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The extension of the EU ETS 1 to maritime transport: impacts on sectoral decarbonisation

Analysis of current and future EU ETS 1 extensions for maritime

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Abstract: The extension of the EU ETS 1 to maritime transport: impacts on sectoral decarbonisation

This publication presents a scenario-based modelling assessment of the EU Emissions Trading System (EU ETS 1) and the FuelEU Maritime Regulation (FEUM), evaluating their individual and combined impacts on the decarbonisation of the European maritime transport sector. Using the PRIMES Maritime and PRIMES-TREMOVE models, the study quantifies emissions, energy use, fuel mix, and system costs across multiple policy scenarios aligned with the EU's Fit-for-55 package and long-term climate targets consistent with the 2040 Climate Target Plan. The EU ETS 1 introduces market-based carbon pricing, incentivising energy efficiency, investments in innovative technology to reduce emissions and low-carbon fuel uptakes, while FEUM mandates progressive reductions in the well-to-wake GHG intensity of onboard energy use, directly steering fuel switching toward renewable and low-carbon fuels (RLCFs). The modelling shows that FEUM exerts a long-term impact on fuel decarbonisation, whereas EU ETS 1 provides short- to medium-term incentives and improves cost-effectiveness. Specifically, the EU ETS 1 enables a lower-cost decarbonisation pathway by replacing internal compliance penalties (shadow costs) with explicit carbon pricing. In this model shadow costs are used to simulate regulatory pressure under FEUM but those costs are not actual payments and thus, do not generate revenues or feedback into the energy system. In contrast, EU ETS 1 payments are real market costs that influence operator decisions and can be reinvested to support clean fuel infrastructure and supply. The EU ETS 1 also stimulates early adoption of energy efficiency measures, particularly in large vessels, further reducing fuel use and compliance costs over time. Together, these two key instruments form a complementary policy architecture that accelerates maritime decarbonisation more effectively than either policy alone. The study also explores the potential benefits of extending EU ETS 1 to small vessels and inland waterways, highlighting additional emissions reductions and fuel transitions. The findings support the strategic integration of regulatory and market-based instruments to achieve climate neutrality in maritime transport by 2050.

Kurzbeschreibung: Die Ausweitung des EU-ETS 1 auf den Seeverkehr: Auswirkungen auf die Dekarbonisierung des Sektors

Diese Publikation analysiert modellgestützt die Auswirkungen des EU-Emissionshandelssystems (EU-ETS 1) und der FuelEU Maritime-Verordnung (FEUM) auf die Dekarbonisierung des europäischen Seeverkehrs. Mithilfe der Modelle PRIMES Maritime und PRIMES-TREMOVE werden Szenarien entwickelt, die Emissionen, Energieverbrauch, Kraftstoffmix und Systemkosten unter verschiedenen politischen Rahmenbedingungen quantifizieren. Der EU-ETS 1 setzt einen marktbasierten CO_2-Preis, der Energieeffizienzmaßnahmen, Investitionen in innovative Technologien zur Emissionsreduzierung und den Einsatz emissionsarmer Kraftstoffe fördert. FEUM verpflichtet hingegen zur schrittweisen Reduktion der Treibhausgasintensität der an Bord verwendeten Energie und lenkt damit gezielt den Kraftstoffwechsel hin zu erneuerbaren und CO_2-armen Kraftstoffen (RLCFs). Die Modellierung zeigt, dass die FEUM langfristig eine Steuerungswirkung auf die Kraftstoff-Dekarbonisierung entfaltet, während der EU-ETS 1 kurzfristig Effizienzmaßnahmen anstößt und die Kosteneffektivität erhöht. Insbesondere ermöglicht der EU-ETS 1 einen kostengünstigeren Weg zur Dekarbonisierung, indem er interne Compliance-Strafen (Schattenkosten) durch eine explizite CO_2-Bepreisung ersetzt. In diesem Modell werden Schattenkosten verwendet, um den regulatorischen Druck unter FEUM zu simulieren, die aber in der Realität nicht bezahlt werden und keine Rückkopplung in das Energiesystem erzeugen. Im Gegensatz dazu sind EU-ETS 1-Zahlungen reale Marktpreise, die Investitionssignale setzen und Einnahmen generieren, die für Infrastruktur und saubere Kraftstoffe verwendet werden können. Die Kombination beider Instrumente beschleunigt die Dekarbonisierung des Sektors deutlich stärker als jedes

Instrument allein. Zusätzlich untersucht die Studie die potenziellen Vorteile einer Ausweitung des EU-ETS 1 auf kleinere Schiffe und die Binnenschifffahrt. Die Ergebnisse unterstreichen die Bedeutung einer strategischen Kombination aus markt- und regulierungsbasierten Instrumenten zur Erreichung der Klimaneutralität im Seeverkehr bis 2050.

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List of abbreviations

Abbreviation	Explanation
AFIR	Alternative Fuels Infrastructure Regulation
CII	Carbon Intensity Indicator
CTP	Climate Target Plan
CH_4	Methane
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
DAC	Direct Air Capture
EC	European Commission
ECA	Emission Control Area
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EEX	European Energy Exchange
EMSA	European Maritime Safety Agency
EU ETS 1	EU Emissions Trading System 1
ETD	Energy Taxation Directive
EU	European Union
FF55	Fit for 55
FEUM	FuelEU Maritime Regulation
GDP	Gross Domestic Product
GFI	Global Fuel Intensity
GHG	Greenhouse Gas
GT	Gross Tonnage
Gtkm	Giga tonne-kilometre
Gpkm	Giga passenger-kilometre
H_2	Hydrogen
IEA	International Energy Agency
IMO	International Maritime Organization
LNG	Liquified Natural Gas
LRF	Linear Reduction Factor
LSFO	Low Sulphur Fuel Oil
LULUCF	Land Use Land Use Change and Forestry
MARPOL	International Convention for the Prevention of Pollution from Ships
MRV	Monitoring, Reporting and Verification
MS	Member States
MSR	Market Stability Reserve

Abbreviation	Explanation
Mtoe	Million Tonnes of Oil Equivalent
N_2O	Nitrous Oxide
NO_X	Nitrogen Oxides
NZF	Net-Zero Framework
OD	Origin-Destination
OPS	On-shore Power Supply
PRIMES	Price-Induced Market Equilibrium System
PtX	Power to X
RED III	Renewable Energy Directive
RES	Renewable Energy Share
RES-T	Renewable Energy Share in Transport
RFNBO	Renewable Fuel of Non-Biological Origin
RLCF	Renewable and Low-Carbon Fuel
SEEMP	Ship Energy Efficiency Management Plan
SO_X	Sulfur Oxides
TtW	Tank-to-Wake
WtT	Well-to-Tank
WtW	Well-to-Wake

Summary

The European Union's maritime transport sector accounts for approximately 4% of the region's CO_2 emissions, which have increased by around fifteen percent since 2015, despite gradual improvements in vessel efficiency. In response, the EU has incorporated maritime transport into its decarbonisation architecture through the European Green Deal, the European Climate Law, and the 2040 Climate Target Plan, which collectively establish a trajectory towards a 90% net Greenhouse Gas (GHG) reduction by 2040 and climate neutrality by 2050. Within the overarching policy framework, two measures are pivotal for maritime transport: the extension of the EU Emissions Trading System (EU ETS 1) to maritime transport and the FuelEU Maritime Regulation (FEUM), which mandates Well-to-Wake (WtW)[1] GHG intensity reductions of the energy used on board, from 2% in 2025 to 80% by 2050 relative to a 2020 baseline.

The chapter presents the main insights derived from the modelling undertaken in conjunction with PRIMES Maritime (for international shipping) and PRIMES-TREMOVE (for domestic shipping and inland waterways). Six scenarios are presented, comparing trajectories with and without the extension of the EU ETS 1 to maritime transport and FEUM, trajectories with the extension of either the EU ETS 1 to maritime transport or FEUM and exploring the extension of EU ETS 1 coverage to small vessels and inland waterways. The primary conclusion of this study is that FEUM exerts a long-term impact on fuel decarbonisation, whereas EU ETS 1 provides short- to medium-term incentives and enhances cost-effectiveness. Specifically, the EU ETS 1 facilitates a cost-efficient decarbonisation pathway by replacing internal compliance penalties (that is, shadow costs) with explicit carbon pricing. The shadow costs employed in the model to simulate regulatory pressure under FEUM are not actual payments and do not generate revenues or feedback into the energy system. In contrast, EU ETS 1 payments are real market costs that influence operator decisions and can be reinvested to support renewable fuel infrastructure, innovative technologies and supply chains. Model results suggest that the EU ETS 1 has a significant impact on the early adoption of energy efficiency measures, particularly in the context of large vessels. This results in a notable reduction in fuel use and compliance costs over time. The combined implementation of the EU ETS 1 and FEUM is indispensable: acting together, they place the sector on a credible decarbonisation path, while either instrument alone falls short of achieving comparable outcomes in time and at least cost.

In the Base Case, which represents the current policy environment in which both instruments are implemented, WtW emissions are projected to decrease from approximately 169 $MtCO_2eq$ in 2015 (161 $MtCO_2eq$ in 2020) to around 55 $MtCO_2eq$ by 2050. The transformation is driven primarily by fuel switching. Renewable and low-carbon fuels (RLCFs) are projected to account for approximately three-quarters of maritime energy consumption by the year 2050, with biofuels (including drop-in fuels and bio-LNG) assuming a dominant role in the near and medium term. Following 2035, renewable fuels of non-biological origin (RFNBOs), such as e-liquids, hydrogen, ammonia and methanol, are expected to experience a substantial increase in their share. Carbon pricing under the EU ETS 1 has been demonstrated to reinforce energy-efficiency improvements through operational and technical measures and enhance the cost-effectiveness of decarbonisation. Meanwhile, FEUM provides the binding driver of the change in the fuel mix.

In a counterfactual scenario, where the absence of both the maritime transport EU ETS 1 and FEUM is assumed, emissions remain predominantly fossil-based and increase by more than threefold by 2050 in comparison to the Base Case. It is evident that the EU ETS 1 results in a

[1] Tank-to-Wake (TtW) emissions refer to those produced by the combustion of fuel onboard a vessel. Well-to-Wake (WtW) encompass the entire lifecycle of the fuel, including extraction, production, transportation, and the TtW emissions by its combustion.

decline in emissions when compared to the counterfactual scenario lacking either policy, with RLCFs attaining nearly 50% of the 2050 energy mix. Nevertheless, the trajectory remains higher than that of the Base Case with both key instruments implemented. When analysing the impact of the FEUM alone, the emissions path is shown to resemble the Base Case yet relies on implicit compliance costs rather than market signals. Furthermore, this approach does not yield any EU ETS 1 revenues. The scenario of the extension of the EU ETS 1 to firstly, small vessels and secondly, large inland waterway vessels close important coverage gaps: emissions from small vessels fall by nearly a third by 2050, and inland-waterway emissions are roughly halved.

The analysis provides a robust foundation for a strategy that preserves the combined architecture of the EU ETS 1 and the FEUM, prepares proportionate EU ETS 1 extensions to uncovered segments and prioritises efficiency throughout the transition.

Policy context and objectives

The policy context for maritime decarbonisation is defined by the European Green Deal and EU Climate Law, which is currently under revision but encompass a legally binding objective of climate neutrality by 2050 for the European economy and an indicative trajectory towards a 90% net GHG reduction by 2040[2] compared with 1990 levels. Within this overarching structure, the 'Fit-for-55' package implements two complementary policies for shipping. Firstly, the EU ETS 1 is extended to cover maritime transport activities, encompassing 100% of emissions from domestic and intra-European Economic Area (EEA) voyages, 50% of emissions from extra-EEA voyages, and 100% of emissions at berth. Secondly, the FEUM Regulation imposes binding WtW GHG-intensity reductions of the energy used on board, compared against a 2020 baseline (91.2 gCO_2e/MJ). While the EU ETS 1 is a market-based instrument, which relies on economic incentives, FEUM is a command-and-control policy, since it mandates specific actions. The implementation of both of these instruments is part of a broader policy framework relevant for the maritime sector encompassing the Renewable Energy Directive (RED III), the Alternative Fuels Infrastructure Regulation (AFIR), and the technical measures adopted under the International Maritime Organization (IMO), including the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Ship Energy Efficiency Management Plan (SEEMP), and the Carbon Intensity Indicator (CII).

The objective of the present study is to first and foremost quantify the joint influence of the EU ETS 1 and FEUM on the decarbonisation pathway of the EU maritime transport sector, including fuel uptake, efficiency, emissions, and costs. The study also explores the counterfactual scenarios of the individual influence of either policy, had either of them not been implemented. In addition, the study assesses the sensitivity to carbon-price trajectories and analyses the implications of closing policy coverage gaps by extending the EU ETS 1 to currently exempt segments. The objective of the analysis is to inform policy design and sequencing over the 2025–2050 period, with a particular emphasis on emissions reduction effectiveness.

Modelling approach and data

The analysis employs the PRIMES modelling suite. PRIMES Maritime projects international maritime transport activity, fuel use, and emissions for each EU Member State, while PRIMES-TREMOVE represents domestic maritime and inland waterways in greater operational detail. The models simulate ship-operator decisions on fleet renewal and retrofits, engine-fuel technology choices, operational practices, and fuel blending. These decisions are subject to technology availability, policy constraints, and price signals. The maritime modules are linked to

[2] The report and modelling do not consider the latest political decision on a EU 2040 target as these were agreed after finalising this report (November 2025).

the broader PRIMES energy-system model, which balances energy supply and demand across sectors and determines pre-tax fuel prices endogenously under a decarbonising system consistent with the 2040 Climate Target Plan. In the present study, the EU ETS 1 carbon-price trajectory is imposed exogenously[3] on the maritime segment and varied in sensitivity cases. The Base EU ETS 1 path exhibits an upward trend from approximately 84 EUR/tCO_2 in 2025 to around 181 EUR/tCO_2 in 2050, with a higher-price variant indicating a more pronounced increase through the mid-century period and a lower-price variant suggesting a more gradual rise through the 2030-2040 decade prior to reaching a steady state. FEUM is represented as a binding WtW intensity constraint, enforced through escalating penalties within the optimization until compliance is achieved.

The model is calibrated based on Eurostat energy balances, EMSA/MRV emissions, the EC transport and energy datasets, and other shipping market sources. The fleet vintage structure, specific energy consumption, and operational parameters by ship type and size are aligned with the 4th IMO GHG Study and other sources. The historical and projected international fossil-fuel prices are derived from JRC-POLES projections, as employed in the 2040 Climate Target Plan impact assessment. Subsequently, PRIMES determines the sector-specific pre-tax prices for liquid fuels, gas, hydrogen, synthetic fuels, and electricity.

The present approach is subject to the following limitations. The carbon prices are exogenously imposed as a policy input to the maritime sector modelling and potential feedback effects from maritime abatement on EU ETS 1 prices, and, by extension, on fuel prices, are not captured (that means fuel prices do not respond to isolated changes in maritime demand). Behavioural responses such as evasive routing or bunkering outside the EU are not dynamically modelled. Technology learning is external and retrofits to dual-fuel engines are represented implicitly via blends. The demand module does not fully segment by vessel class below and above 5,000 gross tonnage (GT), which may soften activity reallocations across sizes. Recent IMO developments on a Global Fuel Intensity standard have not been quantified. These caveats suggest that the results are directionally robust but conservative relative to a globally coordinated regime with stronger price signals.

The modelling could be enhanced by replacing the current use of shadow costs for FEUM compliance with the actual penalties defined in the regulation. Rather than imposing GHG intensity targets as rigid constraints, applying these penalties as explicit price signals would serve to more accurately reflect operator behaviour and cost dynamics in the real world. This approach would also facilitate a more consistent comparison with the EU ETS 1, where carbon prices are paid and generate revenues. It is evident that shadow costs are internal constructs which do not represent actual expenditures or influence fuel supply economics. Therefore, it can be concluded that incorporating real compliance costs would improve the realism and robustness of policy impact assessments.

Scenario framework

The analysis is supported by a series of six scenarios, which collectively provide the analytical framework. The Base Case integrates the maritime transport EU ETS 1 and FEUM with broader Fit-for-55 measures and pertinent IMO instruments, such as EEDI, EEXI, SEEMP and CII. Three counterfactuals remove key pillars: one scenario removes both EU ETS 1 and FEUM for maritime transport, while retaining other measures. The second scenario retains EU ETS 1 but removes the FEUM. The third scenario involves the retention of FEUM, but with the removal of the EU ETS 1 extension to maritime transport. Two further scenarios have been proposed with the aim of extending the scope of the EU ETS 1 to segments that are currently outside of its core scope.

[3] UBA price trajectories are used (Mendelevitch et al. 2024).

The first of these scenarios involves the inclusion of ships below 5,000 GT in international and domestic maritime transport, and large vessels operating on inland waterways. The ETS-only and ETS-extension scenarios are accompanied by high- and low-price EU ETS 1 variants. Collectively, these scenarios serve to isolate the contribution of each policy lever and illuminate the implications of closing coverage gaps.

Results under the current policy framework (Base Case)

Under the combined EU ETS 1 and FEUM architecture, EU maritime transport activity grows with macroeconomic drivers yet progressively decouples from emissions. Freight activity increases. It is estimated that freight activity will increase from approximately 14.9 trillion tonne-kilometres in 2020 to almost 22.0 trillion by 2050. International maritime transport is projected to account for approximately 98% of sea and waterborne freight transport throughout this period. The passenger transport sector has experienced a strong initial recovery from the pandemic, with passenger kilometres rising from approximately 12.6 billion in 2020, followed by a projected steady increase to around 40.1 billion by 2050. This growth is expected to be driven by a balanced contribution from both international and national maritime transport.

Total maritime energy demand is coupled with activity growth, which is projected to increase from approximately 42 Mtoe in 2020 to around 50 Mtoe by 2050. Energy intensity has been shown to improve across various segments. Inland waterways transport exhibits the strongest relative gains, while international maritime transport, which dominates activity, also improves steadily through a combination of more efficient newbuilt vessels, operational measures driven by price signals, and compliance with IMO efficiency instruments.

The most significant transformation occurs in the composition of the fuel mix. By 2025 and 2030, the early adoption of LNG and liquid biofuels will contribute to compliance with the initial FEUM intensity steps. By the year 2040, the use of liquid fossil fuels is projected to decline to approximately two-thirds of energy use as RLCFs diversify. By 2050, the consumption of fossil liquids is projected to decline to approximately 8.1 Mtoe, while LNG consumption is estimated to reach around 4.2 Mtoe. Conversely, the use of biofuels is expected to increase to approximately 21.2 Mtoe, and bio-LNG is anticipated to account for around 2.3 Mtoe. The total amount of RFNBO liquids is estimated to be approximately 4.7 Mtoe, with hydrogen accounting for 3.2 Mtoe, ammonia for 2.6 Mtoe, methanol for 1.9 Mtoe, e-LNG for 0.7 Mtoe, and electricity for around 1.2 Mtoe. In aggregate, RLCFs are projected to account for approximately 75% of maritime energy by 2050.

Consequently, emissions levels exhibit a corresponding response. The WtW GHG emissions have been observed to decrease from approximately 169 MtCO_2eq in 2015 (161 MtCO_2eq in 2020) to around 55 MtCO_2eq in 2050. The most substantial reduction is evident in intra-EU voyages, indicative of comprehensive regulatory coverage (that is, 100% of emissions of voyages in both EU ETS 1 and FEUM). Segments outside the direct scope of EU ETS 1 and FEUM, particularly small vessels and inland waterways, decarbonise more slowly but still benefit from spillovers as fuel suppliers and port infrastructure adjust to serve regulated segments. On an intensity basis, maritime emission intensity is projected to decrease to approximately 21% of its 2015 level by 2050. The observed decomposition indicates that the primary driver of this phenomenon is the declining GHG intensity of the fuel mix, complemented by persistent improvements in energy intensity.

Within the scope of the EU ETS 1, this is applicable only to TtW emissions, which are projected to decrease from approximately 76 MtCO_2eq in 2015 to nearly 12 MtCO_2eq by 2050. At the Base EU ETS 1 price trajectory, the carbon price does not trigger fuel switching on its own beyond what is necessary to meet FEUM targets; instead, FEUM remains binding for the mix, while EU

ETS 1 amplifies efficiency responses and delivers auction revenues that can be recycled to lower compliance costs and accelerate the scale-up of clean fuels. The investment of auction revenues directly into maritime decarbonisation (for example, infrastructure, clean fuel support, innovative low carbon technologies, fleet renewal) is not mandated and is not modelled explicitly in the present analysis. The modelling assumes broader system-level benefits (for example, reduced RLCF prices due to increased supply) but does not simulate targeted reinvestment into the maritime sector.

Counterfactual analysis

The employment of counterfactuals helps to clarify the role of each instrument. When both the EU ETS 1 and FEUM are removed while other measures relevant to the maritime sector remain in effect, the sector will remain overwhelmingly dependent on fossil fuels until 2050. The RLCF penetration is marginal, energy demand is slightly higher owing to lower compliance costs, and WtW emissions reach approximately 174 MtCO2eq in 2050, which is more than triple the amount seen in the Base Case.

