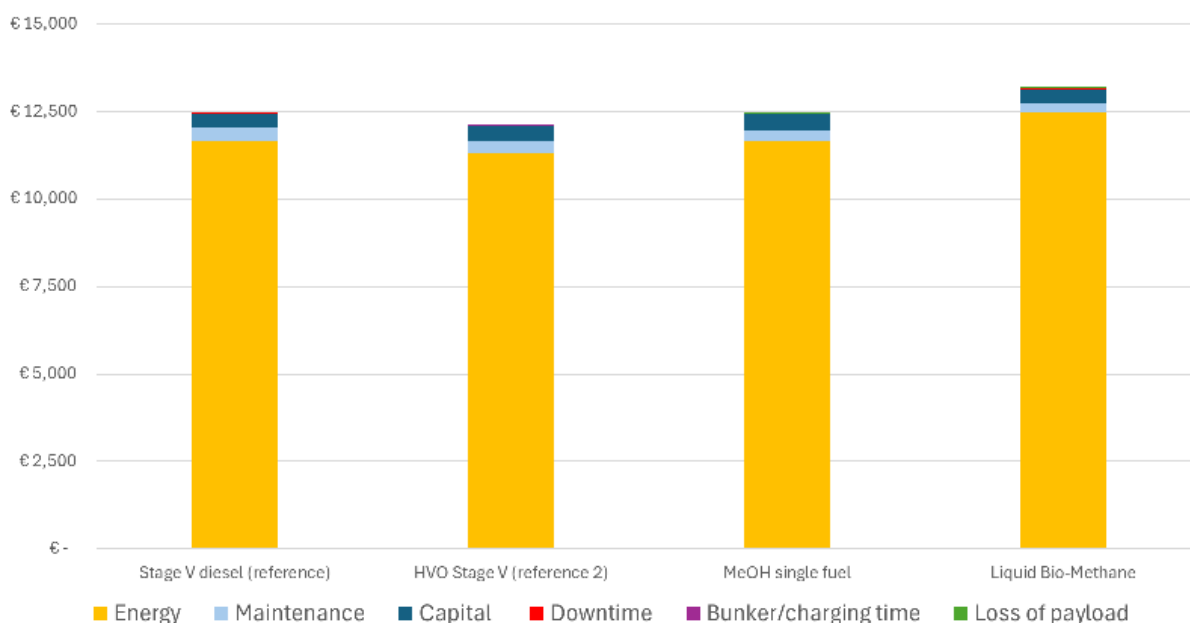


Figure 42 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the pusher with 60% CAPEX funding for the Methanol and Bio-Methane solutions

It can be concluded that, using the average energy prices, the gap with the green methanol solution is closed, while for bio-methane there is still a gap of 6% with the conventional diesel fuel.

4.4.4 TCO per day for the NZE scenario

The NZE scenario reflects a stringent set of measures to promote and support production of renewable fuels and limiting the use of fossil diesel and a strong internalisation of the CO₂e costs for fossil energy. For the pusher the share of capital costs in the TCO is relatively limited. Therefore, it makes sense to look at the impact in case the NZE prices are applied to calculate the TCO per day values.

Table 36 and Figure 43 show presents the outcome of the TCO per day when applying the NZE prices.

Table 36 | Average TCO per day for NZE scenario 2028-2047, pusher

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference 1)	€ 16,506	€ 19,715	€ 18,111	100
Stage V HVO ICE (reference 2)	€ 10,575	€ 15,409	€ 12,992	72
Stage V bio-methanol ICE single fuel	€ 9,148	€ 16,707	€ 12,927	71
Stage V bio-methane ICE single fuel	€ 7,559	€ 19,476	€ 13,518	75

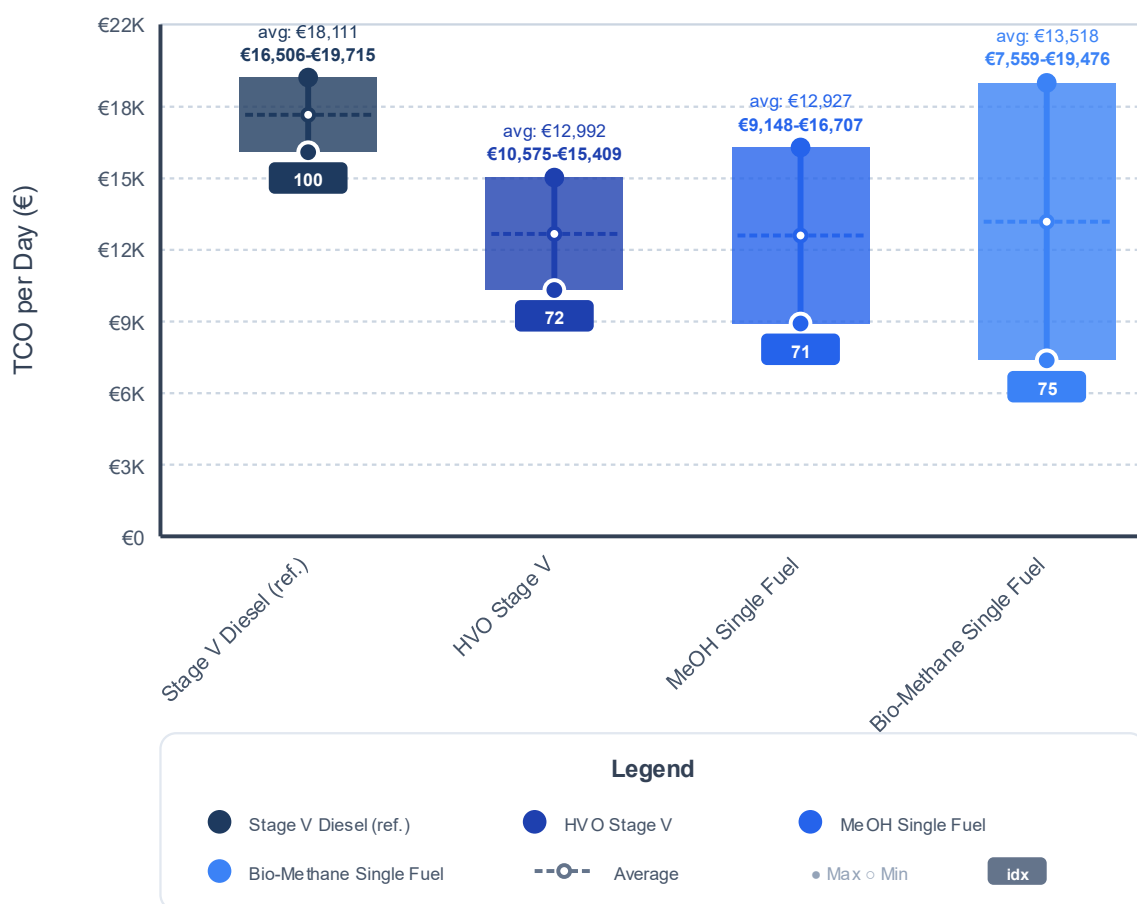


Figure 43 | Average TCO per day for NZE scenario 2028-2047, pusher

As

Table 36 and Figure 43 show, the TCO per day of the Stage V Diesel reference, averaged over the 20-year period, is much more expensive than the renewable options. It will clearly be sensible for the scenario to shift towards using HVO100 instead of diesel. Moreover, the use of renewable methanol is also attractive, although the maximum cost level for methanol is (a bit) higher compared to the maximum cost level expected for HVO100. The bio-methane option shows a relatively large bandwidth. Costs could be lower or higher than methanol or HVO100 systems, depending on the development within the scenario. The following table presents the cost breakdown. For the methanol and Bio-Methane options, the capital costs are higher.

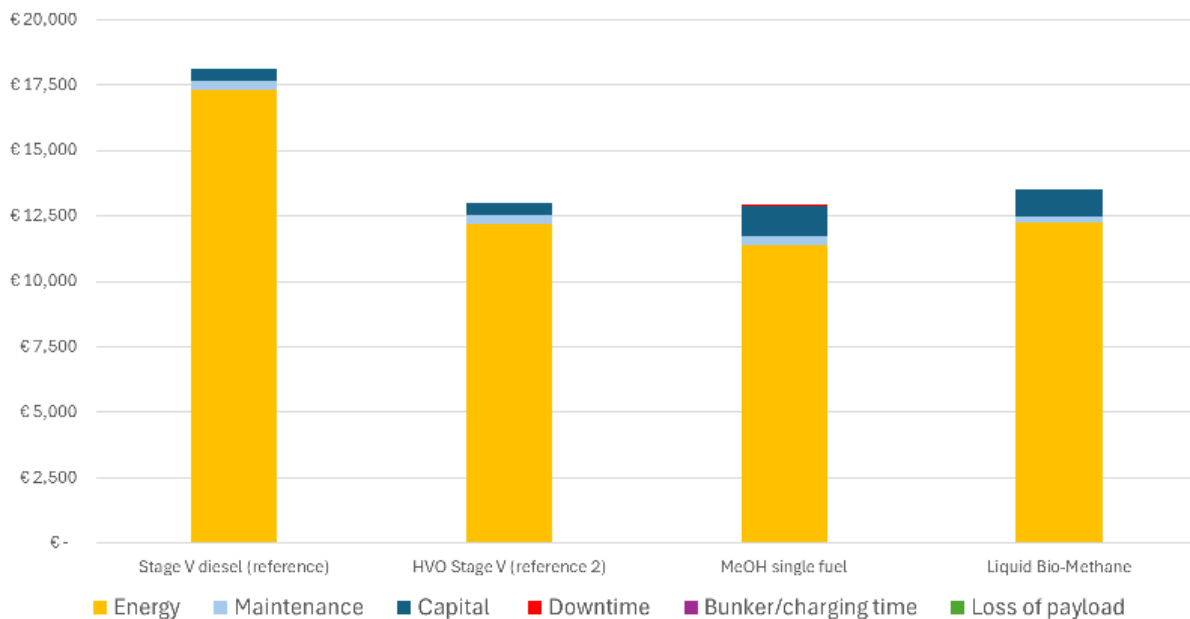


Figure 44 | Cost breakdown of the average TCO per day for the NZE average price scenario for the pusher

4.4.5 TCO per day for the NZE scenario and 60% CAPEX funding

Especially in the NZE scenario there are most likely significant revenues generated for public bodies by means of taxation and Emission Trading Systems. Therefore, one may assume that a viable option could be to spend the revenues on giving a further boost to the uptake of the clean technologies. This section therefore presents the TCO levels per day when applying the NZE scenario for the energy prices combined with 60% funding of the initial capital expenditure (CAPEX) for zero-emission technologies.

Table 37 and Figure 45 present the outcome of the TCO per day when applying the NZE prices in combination with the 60% funding on the initial capital expense for a methanol single fuel, battery-electric or hydrogen system.

Table 37 | Average TCO per day for NZE scenario 2028-2047, pusher and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference 1)	€ 16,506	€ 19,715	€ 18,111	100
Stage V HVO ICE (reference 2)	€ 10,575	€ 15,409	€ 12,992	72
Stage V bio-methanol ICE single fuel	€ 8,476	€ 15,945	€ 12,211	67
Stage V bio-methane ICE single fuel	€ 6,979	€ 18,914	€ 12,947	71

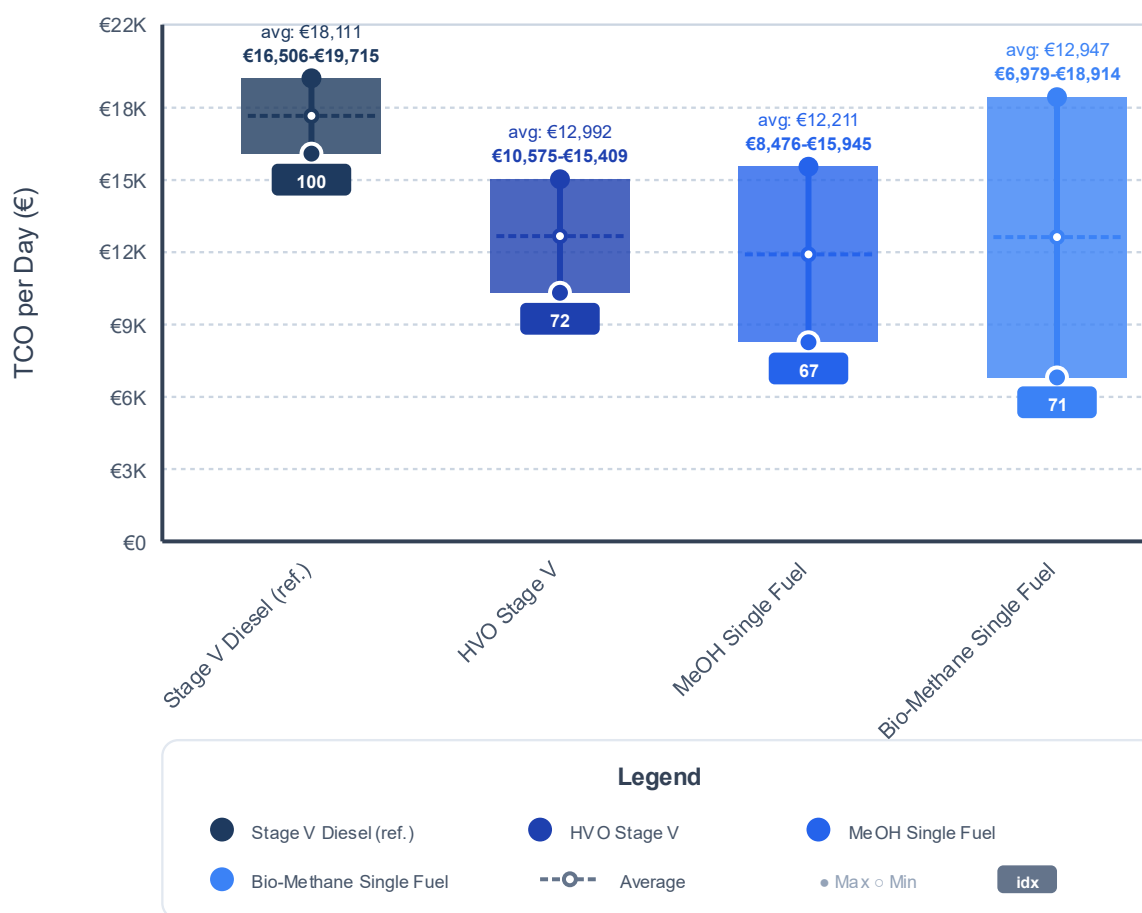


Figure 45 | Average TCO per day for NZE scenario 2028-2047, pusher and 60% CAPEX funding

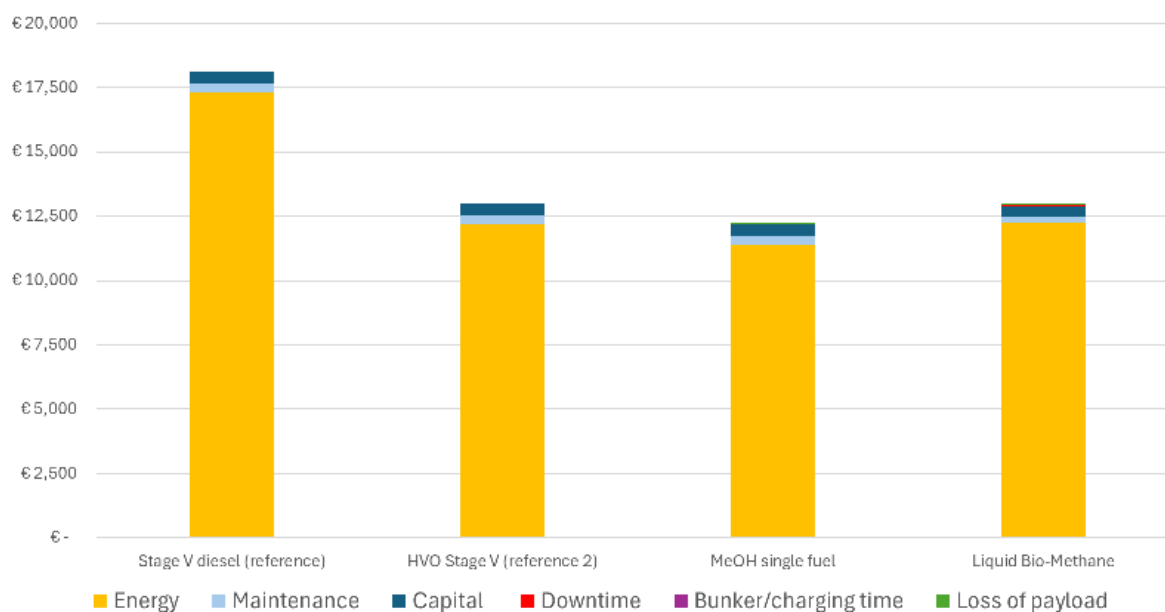


Figure 46 | Cost breakdown of the average TCO per day for the NZE average price scenario for the pusher and 60% CAPEX funding

It can be concluded that both the renewable methanol and the bio-methane options are getting a strong business case in this scenario for this vessel type under the minimum and averaged energy prices. However, for the maximum prices, there is a risk that bio-methane will be more expensive compared to HVO100 and renewable Methanol.