The EU ETS 1, in isolation, has been demonstrated to increase the relative cost of fossil fuels and stimulate significant uptake of RLCFs. By the year 2050, the RLCF share approaches half of maritime energy and emissions fall substantially compared to the no-policy case. In the absence of the FEUM binding trajectory, the mix falls short of the levels required for deep decarbonisation, with 2050 emissions remaining substantially above the Base Case. This outcome indicates that the EU ETS 1 price signal is applied exogenously in the present analysis. It is lower than what is considered in the framework conditions, within which the fuel uptake curves were calibrated to the broader decarbonisation framework, with higher carbon price signals. Price sensitivity variants show that with higher EU ETS 1 price signals, a higher emissions reduction is projected. As such, the level of emissions reduction is dependent on the combination of two factors: the level of the exogenous price signal and the initial calibration of fuel uptake curves that in this case are aligned with the broader EU Green Deal decarbonisation context.

Furthermore, the recycling of EU ETS 1 auction revenues to the maritime sector, while permitted under the regulation, is not modelled explicitly. Whilst the broader energy system benefits from reduced RLCF prices, targeted reinvestment into maritime could yield additional benefits for the sector. In a similar manner, FEUM compliance is represented through internal shadow costs rather than explicit penalties, which limits the realism of cost dynamics and operator responses. Addressing these limitations in future modelling efforts would enhance the robustness of policy impact assessments and more accurately capture the relative contribution of EU ETS 1 and FEUM to maritime decarbonisation.

The model in question incorporates a system of internal penalties, which are applied in instances of non-compliance. These penalties are intended to represent the effort required to meet the WtW intensity targets. The resulting fuel mix and 2050 emissions of the FEUM in isolation scenario are comparable to the Base Case, but the absence of explicit carbon pricing means fewer efficiency incentives and no EU ETS 1 revenues. It is evident that, over time, the EU ETS 1 signal in the Base Case leads to additional efficiency improvements and lower cumulative costs when compared with a mandate-only path.

Carbon pricing under the EU ETS 1 reinforces energy efficiency improvements within the maritime transport sector. This is achieved by incentivizing ship operators, particularly those operating large vessels, to adopt technical and operational measures that reduce fuel consumption. These efficiency gains, although modest in annual terms (for example, up to 1.3% improvement in national maritime transport energy intensity by 2045), accumulate over time and contribute to lower emissions and compliance costs. Furthermore, the EU ETS 1 enhances cost-effectiveness by narrowing the price gap between fossil and renewable fuels, leading to a 3.6-fold increase in RLCF uptake by 2030 in ETS-only scenarios, and nearly 50% RLCF share by 2050. Conversely, FEUM acts as the binding driver of the change in the fuel mix, mandating WtW GHG intensity reductions (for example 80 % by 2050), which the model enforces through penalty-based compliance mechanisms. These mandates result in a 75% RLCF share and nearly 70% emissions reduction by 2050 in the Base Case. The EU ETS 1 provides a market-based signal, fosters efficiency and generates auction revenues which help to support decarbonisation efforts in the maritime sector (up to 9 billion EUR annually in 2030–2040), whereas FEUM ensures regulatory certainty and technology uptake of RLCF.

Extending EU ETS 1 to uncovered segments

As regulated segments decarbonise, the issue of coverage gaps becomes increasingly important. In the Base Case, small vessels, which are not currently subject to neither the EU ETS 1 nor FEUM, are projected to account for approximately one third of residual maritime emissions by 2050, equivalent to approximately 18 $MtCO_2eq$ out of a total of 55 $MtCO_2eq$. The extension of the EU ETS 1 to this segment yields a significant response, with projections indicating that by the year 2050, emissions will have diminished by approximately 32%, reaching approximately 12 $MtCO_2eq$. However, this effect is accentuated by the fact that in the modelling, due to data availability, the small vessels scope includes all vessels below 5 000 GT, that means also those less than 400 GT. The observed effect can be attributed to the increased uptake of biofuels and RFNBOs, which is complemented by modest efficiency gains. The aggregate impact on system-level activity and energy is small.

Inland waterways exhibit similar dynamics, albeit on a reduced scale. In the absence of the EU ETS 1, the segment's RLCF share is projected to exceed 50% by 2050, a consequence of the broader system decarbonisation. The inclusion of large inland vessels within the scope of the EU ETS 1 strengthens incentives for the development of cleaner fuels and higher efficiency. The analysis indicates that this will result in an increase in the RLCF share beyond 80% and reducing 50% emissions in 2050 from around 2.0 $MtCO_2eq$ to roughly 1.0 $MtCO_2eq$. These extensions also generate additional EU ETS 1 revenues that can be allocated for infrastructure and fleet renewal in segments that traditionally face tighter financing constraints.

Costs and ETS price sensitivities

System costs[4] for international maritime transport lie in the range of approximately 78–87 billion EUR in 2030, 83–105 billion EUR in 2040, and 112–143 billion EUR in 2050 across a range of scenarios. It is estimated that fuel-related expenditures, including EU ETS 1 payments where applicable, account for approximately 46% up to 58% of total maritime system costs. As would be anticipated, scenarios involving minimal RLCF deployment exhibit reduced costs in absolute terms but do not meet emission reduction objectives. The Base Case and the FEUM -only path entail greater fuel and capital outlays as clean fuels scale; yet, by replacing internal shadow penalties with explicit price signals and by generating revenues that can be reinvested, the EU ETS 1 improves economic efficiency over time relative to a mandate-only configuration.

Carbon-price sensitivities highlight that higher EU ETS 1 prices accelerate RLCF uptake and reduce ETS-scope emissions in the ETS-only case. In the Base Case, however, FEUM remains the binding determinant of the fuel mix within the price ranges considered, and the primary impact of higher or lower EU ETS 1 prices is transmitted through costs rather than through additional fuel switching. This underscores the complementarity of the two instruments: FEUM is

[4] Including fuel cost, EU ETS 1 costs, Opex, Capex, non-variable fuel costs

responsible for the trajectory of clean-fuel deployment, while the EU ETS 1 enhances efficiency, narrows price gaps, and provides a mechanism for revenue recycling and cross-sectoral cost-efficient abatement.

Limitations and interpretation

The modelling choices and data constraints imply several caveats. The prices of carbon are considered exogenous to maritime and do not impact fuel prices; however, a fully integrated PRIMES system could potentially capture such interactions. The models do not dynamically represent behavioural leakage responses such as rerouting or bunker shifting outside the EU ETS 1 perimeter, which may result in an underestimation of displacement risks. Technology cost learning is applied externally, and the short-term uptake potential via retrofits to dual-fuel engines may be conservative. Demand segmentation by vessel class is partial, which may have a dampening effect on size-based reallocation of activity. Finally, recent developments at the IMO, including the approval of a (draft) binding Global Fuel Intensity Standard as part of the Net Zero Framework (NZF) – which has not yet been adopted -, are not quantified; their inclusion would likely reinforce results by aligning EU and global trajectories and reducing leakage incentives.

The modelling framework could be further improved by aligning the shadow costs used to simulate FEUM compliance with the actual penalties defined in the regulation. Rather than imposing the GHG intensity targets as hard constraints, the model could apply these penalties as explicit price signals, thus allowing for a more realistic representation of operator behaviour and cost dynamics. This would also facilitate a more robust comparison with the EU ETS 1, where carbon prices are paid and generate revenues. In contradistinction to the EU ETS 1 payments, shadow costs are internal model constructs that do not reflect real expenditures or influence fuel supply economics. Scenario results show that FEUM alone can drive substantial decarbonisation. However, without the EU ETS 1, these outcomes rely entirely on regulatory mandates, which evolve their full effect only in the long-term, and implicit penalties, which may not be as economically efficient or flexible as market-based instruments. The incorporation of authentic compliance costs into the modelling process would serve to enhance the robustness of policy impact assessments and facilitate more informed decision-making.

Strategic implications and implementation roadmap

The evidence of this report clearly supports preserving the dual policy architecture for effectiveness in emissions reduction and cost-efficiency. In the second half of the 2020-2030 period priority should be directed towards the operationalisation of EU ETS 1 compliance for maritime transport and the fulfilment of FEUM obligations. This should be complemented by the timely deployment of onshore power supply where mandated, and the early contracting of volumes of RFNBOs alongside sustainable biofuels to meet short-term targets. From 2030 to 2040, the focus will undergo a gradual transition towards the expansion of RFNBO production and the development of port bunkering infrastructure. Concurrently, there will be an advancement in the maturation of ammonia and methanol ship technologies and standards. Furthermore, the retrofitting process will be accelerated in instances where it is deemed cost-effective. During this phase, it is considered prudent to implement the EU ETS 1 coverage for small vessels, with proportionate administrative requirements, and to evaluate the inland waterway extension, relying on the modelling evidence presented here. By the 2040s, with the FEUM targets tightening to 62% by 2045 and 80% by 2050, policy should ensure the persistence of a meaningful carbon price signal, complete missing infrastructure links, and plan for addressing any residual emissions through negative emission options elsewhere in the energy system. Revenue use is pivotal. Using EU ETS 1 revenues for maritime decarbonisation initiatives, encompassing port infrastructure for alternative fuels and onshore power, support for early-adopter vessels and retrofits, and the mitigation of risk in RFNBO supply chains and offtakes, has the potential to reduce compliance costs and accelerate scale-up. At the same time, maintaining coherence with RED III sustainability criteria ensures environmental integrity of biofuels as their role expands in the 2020s and 2030s. Finally, close coordination with the IMO is conducive to minimising leakage risks, providing investment certainty, and leveraging global economies of scale. This may result in faster and cheaper decarbonisation than reflected in the Base Case assumptions.

Zusammenfassung

Der Seeverkehrssektor der Europäischen Union ist für etwa 4% der CO_2 Emissionen der Region verantwortlich, die seit 2015 trotz schrittweiser Verbesserungen der Schiffseffizienz um rund fünfzehn Prozent gestiegen sind. Als Reaktion darauf hat die EU den Seeverkehr durch den Europäischen Green Deal, das Europäische Klimagesetz und den Klimazielplan 2040 in ihre Dekarbonisierungsarchitektur aufgenommen, die gemeinsam einen Kurs für eine Netto-Reduzierung der Treibhausgasemissionen um 90% bis 2040 und Klimaneutralität bis 2050 festlegen. Innerhalb des übergeordneten politischen Rahmens sind zwei Maßnahmen für den Seeverkehr von zentraler Bedeutung: die Ausweitung des EU-Emissionshandelssystems (EU-ETS 1) auf den Seeverkehr und die FuelEU-Maritime-Verordnung (FEUM), die eine Reduzierung der Well-to-Wake-Treibhausgasintensität (WtW)[5] der an Bord verbrauchten Energie von 2% im Jahr 2025 auf 80% bis 2050 gegenüber dem Basisjahr 2020 vorschreibt.

Die folgende Zusammenfassung präsentiert die wichtigsten Erkenntnisse aus den Modellierungen, die in Verbindung mit PRIMES Maritime (für die internationale Schifffahrt) und PRIMES-TREMOVE (für die nationale Schifffahrt und Binnenwasserstraßen) durchgeführt wurden. Es werden sechs Szenarien vorgestellt, in denen die Entwicklung mit und ohne Ausweitung des EU-ETS 1 auf den Seeverkehr und FEUM, mit entweder der Ausweitung des EU-ETS 1 auf den Seeverkehr oder FEUM verglichen und die Ausweitung des EU-ETS 1 auf kleine Schiffe und Binnenwasserstraßen untersucht wird. Die wichtigste Schlussfolgerung dieser Studie ist, dass FEUM einen langfristigen Einfluss auf die Dekarbonisierung von Kraftstoffen hat, während der EU-ETS 1 kurz- bis mittelfristige Anreize bietet und die Kosteneffizienz verbessert. Insbesondere erleichtert das EU-ETS 1 einen kosteneffizienten Dekarbonisierungsweg, indem es interne Compliance-Strafen (das heißt Schattenkosten) durch eine explizite CO_2-Bepreisung ersetzt. Die im Modell zur Simulation des regulatorischen Drucks unter FEUM verwendeten Schattenkosten sind keine tatsächlichen Zahlungen und generieren keine Einnahmen oder Rückkopplungen in das Energiesystem. Im Gegensatz dazu sind die Zahlungen im Rahmen des EU-ETS 1 reale Marktkosten, die die Entscheidungen der Betreiber beeinflussen und zur Unterstützung der Infrastruktur, innovativer Technologien und Lieferketten für erneuerbare Kraftstoffe reinvestiert werden können. Modellierungsergebnisse zeigen, dass der EU-ETS 1 nachweislich einen erheblichen Einfluss auf die frühzeitige Einführung von Energieeffizienzmaßnahmen hat, insbesondere im Zusammenhang mit großen Schiffen. Dies hat im Laufe der Zeit zu einer deutlichen Verringerung des Kraftstoffverbrauchs und der Compliance-Kosten geführt. Die kombinierte Umsetzung des EU-ETS 1 und von FEUM ist unverzichtbar: Zusammen bringen sie den Sektor auf einen glaubwürdigen Dekarbonisierungsweg, während jedes der beiden Instrumente für sich genommen nicht in der Lage ist, vergleichbare Ergebnisse rechtzeitig und zu minimalen Kosten zu erzielen.

Im Basisszenario, das den aktuellen politischen Rahmen mit beiden implementierten Instrumenten umfasst, werden die WtW-Emissionen voraussichtlich von etwa 169 $MtCO_2eq$ im Jahr 2015 (161 $MtCO_2eq$ im Jahr 2020) auf etwa 55 $MtCO_2eq$ bis 2050 sinken. Die Transformation wird in erster Linie durch die Umstellung auf andere Kraftstoffe vorangetrieben. Erneuerbare und kohlenstoffarme Kraftstoffe (RLCFs) werden bis zum Jahr 2050 voraussichtlich etwa drei Viertel des Energieverbrauchs im Seeverkehr ausmachen, wobei Biokraftstoffe (einschließlich Drop-in-Kraftstoffe und Bio-LNG) kurz- und mittelfristig eine dominierende Rolle spielen werden. Nach 2035 wird erwartet, dass erneuerbare Kraftstoffe nicht-biologischen Ursprungs (RFNBOs) wie E-Fuels, Wasserstoff, Ammoniak und Methanol einen erheblichen

[5] Tank-to-Wake-Emissionen (TtW) beziehen sich auf Emissionen, die durch die Verbrennung von Kraftstoff an Bord eines Schiffes entstehen. Well-to-Wake-Emissionen (WtW) umfassen den gesamten Lebenszyklus des Kraftstoffs, einschließlich Förderung, Produktion, Transport und die TtW-Emissionen durch seine Verbrennung.

Anstieg ihres Anteils verzeichnen werden. Die CO_2-Bepreisung im Rahmen des EU-ETS 1 hat nachweislich zu einer Verbesserung der Energieeffizienz durch betriebliche und technische Maßnahmen geführt und die Kosteneffizienz der Dekarbonisierung erhöht. Gleichzeitig liefert FEUM den verbindlichen Treiber für die Veränderungen des Kraftstoffmixes.

Im kontrafaktischen Szenario, ohne den EU-ETS 1 für den Seeverkehr und FEUM, bleiben die Emissionen überwiegend fossil und steigen bis 2050 im Vergleich zum Basisszenario um mehr als das Dreifache. Es ist offensichtlich, dass der EU-ETS 1 im Vergleich zum kontrafaktischen Szenario ohne politische Maßnahmen zu einem Rückgang der Emissionen führt, wobei RLCFs fast 50% des Energiemixes für 2050 ausmachen. Dennoch bleibt die Entwicklung höher als im Basisszenario, bei dem beide Maßnahmen implementiert sind. Bei der Analyse der Auswirkungen von FEUM allein zeigt sich, dass der Emissionspfad dem Basisszenario ähnelt, jedoch eher auf impliziten Compliance-Kosten als auf Marktsignalen beruht. Darüber hinaus bringt dieser Ansatz keine Einnahmen aus dem EU-ETS 1. Das Szenario mit der Ausweitung des EU-ETS 1 auf kleine Schiffe und große Binnenschiffe schließt wichtige Lücken in der Abdeckung: Die Emissionen kleiner Schiffe sinken bis 2050 um fast ein Drittel, und die Emissionen der Binnenschifffahrt werden etwa halbiert.

Die Analyse unterstreicht die Notwendigkeit einer Strategie, die die kombinierte Architektur von EU-ETS 1 und FEUM beibehält, angemessene Erweiterungen des EU-ETS 1 auf nicht abgedeckte Segmente vorbereitet und der Effizienz während des gesamten Übergangs Vorrang einräumt.

Politischer Kontext und Ziele

Der politische Kontext für die Dekarbonisierung des Seeverkehrs wird durch den Europäischen Grünen Deal und das EU-Klimagesetz definiert, welches aktuell novelliert wird und ein rechtsverbindliches Ziel der Klimaneutralität bis 2050 für die europäische Wirtschaft und einen indikativen Pfad zu einer Netto-Reduzierung der Treibhausgasemissionen um 90% bis 2040[6] gegenüber dem Stand von 1990 umfasst. Innerhalb dieser übergreifenden Struktur manifestiert das „Fit-for-55“-Paket zwei sich ergänzende Maßnahmen für den Seeverkehr. Erstens wird der EU-ETS 1 auf den Seeverkehr ausgeweitet und umfasst 100% der Emissionen aus Inlands- und EWR-internen Fahrten, 50% der Emissionen aus Fahrten außerhalb des EWR und 100% der Emissionen am Liegeplatz innerhalb des EWR. Zweitens schreibt die FuelEU-Maritime-Verordnung verbindliche Reduktionen der WtW-Treibhausgasintensität der an Bord verbrauchten Energie vor, gemessen an einem Referenzwert für 2020 (91,2 gCO2e/MJ). Während der EU-ETS 1 ein marktbasiertes Instrument ist, das auf wirtschaftlichen Anreizen beruht, handelt es sich bei FEUM um eine Command-and-Control-Politik, da sie bestimmte Maßnahmen vorschreibt. Die Umsetzung beider Instrumente ist Teil eines umfassenderen politischen Rahmens für den maritimen Sektor, der die Richtlinie über erneuerbare Energien (RED III), die Verordnung über die Infrastruktur für alternative Kraftstoffe (AFIR) und die im Rahmen der Internationalen Seeschifffahrtsorganisation (IMO) verabschiedeten technischen Maßnahmen umfasst, darunter Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Ship Energy Efficiency Management Plan (SEEMP), und der Kohlenstoffintensitätsindikator (CII).

Ziel der vorliegenden Studie ist es vor allem, den individuellen und gemeinsamen Einfluss des EU-ETS 1 und von FEUM auf den Dekarbonisierungsweg des Seeverkehrssektors der EU zu quantifizieren, einschließlich Kraftstoffverbrauch, Effizienz, Emissionen und Kosten. Die Studie untersucht auch die kontrafaktischen Szenarien des individuellen Einflusses beider Maßnahmen, wenn eine von ihnen nicht umgesetzt worden wäre. Darüber hinaus analysiert die

[6] Der Bericht und die Modellierung berücksichtigen nicht die jüngste politische Entscheidung über ein EU-Ziel für 2040, da diese nach Fertigstellung dieses Berichts (November 2025) getroffen wurde.

Studie die Sensitivität gegenüber Kohlenstoffpreisentwicklungen und untersucht die Auswirkungen einer Schließung von Lücken in der Politikabdeckung durch die Ausweitung des EU-ETS 1 auf derzeit ausgenommene Segmente. Ziel der Analyse ist es, Informationen für die Gestaltung und Abfolge der Politik im Zeitraum 2025–2050 zu liefern, wobei ein besonderer Schwerpunkt auf der Wirksamkeit der Emissionsminderung liegt.

Modellierungsansatz und Daten

Die Analyse verwendet die PRIMES-Modellierungssuite. PRIMES Maritime prognostiziert die internationalen Seeverkehrsaktivitäten, den Kraftstoffverbrauch und die Emissionen für jeden EU-Mitgliedstaat, während PRIMES-TREMOVE den inländischen See- und Binnenschiffsverkehr mit größeren operativen Details abbildet. Die Modelle simulieren die Entscheidungen der Schiffsbetreiber hinsichtlich Flottenerneuerung und Nachrüstung, Wahl der Motor-Kraftstoff-Technologie, Betriebspraktiken und Kraftstoffmischung. Diese Entscheidungen unterliegen der Verfügbarkeit von Technologien, politischen Beschränkungen und Preissignalen. Die Seeverkehrsmodule sind mit dem umfassenderen PRIMES-Energiesystemmodell verknüpft, das Energieangebot und -nachfrage über alle Sektoren hinweg ausgleicht und die Kraftstoffpreise vor Steuern endogen im Rahmen eines Dekarbonisierungssystems festlegt, das mit dem Klimazielplan 2040 im Einklang steht. In der vorliegenden Studie wird die CO_2-Preisentwicklung des EU-ETS 1 exogen[7] auf den Seeverkehrssektor angewendet und in Sensitivitätsanalysen variiert. Der Basisverlauf des EU-ETS 1 zeigt einen Aufwärtstrend von etwa 84 EUR/tCO_2 im Jahr 2025 auf etwa 181 EUR/tCO_2 im Jahr 2050, wobei eine Variante mit höheren Preisen einen stärkeren Anstieg bis zur Mitte des Jahrhunderts und eine Variante mit niedrigeren Preisen einen allmählicheren Anstieg in den Jahren 2030 bis 2040 vor Erreichen eines Gleichgewichtszustands nahelegt. FEUM wird als verbindliche WtW-Intensitätsbeschränkung dargestellt, die durch eskalierende Strafen innerhalb der Optimierung durchgesetzt wird, bis die Einhaltung erreicht ist.