4.5 Case 5: 135 metre tanker vessel

This large tanker vessel is used for transporting liquid cargo such as chemicals and oils, including also renewable liquid fuels. The typical vessel which is frequently build during the past decade is 135 metre in length and 11.45 metre width and 3.7 metre draught. This vessel typically has 2 main engines.

4.5.1 Case characteristics

This case concerns the following vessel:

- 2346 kW installed power on the vessel
- Consumption: 350 tons of diesel per year
- Required autonomy: 2 days

The following technologies are in scope and are being compared:

- Stage V with fossil diesel (= first reference)
- Stage V with HVO100 (= second reference)
- Stage V methanol ICE, single fuel
- Full battery electric sailing Swappable batteries in pay-per-use service
- Full battery electric sailing: Fixed batteries on board
- Stage V hydrogen ICE, single fuel
- Hydrogen Fuel cell system
- Stage V bio-methane ICE, single fuel

TCO scenarios simulated:

- STEPS for the energy prices and no grant support
- STEPS and 60% CAPEX support
- NZE for the energy prices, reflecting stringent energy policies
- NZE and 60% CAPEX support

The following capital investments presented in Table 38 and Figure 47 are applicable for these technologies.

Table 38 | Initial capital expenditure for investment, 135 metre tanker vessel

	Initial capital expenditure for investment minimum	Initial capital expenditure for investment maximum	Index compared to CAPEX for Stage V diesel/HVO, average
Stage V diesel / HVO ICE (=reference)	€ 1,063,530	€ 1,747,850	100
Stage V methanol ICE single fuel	€ 3,079,880	€ 3,526,400	250
Battery system swapping	€ 1,509,643	€ 2,314,338	138
Battery system charging	€ 4,145,499	€ 8,443,241	432
Stage V hydrogen ICE single fuel	€ 3,011,980	€ 4,139,720	262
H2 FC green	€ 7,784,592	€ 5,967,374	556
Stage V methane ICE single fuel	€ 2,906,150	€ 3,326,150	236



Figure 47 | Initial capital expenditure for investment, 135 metre tanker vessel

It can be seen, that there is a quite big additional investment which needs to be done in methanol or (bio)-methane systems.

These capital expenses have been included in the calculation of the Total Costs of Ownership. Other elements are the energy costs, maintenance costs and the costs because of downtime, bunkering time and possible payload loss. The results of the TCO calculations are presented in the next sections for the different scenarios and assumptions.

4.5.2 TCO per day for the STEPS scenario

Table 39 and Figure 48 present the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario.

Table 39 | Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference)	€ 1,906	€ 2,610	€ 2,258	100
Stage V HVO ICE (reference 2)	€ 1,741	€ 2,674	€ 2,207	98
Stage V methanol ICE single fuel	€ 1,846	€ 3,418	€ 2,632	117
Battery system swapping	€ 2,097	€ 2,841	€ 2,469	109
Battery system charging	€ 3,378	€ 5,491	€ 4,435	196
Stage V hydrogen ICE single fuel	€ 2,804	€ 6,703	€ 4,754	211
H2 FC green	€ 3,968	€ 8,728	€ 6,348	281
Stage V methane ICE single fuel	€ 1,674	€ 3,569	€ 2,622	116

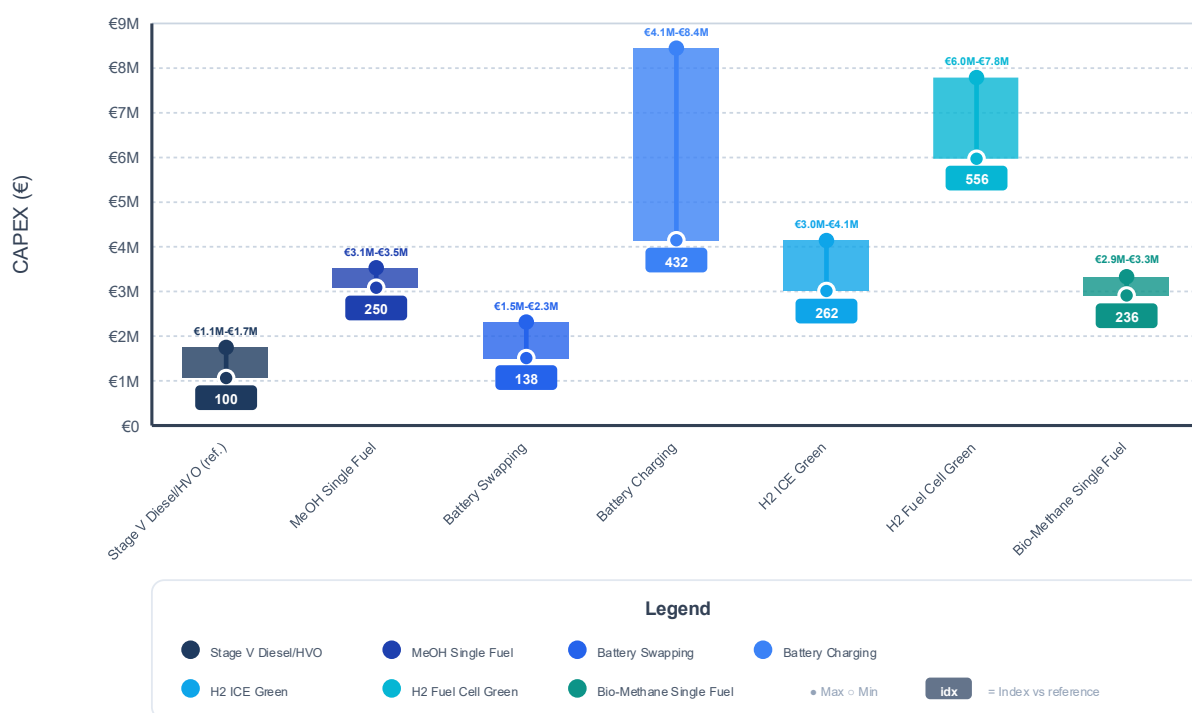


Figure 48 | Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel

It can be concluded that using HVO100 instead of fossil diesel during the 20 years period (2028-2047) will result in a 2% saving at the average energy prices in the STEPS scenario. The other technologies are expected to result in higher costs when comparing the averaged energy cost levels. However, if energy costs for fossil diesel are at the maximum range while the other technologies are at the minimum range, then also the methanol single fuel, bio-methane single fuel and possibly also the

battery swapping solution can be competitive options. The following graph presents the breakdown of cost for the average TCO per technology.

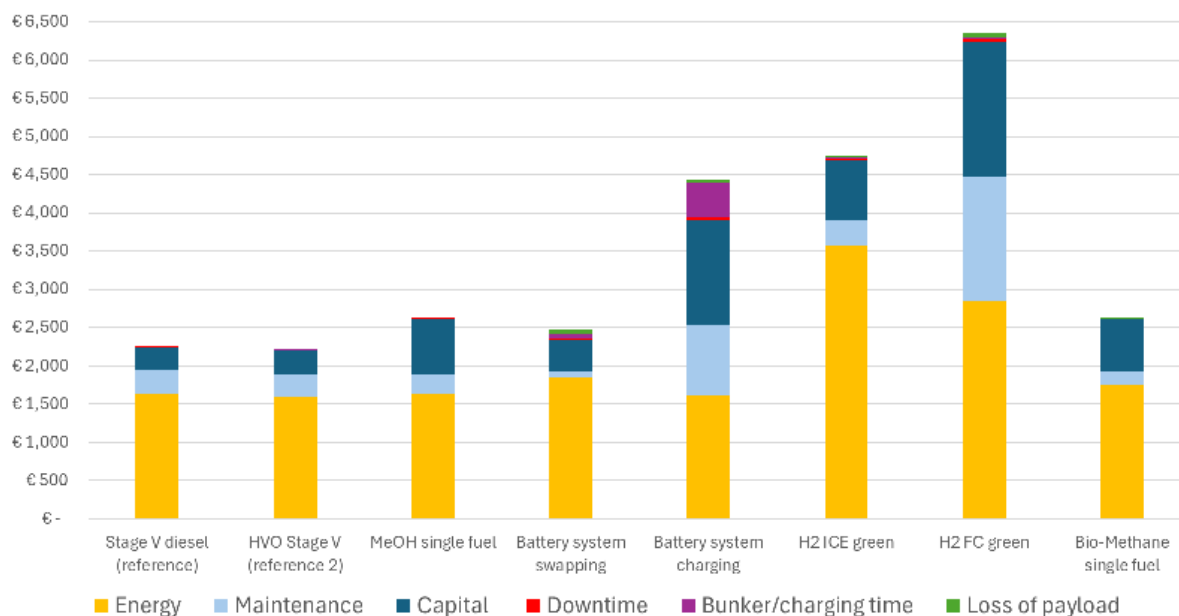


Figure 49 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 135 metre tanker vessel

4.5.3 TCO per day for the STEPS scenario and 60% CAPEX funding

Table 40 and Figure 50 present the overview of the TCO per day averaged for the period 2028-2047 for the STEPS scenario including the assumption that a strong funding would be provided by means of grants to cover 60% of the costs of the initial investment for the Methanol, Battery, Hydrogen and Bio-Methane options. This gives an indication what the impact is of such policy instruments, to close the gap with a Stage V engine running on diesel or HVO100.

Table 40 | Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference)	€ 1,906	€ 2,610	€ 2,258	100
Stage V HVO ICE (reference 2)	€ 1,741	€ 2,674	€ 2,207	98
Stage V methanol ICE single fuel	€ 1,441	€ 2,954	€ 2,197	97
Battery system swapping	€ 1,898	€ 2,537	€ 2,217	98
Battery system charging	€ 2,833	€ 4,381	€ 3,607	160
Stage V hydrogen ICE single fuel	€ 2,408	€ 6,159	€ 4,283	190
H2 FC green	€ 3,231	€ 7,454	€ 5,343	237
Stage V methane ICE single fuel	€ 1,313	€ 3,204	€ 2,258	100

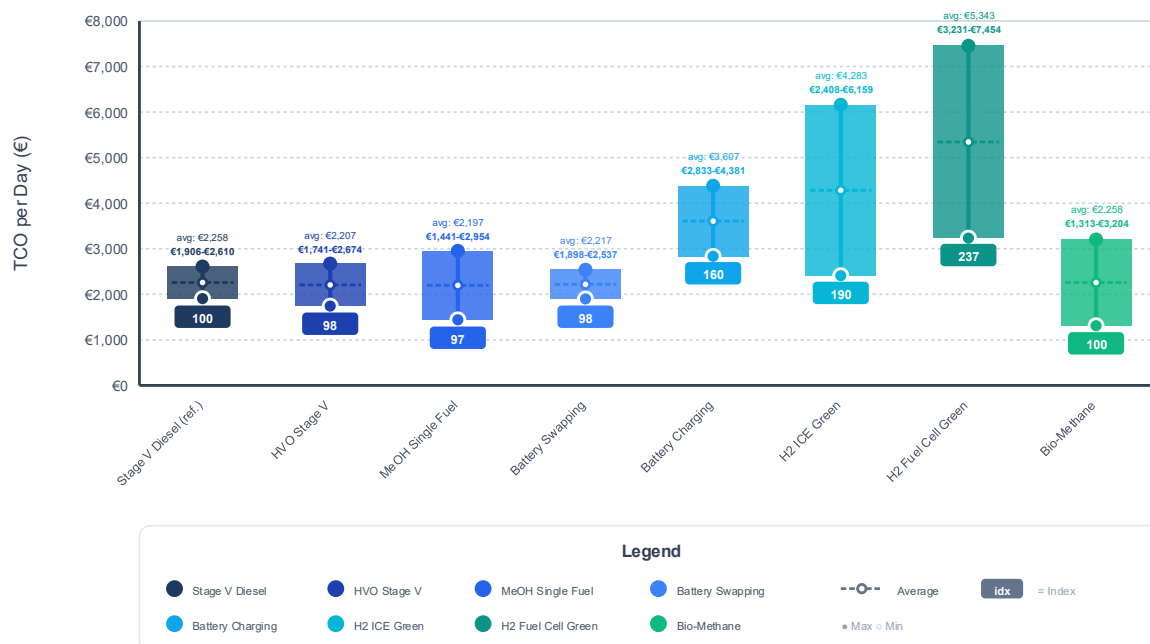


Figure 50 | Average TCO per day for STEPS scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding

It can be concluded that a grant support of 60% results in the situation that methanol, bio-methane and battery swapping become competitive with fossil diesel, assuming the average cost levels for the energy in the STEPS scenario. However, the systems with hydrogen fuel cells and also the systems with fixed batteries and charging from shore still present significant cost gaps in the TCO compared to Stage V fossil diesel or HVO100.

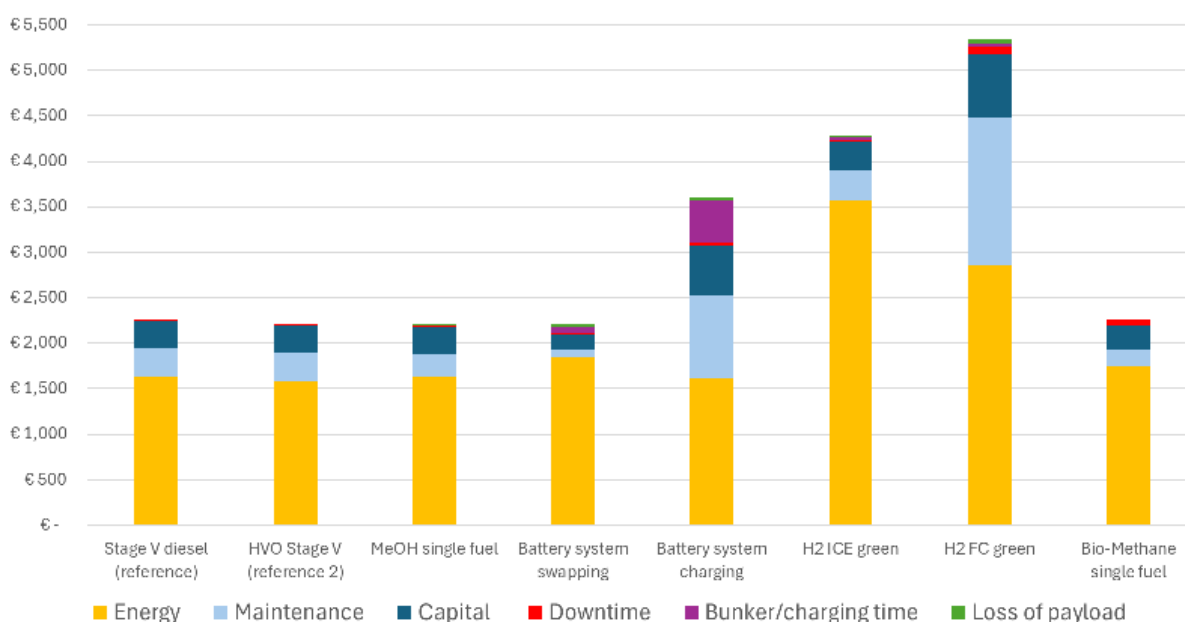


Figure 51 | Cost breakdown of the average TCO per day for the STEPS average price scenario for the 135 metre tanker vessel and 60% CAPEX funding

4.5.4 TCO per day for the NZE scenario

Table 41 and Figure 52 present the outcome of the TCO per day and the breakdown to cost components when applying the NZE prices.

Table 41 | Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference)	€ 2,703	€ 3,405	€ 3,054	100
Stage V HVO ICE (reference 2)	€ 1,869	€ 2,799	€ 2,334	76
Stage V methanol ICE single fuel	€ 2,010	€ 3,187	€ 2,598	85
Battery system swapping	€ 2,097	€ 2,841	€ 2,469	81
Battery system charging	€ 3,269	€ 5,302	€ 4,286	140
Stage V hydrogen ICE single fuel	€ 2,552	€ 4,294	€ 3,423	112
H2 FC green	€ 3,814	€ 6,859	€ 5,336	175
Stage V methane ICE single fuel	€ 1,708	€ 3,565	€ 2,637	86



Figure 52 | Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel

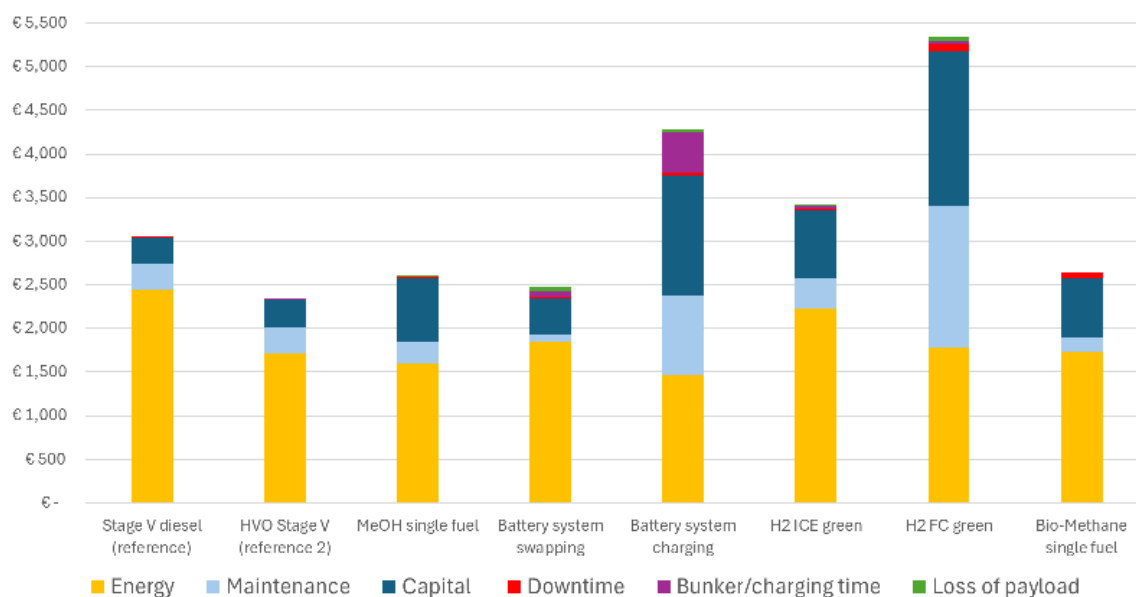


Figure 53 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 135 metre tanker vessel

As result of the higher energy price in the NZE for the fossil diesel, there is a clear economic advantage for using HVO100. Furthermore, assuming the averaged energy prices for NZE also methanol, battery swapping and bio-methane are more competitive compared to fossil diesel.

4.5.5 TCO per day for the NZE scenario and 60% CAPEX funding

Also for this vessel type, another TCO calculation is made assuming the 60% funding of the initial capital expenditure (CAPEX) for zero-emission technologies.

Table 42 and Figure 54 present the outcome of the TCO per day when applying the NZE prices in combination with the 60% funding on the initial capital expense for a methanol single fuel, bio-methane single fuel, battery-electric or hydrogen system.

Table 42 | Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding

	TCO per day minimum	TCO per day maximum	TCO per day average	Index compared to TCO per day Stage V diesel average
Stage V diesel ICE (reference)	€ 2,703	€ 3,405	€ 3,054	100
Stage V HVO ICE (reference 2)	€ 1,869	€ 2,799	€ 2,334	76
Stage V methanol ICE single fuel	€ 1,605	€ 2,723	€ 2,164	71
Battery system swapping	€ 1,898	€ 2,537	€ 2,217	73
Battery system charging	€ 2,724	€ 4,192	€ 3,458	113
Stage V hydrogen ICE single fuel	€ 2,156	€ 3,749	€ 2,953	97
H2 FC green	€ 3,029	€ 5,527	€ 4,278	140
Stage V methane ICE single fuel	€ 1,326	€ 3,128	€ 2,227	73



Figure 54 | Average TCO per day for NZE scenario 2028-2047, 135 metre tanker vessel and 60% CAPEX funding

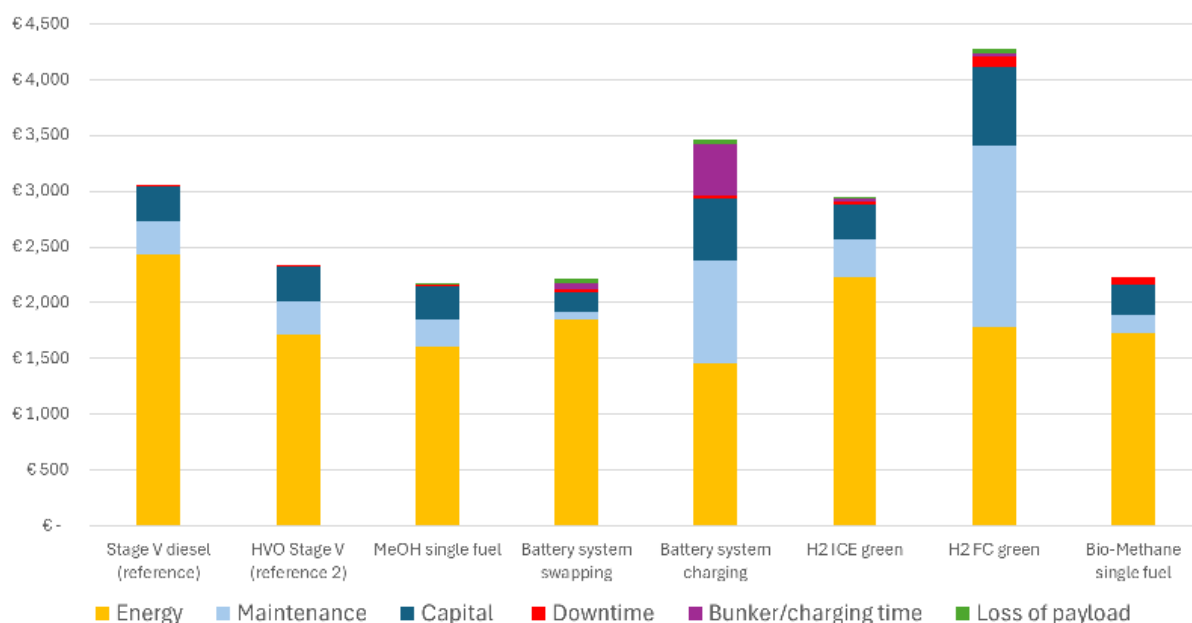


Figure 55 | Cost breakdown of the average TCO per day for the NZE average price scenario for the 135 metre tanker vessel and 60% CAPEX funding

As can be seen, the reduction of CAPEX results in a competitive situation for methanol single fuel, battery swapping and also bio-methane options. The hydrogen combustion solution can be competitive with fossil diesel. Costs for the hydrogen fuel cell solution are relatively high and this is also the case for the fixed batteries charged from shore.

5. Benefits and potential of break-through

5.1 Introduction and scenarios

Based on CCNR projections⁶, the IWT fleet was modelled in the PLATINA4Action Digital Twin (DT) modelling instrument which was developed in WP2 of the PLATINA4Action project. This instrument provides indications on the modal share development resulting from the changed costs of transport and also gives indicative results about the external cost of transport. For the model runs, two energy-transition pathways from the 2021 CCNR study on energy transition, have been applied as inputs to the DT: the conservative scenario and the innovative scenario.

In the conservative pathway, HVO holds the largest share by 2050 in inland navigation, with battery-electric propulsion ranking second. In the innovative pathway, battery-electric propulsion accounts for the largest share by 2050 in inland navigation, followed by methanol internal combustion engines (MeOH ICE).

For road transport, the conservative pathway assumes diesel is phased out by 2045 (See Annex 2). HVO peaks in the same year and then declines to 10% by 2050, while electric propulsion captures the majority of market share. Under the innovative pathway (See Annex 2), diesel is phased out by 2040. HVO again peaks in 2040 and declines further to 5% by 2050, with electric propulsion remaining the dominant option. Rail transport is assumed to become fully electrified by 2050, reflecting current technological trajectories and policy commitments observed across the European market.

5.2 Modal share potential

For the modal share analysis, the following five scenario variables were considered:

- the reference year
- the quality of fairway conditions
- the quality of river information services (RIS)
- the energy-transition pathway
- the price scenarios presented in the previous chapters

In the simulations as discussed in the section, results are reported for either normal or improved fairway conditions, with the occupancy rate of inland vessels set at either 60% or 70%. River Information Services are assumed to be 'advanced' in all cases. The settings and further background of the Digital Twin instrument is further explained in the Deliverable 2.2 which can be found on the [PLATINA4Action website](https://www.platina4action.eu/).

⁶ See the CCNR website for more information and to download the roadmap: <https://www.ccr-zkr.org/12090000-en.html> and the related report (2nd edition Part C: https://ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition2.pdf)

In the model, modal shares shift primarily due to changes in relative generalized transport costs across modes. The methodologies used to estimate transport costs across the three freight transport modes covered in the DT are grounded in cost structures and reflect differences in fuel and energy consumption, propulsion systems, infrastructure charges, labour costs, and handling requirements.

Calculations incorporate both direct operating costs and indirect costs (e.g. wages, congestion, infrastructure use). The aim is to produce a mode neutral, policy sensitive, and transparent cost estimation framework that supports intermodal comparisons under varying assumptions.

Figure 58 to Figure 65 illustrate how modal shares evolve across the two energy-transition pathways (Conservative and Innovative) and the two pricing scenarios (STEPS and NZE).

As highlighted before, a key driver for the modal share of IWT is the energy cost associated with the different propulsion options, together with the assumptions for technology pathway (conservative or innovative). In general, the lower the energy cost for IWT, the more competitive IWT becomes. Additionally, economies of scale mean that a higher occupancy rate, i.e., more cargo per trip, reduces unit transport costs. As a result, assuming a higher IWT occupancy level, leads to a marginal increase in IWT modal share. CAPEX support also reduces the total costs for IWT and therefore also results in a higher modal share.

The NZE scenario leads to the most favourable pricing case for IWT, particularly when the 60% CAPEX support incentive is assumed. This result is closely linked to the CCNR energy-transition pathways used as model inputs. Under the conservative pathway, by 2050 around 50% of the IWT fleet operates on HVO and almost 12% on batteries, with the remainder adopting other alternative propulsion options such as renewable methanol and hydrogen. Under the innovative pathway, batteries become dominant, accounting for around 45% of the IWT fleet, followed by renewable methanol at almost 30%.

By the year 2050, the road fleet is modelled to rely primarily on batteries and HVO, while rail is assumed to be powered by electricity completely. This transition towards electric power from grid making both modes increasingly competitive as well. Overall, the results indicate that renewable energy prices assumed under the NZE scenarios relatively reduce the IWT costs compared to costs for road haulage or rail transport.

Therefore, the IWT competitiveness becomes stronger, which explains the higher IWT modal share outcomes seen under the NZE scenario. Figure 56 and Figure 57 present the TCO development of the alternatives compared to using a Stage V diesel system for the STEPS scenario and for the NZE scenario for a large barge (CEMT class VI).

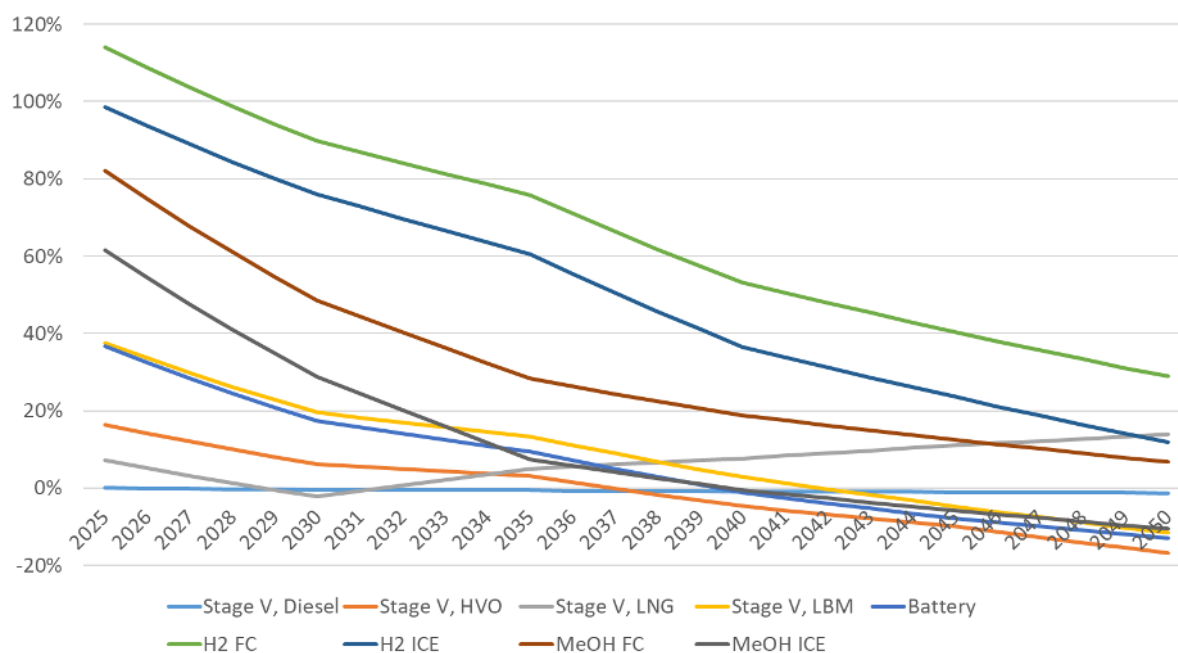


Figure 56 | Projections of Alternative Fuels prices / STEPS scenario (averaged prices) / CEMT Class: VI