Das Modell wird auf der Grundlage der Energiebilanzen von Eurostat, der EMSA/MRV-Emissionen, der Datenreihen der Europäischen Kommission zu Verkehr und Energie sowie anderer Quellen aus dem Schifffahrtsmarkt kalibriert. Die Altersstruktur der Flotte, der spezifische Energieverbrauch und die Betriebsparameter nach Schiffstyp und -größe entsprechen der 4. IMO-Studie zu Treibhausgasen und anderen Quellen. Die historischen und prognostizierten internationalen Preise für fossile Brennstoffe werden aus den JRC-POLES-Prognosen abgeleitet, die in der Folgenabschätzung zum Klimazielplan 2040 verwendet werden. Anschließend ermittelt PRIMES die sektorspezifischen Vorsteuerpreise für flüssige Brennstoffe, Gas, Wasserstoff, synthetische Brennstoffe und Strom.

Der vorliegende Ansatz unterliegt den folgenden Einschränkungen: Die Kohlenstoffpreise werden als politischer Input für die Modellierung des Seeverkehrssektors exogen vorgegeben, und mögliche Rückkopplungseffekte der Emissionsminderung im Seeverkehr auf die EU-ETS-1-Preise und damit auch auf die Kraftstoffpreise werden nicht erfasst (das bedeutet, dass die Kraftstoffpreise nicht auf isolierte Veränderungen der Nachfrage im Seeverkehr reagieren). Verhaltensreaktionen wie Ausweichrouten oder Bunkerungen außerhalb der EU werden nicht dynamisch modelliert. Technologisches Lernen ist extern und Nachrüstungen auf Dual-Fuel-Motoren werden implizit über Kraftstoffgemische dargestellt. Das Nachfragemodul segmentiert nicht vollständig nach Schiffsklassen unter und über 5.000 Bruttoraumzahl (BRZ), was die Umverteilung der Aktivitäten über verschiedene Größen hinweg abschwächen kann. Die jüngsten Entwicklungen der IMO zu einem globalen Kraftstoffintensitätsstandard wurden nicht quantifiziert. Diese Restriktionen deuten darauf hin, dass die Ergebnisse zwar in ihrer Richtung

[7] Es wurden UBA-Preistrajektorien genutzt (Mendelevitch et al. 2024)

robust, aber im Vergleich zu einem global koordinierten System mit stärkeren Preissignalen konservativ sind.

Die Modellierung könnte für zukünftige Analysen verbessert werden, indem die derzeitige Verwendung von Schattenkosten für die Einhaltung der FEUM-Vorschriften durch die in der Verordnung festgelegten tatsächlichen Strafen ersetzt wird. Anstatt GHG-Intensitätsziele als starre Beschränkungen vorzuschreiben, würde die Anwendung dieser Strafen als explizite Preissignale dazu dienen, das Verhalten der Betreiber und die Kostendynamik in der realen Welt genauer widerzuspiegeln. Dieser Ansatz würde auch einen konsistenteren Vergleich mit dem EU-ETS 1ermöglichen bei dem CO_2-Preise gezahlt werden und Einnahmen generiert werden. Es ist offensichtlich, dass Schattenkosten interne Konstrukte sind, die keine tatsächlichen Ausgaben darstellen und keinen Einfluss auf die Wirtschaftlichkeit der Kraftstoffversorgung haben. Daher kann der Schluss gezogen werden, dass die Einbeziehung der tatsächlichen Compliance-Kosten den Realismus und die Robustheit der politischen Folgenabschätzungen verbessern würde.

Szenario-Rahmen

Die Analyse stützt sich auf eine Reihe von sechs Szenarien, die zusammen den analytischen Rahmen bilden. Das Basisszenario integriert das EU-ETS 1 für den Seeverkehr und FEUM mit umfassenderen Fit-for-55-Maßnahmen und einschlägigen IMO-Instrumenten, wie EEDI, EEXI, SEEMP und CII. Drei kontrafaktische Szenarien entfernen wichtige Säulen: In einem Szenario werden sowohl EU-ETS 1 als auch FEUM für den Seeverkehr entfernt, während andere Maßnahmen beibehalten werden. Das zweite Szenario sieht die Beibehaltung des EU-ETS 1 vor, jedoch ohne FEUM. Das dritte Szenario sieht die Beibehaltung von FEUM vor, jedoch ohne EU-ETS 1 für den Seeverkehr. Zwei weitere Szenarien wurden vorgeschlagen, um den Anwendungsbereich des EU-ETS 1 auf Segmente auszuweiten, die derzeit nicht zu seinem Kernbereich gehören. Das erste dieser Szenarien sieht die Einbeziehung von Schiffen unter 5.000 BRZ im internationalen und nationalen Seeverkehr sowie von großen Schiffen, die auf Binnenwasserstraßen verkehren, vor. Die Szenarien „nur EU-ETS 1“ und „EU-ETS-1-Ausweitung“ werden von Varianten des EU-ETS 1 mit hohen und niedrigen Preisen begleitet. Zusammen dienen diese Szenarien dazu, den Beitrag jedes politischen Hebels zu isolieren und die Auswirkungen der Schließung von Deckungslücken aufzuzeigen.

Ergebnisse unter den aktuellen politischen Rahmenbedingungen (Basisszenario)

Unter der kombinierten EU-ETS 1- und FEUM-Architektur wächst die Seeverkehrsaktivität in der EU mit den makroökonomischen Treibern, entkoppelt sich jedoch zunehmend von den Emissionen. Die Frachtaktivität nimmt zu. Es wird geschätzt, dass die Frachtaktivität von etwa 14,9 Billionen Tonnenkilometern im Jahr 2020 auf fast 22,0 Billionen im Jahr 2050 steigen wird. Der internationale Seeverkehr wird in diesem Zeitraum voraussichtlich etwa 98% des Güterverkehrs auf See- und Wasserwegen ausmachen. Der Personenverkehrssektor hat sich nach der Pandemie zunächst stark erholt: Die Passagierkilometer stiegen von etwa 12,6 Milliarden im Jahr 2020 und werden bis 2050 voraussichtlich stetig auf rund 40,1 Milliarden ansteigen. Dieses Wachstum wird voraussichtlich durch einen ausgewogenen Beitrag sowohl des internationalen als auch des nationalen Seeverkehrs getragen werden.

Der gesamte Energiebedarf im Seeverkehr geht mit einem Anstieg der Aktivitäten einher, der von etwa 42 Mtoe im Jahr 2020 auf etwa 50 Mtoe im Jahr 2050 zunehmen soll. Die Energieintensität hat sich in verschiedenen Segmenten verbessert. Der Binnenschiffsverkehr verzeichnet die stärksten relativen Zuwächse, während sich auch der internationale Seeverkehr, der die Aktivitäten dominiert, durch eine Kombination aus effizienteren Neubauten, preisgesteuerten betrieblichen Maßnahmen und der Einhaltung der IMO-Effizienzinstrumente stetig verbessert.

Die bedeutendste Veränderung findet sich in der Zusammensetzung des Kraftstoffmixes. Bis 2025 und 2030 wird die frühzeitige Einführung von LNG und flüssigen Biokraftstoffen zur Einhaltung der ersten FEUM-Intensitätsziele beitragen. Bis zum Jahr 2040 wird der Verbrauch flüssiger fossiler Kraftstoffe voraussichtlich auf etwa zwei Drittel des Energieverbrauchs zurückgehen, da sich die RLCFs diversifizieren. Bis 2050 wird der Verbrauch fossiler Flüssigbrennstoffe voraussichtlich auf etwa 8,1 Mtoe zurückgehen, während der LNG-Verbrauch schätzungsweise etwa 4,2 Mtoe erreichen wird. Umgekehrt wird erwartet, dass die Verwendung von Biokraftstoffen auf etwa 21,2 Mtoe steigen wird und Bio-LNG etwa 2,3 Mtoe ausmachen wird. Die Gesamtmenge an RFNBO-Flüssigkeiten wird auf etwa 4,7 Mtoe geschätzt, wobei Wasserstoff 3,2 Mtoe, Ammoniak 2,6 Mtoe, Methanol 1,9 Mtoe, e-LNG 0,7 Mtoe und Strom etwa 1,2 Mtoe ausmachen. Insgesamt werden RLCFs bis 2050 voraussichtlich etwa 75 % der maritimen Energie ausmachen.

Infolgedessen zeigen die Emissionswerte eine entsprechende Reaktion. Die Modellergebnisse zeigen, dass die WtW-Treibhausgasemissionen von etwa 169 $MtCO_2eq$ im Jahr 2015 (161 $MtCO_2eq$ im Jahr 2020) auf etwa 55 $MtCO_2eq$ im Jahr 2050 sinken werden. Die deutlichste Verringerung ist bei Fahrten innerhalb der EU zu beobachten, was auf eine umfassende regulatorische Abdeckung hindeutet (das heißt 100 % der Emissionen auf Fahrten sowohl im EU-ETS 1 als auch in FEUM). Segmente außerhalb des direkten Geltungsbereichs von EU-ETS 1 und FEUM, insbesondere kleine Schiffe und Binnenwasserstraßen, werden langsamer dekarbonisiert, profitieren aber dennoch von Spillover-Effekten, da sich Kraftstofflieferanten und Hafeninfrastrukturen anpassen, um regulierte Segmente zu bedienen. Auf Intensitätsbasis wird die Emissionsintensität des Seeverkehrs bis 2050 voraussichtlich auf etwa 21 % des Niveaus von 2015 sinken. Die beobachtete Zerlegung zeigt, dass der Hauptgrund für dieses Phänomen die sinkende Treibhausgasintensität des Kraftstoffmixes ist, ergänzt durch anhaltende Verbesserungen der Energieintensität.

Im Rahmen des EU-ETS 1 gilt dies nur für TtW-Emissionen, die voraussichtlich von etwa 76 $MtCO_2eq$ im Jahr 2015 auf fast 12 $MtCO_2eq$ bis 2050 sinken werden. Bei der Basispreisentwicklung des EU-ETS 1 löst der Kohlenstoffpreis allein keine Kraftstoffumstellung aus, die über das zur Erreichung der FEUM-Ziele erforderliche Maß hinausgeht. Stattdessen bleibt FEUM für den Mix verbindlich, während das EU-ETS 1 Effizienzmaßnahmen verstärkt und Auktionserlöse generiert, die zur Senkung der Compliance-Kosten und zur Beschleunigung der Einführung sauberer Kraftstoffe wiederverwendet werden können. Die Rückführung der Auktionserlöse direkt in die Dekarbonisierung des Seeverkehrs (zum Beispiel Infrastruktur, Förderung sauberer Kraftstoffe, innovative Technologien, Flottenerneuerung) ist nicht im Rahmen vorgeschrieben und wird in der vorliegenden Analyse nicht explizit modelliert. Die Modellierung geht von umfassenderen Vorteilen auf Systemebene aus (zum Beispiel niedrigere RLCF-Preise aufgrund des erhöhten Angebots), simuliert jedoch keine gezielten Reinvestitionen in den Seeverkehrssektor.

Kontrafaktische Analyse

Die Verwendung von kontrafaktischen Szenarien hilft, die Rolle der einzelnen Instrumente zu verdeutlichen. Wenn sowohl das EU-ETS 1 als auch die FEUM abgeschafft werden, während andere für den Seeverkehr relevante Maßnahmen in Kraft bleiben, wird der Sektor bis 2050 weiterhin überwiegend von fossilen Brennstoffen abhängig sein. Die Marktdurchdringung von RLCF ist marginal, der Energiebedarf ist aufgrund geringerer Compliance-Kosten etwas höher, und die WtW-Emissionen erreichen im Jahr 2050 etwa 174 $MtCO_2eq$, was mehr als dem Dreifachen des Basiswerts entspricht.

Es hat sich gezeigt, dass das EU-ETS 1 für sich genommen die relativen Kosten fossiler Brennstoffe erhöht und die Nutzung von RLCFs erheblich fördert. Bis zum Jahr 2050 nähert sich der RLCF-Anteil der Hälfte der maritimen Energie, und die Emissionen sinken im Vergleich zum No-Policy-Szenario erheblich. Ohne die verbindliche FEUM -Zielvorgabe bleibt der Mix hinter den für eine tiefgreifende Dekarbonisierung erforderlichen Werten zurück, sodass die Emissionen im Jahr 2050 deutlich über dem Basiswert liegen. Dieses Ergebnis zeigt, dass das Preissignal des EU-ETS 1 in der vorliegenden Analyse exogen angewendet wird. Es ist niedriger als der, der in den Rahmenbedingungen berücksichtigt wurde, wo die Kraftstoffaufnahmekurven auf den breiteren Dekarbonisierungsrahmen mit höheren Kohlenstoffpreissignalen kalibriert wurden. Preissensitivitätsvarianten zeigen, dass bei höheren EU-ETS-1-Preissignalen eine höhere Emissionsminderung prognostiziert wird. Somit hängt das Ausmaß der Emissionsminderung von der Kombination zweier Faktoren ab: dem Niveau des exogenen Preissignals und der anfänglichen Kalibrierung der Kraftstoffaufnahmekurven, die in diesem Fall auf den umfassenderen Dekarbonisierungskontext des EU-Green Deal abgestimmt sind.

Darüber hinaus wird die Rückführung der EU-ETS-1-Auktionserlöse in den Seeverkehrssektor, obwohl dies gemäß der Verordnung zulässig ist, nicht explizit modelliert. Während das Energiesystem insgesamt von niedrigeren RLCF-Preisen profitiert, könnte eine gezielte Reinvestition in den Seeverkehrssektor zusätzliche Vorteile für diesen Sektor mit sich bringen. In ähnlicher Weise wird die Einhaltung der FEUM-Vorschriften durch interne Schattenkosten und nicht durch explizite Strafen dargestellt, was die Realitätsnähe der Kostendynamik und der Reaktionen der Betreiber einschränkt. Die Berücksichtigung dieser Einschränkungen in künftigen Modellierungsbemühungen würde die Robustheit der politischen Folgenabschätzungen verbessern und den relativen Beitrag von EU-ETS 1 und FEUM zur Dekarbonisierung des Seeverkehrs genauer erfassen.

Das betreffende Modell beinhaltet ein System interner Strafen, die bei Nichteinhaltung der Vorschriften verhängt werden. Diese Strafen sollen den Aufwand widerspiegeln, der zur Erreichung der WtW-Intensitätsziele erforderlich ist. Der resultierende Kraftstoffmix und die Emissionen für 2050 sind mit dem Basisszenario vergleichbar, aber das Fehlen einer expliziten CO_2-Bepreisung bedeutet weniger Effizienzanreize und keine EU-ETS 1-Einnahmen. Es ist offensichtlich, dass der EU-ETS 1 im Basisszenario im Laufe der Zeit zu zusätzlichen Effizienzsteigerungen und niedrigeren kumulativen Kosten führt als ein reiner Mandatsansatz wie bei der FEUM.

Die CO_2-Bepreisung im Rahmen des EU-ETS 1 verstärkt die Energieeffizienzverbesserungen im Seeverkehrssektor. Dies wird erreicht, indem Schiffsbetreiber, insbesondere Betreiber großer Schiffe, Anreize erhalten, technische und betriebliche Maßnahmen zur Senkung des Kraftstoffverbrauchs zu ergreifen. Diese Effizienzgewinne sind zwar auf Jahresbasis gering (zum Beispiel bis zu 1,3 % Verbesserung der nationalen Energieintensität im Seeverkehr bis 2045), summieren sich jedoch im Laufe der Zeit und tragen zu geringeren Emissionen und Compliance-Kosten bei. Darüber hinaus verbessert der EU-ETS 1 die Kosteneffizienz, indem er die Preisdifferenz zwischen fossilen und erneuerbaren Kraftstoffen verringert, was zu einer 3,6-fachen Steigerung der RLCF-Nutzung bis 2030 in reinen ETS-Szenarien und einem RLCF-Anteil von fast 50 % bis 2050 führt. Umgekehrt fungiert FEUM als verbindlicher Treiber für die Änderungen des Kraftstoffmixes und schreibt eine Verringerung der WtW-Treibhausgasintensität vor (zum Beispiel 80 % bis 2050), die das Modell durch strafbasierte Compliance-Mechanismen durchsetzt. Diese Vorgaben führen im Basisszenario zu einem RLCF-Anteil von 75 % und einer Emissionsreduktion von fast 70 % bis 2050. Der EU-ETS 1 liefert ein marktbasiertes Signal, fördert die Effizienz und generiert Auktionserlöse (bis zu 9 Milliarden Euro jährlich in den Jahren 2030–2040), welche die Dekarbonisierung des Seeverkehrssektors unterstützen können, während FEUM für Rechtssicherheit und die technologische Einführung von RLCF sorgt.

Ausweitung des EU-ETS 1 auf nicht erfasste Segmente

Mit der Dekarbonisierung regulierter Segmente gewinnt das Thema Deckungslücken zunehmend an Bedeutung. Im Basisszenario wird davon ausgegangen, dass kleine Schiffe, die derzeit weder dem EU-ETS 1 noch FEUM unterliegen, bis 2050 etwa ein Drittel der verbleibenden Emissionen im Seeverkehr ausmachen werden, was etwa 18 MtCO_2eq von insgesamt 55 MtCO_2eq entspricht. Die Ausweitung des EU-ETS 1 auf dieses Segment führt zu einem deutlichen Effekt: Prognosen zufolge werden die Emissionen bis zum Jahr 2050 um etwa 32 % auf etwa 12 MtCO_2eq sinken. Dieser Effekt wird jedoch dadurch verstärkt, dass in der Modellierung aufgrund der Datenverfügbarkeit der Bereich der kleinen Schiffe alle Schiffe unter 5 000 BRZ umfasst, das heißt auch solche unter 400 BRZ. Der beobachtete Effekt ist auf die vermehrte Nutzung von Biokraftstoffen und RFNBOs zurückzuführen, die durch moderate Effizienzsteigerungen ergänzt wird. Die Gesamtwirkung auf die Aktivitäten und den Energieverbrauch auf Systemebene ist gering.

Binnenwasserstraßen weisen eine ähnliche Dynamik auf, wenn auch in geringerem Umfang. Ohne den EU-ETS 1 wird der RLCF-Anteil des Segments bis 2050 voraussichtlich 50 % übersteigen, was eine Folge der umfassenderen Dekarbonisierung des Systems ist. Die Einbeziehung großer Binnenschiffe in den Geltungsbereich des EU-ETS 1 stärkt die Anreize für die Entwicklung sauberer Kraftstoffe und höherer Effizienz. Die Analyse zeigt, dass dies zu einem Anstieg des RLCF-Anteils auf über 80 % und zu einer Verringerung der Emissionen um 50 % im Jahr 2050 von etwa 2,0 MtCO_2eq auf etwa 1,0 MtCO_2eq führen wird. Diese Erweiterungen generieren auch zusätzliche EU-ETS-1-Einnahmen, die für die Erneuerung der Infrastruktur und der Flotte in Segmenten verwendet werden können, die traditionell mit strengeren Finanzierungsbeschränkungen konfrontiert sind.

Kosten und EU-ETS 1-Preissensitivitäten

Die Systemkosten[8] für den internationalen Seeverkehr liegen in verschiedenen Szenarien zwischen etwa 78 und 87 Mrd. EUR im Jahr 2030, 83 und 105 Mrd. EUR im Jahr 2040 und 112 und 143 Mrd. EUR im Jahr 2050. Es wird geschätzt, dass die Kraftstoffkosten, einschließlich der gegebenenfalls anfallenden EU-ETS-1-Zahlungen, zwischen 46 % und 58 % der gesamten Kosten des Seeverkehrssystems ausmachen. Wie zu erwarten, weisen Szenarien mit minimalem Einsatz von RLCF zwar geringere Kosten in absoluten Zahlen auf, erfüllen jedoch nicht die Emissionsminderungsziele. Das Basisszenario und der reine FEUM-Pfad sind mit höheren Kraftstoff- und Kapitalausgaben verbunden, da saubere Kraftstoffe an Bedeutung gewinnen. Durch den Ersatz interner Schattenstrafen durch explizite Preissignale und die Generierung von Einnahmen, die reinvestiert werden können, verbessert das EU-ETS 1 jedoch im Laufe der Zeit die wirtschaftliche Effizienz im Vergleich zu einer reinen Mandatskonfiguration.