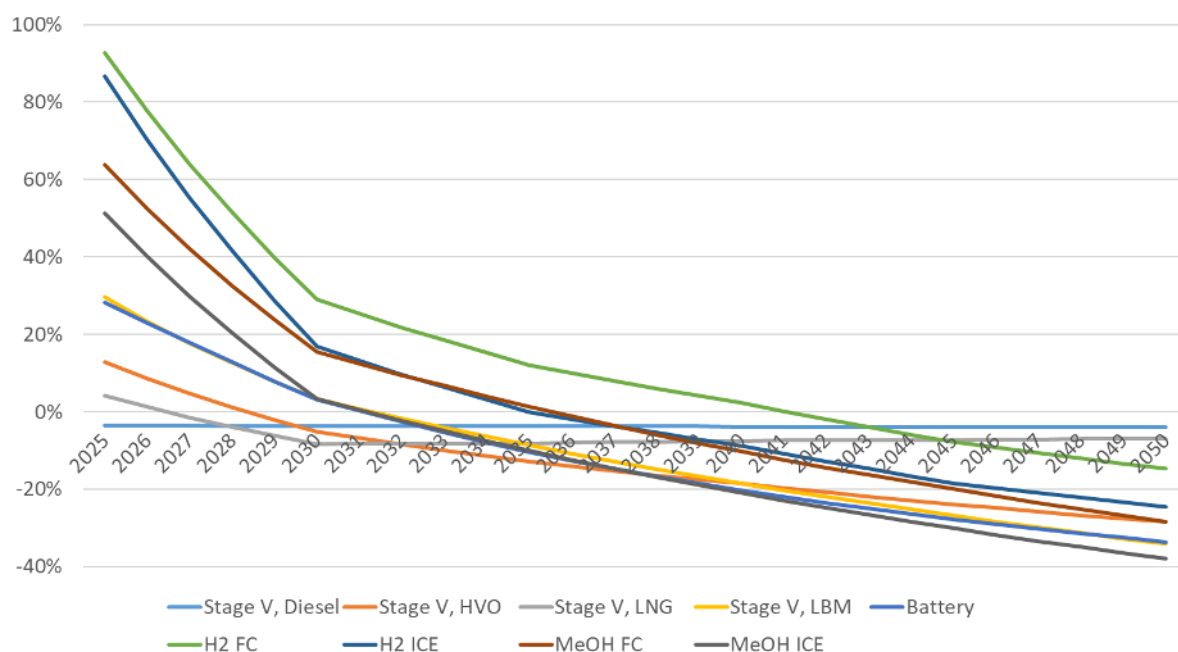


Figure 57 | Projections of alternative fuels prices / NZE scenario (averaged prices) – 60% CAPEX / CEMT Class: VI

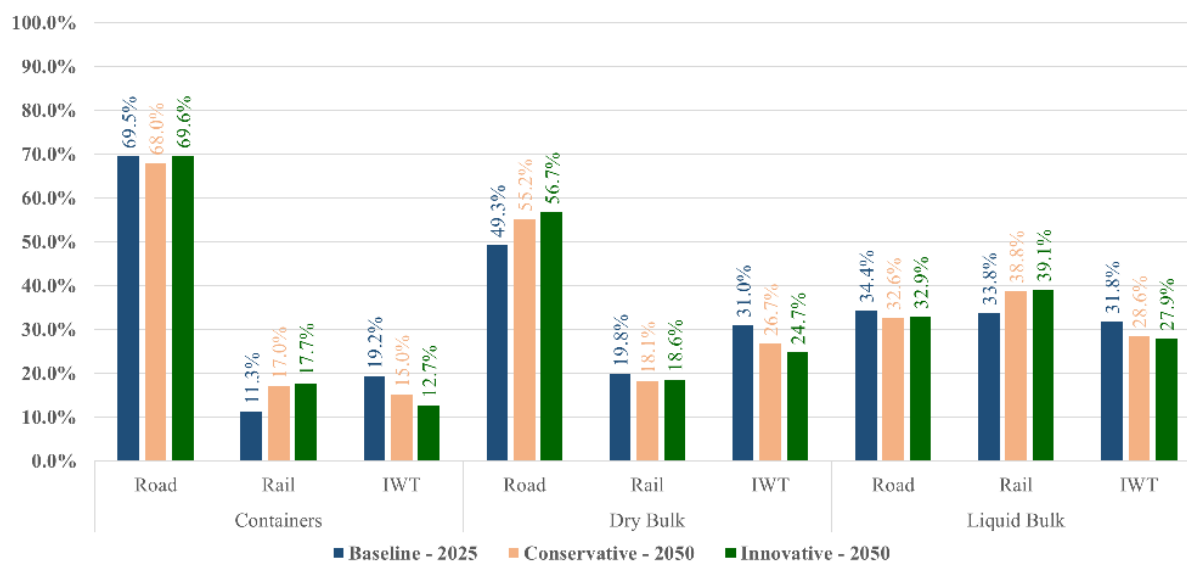


Figure 58 | Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: STEPS scenario (averaged prices)

STEPS combined with normal fairway conditions and an occupation rate of 60% is the least favourable scenario for IWT. For this setting of the model, the results point towards a decline of market share by 2050 compared to the baseline 2025 at both energy pathway scenarios (conservative and innovative).

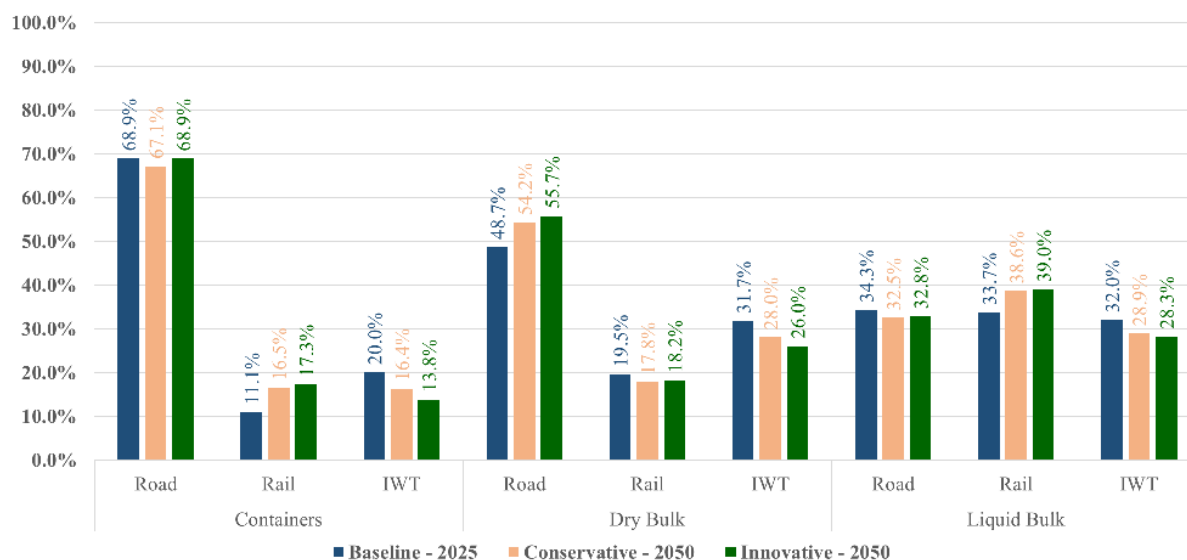


Figure 59 | Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: STEPS scenario (averaged prices)

Figure 59 shows the modal share results when taking into account improved fairway conditions and higher occupation rate of vessels. This leads to a marginal increase in IWT's market compared to the scenario results presented in Figure 58. However, the market share would still be lower in the year 2050 compared to the baseline for 2025.

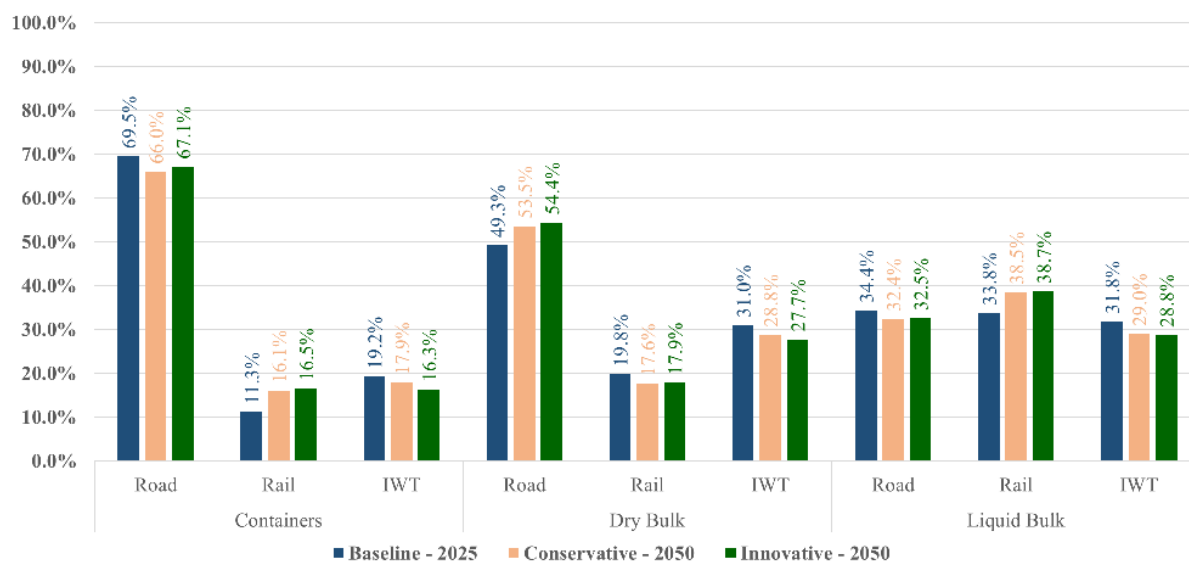


Figure 60 | Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: STEPS scenario (averaged prices) - 60% CAPEX

Figure 60 presents the impact of a funding on capital investments of 60%. It can be seen, that the competitiveness of IWT improves significantly when assuming such an intervention measure. The market shares of IWT for all cargo groups improve compared to Figure 59 by 2050. The scenario using STEPS energy prices and the conventional settings for the technology uptake and energy share in IWT seems to perform slight better than the innovative pathway.

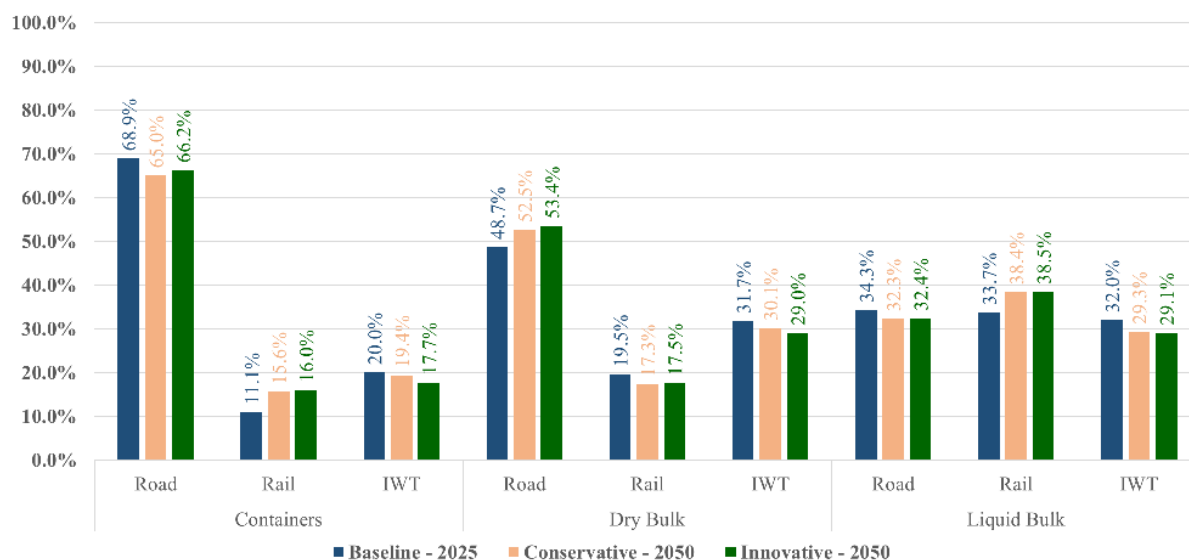


Figure 61 | Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: STEPS scenario (averaged prices) - 60% CAPEX

Figure 61 shows that in the same scenario, improved fairway conditions and higher occupation rate, lead to a marginal increase in IWT's market compared to Figure 60 but still they are lower to the 2025 baseline results.

Figure 62 presents the impact of using the NZE scenario for the energy prices. IWT then records a substantially higher market share in 2050 compared to 2025, with a gain of around 5% for the containers market, even at normal fairway conditions and a relatively low occupation rate of 60%. It can also be seen that the innovative pathway for the uptake of technology in IWT performs better in NZE compared to the conservative pathway. The only segment where we see a decline is in the liquid bulk at around 1.6%. The decline is however smaller compared to the decline seen in STEPS. Clearly the assumptions on the energy price development in NZE, are favourable for the competitiveness of IWT, especially when IWT will follow the innovative pathway, which assumes a higher share of battery electric propulsion.

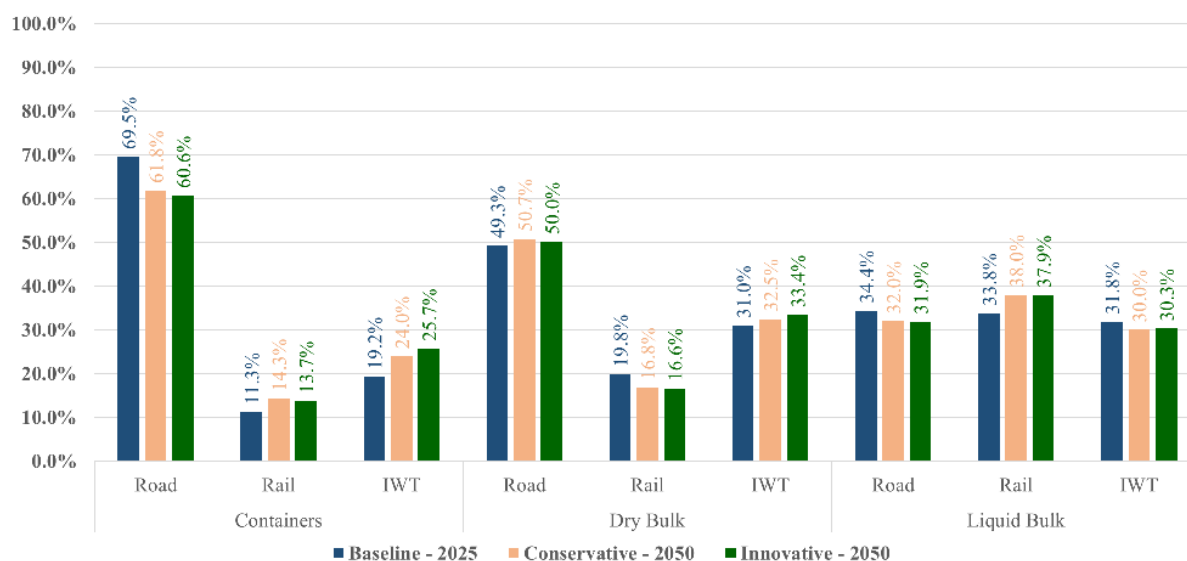


Figure 62 | Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: NZE scenario (averaged prices)

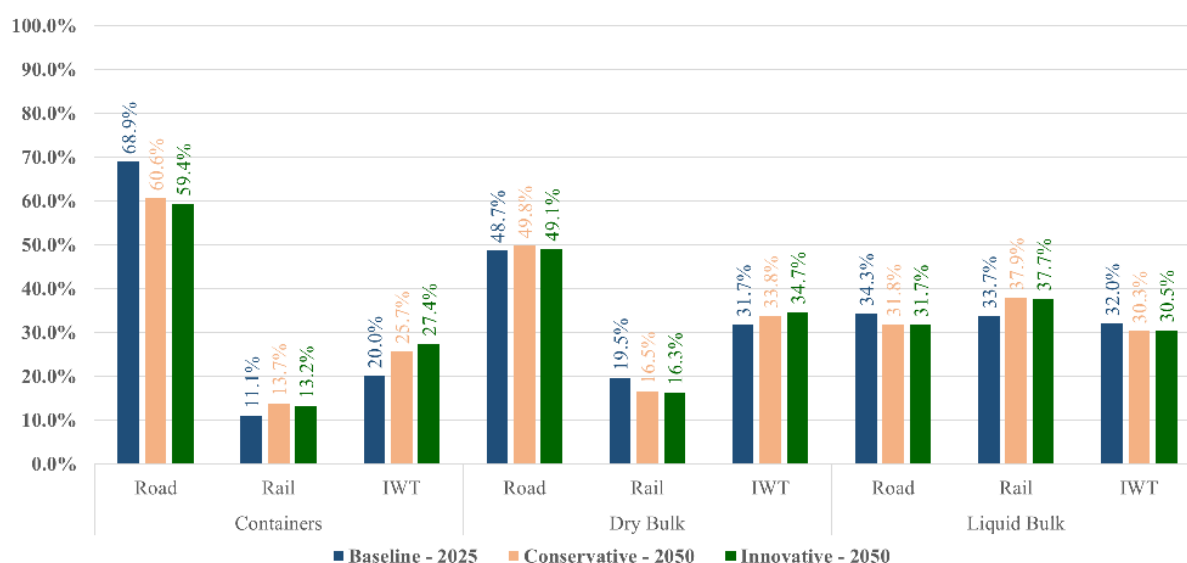


Figure 63 | Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: NZE scenario (averaged prices)

Figure 63 shows the impact when at the NZE energy prices scenario there would be improved fairway conditions and a higher load rate of the vessels (70%). This leads to a marginal further increase of IWT's market share for containers and dry bulk compared with the scenario applied for Figure 62 while liquid bulk is still declining marginally.