Die Sensitivität gegenüber dem Kohlenstoffpreis zeigt, dass höhere EU-ETS-1-Preise die Einführung von RLCF beschleunigen und die ETS-Emissionsmengen im Fall „nur EU-ETS 1" reduzieren. Im Basisszenario bleibt FEUM jedoch der einflussreichste Faktor für den Kraftstoffmix innerhalb der betrachteten Preisspannen, und die primären Auswirkungen höherer oder niedrigerer EU-ETS-1-Preise werden eher über die Kosten als über zusätzliche Kraftstoffumstellungen weitergegeben. Dies unterstreicht die Komplementarität der beiden Instrumente: FEUM ist für den Verlauf der Einführung sauberer Kraftstoffe verantwortlich,

[8] Einschließlich Kraftstoffkosten, EU-Emissionshandelskosten, Betriebskosten, Investitionskosten und nicht-variabler Kraftstoffkosten.

während der EU-ETS 1 die Effizienz steigert, Preisunterschiede verringert und Einnahmen generiert, die potenziell für die Unterstützung der Dekarbonisierung im Seeverkehrssektor verfügbar sind und eine sektorübergreifende kosteneffiziente Emissionsminderung garantiert.

Einschränkungen und Interpretation

Die Modellierungsentscheidungen und Datenbeschränkungen erfordern einige Vorbehalte. Die Kohlenstoffpreise werden als exogen für den Seeverkehr betrachtet und haben keinen Einfluss auf die Kraftstoffpreise; ein vollständig integriertes PRIMES-System könnte solche Wechselwirkungen jedoch potenziell erfassen. Die Modelle stellen Verhaltensänderungen wie Umleitungen oder Bunkerwechsel außerhalb des EU-ETS-1-Perimeters nicht dynamisch dar, was zu einer Unterschätzung der Verdrängungsrisiken führen kann. Technologiekosteneffekte werden extern berücksichtigt, und das kurzfristige Potenzial für die Umrüstung auf Dual-Fuel-Motoren könnte konservativ eingeschätzt sein. Die Nachfragesegmentierung nach Schiffsklassen ist unvollständig, was sich dämpfend auf die größenbasierte Umverteilung der Aktivitäten auswirken könnte. Schließlich werden die jüngsten Entwicklungen bei der IMO, darunter die Verabschiedung (im Entwurf) eines verbindlichen globalen Kraftstoffintensitätsstandards als Teil des Net Zero Frameworks (NZF) – der noch nicht verabschiedet wurde, nicht quantifiziert; ihre Einbeziehung würde die Ergebnisse wahrscheinlich verstärken, indem sie die Entwicklung in der EU und weltweit angleichen und Anreize für Verlagerungseffekte verringern würde.

Der Modellierungsrahmen könnte weiter verbessert werden, indem die Schattenkosten, die zur Simulation der Einhaltung der FEUM-Vorschriften verwendet werden, an die in der Verordnung festgelegten tatsächlichen Strafen angepasst werden. Anstatt die Treibhausgasintensitätsziele als harte Vorgaben vorzugeben, könnte das Modell diese Strafen als explizite Preissignale anwenden und so eine realistischere Darstellung des Verhaltens der Betreiber und der Kostendynamik ermöglichen. Dies würde auch einen robusteren Vergleich mit dem EU-ETS 1 ermöglichen bei dem CO_2-Preise gezahlt und Einnahmen generiert werden. Im Gegensatz zu den Zahlungen im Rahmen des EU-ETS 1 sind Schattenkosten interne Modellkonstrukte, die keine realen Ausgaben widerspiegeln und keinen Einfluss auf die Wirtschaftlichkeit der Kraftstoffversorgung haben. Die Szenarioergebnisse zeigen, dass die FEUM allein eine erhebliche Dekarbonisierung bewirken kann. Ohne das EU-ETS 1 hängen diese Ergebnisse jedoch vollständig von regulatorischen Vorgaben, welche ihren vollen Effekt erst langfristig erzielen, und impliziten Strafen ab, die möglicherweise nicht so wirtschaftlich effizient oder flexibel sind wie marktbasierte Instrumente. Die Einbeziehung authentischer Compliance-Kosten in den Modellierungsprozess würde dazu beitragen, die Robustheit der politischen Folgenabschätzungen zu verbessern und eine fundiertere Entscheidungsfindung zu ermöglichen.

Strategische Implikationen und Roadmap für die Umsetzung

Die Erkenntnisse dieses Berichts sprechen klar dafür, die duale Politikarchitektur beizubehalten, um eine wirksame Emissionsminderung und Kosteneffizienz zu erreichen. In der zweiten Hälfte des Zeitraums 2020-2030 sollte der Schwerpunkt auf der Umsetzung der EU-ETS-Konformität für den Seeverkehr und der Erfüllung der FEUM-Verpflichtungen liegen. Ergänzt werden sollte dies durch den rechtzeitigen Einsatz von Landstromversorgung, wo dies vorgeschrieben ist, und die frühzeitige Kontrahierung von Mengen an RFNBOs neben nachhaltigen Biokraftstoffen, um die kurzfristigen Ziele zu erreichen. Von 2030 bis 2040 wird sich der Schwerpunkt schrittweise auf die Ausweitung der RFNBO-Produktion und den Ausbau der Hafenbunkerinfrastruktur verlagern. Gleichzeitig wird es Fortschritte bei der Weiterentwicklung der Technologien und Standards für den Einsatz von Ammoniak und Methanol in Schiffen geben. Darüber hinaus wird der Umrüstungsprozess in Fällen, in denen dies als kosteneffizient erachtet wird, beschleunigt.

In dieser Phase erscheint es sinnvoll, den EU-ETS 1 für kleine Schiffe mit angemessenen Verwaltungsanforderungen umzusetzen und die Ausweitung auf die Binnenschifffahrt auf der Grundlage der hier vorgestellten Modellierungsergebnisse zu evaluieren. Mindestens bis zum Jahr 2040, wenn die FEUM-Ziele bis 2045 auf 62 % und bis 2050 auf 80 % verschärft werden, sollte die Politik dafür sorgen, dass ein aussagekräftiges CO_2-Preissignal bestehen bleibt, fehlende Infrastrukturverbindungen vervollständigt werden und Pläne zur Beseitigung verbleibender Emissionen durch Negativemissionsoptionen an anderer Stelle im Energiesystem erstellt werden. Die Verwendung der Einnahmen aus dem EU-ETS 1 ist von entscheidender Bedeutung. Die Nutzung eines Teils der Einnahmen aus dem EU-ETS 1 für Initiativen zur Dekarbonisierung des Seeverkehrs, darunter Hafeninfrastruktur für alternative Kraftstoffe und Landstrom, Unter-stützung für Early-Adopter-Schiffe und Nachrüstungen sowie die Minderung von Risiken in den Lieferketten und Abnahmen von RFNBO, hat das Potenzial, die Compliance-Kosten zu senken und die Skalierung zu beschleunigen. Gleichzeitig gewährleistet die Einhaltung der Nachhaltigkeitskriterien der RED III die Umweltverträglichkeit von Biokraftstoffen, deren Bedeutung in den 2020er und 2030er Jahren zunehmen wird. Schließlich trägt eine enge Zusammenarbeit mit der IMO dazu bei, Verlagerungsrisiken zu minimieren, Investitionssicherheit zu schaffen und globale Skaleneffekte zu nutzen. Dies könnte zu einer schnelleren und kostengünstigeren Dekarbonisierung führen, als in den Annahmen des Basisszenarios vorgesehen.

1 Introduction

Maritime transport accounts for approximately 4 % of total CO_2 emissions in the European Union (EU), a share that has grown by roughly 15 % since 2015 despite gradual improvements in vessel energy efficiency and carbon intensity (EEA-EMSA, 2025). This trend reflects the continued growth in maritime activity, only briefly interrupted by the COVID-19 pandemic. Considering the persistent emissions increase and as part of its long-term climate strategy, the EU has integrated maritime transport into its broader decarbonisation framework under the European Green Deal (EC, 2019) and the EU Climate Law (Regulation (EU) 2021/1119). These initiatives mandate a 55 % net reduction in Greenhouse Gas (GHG) emissions by 2030 (relative to 1990 levels) and climate neutrality by 2050 (EC, 2019). Building on this trajectory, the European Commission (EC) proposed in its Climate Target Plan (CTP) for 2040 a new economy-wide target of a 90 % net reduction in GHG emissions by 2040 compared to 1990, further reinforcing the need for deep and sustained decarbonisation across all sectors, including maritime transport (EC, 2024c).

To steer the maritime transport sector in support of these objectives, the EU's "Fit-for-55" legislative package introduced key regulatory instruments targeting maritime emissions (EC, 2021a). Among the most prominent measures are the inclusion of the sector in the EU Emissions Trading System (EU ETS 1) (Directive 2023/959) and the adoption of the FuelEU Maritime Regulation (FEUM) (Regulation (EU) 2023/1805). The EU ETS 1 applies market-based carbon pricing to emissions from voyages within the European Economic Area (EEA), to emissions at berth, as well as to 50 % of emissions from incoming and outgoing international voyages. The objective of the EU ETS 1 in maritime is to provide a market-based signal that incentivizes improvements in energy efficiency, supports the uptake of low-carbon solutions, and contributes to narrowing the price gap between conventional and Renewable and Low-Carbon maritime Fuels (RLCF). By integrating maritime into the broader EU ETS 1 framework, it induces interactions with GHG mitigation efforts in other covered sectors, namely aviation, power generation, and industry, aligning them under a common carbon price signal thus enabling cross-sectoral cost-effective abatement. Complementing this, the FEUM Maritime Regulation establishes binding targets for the well-to-wake (WtW) GHG intensity of energy used onboard ships, starting with a 2 % reduction in 2025 and rising to 80 % by 2050, relative to a 2020 baseline level. This regulation supports the uptake of RLCFs, advanced biofuels, and e-fuels (or Renewable Fuels of Non-Biological Origin; RFNBOs), and electricity, thereby promoting the fuel transition necessary for sectoral decarbonisation.

Hence, the EU ETS 1 and FEUM form together a complementary policy architecture for the maritime transport sector: the EU ETS 1 addresses cost internalization and cross-sectoral carbon pricing, while FEUM incentivizes deployment of renewable fuels in maritime transport. Moreover, EU ETS 1 is likely to be the main incentive to reduce short-term emissions while FEUM steers the decarbonisation effects in the longer term. As shown in Wissner et al. (2024), the transition to climate neutrality of the maritime transport sector will be intensified through the EU ETS 1 together with other instruments, particularly the FuelEU Maritime Regulation. The latter was in a qualitative assessment deemed to represent a complementary and stronger incentive for the sector. Based on this initial idea of these policy measures being complementary, we assess the following two questions in this report:

- To what extent do the EU ETS 1 extension to maritime transport and the FuelEU Maritime Regulation contribute to the decarbonisation of the European maritime transport sector, and

- how do they interact in shaping the decarbonisation trajectory across covered and non-covered segments, as assessed through scenario-based modelling?

To answer these questions, scenario-based modelling is used to explore what the interaction between the two policies could achieve regarding beneficial effects and emissions reductions than what either policy would achieve in isolation. The analysis also considers a wide range of additional EU-level policies and regulatory measures that shape the maritime transport sector's decarbonisation path. These include:

- the Renewable Energy Directive (RED III) (Directive (EU) 2023/2413), which sets binding targets for the share of renewable energy in transport or a binding target to reduce GHG intensity target of transport fuels by 2030 in transport, including maritime transport, and promotes the production and use of renewable fuels (advanced biofuels, other biofuels, RFNBOs, renewable electricity);
- the Alternative Fuels Infrastructure Regulation (AFIR) (Regulation (EU) 2023/1804), which mandates the deployment of shore-side electricity and alternative fuel refuelling infrastructure at ports (for example Onshore Power Supply – OPS; Liquified Natural Gas bunkering – LNG; monitoring demand and supply of RFNBOs); and
- the proposed revision of the Energy Taxation Directive (ETD) (EC, 2021b), which seeks to align tax rates with environmental performance of fuels by introducing taxation based on carbon content and energy value, thereby also incentivizing the uptake of RLCFs in maritime transport.

In addition to these EU measures, the regulatory framework also includes a set of technical policy measures adopted under the International Maritime Organization (IMO). These consist of:

- the Energy Efficiency Design Index (EEDI), which imposes mandatory design efficiency standards for new vessels (IMO, 2014);
- the Energy Efficiency Existing Ship Index (EEXI), which sets retrofit-based efficiency standards for existing ships (IMO, 2021);
- the Ship Energy Efficiency Management Plan (SEEMP), which requires all ships to implement energy efficiency planning and monitoring (IMO, 2022); and
- the Carbon Intensity Indicator (CII), which mandates operational carbon intensity reductions for ships above 5,000 gross tonnage (GT) (IMO, 2021).

These IMO measures play a critical role in influencing fleet renewal strategies, retrofit investments, and ship operations. Although the primary focus of this report is on EU-level policy measures, recent international developments are also relevant to the context. In April 2025, the IMO Member States agreed on a draft text for the Net-Zero Framework (NZF) which includes a binding Global Fuel Intensity (GFI) standard requiring ships to progressively reduce the GHG intensity of their energy use (IMO, 2025). It is unclear at the time of writing when the NZF may be adopted and come into force. While this global regulation is not directly assessed in the present study, it reinforces the trajectory set by EU policy and adds global significance to the analysis.

The scenario-based analysis is conducted using the PRIMES Maritime model (E3Modelling, 2018), a detailed techno-economic model of the EU maritime transport sector that captures the compliance behaviour of ship operators across vessel segments and types under varying policy, fuel, and price conditions. PRIMES Maritime accounts for the high granularity and segmentation of the maritime sector, including vessel size, age, operational profile (that is, different energy efficiency curves and speed profiles for the various vessel types and sizes), and route characteristics. The model is fully integrated with the broader PRIMES energy system model, which simulates the transition of the EU energy system toward decarbonisation, enabling the integrated assessment of cross-sectoral interactions under the EU ETS 1.

The context in which the scenario-based analysis is conducted is aligned with the EU's long-term climate policy objectives, including the 2050 climate neutrality goal. The scenarios are set-up so as to quantify the impacts of the EU ETS 1 and FuelEU Maritime Regulation, to explore the potential inclusion of currently exempted vessel segments such as small ships and inland waterway transport, and to evaluate their sensitivity to carbon price developments.

The remainder of the report is structured as follows. Chapter 2 presents the PRIMES and the PRIMES Maritime modelling framework, describing its maritime-specific features, policy implementation logic, and key limitations. Chapter 3 details the modelling inputs, and assumptions including fuel and carbon price trajectories, technology costs, and the full range of scenarios analysed. Chapter 0 presents the modelling results, covering GHG emissions, energy use, technology uptake, abatement costs, and the outcomes of sensitivity analyses. Finally, Chapter 5 concludes the report by interpreting the results, in light of the research question, discussing implications, and outlining limitations.

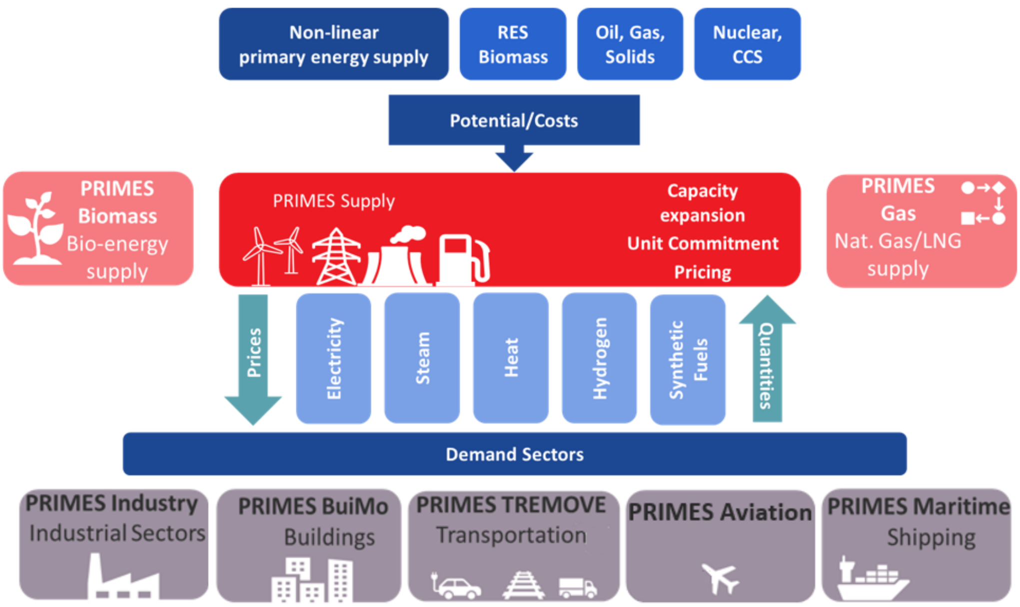
2 Methodological approach

2.1 PRIMES modelling framework

To quantify the scenario impacts, the study applies the PRIMES modelling suite – a detailed energy systems model widely used in EU policy assessments. PRIMES (Price-Induced Market Equilibrium System) projects the development of the energy system of EU Member States (MS) individually and dynamically over time, producing projections from 2020 to 2070 in five-year steps (PRIMES, 2023a). It covers energy balances, CO_2 and other GHG emissions, technology deployment, energy prices, system costs, and investments across all sectors, both supply and demand. The model captures the behaviours of transport segments, including vessel operators, households, industries, and utilities, which respond to energy prices, technology availability, and policy signals. It includes market imperfections and behavioural aspects, making it suitable for analysis of policy design and evaluation.

PRIMES comprises sectorial sub-models, that represent the corresponding sector specificities. The supply-side modelling is integral to PRIMES. It simulates fuel production pathways, including, for example, liquid fossil fuels (for example diesel, gasoline, fuel oil), hydrogen, synthetic methane, ammonia, and biofuels, as well as CO_2 capture, reuse, and storage. The model accounts for bioenergy supply potentials, energy imports, and infrastructure constraints, ensuring realistic projections of alternative fuel availability and costs. It links demand with endogenous fuel supply and allocates energy resources across sectors based on market competition and technical feasibility. Fuel prices across all segments and therefore maritime fuels, for example LNG, low sulphur fuel oil (LSFO), biofuels or e-fuels (liquid including, for example, methanol and gaseous), hydrogen, are endogenously determined, reflecting production costs, taxes (for example under EU ETD), and carbon pricing (for example under EU ETS 1). The model also considers regulatory instruments like blending mandates and FuelEU Maritime obligations. Figure 1 presents schematically the PRIMES energy system model and its modular structure.

Figure 1: Schematic representation of the PRIMES modelling suite



Source: PRIMES

The demand-side modelling of PRIMES covers all transport sectors such as road, rail, national and international aviation and maritime transport considering available fuels and technologies. The model includes infrastructure refuelling and recharging development – for example for alternative fuels or for electric vehicles. It also covers non-transport sectors such as residential and commercial buildings and industry.

Within PRIMES, maritime transport is modelled through two complementary modules: PRIMES Maritime and PRIMES-TREMOVE (E3Modelling, 2018). PRIMES Maritime projects international maritime transport activity, and related energy and emissions based on trade and transport demand, while PRIMES-TREMOVE captures national maritime transport and inland waterways in high detail. These models among others project future developments on transport activity, fuel consumption, upstream and downstream GHG emissions (for example CO_2, CH_4, and N_2O emissions), and investment costs in newbuilt vessels. They reflect the evolving structure of the EU fleet by ship type, size, and fuel technology.

The combination of these two models (PRIMES Maritime and PRIMES-TREMOVE) allows capturing explicitly the whole of the EU maritime transport activity (intra-EU, extra-EU, domestic maritime transport and inland waterways transport), and projecting the impacts of policy options across the whole fleet.

2.2 PRIMES Maritime

The aim of the PRIMES Maritime model is to perform long-term energy and emission projections for the international maritime transport sector of the EU, until 2070, for each EU MS separately. The coverage of the model includes the European intra-EU maritime sector as well as the extra-EU maritime trade coming in and out of each EU MS; trade between non-EU countries is not modelled.

The model consists of a modular structure:

- the demand module projects maritime activity for each EU MS by type of cargo and by corresponding partner. Econometrical functions relate future demand for maritime transport services with economic drivers including Gross Domestic Product (GDP), energy demand (oil, coal, LNG), international fuel prices, and bilateral trade by type of product;
- the supply module simulates a virtual operator controlling the EU fleet, which performs the requested maritime transport services and allocates the vessels to activity in various markets (the EU MS and the extra-EU area that trades with the EU) where different regulatory regimes may apply, such as Emission Control Area (ECA) zones).

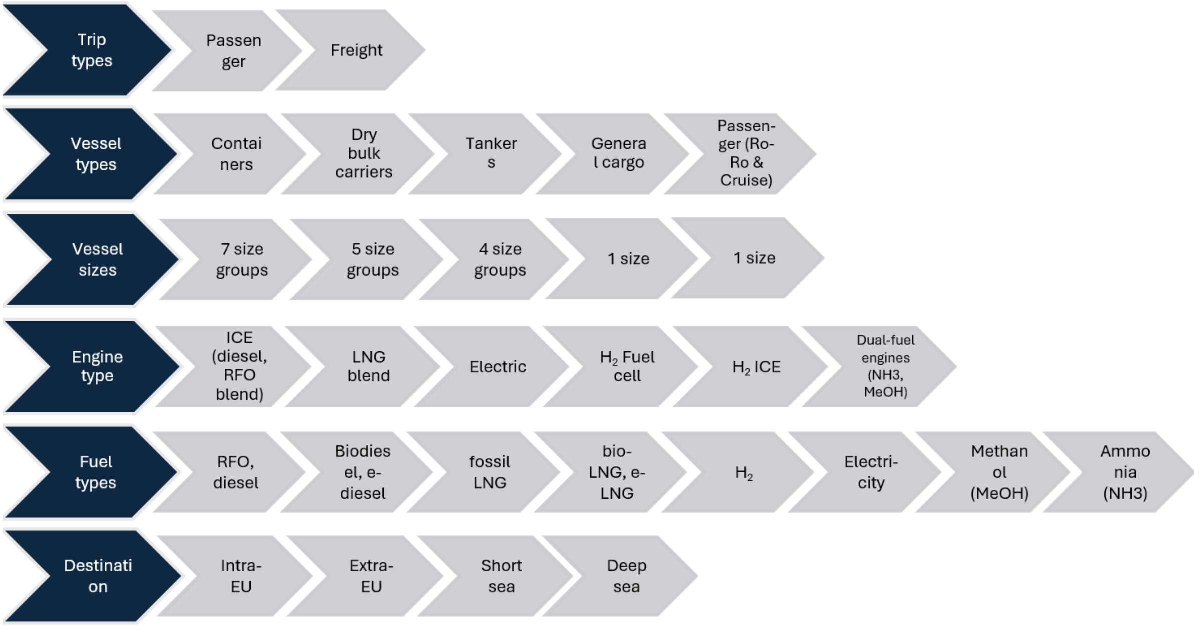
The policy input includes emissions regulations (CO_2 and air pollution, specifically reflecting the ECA zones), and carbon intensity and energy efficiency standards (that is, CII, EEDI, EEXI, SEEMP) and fuel mandates (that is, FEUM). The fleet of vessels disaggregates into several categories depending on cargo types.

Figure 2 presents in more detail the segmentation of the PRIMES Maritime model. The detailed modelling scope and segmentation is presented in Table 7, Source: PRIMES Maritime

Table 8 and Source: PRIMES-TREMOVE

Table 9 in the "Annex – Detailed segment representation in the modelling".

Figure 2: Segmentation of PRIMES Maritime



Source: PRIMES Maritime

Notes: [a] Short sea shipping is the maritime transport of goods over relatively short distances. In the context of EU, it is defined between EU ports and ports in geographical Europe, on the Mediterranean (for example Algeria, Egypt), Black Seas (for example Georgia, Ukraine), EEA countries (for example Iceland, Norway), and candidate countries (for example Montenegro, Türkiye). It also includes feeder services: a short-sea network between ports with the objective of consolidating or redistributing freight to or from a deep sea service in one of these ports.

[b] Deep sea shipping refers to the maritime transport of goods on intercontinental routes, crossing oceans.

2.2.1 Modelling mechanisms and decision making

The model is dynamically solving for the balance between supply and demand, considering vessel vintages and fleet renewal requirements with a stock-flow relationship. Capital turnover is explicit in the model influencing the pace of fuel substitution.

The decision problem in PRIMES Maritime considers simultaneously the engine fuel-technology selection for new vessels or retrofitting of existing vessels decision, the fleet assignment among the origin-destination pairs, and the fuel choice.

The engine-fuel technology selection provides the distribution of new technologies based on capital and fuel costs, taking into account also energy efficiency improvement possibilities. Specifically, technical efficiency improvements are included based on a calibrated discrete choice model that provides the distribution of technologies separately for each fuel-technology engine based on cost-efficiency improvement curves. With regards to operational efficiency improvements, fleet operators optimally choose the vessels speed based on speed-fuel consumption curves. Further operational energy efficiency improvements, such as just-in-time arrivals, ship conditioning and biofouling management have been introduced as hidden costs in the model's cost functions. Apart from the GHG and fuel cost savings due to speed reduction choice, the mechanism also considers the increase in operational costs due to the increased trip duration, for instance, owing to higher on-board labour costs, and a client penalty.

On existing vessels, the impact of enhancing technical interventions that improve their energy efficiency is also included. Based on literature, specific technical measures were identified potentially to improved energy efficiency of the existing and future maritime fleet. Such measures were translated to vessel type and size specific cost-efficiency improvement curves used by PRIMES Maritime in relation to the technical efficiency of the existing fleet (see also Section 2.2.4 and Section 3.1). For fleet assignment among the origin and destination pairs, the available vessels are optimally assigned by minimizing total operational and fuel costs to the origin-destination pairs so that total demand is satisfied, considering various constraints such as related infrastructure availability (and scenario-dependent developments over time), ECAs and maximum vessel mileage.

The fuel choice module estimates the blend based on an explicit fuel cost (including carbon pricing based on EU ETS 1). The choice of fuel mix for new vessels is based on techno-economic assumptions applying discrete choice modelling. Specifically, the PRIMES Maritime projects fuel choice based on:

- the choice of fuel technology for newbuilt ships made over time, either to replace ships that are scrapped after the end of their assumed lifetime, or to cover new demand. In this mechanism, whenever new ships are anticipated in the fleet, the model simulates ship-owners' ship purchasing decisions to invest on certain fuel technologies optimizing their decision considering projected variable (including fuel) expenditures, operational expenditures and capital expenditures of the new ships at a 5-year timeframe. In making these decisions, the model includes a set of techno-economic data considering the projected development over time of the capital costs and energy performance for the ships of different technologies, with less mature technologies, generally projected to show a steeper cost reduction over time. These ship purchase decisions account for taxes, subsidies and regulatory requirements when considering these choices. With this mechanism, the fleet is gradually replenished.
- the choice of fuel blend used to optimize operational fuel cost within the technological constraints of the fleet operating each year and considering the regulatory requirements imposed by regulation. This fuel blend can vary depending on different regulations applying to different ship sizes or types of trips, for example, different EU ETS 1 provisions for intra-EU and extra-EU trips.

The model projects bunker fuel consumption across fuel types and derived Well-to-Tank (WtT) and Tank-to-Wake (TtW) GHG emissions, including methane slippage emissions from combustion. Energy consumption is based on specific fuel consumption functions, which use cost-efficiency curves to summarize efficiency possibilities. Operating (for example speed) or other conditions (for example age) affect the specific energy consumption of the vessels.

2.2.2 Key EU policy representation

EU ETS 1 extension to maritime transport

To model overarching and cross-sectoral policies such as the EU ETS 1, PRIMES employs an iterative process to determine EU ETS 1 carbon prices over time, which are then used as a carbon price variable across the different supply and demand sub-modules. The process begins with an initial approximation of the trajectory for EU ETS 1 carbon prices. Following this initial assumption, the PRIMES model runs its various sub-models and loops to find market equilibrium across the entire projection horizon. During this process, the demand and supply sub-models, which apply inter-temporal foresight (shorter for demand, longer for supply reflecting how real-world decisions are taken), are influenced by the anticipated EU ETS 1 carbon prices, affecting agents' decisions. After a full model iteration for the projection horizon, the resulting emissions are compared against the set targets. Based on the deviation from these targets, the EU ETS 1 prices are readjusted, depending on the surplus of allowances compared to their expected flow. A high surplus implies that allowance holders tend to sell, as they anticipate a long wait (Hoteling rule). Conversely, agents who use allowances to justify emissions become risk-averse in situations of high surpluses, perceiving high regulatory uncertainty when the market is destabilized. This leads to reluctance in banking allowances during periods of low prices when high surpluses persist. This process ensures consistency with the Market Stability Reserve (MSR), while being consistent with the overall climate ambition effort of the EU. Such ambition is, for example, stipulated by the CTP based on which the scenarios of the present study are built on. The resulting carbon price is the one used across sectors.

Importantly, in the modelling of the scenarios in this study using PRIMES Maritime, the EU ETS 1 price trajectory provided by UBA is applied, rather than the one endogenously derived by PRIMES through its standard market-based process as described above. The EU ETS 1 price trajectory is thus treated as an exogenous policy input variable varying from the mechanism described above. As an exogenous variable, it signals an increase in maritime transport costs due to the inclusion of fossil fuel emissions under the EU ETS 1, thereby making RLCFs, technologies, and efficiency options more economically attractive, without feeding back the demand changes to PRIMES. A sensitivity analysis is also conducted to assess the influence of this exogenous price path on the model results.

Regarding the scope of the policy and its implementation in PRIMES Maritime, the EU ETS 1 is extended to cover also GHG emissions from maritime transport (excluding ships below 5,000 gross tonnage (GT), inland waterway vessels, and some other special ship categories[9]). This includes CO_2 emissions from 2024 onwards while, CH_4 and N_2O emissions are covered from 2026. The system covers:

- all emissions generated while ships are at berth within an EU/EEA port[10];
- all emissions from domestic voyages, that is, voyages taking place entirely within a single MS;
- all emissions from intra-EU/EEA[10] voyages (as defined in the MRV scope[11]), that is, voyages between ports in different EU/EEA countries;
- 50 % of emissions from extra-EU/EEA[10] voyages (as defined in the MRV scope[11]), that is, voyages between EU/EEA ports and ports outside the EU/EEA.

FuelEU Maritime Regulation

In the model, fuel choice is governed by the minimization of total costs, including penalties and policy-induced incentives, thereby allowing regulatory measures to steer decisions toward lower-emission fuels. Not all fuel and technology options are assumed to be available from the

[9] Warships, naval auxiliaries, fish-catching or fish-processing ships, wooden ships of a primitive build, ships not propelled by mechanical means, or government ships used for non-commercial purposes.

[10] The EU ETS extension in maritime is applicable to EEA voyages. Whilst PRIMES Maritime applies the EU ETS to Origin-Destination pairs of the EEA, the reporting presented in this study is provided for the EU MS. The scope ETS Maritime policy, notably, applies to EEA voyages, that is, including also trade of EU countries with Norway and Iceland. In the modelling, voyages between EU and specific EEA countries (for example Norway, Iceland) are included in ETS as part of the extra-EU voyages. Extending the intra-EU to intra-EEA scope and the application of ETS would not alter the modelling results and findings, for example fuel supply mix, vessel technological mix, owing to the comparably small level of trade volume between EU and Norway and Iceland. It would have a minor influence on the level of ETS emissions and energy demand, which can be estimated based on post-model estimates.

[11] PRIMES Maritime applies the territoriality principle for activity and energy consumption. In the calibration process, this means that the energy used for the 50 % for incoming and outgoing extra-EU voyages and 100 % of the incoming and outgoing intra-EU voyages reflects the volume reported in the Energy Balances. To align the model's maritime emissions (intra- and extra-EU) with the Monitoring Reporting and Verification (MRV) scope, we apply a factor that shifts energy/emissions from intra-EU to extra-EU voyages.

base year; instead, their market entry, commercial and technical maturity evolve over time, shaped by assumptions on technology readiness and potential uptake rates. This is operationalized in the model through technological maturity factors and potential deployment curves. The context in which scenario quantification takes place, such as the one framed around the CTP, includes a consistent set of parameterizations for these factors and curves, reflecting the understanding that technology deployment and maturity is driven by systemic decarbonisation efforts across the entire energy system, not just within the maritime sector.

The projected fuel mix for technologies is determined via discrete choice functions, which reflect the relative cost competitiveness of all different fuels over time, including RFNBOs, biofuels, and others. Consequently, the uptake of RLCFs is influenced by their relative price signals in each period guided by potential deployment curves. Price signals include direct payments such as carbon pricing or taxation or hidden non-payable penalty factors and subsidies. Regulatory mechanisms such as the FuelEU Maritime Regulation are modelled through iteratively increasing penalty factors, applied in each simulation round until the regulatory blending or GHG intensity targets are satisfied. Given that FEUM sets targets on a WtW basis, the associated penalties account for full lifecycle GHG emissions, including non-CO_2 gases from 2030 onward. This cost-based optimization approach ensures that the fuel choice module adjusts to incorporate RLCFs where needed to meet targets in the most cost-effective way.

Regarding the scope of the policy and its implementation in PRIMES Maritime, the FuelEU Maritime Regulation has the same scope as the EU ETS 1 extension to the sector. It applies to all ships (excluding ships of below 5,000 GT, inland waterway vessels and some other special ship categories[9]) in respect to 100 % of the energy used during intra-EU/EEA voyages and port stays, and 50 % of the energy used on extra-EEA voyages. This means that for extra-EU/EEA voyages, the effective requirement modelled is that of meeting half the GHG reduction target. The regulation is also mandating the use of OPS or alternative zero-emission technologies in ports for specific vessel types (container and passenger ships) from 2030 onwards.

The GHG intensity reduction target of the energy used onboard ships for a given year is defined as a percentage of reduction compared to the reference value for 2020 (that is, 91.2 gCO_2eq/MJ) as can be seen in Table 1 (based on EU (2023b)).

Table 1: Annual average carbon intensity reduction compared to the average in 2020

	2025	2030	2035	2040	2045	2050
Reduction of GHG intensity of the energy used onboard ships	-2 %	-6 %	-14.5 %	-31 %	-62 %	-80 %
GHG intensity of the energy used onboard ships (gCO_2eq/MJ)	89.4	85.7	77.9	62.9	34.6	18.2

Source: PRIMES Maritime & PRIMES-TREMOVE

In the modelling, the interplay between policies is explicitly captured: while the EU ETS 1 introduces a direct carbon cost on TtW emissions, FEUM exerts an indirect compliance cost on WtW emissions. Thus, EU ETS 1 payments appear as visible market costs (auction payments), whereas FEUM penalties function more as a compliance cost embedded in the optimization logic.

Alternative Fuels Infrastructure Regulation (AFIR) and Renewable Energy Directive (RED III)

These Regulations are included with the AFIR provisions accounted for fuel and OPS availability and overall MS compliance with RED requirements considered for accounting for the energy used by the maritime sector as well as other transport and non-transport sectors. In the energy system this is expressed through the contribution of maritime to RED III targets (overall Renewable Energy Share, RES; Renewable Energy Share in Transport, RES-T; or GHG intensity target; sub-targets on RFNBOs and advanced biofuels).

Energy Taxation Directive (EU ETD)

While the proposal is not final, it is included in its currently negotiated form (as of 8/2024) where full tax exemptions for maritime fuels are stopped and fuels will start being taxed according to their energy content and environmental performance rather than their volume. After 2030, the scenarios assume a gradual increase in excise taxes on RFNBOs and advanced biofuels. This reflects the rationale that, as fossil fuels are phased out, introducing excise duties on RFNBOs and advanced biofuels fuels helps preserve public revenues from fuel taxation and offsets the decline in tax income linked to reduced fossil fuel consumption. For advanced fuels in maritime the excise tax rate is from less than 1 EUR/toe in 2030 to up to 20 EUR/toe in 2050, thus not a determining factor of the end-user fuel price. Yet, excise taxes are considerably higher in other segments, thereby affecting the uptake of fuels and the cost reduction due to scale.

Spillover effects

Although small vessels and inland waterway vessels are not formally covered under the scope of EU ETS 1 or FEUM, spillover effects are anticipated, owing to the adoption of RLCFs fuels by large vessels to comply with their regulatory obligations. Fuel suppliers and port infrastructure adapt accordingly and this growing availability is likely to create conditions conducive to voluntary uptake by smaller vessels and inland waterway operators.

2.2.3 Limitations

While the modelling framework applied in this study provides a robust basis for assessing the impacts of key decarbonisation policies in the maritime sector, certain variables as applied in this study, or structural and methodological limitations should be acknowledged to properly contextualise the results presented thereafter.

Exogenous fuel price and carbon price: The pre-tax fuel prices used in the modelling are derived from the full PRIMES energy system model, where fuel supply and demand are balanced across sectors under an economy-wide decarbonisation context consistent with the 2040 CTP. In this framework, fuel prices reflect an internally consistent carbon price trajectory that is endogenously determined. Fuel prices are a key determinant of operator decisions, influencing fuel uptake, technology selection, and activity growth. While the projections used in this study are internally consistent, alternative price trajectories could lead to different outcomes. These could be explored through a dedicated sensitivity analysis on fuel prices, though such an analysis is not included in the present report.

The carbon price applied to maritime emissions in this study does not follow that trajectory; instead, it is exogenously imposed as a policy input. As a result, potential feedback effects from maritime abatement on EU ETS 1 prices, and, by extension, on fuel prices, are not captured. The working assumption is that fuel prices do not respond to isolated changes in maritime demand. A fully integrated approach with the PRIMES system would be required to reflect such cross-sectoral interactions and to assess maritime policy impacts within a unified EU ETS 1 and fuel price formation mechanism.

Limited demand segmentation by vessel class: while the supply module of PRIMES Maritime treats large vessels (5,000 GT and above) and small vessels (under 5,000 GT) as distinct supply segments (that is, distinct characteristics such as fuel use, technology adoption, and energy efficiency responses to policy) they are part of a single demand segment in the demand module. Demand segmentation is based solely on freight and passenger transport, so policies targeting large vessels might also influence the activity of small vessels. Consequently, policies that target large vessels (for example ≥5,000 GT) may indirectly influence demand patterns of smaller vessels in the model. Similarly, the distinct supply segments for domestic maritime transport and inland waterways transport are combined into a single demand segment (freight and passenger domestic waterborne transport). As a result, changes in the generalized supply cost of domestic maritime transport can slightly affect inland waterways activity as well.

Supply-side size segmentation: PRIMES Maritime does not explicitly split the maritime fleet along the threshold of 400 GT. Therefore, when modelling impacts of extending the EU ETS 1 to smaller vessels below 5,000 GT, also those under 400 GT are affected, and the impacts presented include also these in their extended scope. Including all small vessels activity under the EU ETS 1 could potentially lead to a slight overestimation on impacts (for example higher emission mitigation owing to the extension).

Optimization of Origin-Destination (OD) pair assignment: while the OD pair assignment optimizes the vessel technology allocation, the demand allocation of vessel sizes for each OD pair (that is, the proportion of demand served by each vessel size) is determined by the distance of the OD pair and remains fixed across all scenarios, regardless of the scenario-specific conditions. This limits the responsiveness to cost conditions and policy stimuli to re-allocate demand to different vessel sizes between scenarios.

Technology representation and technological learning: While the model explicitly incorporates the use of clean fuels in single-fuel engine newbuild vessels, it implicitly models retrofitting of existing stock to dual-fuel engine through the fuel mix in diesel and fuel oil blends. This modelling limitation, together with cost and deployment uncertainties, may slightly underestimate the short-term uptake potential of alternative fuels by 2030. Moreover, technology cost reductions over time are elaborated externally and do not emerge endogenously from additional market uptake or scale effects.

Partial coverage of leakage effects: The model does not explicitly account for activity leakage effects that may arise from unilateral EU measures, such as the relocation of refuelling, rerouting of voyages, or evasive port calls outside the EU ETS 1 scope. While the model estimates emissions based on vessel activity and regulatory coverage, behavioural responses by operators seeking to minimise compliance costs, particularly in extra-EU contexts, are not dynamically represented. As a result, potential changes in trade flows or emissions displacement to non-regulated regions may be underestimated.

2.2.4 Model calibration and projections

The model is calibrated to statistical data up to the year 2022 and includes the impact of the COVID-19 pandemic in 2020. In particular, the model is calibrated in the Eurostat energy balances published in early 2024 (which includes data up to 2022) as a cut-off date and through shift factors it is calibrated to MRV-reported maritime emissions (EMSA, 2024). Additional model parameters are derived from various data sources, including the DG MOVE's Statistical Pocketbook (EC, 2024b), Eurostat transport database (EUROSTAT, 2025), Clarksons SIN database (Clarksons Research, 2025), and the Fourth IMO GHG Study (IMO, 2020). Specifically:

- on disaggregation of freight and passenger activity the Eurostat bilateral tones traded and passengers transported is used;
- on stock, DG MOVE's Statistical Pocketbook is used to calibrate the total stock, the stock fusion is based on the Clarksons SIN database, age, vessel type and vessel size distribution in calibrated to the Fourth IMO GHG study (IMO, 2020);
- the specific energy consumption, mileage and vessel speed of the various vessel types and sizes is based on the Fourth IMO GHG study (IMO, 2020);
- the initial age distribution of the existing fleet is based on ISL statistics yearbook. Data is then updated based on available sources. For example, the age structure of the existing passenger vessels is updated by using the world-wide age distribution of Ro-Pax and Cruise vessels from Clarksons (Clarksons Research, 2025). Based on the base year, probability of survival curves is calibrated for each ship type. Age distribution is further differentiated per vessel size based on the calibration procedure.

Given historical fuel prices for the years 2010, 2015, and 2020 the calibration process optimally assigns the available fleet, categorized by vessel type, size, and fuel technology, to meet the bilateral trade flows. At the same time, it ensures that country-level activity and fuel consumption targets for each fuel type are satisfied. To achieve this, the calibration estimates several key parameters such as OD routing coefficients, specific energy consumption adjustment factors, fuel supply availability and technical maturity levels, and hidden costs associated with vessel engine technologies. These parameters are then projected into years 2025 to 2070.

Beyond the historical years, certain parameters of the PRIMES Maritime model, particularly within its fuel mix module, such as fuel maturities and subsidies, are calibrated for the period 2025 to 2070 for a baseline scenario. Using the projected price trajectory and any regulatory frameworks associated with this baseline (for example, EU ETS 1 and FuelEU Maritime Regulation), the calibration process adjusts these parameters to ensure that the emission reduction targets implied by these policies are met. This is achieved by minimizing both fuel subsidies and indirect compliance costs. Once calibrated, these parameters are used for scenarios that fall within the same scenario group as the baseline, ensuring comparability.