Another substantial boost of market share can be achieved when applying the funding support at the NZE pricing scenario, which is presented in the Figure 64.

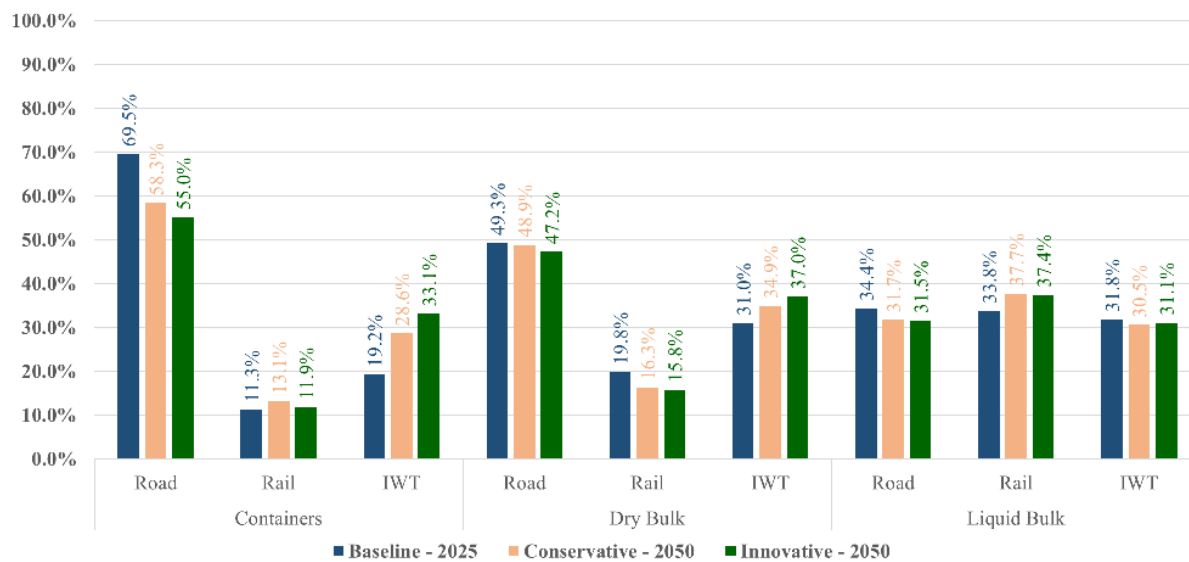


Figure 64 | Modal Share Results / Fairway Conditions: Normal / Occupation Rate: 60% / Price Scenario: NZE scenario (averaged prices) - 60% CAPEX

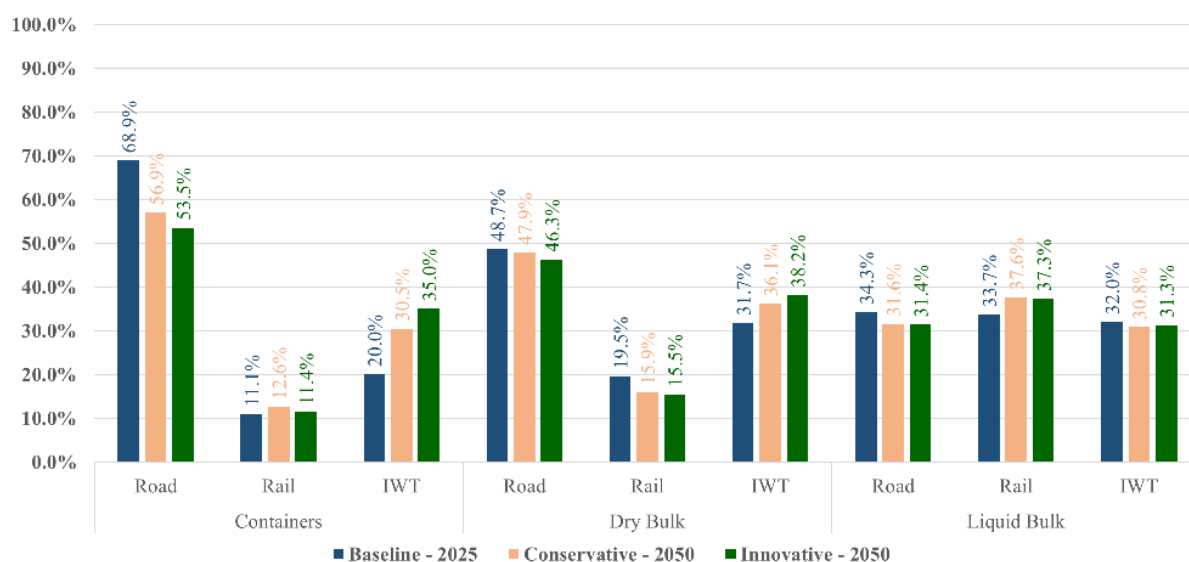


Figure 65 | Modal Share Results / Fairway Conditions: Improved / Occupation Rate: 70% / Price Scenario: NZE scenario (averaged prices) - 60% CAPEX

Improved Fairway Conditions and higher Occupation Rate, can further increase IWT's market share which is presented in Figure 65. These settings lead to the most favourable results for the modal share of IWT. Most significant impacts are resulting from the energy prices at the NZE scenario (internalisation of CO2e costs) and the intervention measure 60% CAPEX funding. The impact of changing the occupation from 60% to 70% has a smaller contribution on increasing the modal share of IWT.

Table 43 presents a summarising overview of the modal share results for the applied scenario settings. The data have been graphically presented in Figure 66 and Figure 67.

Table 43 | Summarising table of the modal share results for the Digital Twin scenarios for 2050 compared to baseline 2025

#	Pathway	Scenario for 2050	CAPEX funding	Fairway conditions	Occupation rate	IWT modal share Containers	IWT modal share Dry Bulk	IWT modal share Liquid Bulk
S1	Conservative	STEPS	no	Normal	60%	15.0%	26.7%	28.6%
S2	Innovative	STEPS	no	Normal	60%	12.7%	24.7%	27.9%
S3	Conservative	STEPS	no	Improved	70%	16.4%	28.0%	28.9%
S4	Innovative	STEPS	no	Improved	70%	13.8%	26.0%	28.3%
S5	Conservative	STEPS	60%	Normal	60%	17.9%	28.8%	29.0%
S6	Innovative	STEPS	60%	Normal	60%	16.3%	27.7%	28.8%
S7	Conservative	STEPS	60%	Improved	70%	19.4%	30.1%	29.3%
S8	Innovative	STEPS	60%	Improved	70%	17.7%	29.0%	29.1%
S9	Conservative	NZE	no	Normal	60%	24.0%	32.5%	30.0%
S10	Innovative	NZE	no	Normal	60%	25.7%	33.4%	30.3%
S11	Conservative	NZE	no	Improved	70%	25.7%	33.8%	30.3%
S12	Innovative	NZE	no	Improved	70%	27.4%	34.7%	30.5%
S13	Conservative	NZE	60%	Normal	60%	28.6%	34.9%	30.5%
S14	Innovative	NZE	60%	Normal	60%	33.1%	37.0%	31.1%
S15	Conservative	NZE	60%	Improved	70%	30.5%	36.1%	30.8%
S16	Innovative	NZE	60%	Improved	70%	35.0%	38.2%	31.3%
Baseline 2025:						19.2%	31.0%	31.8%

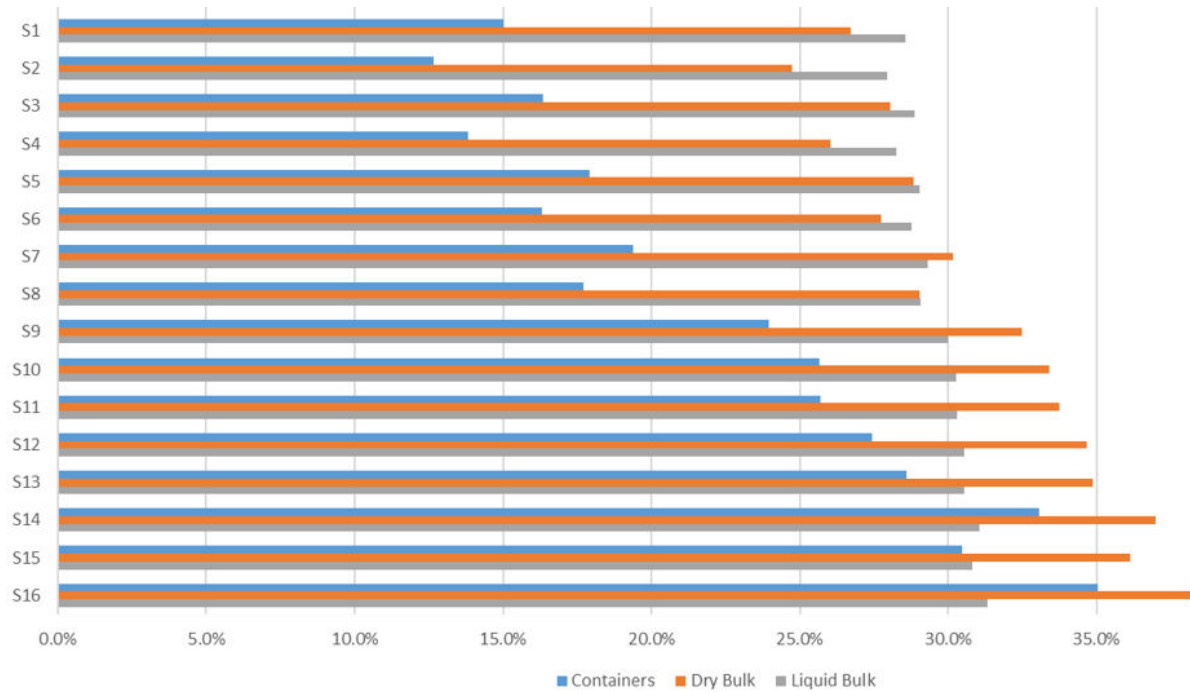


Figure 66 | Modal Share Results – scenarios compared

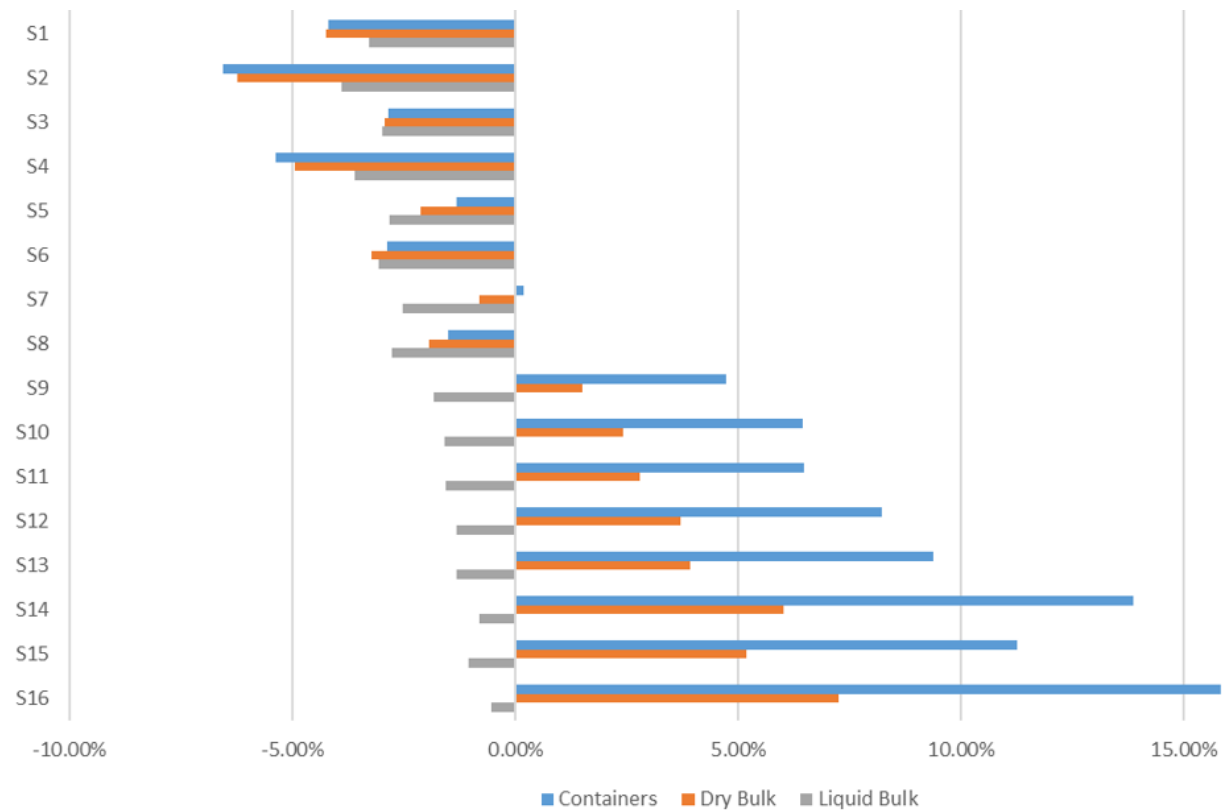


Figure 67 | Modal Share Results – scenarios compared with current modal share (baseline)

It can be concluded that most of the STEPS runs do not result yet in maintaining the market share of IWT. However, when applying also the CAPEX support measure and also having favourable occupation rates and fairway conditions, there is a significant improvement but not enough prevent losing market share compared to the 2025 baseline.

Furthermore, a clear finding is that all scenarios using NZE price levels for 2050 (S9-S16) result in a strong gain of market share of IWT for containers and dry bulk. The market of liquid bulk still shows a small decline at NZE scenario. However, this market does not seem not very sensitive to costs when looking at the modal share impact. Most of the liquid cargo seems to be 'captive' for IWT.

With respect to the commodity types, it can be observed that there is a difference in the modal share impact between containers, dry bulk and liquid bulk transport. Modal share is determined by the changes in parameters which affect the generalised costs for IWT services. The market of container transport seems most sensitive to the changes of parameter settings while dry bulk is less sensitive and liquid bulk shows the smallest sensitivity to changes in the costs. From an economic perspective, the relatively low-price sensitivity of liquid bulk transport is plausible and consistent with the characteristics of this market. A substantial share of liquid bulk volumes transported by inland waterways can be considered captive cargo, meaning that these flows have limited opportunities to shift to alternative transport modes in response to changes in relative transport costs. This is partly explained by the nature of the commodities transported, the specialised infrastructure required for their handling, and the strong integration of inland waterway transport into long-term industrial supply chains. Furthermore, liquid bulk transport is frequently organised through long-term contractual arrangements, which further limit short-term adjustments in modal choice.

It can therefore be concluded that increasing the competitiveness for container transport services by IWT and for the dry cargo transport services by IWT provides has the biggest impact on modal share.

5.3 Potential to reduce external costs

The external cost estimates calculated by the Digital Twin (DT) are based on the European Commission's Handbook on the External Costs of Transport and cover air pollution, climate change, well-to-tank emissions, congestion, noise and accidents.

Congestion costs are applied only to road transport, while noise costs are applied to both road and rail. The external cost factors used for the 2025 baseline were applied unchanged in the future projections, as no robust forward-looking forecasts are available for the external cost components. However, of course the performance on emissions is taken into account, based on the projections on the technology uptake in road, rail and IWT.

As a result, changes in total external costs over time are driven primarily by a different technology mix (e.g. much more electrification) and by modal share shifts, which reflect, among other inputs, the assumed energy-transition pathways and price scenarios. Each external-cost component is calculated by combining:

- the mode shares derived from the scenarios described above;

- the relevant external-cost factors for each mode and the share of specific propulsion technology and energy type
- the total cargo volumes transported by commodity group within the regions analysed under the PLATINA4Action project.

Figure 68 shows that total external costs decline substantially - by nearly 43% on average relative to the 2025 baseline. All three commodity groups follow a similar pattern. The largest reduction occurs under the NZE (averaged prices) - 60% CAPEX - innovative pathway in 2050 (approximately 46%). Differences across the price scenarios are small: the lowest reduction is observed under the STEPS (averaged prices) - conservative pathway in 2050, at around 37%, implying a spread of less than 10 percentage points across scenarios.

Figure 69, Figure 70 and Figure 71 present the breakdown of external costs by price scenario. As transport shifts towards more sustainable propulsion options over time, the composition of road external costs changes markedly: while air pollution and climate change dominate in 2025, accident and congestion costs become the largest component by 2050 across all price scenarios.

The total external costs presented in Figure 72, Figure 73 and Figure 74 represent the sum of all external cost components, expressed in million euros. Across the eight scenarios analysed (four price scenarios, each assessed under two energy-transition pathways), the assumptions for fairway conditions, River Information Services (RIS), and occupancy rate were held constant in the Digital Twin. Fairway conditions were set to Normal, RIS to Advanced, and the occupancy rate to 60% throughout.

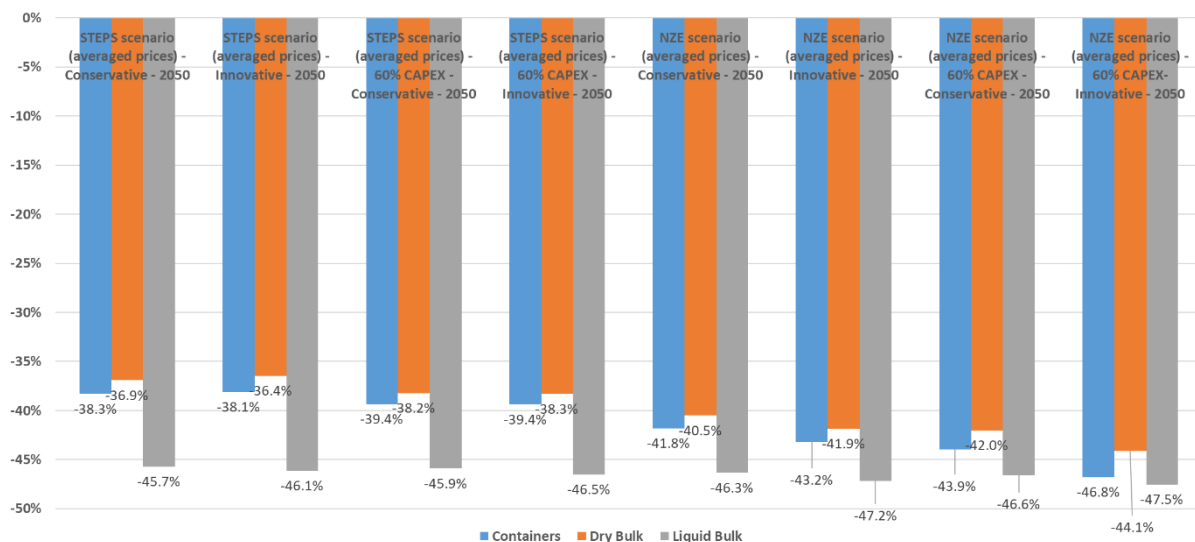


Figure 68 | Change in Total External Costs relative to the 2025 baseline, by price scenario [%]

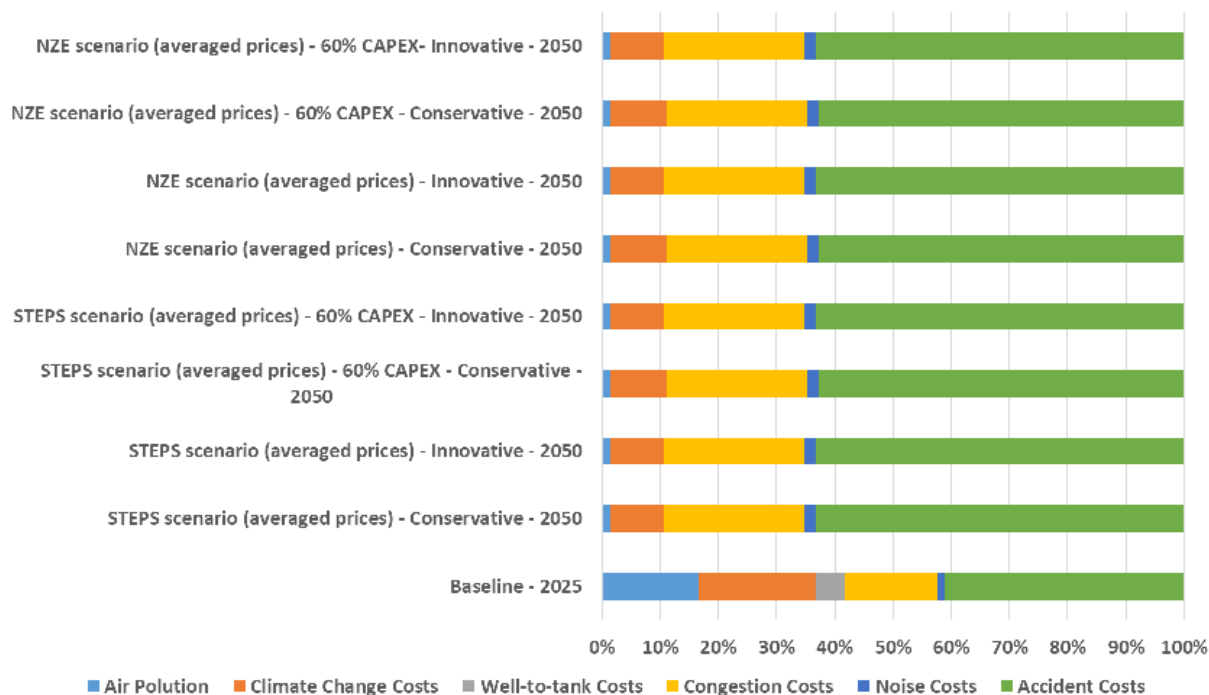


Figure 69 | External cost breakdown by price scenario – Containers - Road [%]

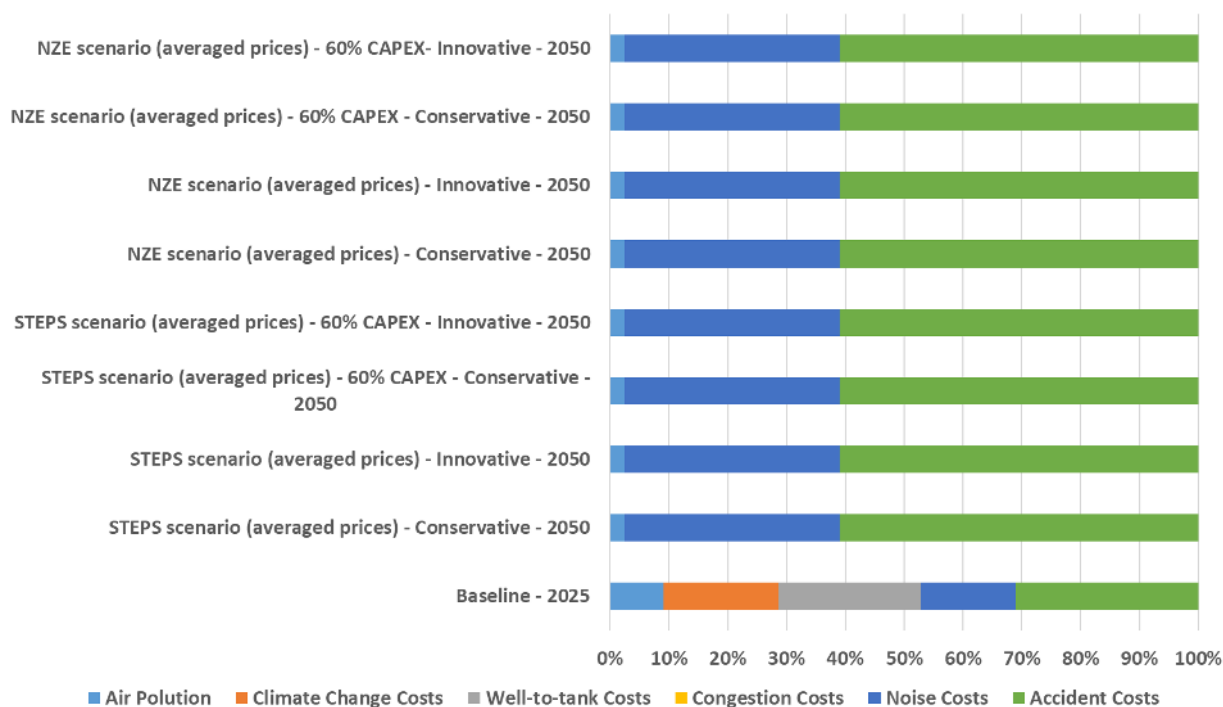


Figure 70 | External cost breakdown by price scenario – Containers - Rail [%]

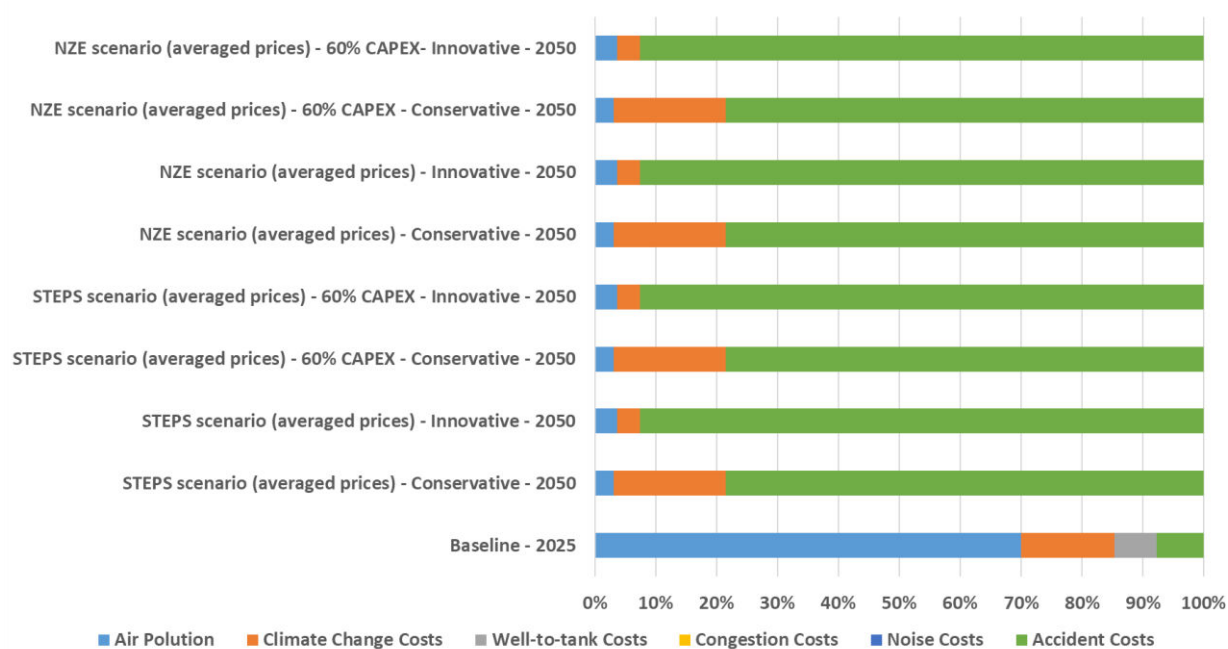


Figure 71 | External cost breakdown by price scenario – Containers - IWT [%]