2.2.5 Indicators

The key indicators presented in the analysis, collectively describe the evolution of the maritime transport sector under different policy scenarios. The indicators broadly cover maritime activity, energy demand, fuel mix, GHG emissions, and overall system costs, and other parameters (for example intensity indicators). Specifically:

- maritime activity, for both freight and passenger transport, is reported by shipping segment: international maritime transport, domestic maritime transport, and inland waterways transport;
- energy demand is shown as total consumption per shipping segment and further disaggregated by fuel type;
- the energy demand is disaggregated to the following fuel types: liquid fossil fuels, LNG, liquid biofuels, bio-LNG, e-liquids, e-LNG, ammonia, methanol, hydrogen, and electricity;
- GHG emissions are provided per shipping segment, and for international maritime also by operational area (intra-EU and extra-EU). Emissions are also disaggregated into WtT, TtW, and methane slippage components;

- in addition, the study reports on the energy and emissions intensity of maritime activity and its projected evolution;
- the total system costs associated with international maritime transport in the EU are also quantified.

Due to the different sectoral segmentation of the models used in the present study (PRIMES Maritime and PRIMES-TREMOVE), where possible, these projections provide information on the minimum common denominator regarding the different segmentations of maritime activity, such as the different types of maritime transport. Where relevant, results are also presented by vessel size category, distinguishing ships above and below 5,000 GT. All indicators are projected through to 2050.

The "Annex – Analytical scenario results" provides further disaggregation that support the analysis, such as, activity by vessel type, cost breakdown to total costs, fuel costs, operational and non-fuel variable costs, and capital costs, and external costs associated with air pollutants.

2.3 Methodological note on the modelling

The following methodological note focusses on one of the most critical components in the modelling methodology applied above: the fuel mix submodule. While conducting the modelling above, it was found that the calibration of the fuel mix submodule could deserve further refinement and could thus potentially improve the findings.

How the fuel mix submodule works

This submodule estimates fuel shares using a discrete choice model, based on the generalized cost and maturity of each fuel. The generalized cost includes the fuel price (EUR/toe), a subsidy (EUR/toe), and a shadow cost (EUR/tCO_2). Additionally, this cost is adjusted by a penalty factor, which is a non-linear function of the ratio between estimated consumption and the fuel's maximum potential consumption. Therefore, before executing the fuel mix submodule, it is necessary to calibrate it by making reasonable assumptions about several hidden parameters: fuel maturities, subsidies, shadow cost, and the parameters of the maximum potential curves.

The calibration of the fuel mix submodule is performed as follows: given exogenous fuel shares, fuel prices and EU ETS 1 price trajectories, the hidden parameters are adjusted so that: the estimated fuel shares are as close as possible to the exogenous ones, and the subsidies and the shadow cost are minimized subject to various intertemporal constraints on maturities and maximum potential curve parameters.

Once calibrated, the fuel mix submodule is used to run scenarios with fixed values for fuel maturity, subsidies, and potential curve parameters. The shadow cost, however, retains limited flexibility and is adjusted to ensure compliance with the FEUM GHG intensity target. In this context, the shadow cost serves as an internalized cost of non-compliance, representing the marginal economic signal needed to achieve the target. Its value varies across scenarios depending on factors such as the EU ETS 1 price trajectory, allowing the model to just meet the FEUM target under different conditions.

Potential refinements

A key limitation of the current calibration is that the hidden parameters are allowed to span a wide range of values, resulting in numerous combinations that can satisfy the FEUM target. This can lead to either low or high shadow cost values, which in turn influence the perceived role of the EU ETS 1. When the shadow cost is low relative to the ETS price, EU ETS 1 appears to be the main driver of compliance. Conversely, a high shadow cost diminishes the impact of EU ETS 1.

The robustness of our findings could be improved by constraining the value of the shadow cost to the official FuelEU Maritime Regulation non-compliance penalty, which is 2400 Euro per tonne of VLSFO-equivalent energy, that is, approximately 730 EUR/tCO_2. Assuming that this penalty is sufficient to induce compliance, the shadow cost should reflect the marginal cost of abatement at the point where the target is met. In other words, the shadow cost should equal the penalty rate at the compliance threshold.

Therefore, based on this approach, the fuel mix submodule should be recalibrated (re-estimate the values of the hidden parameters) so that the base case scenario (with medium EU ETS 1 price trajectory) meets the FEUM target, with the shadow cost fixed at 730 EUR/tCO_2. Once calibrated, the rest of the scenarios should run while keeping the value of hidden parameters (fuel subsidies, maturity and maximum potential curves) fixed. Sensitivity scenarios with low and high EU ETS 1 price trajectories should also be run using the same fixed shadow cost. In the low ETS price case, the target may not be met, while in the high price case, it may be exceeded. Regardless of the outcome, the FuelEU Maritime Regulation remains active due to the fixed shadow cost, allowing for a clearer assessment of the EU ETS 1 price influence. Scenario 2 should be run with both EU ETS 1 price and shadow cost set to zero, while for Scenario 3 only the shadow cost should be set to zero. The remaining scenarios should maintain the fixed shadow cost and vary the level or scope of the EU ETS 1. To better understand the economic implications, the total shadow costs, defined as the product of the shadow cost and the associated CO_2 emissions, can be calculated and presented.

One more limitation of the modelling methodological framework is that feedback effects from carbon pricing or regulatory mandates into fuel prices are not captured. As a sector-specific energy system model focused on maritime transport, PRIMES Maritime does not simulate fiscal or macroeconomic mechanisms such as revenue recycling. In scenarios where EU ETS 1 Regulation is not activated, this could result in higher costs for clean fuels. This can be addressed by qualitatively adjusting clean fuel prices in scenarios without EU ETS 1 (for example, Scenarios 2 and 4), to reflect the absence of market incentives and better approximate real-world dynamics.

Another area for improvement in the modelling framework is the integration of updated data and a broader technology portfolio. Currently, the model is fully calibrated for 2020 using detailed data on energy consumption, activity levels, and stock technology shares. However, for 2025, the calibration is only partial due to limited data availability at the time. As more data for 2025 becomes available, it should be incorporated to enhance model accuracy. Additionally, some technological developments, such as vessel retrofitting for ammonia or methanol engines and the deployment of electric vessels, are currently modelled implicitly. These should be explicitly represented in future versions to improve precision.

While these enhancements (carbon pricing feedback, data updates, technology expansion, and possibly increased model granularity) would strengthen the modelling foundation, they are not expected to significantly alter the results or conclusions of this exercise. In contrast, the calibration methodology of the fuel mix submodule remains a critical factor that could materially affect the outcomes.

3 Assumptions and Scenarios

3.1 Assumptions

3.1.1 Exogenous inputs

The Base Case and the Scenarios developed in this study are built on a scenario that is quantified with PRIMES considering economic drivers such as population, GDP growth, and other drivers aligned with EU scenario projections within the broader EU Green Deal decarbonisation context and the 2040 Climate Target Plan target, suggesting that maritime transport projections take place in a trajectory of a climate neutral EU economy in 2050.

Table 2: Exogenous assumptions and sources used in the modelling of the Base Case and the Scenarios

Driver	Source
Macroeconomic drivers (GDP projections)	(DG ECFIN, 2022)
Population growth	(EUROSTAT, 2022)
International energy prices	Supply cost-curves and demand projections from POLES-JRC (EC, 2022)
Techno-economic performance	Technology assumptions prepared in the context of the Climate Target Plan 2040 (EC, 2024a)

Source: Own compilation

3.1.2 Fuel prices

The fuel prices used in the modelling are based on the endogenous price estimates of PRIMES. Using as an input international fossil fuel prices (see “Annex – Endogenous fuel price estimates”), PRIMES simulates a well-functioning market where supply of fuels and other energy carriers meets the demand from all sectors. The PRIMES pricing module calculates supply costs by sector and determines product/fuel prices by sector based on marginal costs and an allocation of fixed and capital costs depending on assumptions about market conditions. A market balancing routine ensures demand and supply equilibrium in all markets simultaneously, as a result of market clearing prices, after iterations involving all the modules, thus closing the supply-demand-price loop.

For the Base Case and the different Scenarios explored in this study, a single fuel price scenario is used, which is an input in PRIMES Maritime and PRIMES-TREMOVE considering the said decarbonisation context. The working assumption between Scenarios is that fuel prices are not responding to isolated changes in specific maritime policies (for example, due to demand change for a specific fuel). The pre-tax fuel prices used in the Scenarios is presented in Table 3. Pre-tax prices indicate values excluding all forms of taxation, such as excise taxes, VAT, national carbon taxes, carbon pricing, etc. To note that fuel prices, as incorporated in the model differ by MS; weighed average prices for the EU are presented.

The fuel choice in PRIMES Maritime lies within the context of minimizing expenses, allowing policy measures to influence the choice towards cleaner fuels. Besides the relative price difference between fuels, other factors that may influence the consumption level and share of different fuels in the maritime mix are technological maturity, potential/availability, other technical or operational measures, etc. (see also Section 2.2.1).

A comparison of the PRIMES fuel price estimates with other publicly available projections, such as those from the Fourth IMO GHG Study (IMO, 2020), Maersk's Documentation of assumptions (Maersk, 2022), and DNV's Energy Transition Outlook (DNV, 2022), suggests that while fossil fuels and LNG are consistently projected as the least costly options through 2025, there is a considerable variability in the expected costs of alternative fuels. For example, PRIMES estimates marine diesel at 815 EUR/toe in 2030, which falls within the range of other projections (typically 589–880 EUR/toe), while PRIMES prices for e-fuels, such as e-methanol (3,720 EUR/toe in 2030), are towards the higher end of the range found in the literature (ranging from around up to 3,660 EUR/toe). This suggests relatively conservative assumptions in PRIMES regarding the pace of cost reductions for emerging efuels. The observed differences across sources primarily derive from divergent assumptions on carbon pricing trajectories, fuel production technologies, and global supply-demand dynamics.

Table 3: Maritime pre-tax fuel prices used in the modelling in EUR '15/toe (rounded weighted average prices for EU) in the Base Case and the Scenarios, based on PRIMES

Fuel type	EUR '15/toe			
	2025	2030	2040	2050
marine diesel	710	815	850	970
RFO	560	670	690	800
LNG	780	750	770	770
bio-RFO	1,170	1,320	1,320	1,250
bio-diesel	1,530	1,640	1,590	1,450
bio-LNG	970	1,020	1,095	1,070
e-fuels	4,140	3,660	2,570	2,050
e-LNG	3,750	3,280	2,400	1,740
e-Ammonia	2,620	3,010	2,700	2,600
e-Methanol	3,230	3,720	3,340	3,210
Green Hydrogen	3,490	4,010	3,610	3,420
electricity	2,350	2,380	2,280	2,340

Source: PRIMES Maritime & PRIMES-TREMOVE

3.1.3 EU ETS 1 price trajectory

In the Base Case and the Scenarios, the following EU ETS 1 carbon price rates have been applied (Table 4). High- and low-price EU ETS 1 price trajectories are also developed and used in sensitivity runs.

The Base-price trajectory used in the modelling is provided by UBA. Historical and future prices are based on the European Energy Exchange (EEX), Carbon Pulse (2023) and the International Energy Agency (IEA).

A sensitivity around the above-mentioned base EU ETS 1 carbon price trajectory is formulated for 2030 onwards, around the EC's recommendations for key parameters underpinning the National Energy and Climate Plans of MS (With Expected Measures trajectory; WEM). Specifically:

In the low-price trajectory variant, the following assumptions are applied:

- an EU ETS 1 price of 58 EUR '22/tCO2 in 2025, representing a moderate near-term reduction compared to the average auction price in 2024 levels (~65 EUR/tCO2);
- a growth between 2025 and 2030, aligned with the Base-price trajectory rate over the same period;
- a relative stabilization of the EU ETS 1 price thereafter.

In the high-price trajectory variant, the following assumptions are applied:

- base-price levels are applied for 2025;
- compared to the low-price trajectory an increase is assumed for 2030–2035, reflecting reduced allowance availability and the depletion of lower-cost abatement options, alongside the implementation of policy amendments and outcomes of legislative reviews (BNEF, 2024);
- the WEM ETS price trajectory is maintained from 2040 onward.

Table 4: EU ETS 1 price trajectory assumptions in EUR '22/tCO2

EUR '22/tCO2	2025	2030	2035	2040	2045	2050
Base-price trajectory	84	122	140	158	170	181
Low-price trajectory	58	64	57	98	140	181
High-price trajectory	84	122	146	182	209	230

Source: PRIMES Maritime & PRIMES-TREMOVE

3.1.4 Emission factors

The FuelEU Maritime Regulation applies a life-cycle emissions accounting approach, encompassing emissions from both the production (WtT) and combustion (TtW) of fuels. Together, these account for the full well-to-wake (WtW) emissions, which form the basis for determining the GHG intensity reduction trajectory when compared against the benchmark value. The WtW emission factor of the fuel mix in 2020 is close to the GHG reference value of 91.2 gCO2eq/MJ which was defined in the FuelEU Maritime Regulation. The WtW emission factors used in the modelling are presented in Table 5.

Table 5: WtW emission factors used in the modelling (excl. slippage) [a]

Fuel type	WtW emission factor (tCO2eq/toe)
Diesel	3.7
Fuel oil	3.8
LNG	3.1

Fuel type	WtW emission factor (tCO2eq/toe)
E-liquids	0
E-gas / e-LNG	0
Biofuels	0.4-1[b]
Biomethane	0.4
Green Hydrogen	0
Electricity	see footnote c

Source: PRIMES Maritime & PRIMES-TREMOVE

Notes: [a] The modelling includes additional emission factors for slippage emissions of methane (between 0.3-4 gCO2eq/kWh) and nitrous oxides (0.01-0.03 gCO2eq/kWh) depending on the engine type.

[b] Depending on the biofuel type.

[c] Country-dependent. The EU average ranges from 3.36 tCO2eq/toe in 2015, to 0.98 tCO2eq/toe in 2030, to 0 tCO2eq/toe in 2040 onward

WtT emission factors for diesel, fuel oil, and LNG are based on Lindstad (2019), in line with the FuelEU Maritime Regulation and the (EEA-EMSA, 2025). Hydrogen is assumed to be produced from renewable electricity and is therefore assigned a zero-emission factor for statistical and modelling purposes. Similarly, synthetic fuels (for example e-fuels, e-gas, ammonia, methanol), whose carbon content is assumed to be captured from the atmosphere via biogenic carbon or Direct Air Capture (DAC), are also attributed a zero-emission factor. For biofuels and biomethane, WtT emissions are linked to feedstock production and transport, and are derived from the PRIMES Biomass Supply model. Emissions from land-use change, whether direct or indirect, are excluded. Finally, the emission factor for electricity is country-specific, reflecting the carbon intensity of national power generation mix.

3.2 Base Case and Scenarios

This section describes the Base Case (or Baseline) scenario developed in this study, along with the various quantified Scenarios, to illustrate the combined impact of the EU ETS 1 extension to maritime and the FuelEU Maritime Regulation, their individual effects, as well as the projected implications of extending the EU ETS 1 to small vessels and inland waterways.

The Base Case and all Scenarios apply the assumptions presented in Section 3.1.

3.2.1 Base case

Assesses maritime decarbonisation with both EU ETS 1 and FEUM in place, aligned with the broader "Fit-for-55 package" and long-term EU targets.

The **Base Case (Scenario 1)** provides a reference trajectory under "no additional policy change" assumptions. It serves as a benchmark to assess the impacts of various alterations to its set-up such as inclusion of additional policies, removal of existing regulations, extension of policies to new segments, and other impacts such as those of energy prices, levels of taxation and technology costs.

Regarding the policy context reflected in the Base Case, up until 2030, it incorporates the "Fit-for-55" package, notably:

- the FuelEU Maritime Regulation, which applies to all ships above 5,000 GT. The regulation covers energy used at berth, energy used for domestic and international intra-EU voyages, and 50 % of energy used on extra-EU voyages;
- the extension of the EU ETS 1 to maritime transport, covering emissions over the same geographical scope as FEUM;
- it embeds existing efficiency and environmental regulations applicable to maritime transport, notably the EEDI, the EEXI, the SEEMP, and MARPOL Annex VI standards on NO_x and SO_x, as implemented through the EU Sulphur Directive and related legislation;
- it reflects existing short-term IMO measures, and most notably the CII;
- beyond maritime, the Base Case includes regulations indirectly impacting maritime decarbonisation (for example RED III, ETD other sector ETS, AFIR).

Reflecting the policy environment beyond 2030, the Base Case is developed within a broader policy and regulatory context that guides the energy system toward meeting long-term decarbonisation objectives, and in particular the 90 % net GHG emissions reduction target in 2040 compared to 1990, and net zero emissions in 2050. The maritime sector through its decarbonisation pathway contributes to these targets. Specifically, the decarbonisation trajectory of the maritime sector:

- includes the continued implementation of the FuelEU Maritime Regulation;
- considers continuation of EU ETS 1, diverging, however, from the carbon price levels of the overall trajectory (see Section 00).

The Base Case and the rest of the Scenarios developed in this study do not incorporate IMO's Net Zero target nor the indicative checkpoints.

The Base Case, and all Scenarios, considers that EU ETS 1 revenues from carbon pricing are not recycled back to the sector directly.

3.2.2 Scenarios

The Scenarios are built to explore a series of counterfactuals that modify the assumptions of the Base Case. They evaluate the impacts of removing key "Fit-for-55" Regulations (EU ETS 1 and FEUM) individually and in combination. Additional scenarios examine alternative policy configurations by extending the coverage the EU ETS 1 to vessels below 5,000 GT and to inland waterway transport. These scenarios provide insights into the relative contribution of each policy and the implications of broadening their scope.

Compared to the Base Case, the following Scenarios are developed:

Absence of Fit-for-55 maritime policies (Scenario 2):

Evaluates the combined impact of removing both the EU ETS 1 and FEUM policies, within an otherwise decarbonisation-aligned context.

Scenario 2, quantifies the combined effect of removing two key maritime decarbonisation policies, that is, the extension of EU ETS 1 in maritime and the FuelEU Maritime Regulation. This scenario otherwise occurs within a decarbonisation context in line with the "Fit-for-55" policy package (similar to the Base Case scenario) meaning that it includes the impact of other "Fit-for-55" policies and the of IMO measures. This scenario can thus be used to derive insights on the joint impact of two instrumental policies on maritime decarbonisation, when compared to the Base Case.

Absence of FEUM (Scenario 3):

Isolates the effect of EU ETS 1 by removing FEUM blending targets while maintaining carbon pricing and other Fit-for-55 elements.

Scenario 3 quantifies the effect or removing the impact of the FuelEU Maritime Regulation (that is, the GHG intensity reduction target is not met in the projection period). It includes the impact of the extension of EU ETS 1 in maritime (that is, the relative price difference of fossil versus non-fossil fuels in maritime is affected by the assumed carbon price). This scenario otherwise occurs within a decarbonisation context in line with the "Fit-for-55" policy package (same as the Base Case scenario) meaning that it includes the impact of other "Fit-for-55" policies and the impact of IMO measures. This scenario can thus be used to derive insights on the impact of the extension of EU ETS 1 in maritime, when compared to the Base Case.

Absence of EU ETS 1 extension to maritime (Scenario 4):

Assesses the role of FEUM as a standalone driver of fuel switching and emission reduction, without carbon pricing.

Scenario 4, quantifies the effect or removing the impact of the extension of EU ETS 1 in maritime (that is, the relative price difference of fossil versus non-fossil fuels in maritime is not affected by the assumed carbon price). It includes the impact of the FuelEU Maritime Regulation (that is, the GHG intensity reduction target is met in the projection period). Same as in the Base Case, this scenario otherwise occurs within a decarbonisation context in line with the "Fit-for-55" policy package, meaning that it includes the impact of other "Fit-for-55" policies and the impact of IMO measures. This scenario can thus be used to derive insights on the impact of the FuelEU Maritime Regulation when compared to the Base Case.

EU ETS 1 extension to smaller ships (Scenario 5):

Explores the potential emission reduction and fuel-switching impacts of including ships below 5,000 GT in the EU ETS 1, without FEUM obligations.

Scenario 5 is developed to assess the impact of extending the EU ETS 1 Maritime Regulation to cover also smaller ships below 5,000 GT (see Section 2.2.3). This scenario does so by adding the extension of the EU ETS 1 to the Base Case scenario (Scenario 1). The scenario retains the scope on emissions coverage (that is, 100 % emissions at berth, 100 % of intra-EU and 50 % of extra-EU emissions) also to small vessels. Importantly, in Scenario 5 the small vessels segment is not covered by the FuelEU Maritime Regulation. Same as all other Scenarios, this scenario occurs within a decarbonisation context in line with the "Fit-for-55" policy package, meaning that it includes the impact of all other policies therein.

EU ETS 1 extension to inland waterways (Scenario 6):

Assesses the effects of applying EU ETS 1 to large vessels in inland waterway transport, expanding carbon pricing to this currently exempt segment.

Scenario 6 is quantified to assess the potential impacts of extending the EU ETS 1 scope to also cover large vessels in inland waterway transport. Importantly, in Scenario 6 the inland waterways transport segment is not covered by the FuelEU Maritime Regulation. Similarly to other scenarios, Scenario 6 occurs within a decarbonisation context in line with the "Fit-for-55" policy package (same as the Base Case scenario) meaning that it includes the impact of all other policies therein.

In addition, owing to the uncertainty of the EU ETS 1 carbon price trajectory in the mid- and long-term the sensitivity of scenarios on carbon pricing is also assessed by using the EU ETS 1 price trajectories presented in Section 0 (Table 4). Sensitivity variants are quantified for 5 Scenarios in total (including the Base Case). The scenario matrix is presented in Table 6.

Table 6: Simplified scenario matrix

	Brief description	EU ETS 1 Extension to Maritime (curent scope)	FuelEU Maritime Regulation (curent scope)	Other "Fit-for-55" policies and IMO measures	Extension of EU ETS 1 to small vessels	Extension of EU ETS 1 to inland waterways
Base Case [a]	Includes all current legislative framework	✓	✓	✓	×	×
Scenario 2	Exclusion of Maritime from key Fit-For-55 policies	×	×	✓	×	×
Scenario 3 [a]	No FuelEU Maritime Regulation	✓	×	✓	×	×
Scenario 4 [a]	Exclusion of Maritime from EU ETS 1	×	✓	✓	×	×
Scenario 5 [a]	EU ETS 1 extension to smaller ships	✓	✓	✓	✓	×
Scenario 6 [a]	EU ETS 1 extension to inland waterways	✓	✓	✓	×	✓

Source: PRIMES Maritime & PRIMES-TREMOVE

Note: [a] Includes the quantification of a high and low sensitivity variant.

4 Results

This section presents the projected evolution of the EU shipping sector with respect to key indicators, including activity levels, energy consumption, fuel mix, and GHG emissions. The results are model-based projections under a set of assumptions and should be interpreted within the scope, assumptions, and limitations of the modelling framework that are presented in earlier sections (Section 2 and 3). Results represent projections on the evolution of maritime transport rather than precise forecasts.

The section begins with the Base Case scenario, illustrating the sector's trajectory under the current policy framework and drivers (see Section 3). This is followed by a comparative analysis of Scenarios 2–4, which quantify the individual and combined impacts of selected policy interventions (that is, EU ETS 1 and FEUM), relative to the Base Case. Scenarios 5 and 6 explore the potential implications of extending the EU ETS 1 to currently excluded vessel segments.

Results are shown over the 2025–2050 horizon and are contextualized with historical data for 2015–2020. The analysis covers three main shipping segments (international maritime transport, national maritime transport, and inland waterways transport).

The section presents in graphical format the main results. Tables with the numerical data that are presented in the various figures are included in the "Annex – Data tables". More detailed results are provided as electronic supplementary material ("Annex – Analytical scenario results").

4.1 Projections under the current policy framework

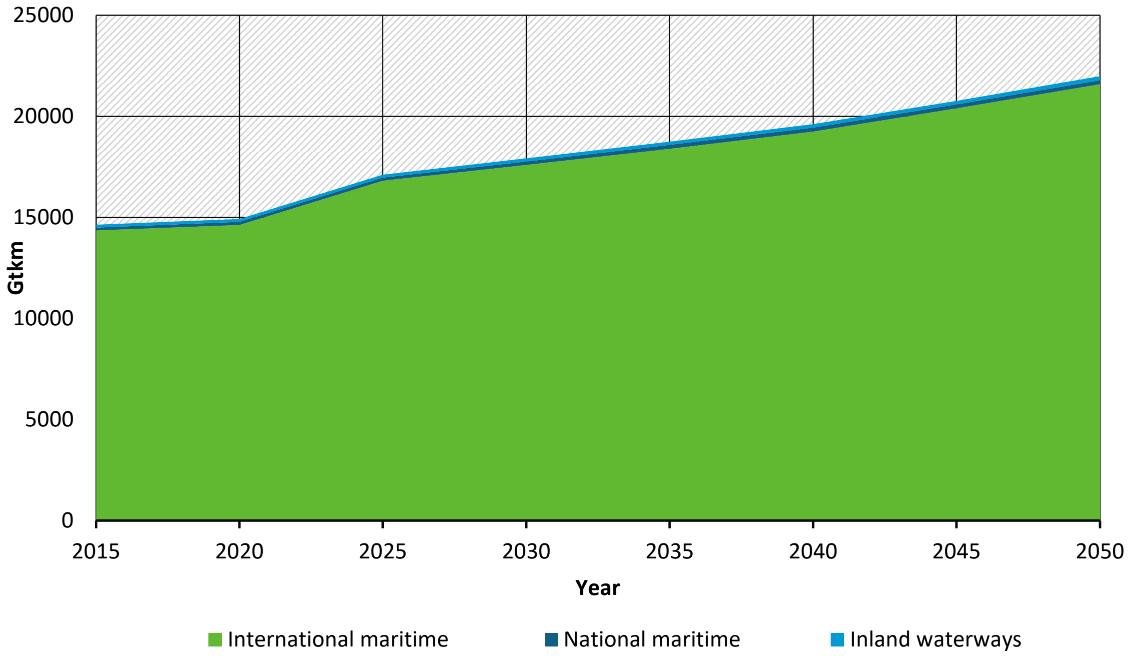
The projections and analysis presented in this section relates with the Base Case scenario.

4.1.1 Maritime transport activity

International maritime transport is responsible for the majority of the freight transport activity of the EU transport sector, representing more than 98 % of freight trade by the sea or inland waterways (in tonne-km). In the Base Case, EU shipping activity is projected to experience a strong growth. As shown in Figure 3, following a temporary stagnation in 2020 due to the COVID-19 pandemic, activity increases at an annual rate of 1.8 % between 2020 and 2030, then gradually slows to 1 % per year from 2030 to 2050. The higher growth in the first period is driven by the post-pandemic recovery in trade. The slowdown after 2030 reflects broader economic and trade dynamics, such as lower marginal trade intensity in mature economies and reduced expansion of extra-EU trade routes, particularly for bulk carriers and general cargo vessels, partly offset by the continued growth in container shipping (see "Annex – Analytical scenario results"). Similar growth trends are projected for national maritime transport. The small contribution of freight transport through inland waterways is set on a continuously growing and stable trajectory at 1.1 % per year over the whole projection period 2020-2050, reflecting EU actions such as the European Commission's Sustainable & Smart Mobility Strategy and Action Plan (EC, 2020). As both national maritime transport and inland waterways transport represent a smaller share of total activity they contribute less to the overall sector growth.

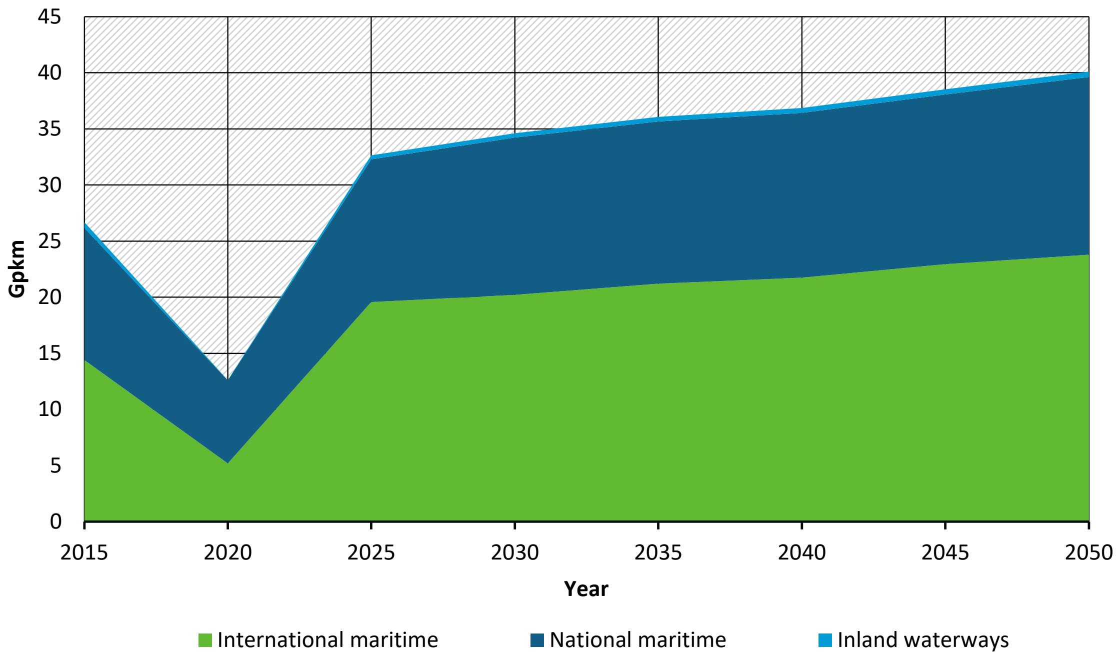
In passenger transport, national and international maritime transport segments contribute roughly equally to total activity and its growth (Figure 4). Following a sharp decline due to the COVID-19 pandemic, which impacted passenger transport across all modes, including maritime, the recovery is projected to be stronger in the period 2025-2030, with activity growing at around 0.6 % annually in international maritime transport and around 2 % in the other segments. After 2030, growth of passenger transport moderates to below 1 % per year.

Figure 3: Freight transport activity of the EU shipping sector by segment, in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 4: Passenger transport activity of the EU shipping sector by segment, in the Base Case

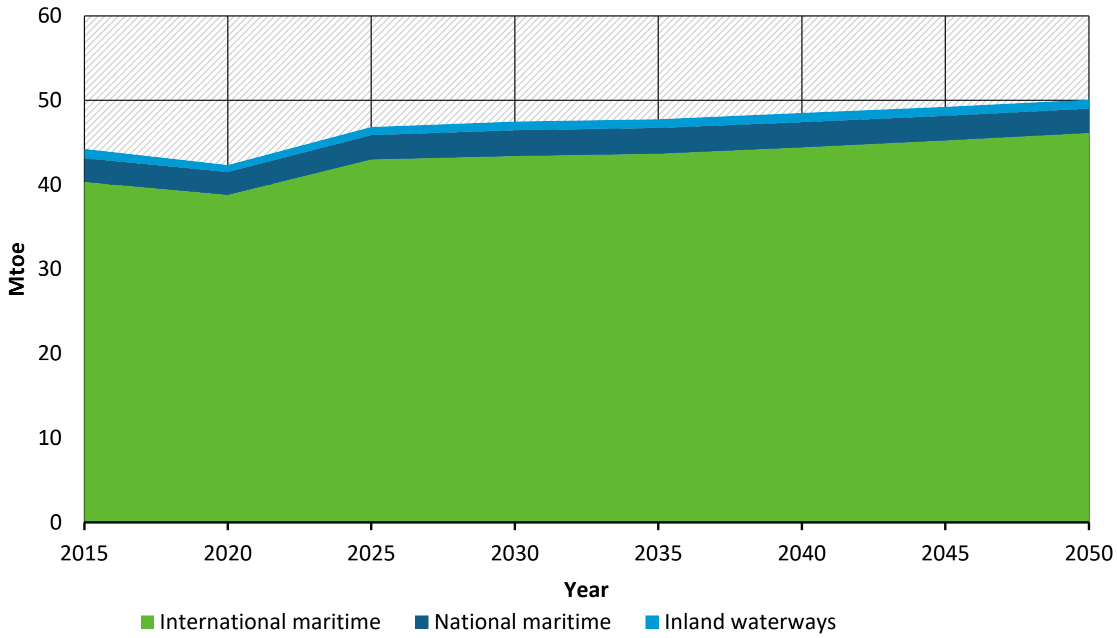


Source: PRIMES Maritime & PRIMES-TREMOVE

4.1.2 Energy consumption and fuel mix in maritime transport

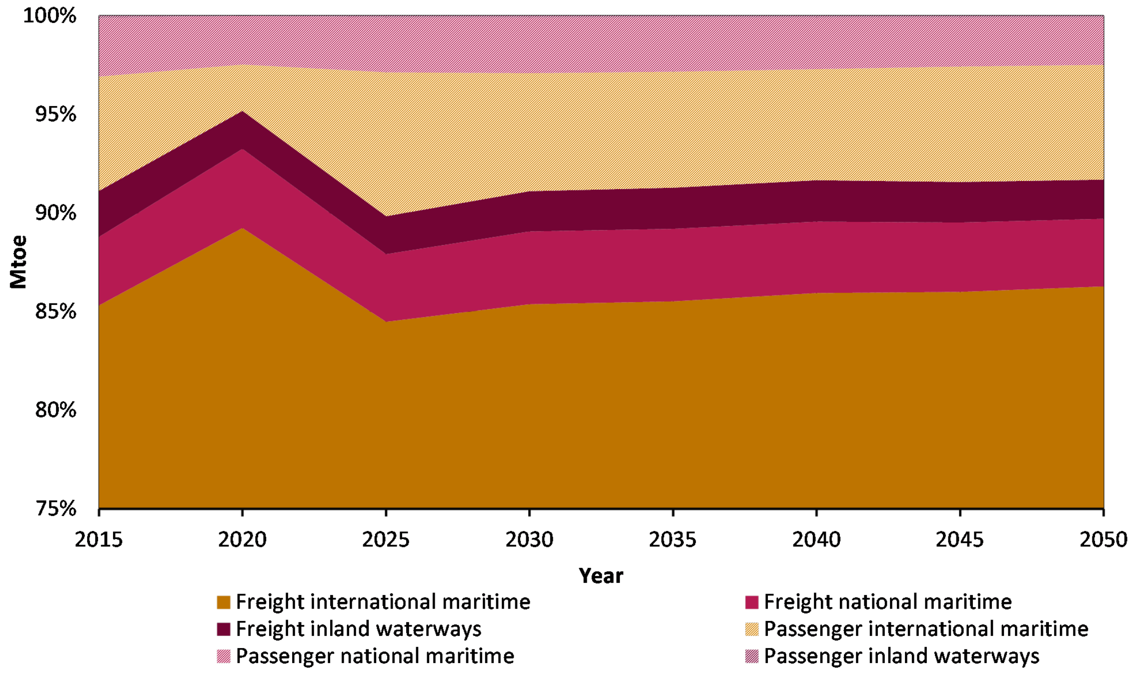
In the Base Case scenario, the energy consumption of the EU maritime transport sector, both passenger and freight, is projected to grow steadily over the period 2015–2050, in line with the overall increase in transport activity. Total sectoral energy demand rises from around 44 Mtoe in 2015 (42 Mtoe in 2020, lower primarily due to the overall activity trend and a reduction in passenger maritime transport) to 47.5 Mtoe in 2030, marking a 7 % increase over that period. This upward trend continues beyond 2030, reaching 50.1 Mtoe by 2050 (Figure 5). The growth is primarily driven by the international maritime transport segment, which accounts for over 90 % of total energy consumption (Figure 6), while representing 98 % of sea- and waterborne freight activity and nearly 60 % of passenger activity (Figure 3 and Figure 4). Despite the continuous rise in activity, the relatively stable share and energy demand of the international maritime transport segment is attributed to its gradually improving energy intensity (Figure 7). The policy framework embedded in the Base Case scenario induces both technical and operational efficiency improvements, particularly in the early part of the time horizon and more prominently than in other segments, either directly (for example through the CII) or indirectly via the model's optimization procedures, as a response to higher fuel prices resulting from carbon pricing or GHG intensity reduction mandates (Section 2.2.1). In the longer term, new vessels tend to be more efficient than the fleet average, due to the adoption of improved technologies (for example EEDI), which helps lower the overall fleet average. The somewhat lower pace of improvement of international maritime transport compared to the other segments is two-fold: firstly, due to different techno-economic assumptions for larger vessels that the international maritime transport segment is predominantly composed of compared to their shares in domestic maritime transport and inland waterways transport, and secondly, due to the fact that there are already significant improvements achieved in the international maritime transport sector, and compared to the other segments further improvements could be harder to achieve due to lower marginal cost savings.

Figure 5: Energy consumption of the EU shipping sector by segment, in the Base Case



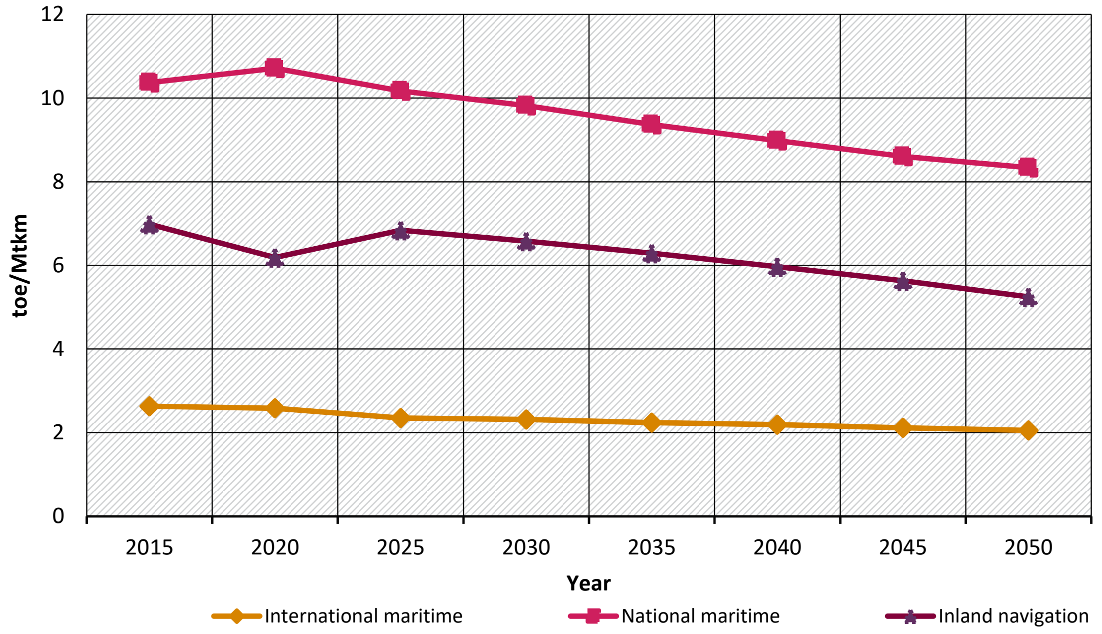
Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 6: Share of energy consumption by shipping segment, in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 7: Energy intensity of EU freight maritime transport by shipping segment, in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 8 presents the low-carbon fuel trajectory in maritime. In the Base Case, the low- and zero-carbon fuel uptake is observed already in the early period of the time horizon owing to the increase of LNG and liquid biofuels, representing 2 % and 1.3 % of the fuel mix in 2025, respectively. This uptake is governed by the recent orderbook on LNG vessels and the historical uptake of marine biofuels, adequate to meet the FuelEU Maritime Regulation target in 2025.

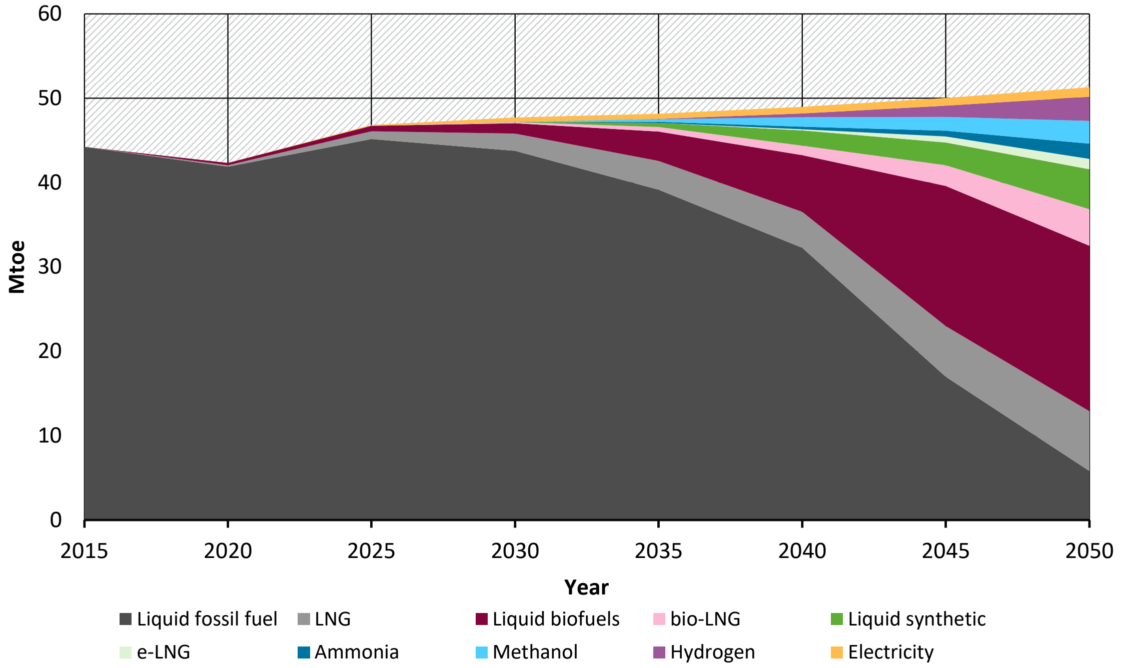
By 2030, driven by the intensification of the FEUM target, the uptake of lower-emission LNG and liquid biofuels increases, biomethane is introduced into the liquefied gas mix, and electricity is consumed by electric vessels, in addition to OPS that reflecting the provisions of the FuelEU Maritime Regulation and the AFIR.