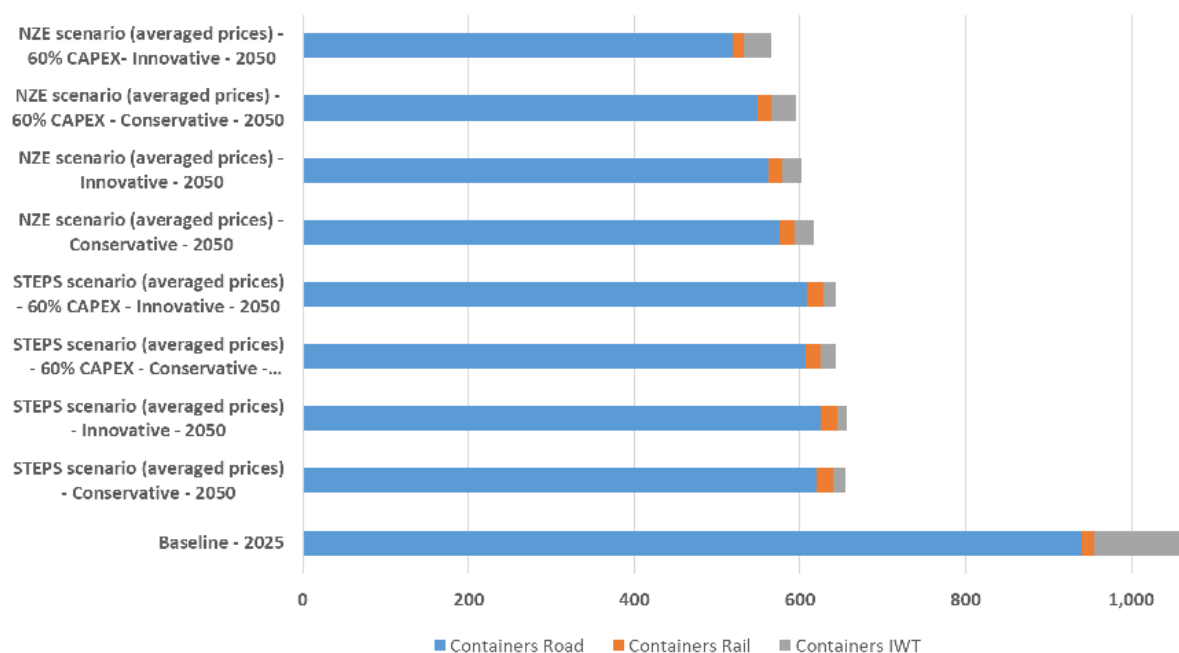


Figure 72 | Total External Costs in mil EURO - Containers

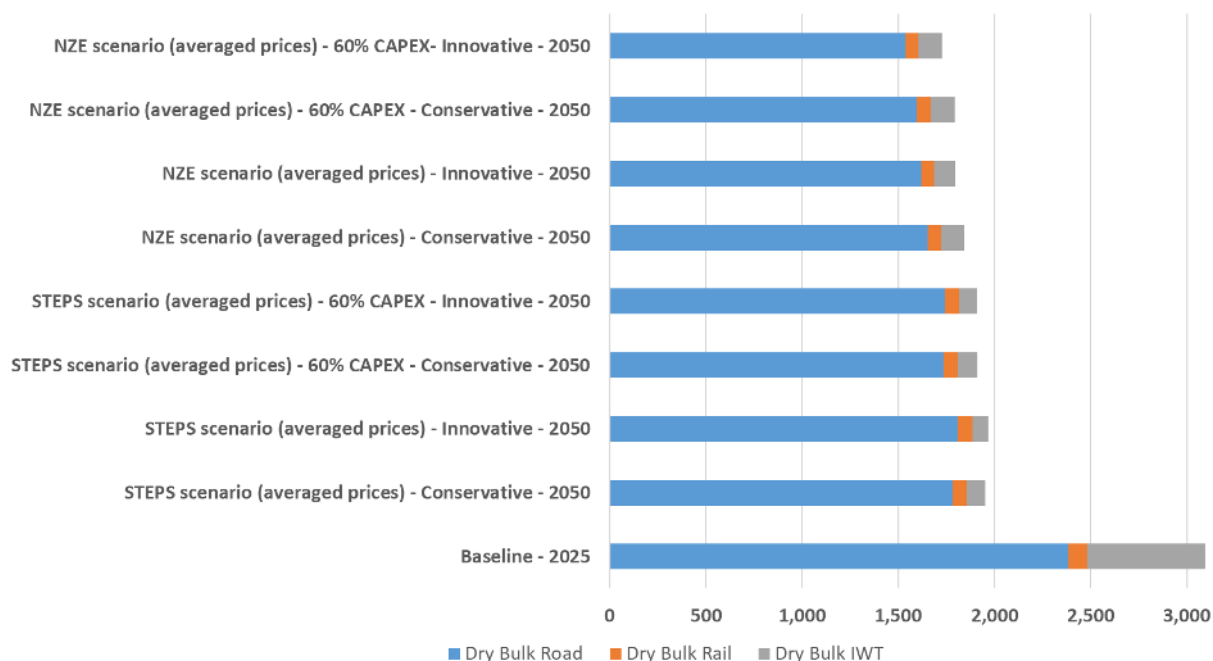


Figure 73 | Total External Costs in mil EURO – Dry Bulk

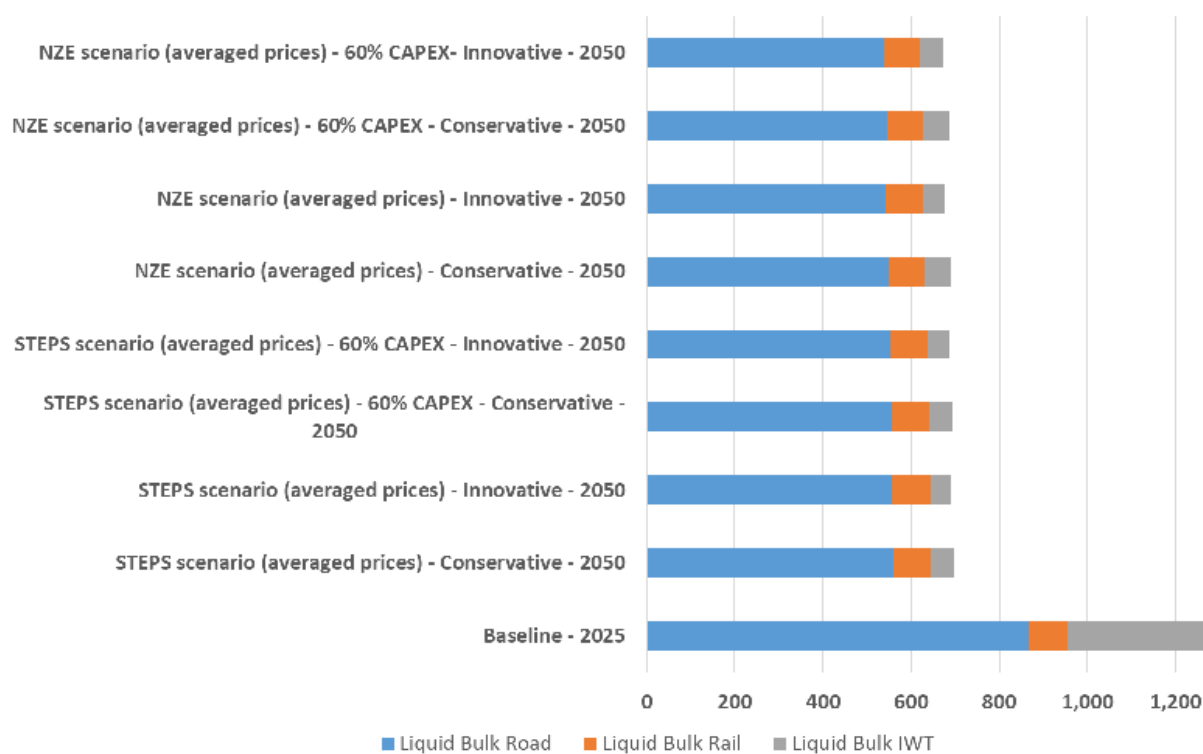


Figure 74 | Total External Costs in mil EURO – Liquid Bulk

Figure 75 presents the breakdown of external costs for inland waterway transport (IWT) for containers. Congestion and noise costs are not applied to IWT as the external costs handbook does not provide figures.

Depending on the scenario, total external costs in IWT have declined in 2050 by approximately 70% - 89% relative to the baseline 2025, while there is of course also the impact of the modal share resulting in a different transport performance. It can be seen that for both the STEPS and NZE scenarios, the air pollution costs (blue coloured bars) have declined to insignificant values. Accident / safety costs are the main cost remaining in 2050 for IWT.

As can be seen, at the NZE scenario energy prices, the total the external costs are higher compared to the scenarios based on STEPS energy prices. This however only because of the growth in modal share resulting from the higher transport performance due to increased competitiveness of IWT at NZE scenario.

As indicated, the NZE scenario leads for the whole land transport system, to the lowest external costs, because external costs in 2050 are still higher for road transport and rail transport compared to transport by IWT. This is explained by the much better performance of IWT on safety, noise and congestion costs compared to road and rail transport.

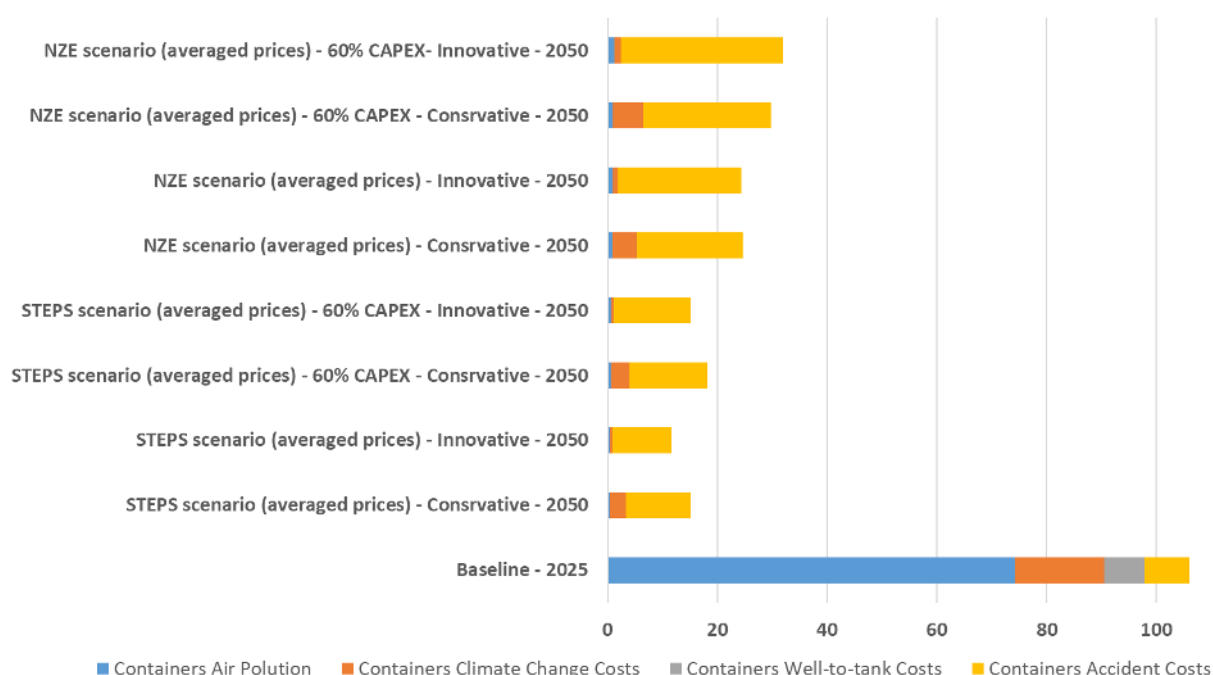


Figure 75 | IWT External costs in mil EURO

6. Scenarios for policy intervention

6.1 Energy policies

From both the analyses on business level (individual vessel) as presented in chapter 4 and also the extrapolation as presented in chapter 5 it is clear, that the energy price scenarios have a decisive role in the economic feasibility and also in the modal share of IWT.

The TCO analyses in chapter 4 makes clear that from the viewpoint of the vessel owner/operator the price gap between fossil diesel and renewable energy needs to be closed. This can be done by increasing the price of fossil diesel as a result of internalising the external costs for greenhouse gas emissions and by setting targets to energy suppliers to lower the GHG emissions or to supply a certain share of renewable energy to the market.

Furthermore, the NZE scenario shows that, also from the macro economic viewpoint, there is a strong impact on modal share with such energy policies. The intrinsic benefit of IWT as the highly energy efficient mode of transport is becoming apparent and more and more important at higher energy costs. The high performance on energy efficiency per ton kilometre leads to a positive impact on the modal share of IWT as presented in the previous chapter. This is especially seen at the NZE scenario which assumes lower prices for renewable energy compared to STEPS. The STEPS scenario shows also the risks: if the renewable energy remains too expensive, the competitive position of IWT is affected, resulting into a loss of modal share. The loss of modal share next leads to higher external cost, because of higher costs for accidents, congestion and noise in road and rail transport.

Table 44 | Comparison of NZE scenario with STEPS on average modal share of IWT

Scenario	IWT modal share Containers	IWT modal share Dry Bulk	IWT modal share Liquid Bulk
STEPS 2050 (average S1-S8)	16%	28%	29%
NZE 2050 (average S9-S16)	29%	35%	31%
Baseline 2025	19%	31%	32%

At NZE price levels, the modal share of IWT in the container market is clearly showing a strong gain and also a significant gain in dry bulk compared to the baseline 2025. The STEPS scenario however, shows a decline for all market segments compared to the baseline 2025. This indicates that the container market are most sensitive to energy price changes in relation to the assumed technologies on board. Compared to the STEPS scenario, assuming the energy prices at the NZE scenario results in:

- +13% share in containers, a relative growth of 78% compared to STEPS
- +7% share in dry bulk, a relative growth of 27% compared to STEPS
- +2 % share in liquid bulk, a relative growth of 6% compared to STEPS

In particular, making sure that renewable energy prices for inland waterway container transport brings significant added value because of increased modal share and less external costs.

Furthermore, next to transport cost savings, a modal shift from road to IWT also brings further reductions of external costs as congestion and noise costs are reduced. The NZE scenario compared to the STEPS scenario, generates 4.1% saving of the overall external costs of transport, around 670 million euros per year in 2050 for the transport flows which were modelled in the Digital Twin.

6.2 Grant funding to support investments

There is also a strong impact seen in the simulated measure to provide a 60% fund on capital investments. The business case for (near) zero-emission technologies will get much better when having these financial support measures. In particular, the battery electric and fuel cell electric solutions would benefit from these support measures.

It also becomes clear from the modal share assessments that the 60% funding on capital investments results a clear improvements of the competitiveness of IWT.

Table 45 | Comparison of Impact of CAPEX support (60%)

Scenario	IWT modal share Containers	IWT modal share Dry Bulk	IWT modal share Liquid Bulk
Average modal share without CAPEX support	20%	30%	29%
Average modal share with 60% CAPEX support	25%	33%	30%

With the CAPEX support, the IWT modal share improves:

- +5% in container transport, a relative growth of 24% compared to no CAPEX support
- +3% in dry bulk transport, a relative growth of 9% compared to no CAPEX support
- +1% in liquid transport, a relative growth of 2% compared to no CAPEX support

In particular, providing CAPEX support to container vessels and dry cargo vessels therefore gives a big positive impacts.

Annex 1 applied external cost values in the Digital Twin

Road	0.00029 [€/tkm]	Air Pollution
Rail	0.00004 [€/tkm]	
IWT	0.00004 [€/tkm]	
HGV Diesel Euro 5 [20 - 26 t]	0.00580 [€/tkm]	
Large Urban Bus Electric	0.00010 [€/tkm]	
HGV LNG	0.00030 [€/tkm]	
Long Freight Train - Diesel	0.0007 [€/tkm]	
Long Freight Train - Electric	0.00004 [€/tkm]	
IWT CCNR 2	0.00530 [€/tkm]	
IWT Rest	0.00004 [€/tkm]	
Road	0.00200 [€/tkm]	Climate Change Costs
Rail	0.00000 [€/tkm]	
IWT	0.00004 [€/tkm]	
HGV Diesel Euro 5 [20 - 26 t]	0.00690 [€/tkm]	
Large Urban Bus Electric	0.00000 [€/tkm]	
HGV LNG	0.00210 [€/tkm]	
Long Freight Train - Diesel	0.0016 [€/tkm]	
Long Freight Train - Electric	0.00000 [€/tkm]	
IWT CCNR 2	0.00110 [€/tkm]	
IWT Rest	0.00004 [€/tkm]	
Road	0.00061 [€/tkm]	Well-to-tank Costs
Rail	0.00110 [€/tkm]	
IWT	0.00110 [€/tkm]	
HGV Diesel Euro 5 [20 - 26 t]	0.00160 [€/tkm]	
Large Urban Bus Electric	0.00640 [€/tkm]	
HGV LNG	0.00030 [€/tkm]	
Long Freight Train - Diesel	0.0003 [€/tkm]	
Long Freight Train - Electric	0.00110 [€/tkm]	
IWT CCNR 2	0.00050 [€/tkm]	
IWT Rest	0.00110 [€/tkm]	
Road - Delay Costs	0.00450 [€/tkm]	Congestion
Road - Deadweight loss Costs	0.00050 [€/tkm]	
Road	0.00040 [€/tkm]	Noise Costs
Rail	0.00060 [€/tkm]	
HGV Diesel Euro 5 [20 - 26 t]	0.00160 [€/tkm]	
Long Freight Train - Diesel	0.0004 [€/tkm]	
Long Freight Train - Electric	0.00060 [€/tkm]	
Road	0.01300 [€/tkm]	Accidents
Rail	0.00100 [€/tkm]	
IWT	0.00100 [€/tkm]	

Annex 2 applied technology shares in Road and IWT

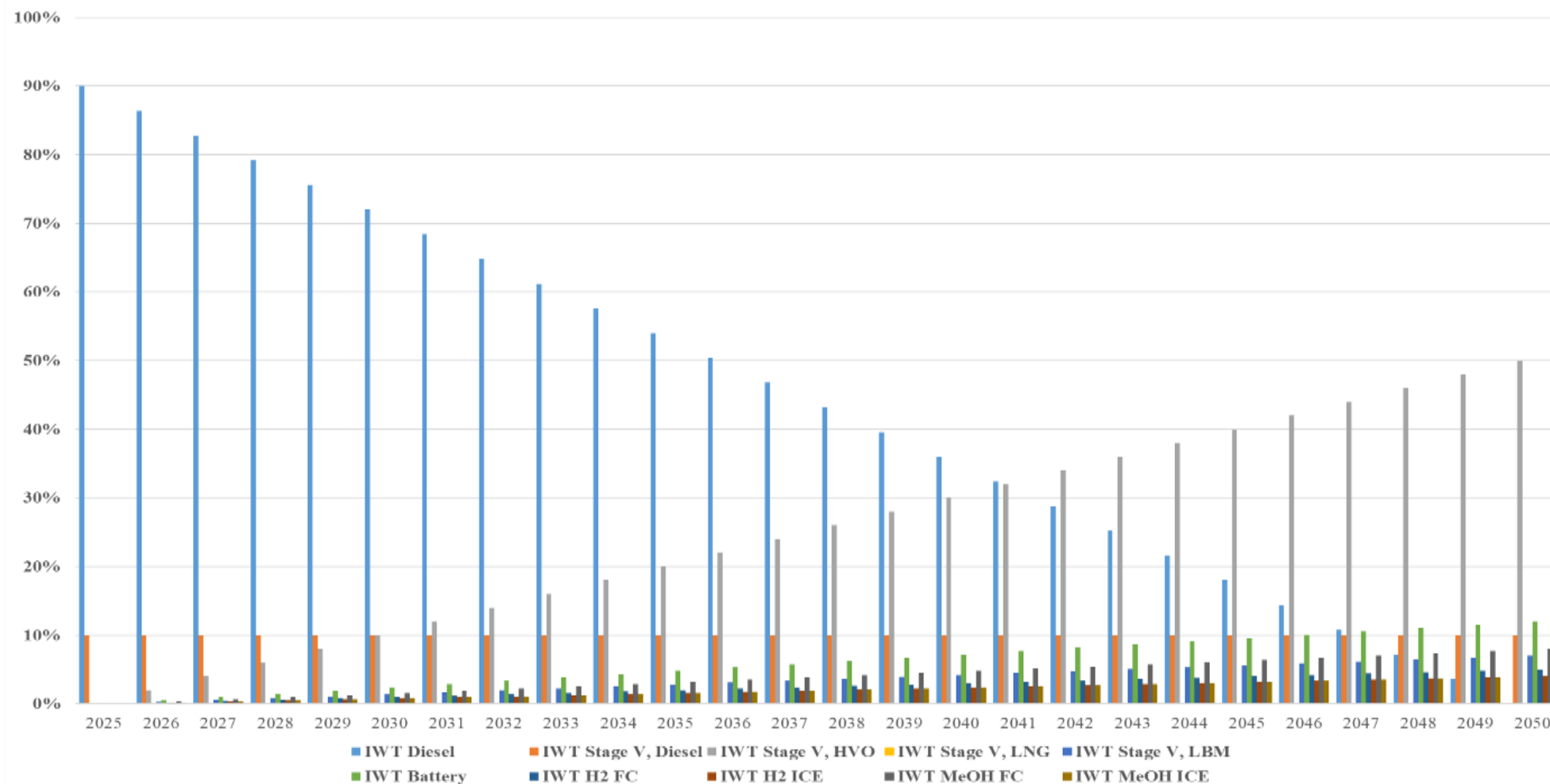


Figure 76 | Energy Transition Pathway – Conservative – IWT

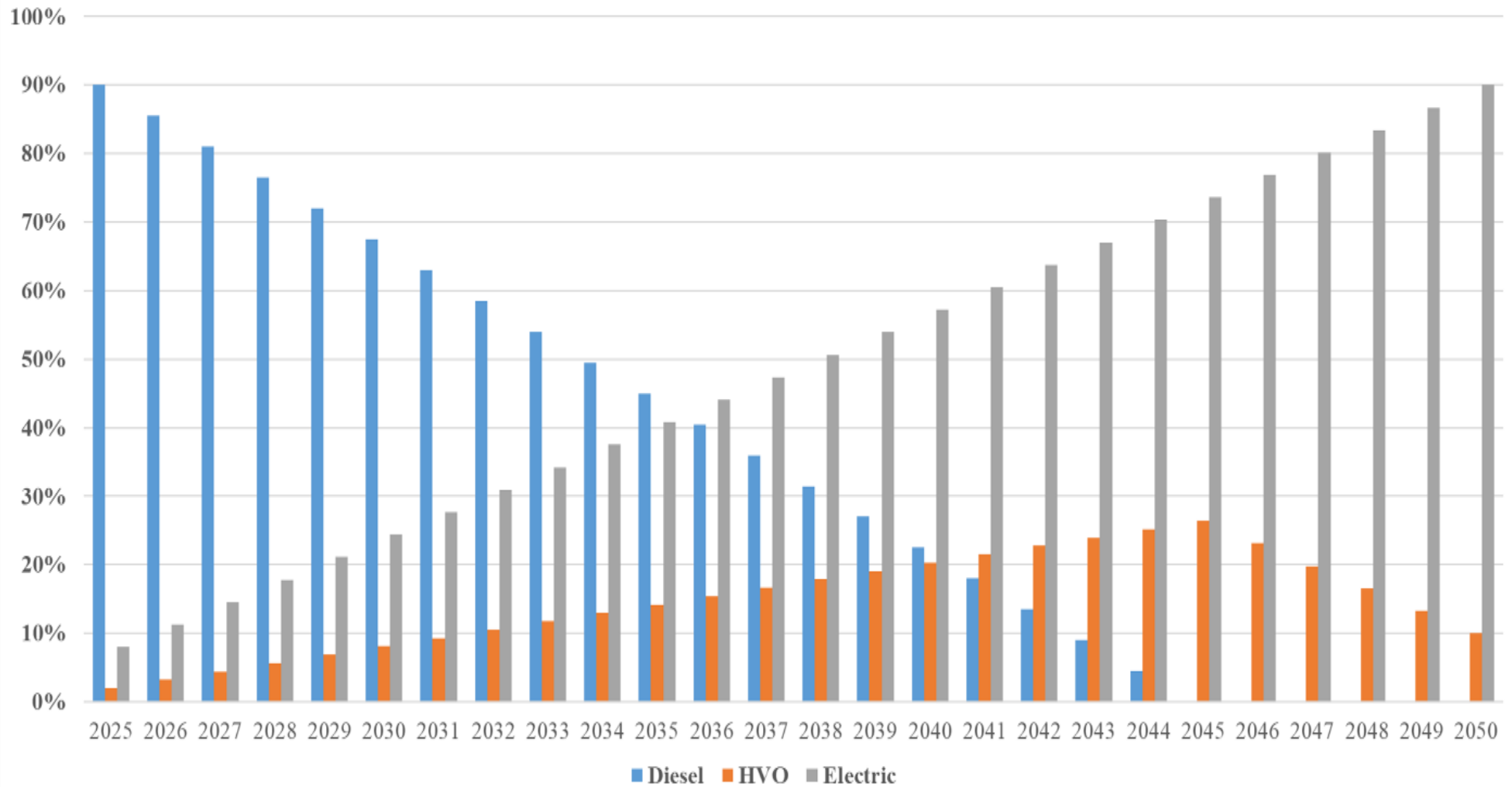


Figure 77 | Energy Transition Pathway – Conservative – Road

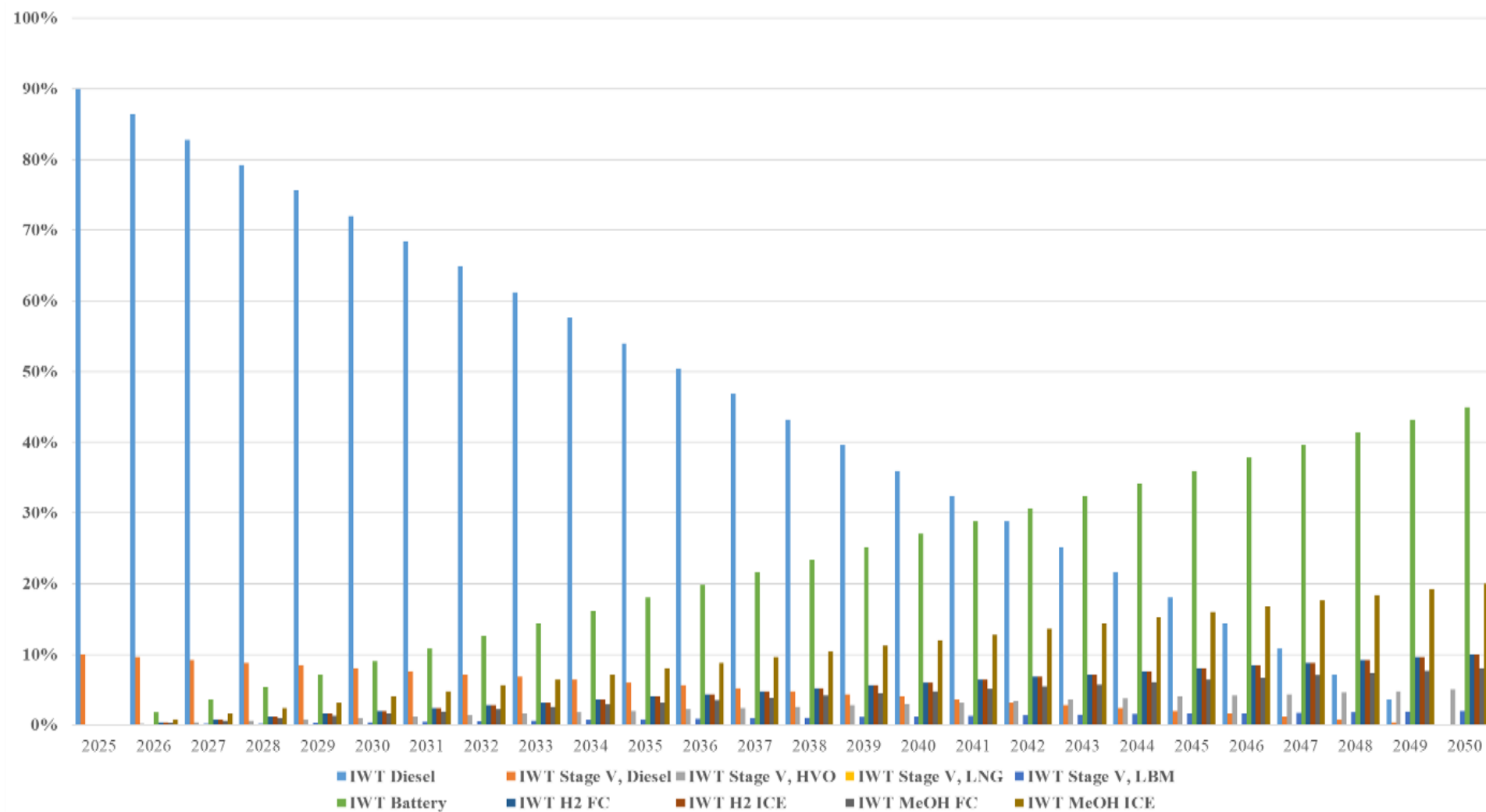


Figure 78 | Energy Transition Pathway – Innovative – IWT

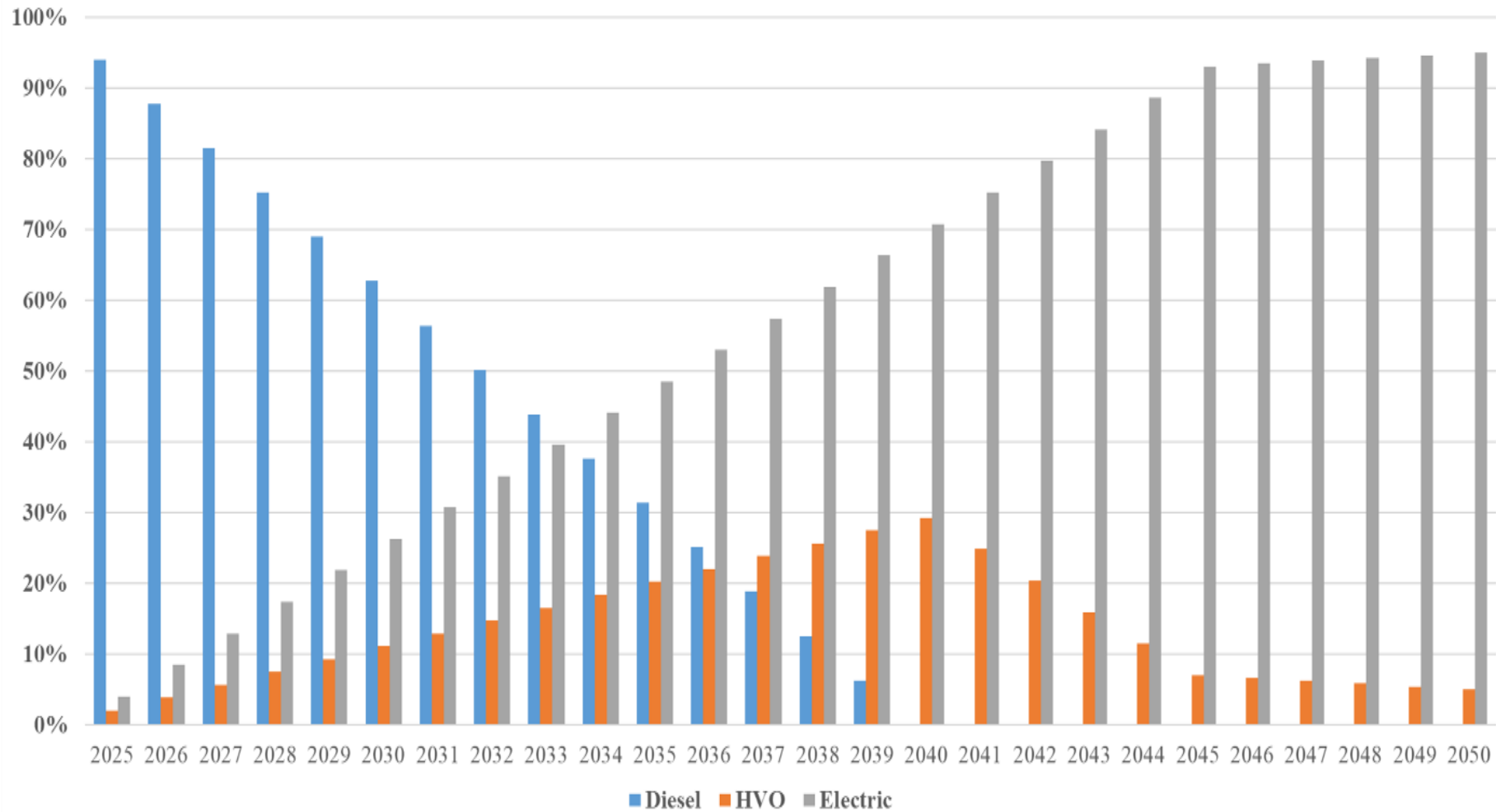


Figure 79 | Energy Transition Pathway – Innovative – Road

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