According to the modelling results, within a decade, the share of liquid fossil fuels in maritime energy consumption is projected to decline to below 94 % by 2030, down from nearly 100 % in 2020. In the following decade (2030-2040), the maritime fuel mix diversifies significantly. In the projections, liquid fossil fuels (marine diesel and heavy fuel oil) account for two-thirds of total maritime energy consumption, and together with fossil LNG, they comprise approximately 75 %. The remaining share is primarily covered by biofuels and liquid e-fuels, contributing around 7.1 Mtoe and 1.9 Mtoe, respectively. Ammonia, methanol and hydrogen comprise 4% of the fuel mix. Biomethane and e-LNG contribute by 0.7 Mtoe and 0.1 Mtoe, respectively to the sector's energy demand. Electrification continues to expand within the maritime segment, primarily on container ships but also passenger vessels. Its contribution remains limited to no more than 2% of the total energy mix, and for other vessel types it is notably less than 1%.

The sharp tightening of the FEUM target on GHG intensity (from 31 % in 2040 to 80 % in 2050) drives a surge in demand for near-zero carbon fuels. Liquid biofuels (including biodiesel and bio-heavy fuel oil) emerge as the dominant marine fuel, accounting for 42 % of the fuel mix. When combined with bio-LNG, biomass-based fuels make up almost half of total maritime energy consumption. RFNBOs account for approximately one-quarter of the maritime fuel mix, with an increasingly diversified range of fuel options. Hydrogen, ammonia and, to a lesser extent, methanol (used either in dedicated dual-fuel engines or directly in purpose-built vessels) constitute the main synthetic fuels, representing 15 % of the total fuel mix. Liquid and gaseous e-fuel blends contribute an additional 11 % of energy consumption. Electricity use increases in line with rising activity, although its overall share remains unchanged from 2040 levels (approximately 2 %).

As seen over the projection period, the renewable and low-carbon fuel (RLCF) mix in maritime increases notably. In the Base Case, this trajectory is primarily governed by the FuelEU Maritime Regulation, which is modelled as a regulatory constraint setting minimum levels for GHG intensity through RLCF blending. The model ensures compliance with these mandates, which effectively determine the overall uptake trajectory for low-carbon fuels. The EU ETS 1 operates as a price signal encouraging emissions reductions beyond the mandate, where cost-effective. However, the EU ETS 1 price signal alone does not result in additional uptake of clean fuels beyond what is required to meet the GHG intensity target of the FuelEU Maritime Regulation. While the EU ETS 1 plays a fundamental role in narrowing the price gap between low- and zero-carbon fuels and fossil fuels (thereby enhancing the competitiveness of RLCFs; see also Section 5), it also provides important demand signals and investment incentives for alternative fuel suppliers and infrastructure. Revenues generated through the EU ETS 1 are essential for supporting early deployment and scaling up zero-carbon fuel production. These effects are indirectly transmitted to the maritime sector reflected via the RLCF price, through the investment and expenditures required for the segment to decarbonize.

Figure 8: Energy consumption in the EU shipping sector by fuel type, in the Base Case

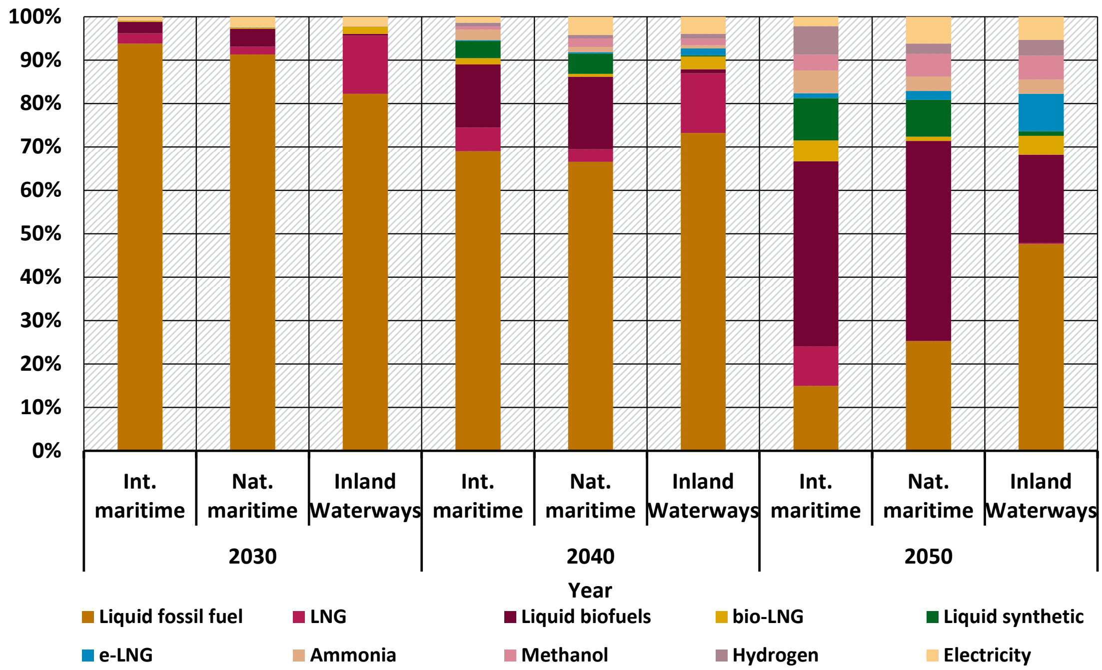


Source: PRIMES Maritime & PRIMES-TREMOVE

The trends observed for the overall maritime sector are largely confirmed when disaggregated into international maritime transport, national maritime transport, and inland waterways transport. The main observations by segment for 2030 and 2050, as presented in Figure 8, show that international maritime transport is the primary driver of the transition and the uptake of RLCFs. This segment accounts for over 90 % of total maritime energy consumption and it also represents approximately 86 % of RLCF use in 2030 and 94 % in 2050. This highlights the critical role of international maritime transport in decarbonisation but also implies that uptake occurs across other segments. In 2030, RLCFs make up around 6 % of the international maritime transport fuel mix, while the share in national maritime transport reaches 9 % and in inland navigation nearly 18 % (primarily due to LNG uptake). The increased LNG consumption in inland waterways observed in 2030 is driven by improvements in vessel maturity, lower capital costs, and favourable LNG prices. However, as these comparative advantages diminish over time and alternative fuels become more competitive, LNG gradually phases out toward 2050. The long-term uptake rates reverse in 2050, where the RLCFs mix are more than 85 % in international maritime transport, 75 % in national maritime transport and 52 % in inland navigation transport. The lower uptake rates in the latter two segments are because they are comprised by a higher share of smaller or inland waterway vessels that are not covered by the key regulations supporting the penetration bulk of RLCFs in the maritime fuel mix. Nonetheless, spillover effects (see Section 2.2.1) due to the availability of infrastructure and supply of alternative fuels at lower costs owing to dynamics induced on the supply-side owing to the decarbonisation trajectory of the energy system.

In the Base Case, the carbon price sensitivity scenarios do hardly the energy mix or the level of RLCF consumption, as the assumed carbon prices do not significantly influence maritime activity. At these price levels, the blending mandate remains the binding constraint, meaning the scenario does not result in an overshoot of the GHG intensity target. The primary effect of the sensitivity scenarios lies in their impact on total system costs for the maritime sector, driven mainly by fuel costs (including carbon payments). This impact is more pronounced in the early part of the projection period, with fuel costs decreasing by 9 % under the low-price trajectory and increasing by 0.7 % under the high-price trajectory in 2030. By mid-century, the impact is marginal, with changes of just -0.1 % and +0.1 %, respectively.

Figure 9: Fuel mix of the EU shipping sector by shipping segment in 2030, 2040 and 2050, in the Base Case



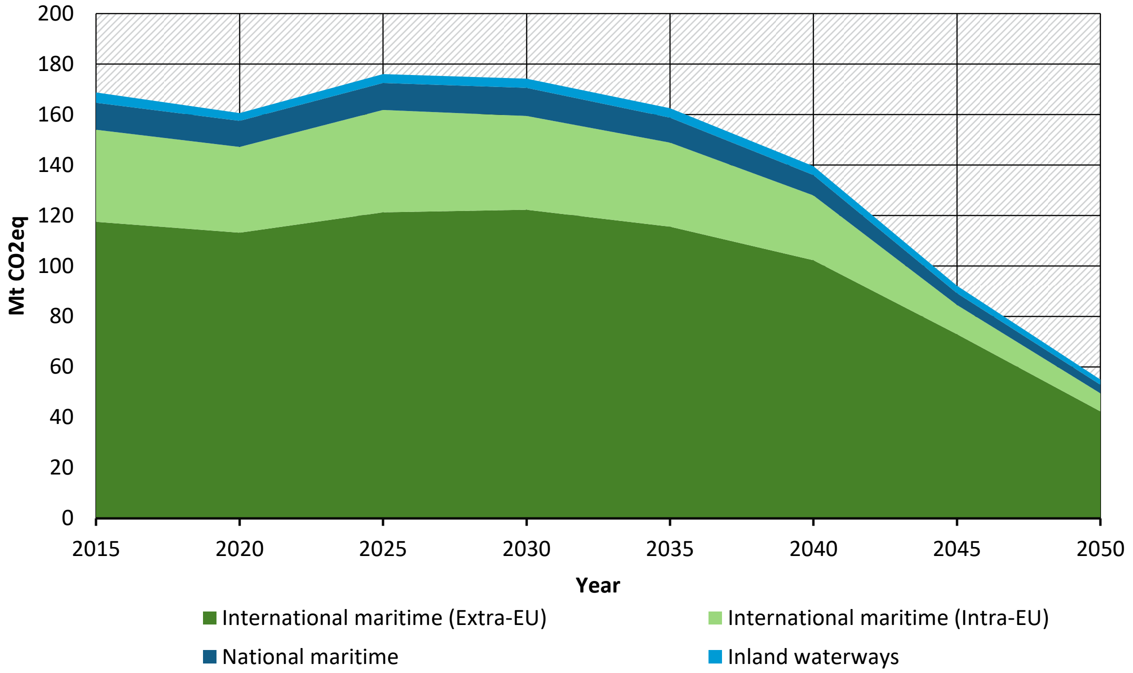
Source: PRIMES Maritime & PRIMES-TREMOVE

4.1.3 GHG emissions trajectory of maritime transport

The GHG emissions from maritime transport, after a sharp rebound following the post-COVID-19 recovery, are projected to plateau during the period 2025–2030. Thereafter, emissions follow a declining trajectory, reaching a reduction of approximately 67 % by 2050 compared to 2015/2020 levels. International maritime transport is expected to account for around 90 % of total GHG emissions from the EU shipping sector throughout 2025–2050, reflecting its major share in energy consumption. The majority of these emissions are linked to extra-EU voyages, which increase their share from 69 % in 2025 to 77 % in 2050. Intra-EU voyages decline from 23 % to 13 % over the same period, while domestic maritime transport maintains a stable contribution of about 6 %. The inland waterways segment accounts for 2 – 4 % of total maritime GHG emissions.

The strongest emissions reduction is observed in intra-EU voyages, where GHG emissions drop by 80 % by 2050 relative to 2015, reflecting full regulatory coverage under the EU ETS 1 and FEUM, with the exception of small vessels. In contrast, inland waterways, which are currently outside the scope of these regulations, achieve the lowest emissions reduction (that is, 51 % by 2050 compared to 2015). Nonetheless, this decline is still notable, driven by spillover effects from the decarbonisation of other segments and the improved availability and affordability of RLCFs. Similarly, the more moderate reduction in domestic maritime transport emissions is linked to the higher share of smaller vessels (below 5,000 GT), which are excluded from the "Fit-for-55" maritime regulations.

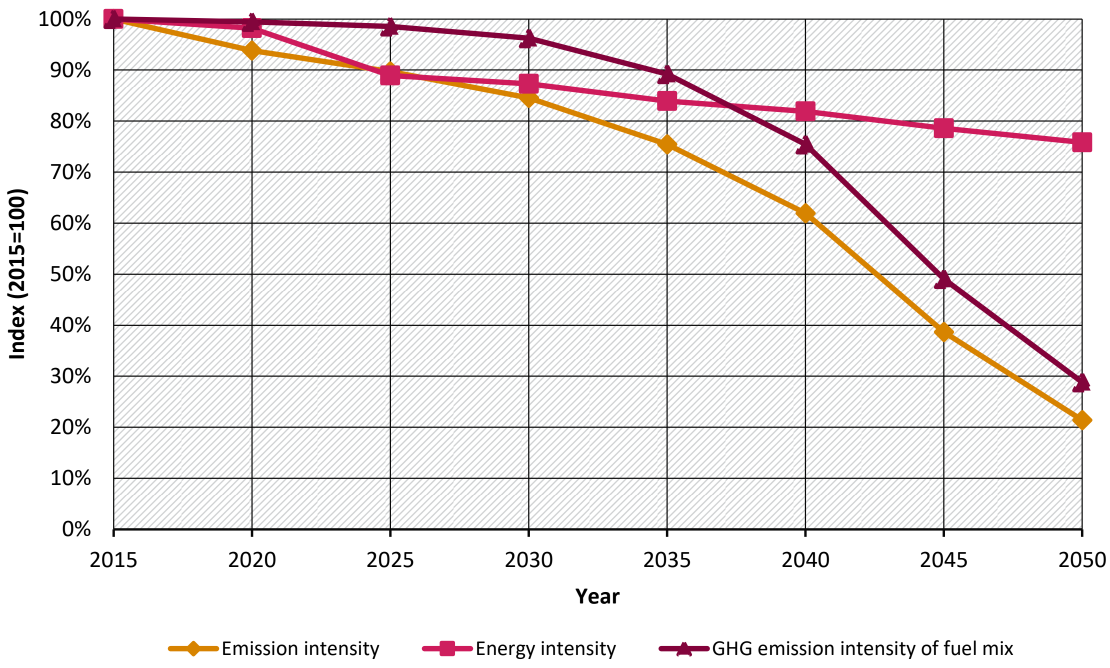
Figure 10: GHG emissions of the EU shipping sector by segment, in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

The results presented in Figure 12 show that in the Base Case, under the assumed carbon price, the decoupling of CO_2 emissions from energy use is evident, demonstrated by the substantial decline in overall emission intensity in maritime transport, reaching 21 % of 2015 levels by 2050. This reduction is driven by both improvements in energy efficiency and a significant shift toward renewable and renewable and low-carbon fuels. While energy intensity decreases moderately (to 76 % in 2050 compared to the index year 2015), reflecting technical and operational efficiency gains, the GHG intensity of the fuel mix drops more sharply, to 29 %, highlighting the dominant role of maritime fuel decarbonisation. The steeper decline in overall emission intensity compared to its individual components illustrates the compounded effect of these two drivers, with fuel switching emerging as the primary lever for emission reduction in the long term.

Figure 11: GHG emissions intensity of international maritime transport, in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

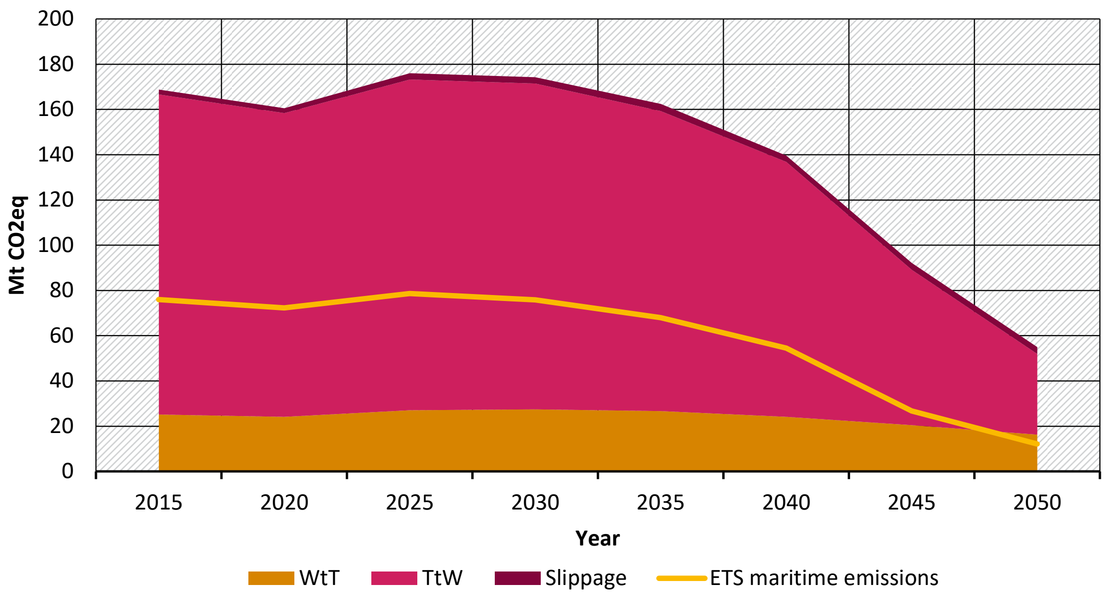
In the Base Case, which reflects the combined implementation of the EU ETS 1 extension to maritime and the FuelEU Maritime Regulation, TtW CO_2 emissions from the EU maritime transport sector are projected to decline significantly over the period to 2050. Compared to 2015/2020 levels temporarily increase by approximately 2 % in 2030, 20 % in 2040 and 75 % in 2050. This downward trajectory is driven by the combined effect of carbon pricing and GHG intensity reduction mandates, which stimulate a shift toward RLCFs as well as improvements in energy efficiency, both operational and technical, as captured endogenously by the model.

The share of emissions from the production and transportation of maritime fuels (WtT), represent about 15 % of total lifecycle emissions in the period up to 2030, increasing gradually in the period leading to 2050, from 16 % to 30 %. The increase in their overall contribution is due to the penetration of biofuels that are associated with emissions at the production phase. This demonstrates the significant contribution that the EU maritime sector may have in inducing emissions along the supply chain. In the modelling, synthetic fuels production is not associated with emissions as their production is based on renewable hydrogen production and biogenic carbon or carbon capture from the air. Slippage emissions increase their share from around 2 % in the period 2015-2030 up to 2050, owing to the higher penetration of biomethane and clean gas in the energy mix.

Figure 12 further presents projections that suggest that the maritime categories covered by the EU ETS 1 still emit approximately 54.5 $MtCO_2eq$ in 2040 and 12.1 MtCO2eq in 2050. Under the continuation of the current Linear Reduction Factor (LRF), set at 4.3 % from 2024 and increasing to 4.4 % from 2028, the emissions cap under the EU ETS 1 would approach zero by around 2040. In this context, the GHG intensity targets set by the FuelEU Maritime Regulation emerge as the primary driver of emissions reductions in the sector. At the corresponding EU ETS 1 price levels, there is no overshoot in emissions, meaning that any residual maritime emissions are offset elsewhere in the energy system, such as through negative emissions from supply-side technologies (for example carbon capture and storage) or removals in the Land Use, Land Use Change and Forestry (LULUCF) sector. It is important to note that the IMO has established indicative emission reduction checkpoints and, as of April 2025, agreed on a (draft) binding Global Fuel Intensity (GFI) standard aimed at achieving near-zero emissions by around 2050, as part of the NZF, which has yet to be adopted. However, the Base Case and the scenarios assessed in this study do not incorporate these recent targets or checkpoints. In view of this, the projected emissions reductions, particularly for international maritime transport and the large vessels covered by the EU ETS 1, are likely conservative. Inclusion of the IMO measures would further accelerate the decarbonisation trajectory, given the substantial overlap in scope between these global standards and the EU policy framework. By 2050, the maritime segments currently covered by the EU ETS 1 are projected to account for about one-fifth of total GHG emissions from the EU maritime sector. The remaining emissions (approximately 43 $MtCO_2eq$) remain substantial, underscoring the need for further mitigation efforts. These could involve expanding the scope of existing policies to cover currently excluded segments or compensating for residual emissions through negative emission solutions elsewhere in the energy system.

Following the projection of the energy mix in the sensitivity variants, the Base Case GHG emissions trajectory does not exhibit a difference between the high- and low-price trajectory.

Figure 12: GHG emissions of international maritime transport by emission category (Well-to-Tank, Tank-to-Wake, Slippage), in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

Note: EU ETS 1 maritime transport emissions (yellow line) include TtW emissions of EU shipping segments and sizes covered under EU ETS 1 – that is, large vessels in international and national maritime transport, and voyage scope – 100 % domestic and intra-EU voyages and 50 % extra-EU voyages

4.2 Assessment of individual and combined policy impacts

This section assesses the impact of the key decarbonisation policies (specifically the EU ETS 1 extension to maritime and the FuelEU Maritime Regulation) by comparing counterfactual scenarios in which these policies are individually or jointly removed from the Base Case. The results are presented in a comparative manner to isolate and quantify the contribution of each policy to emissions reduction, fuel mix evolution, and energy use across the maritime sector. Additional indicators on technical efficiency and cost evolution are also presented to highlight broader economic and policy-relevant dimensions of the analysis. The scenarios presented in this section are Scenario 2 (removal of both EU ETS 1 extension to maritime and FuelEU

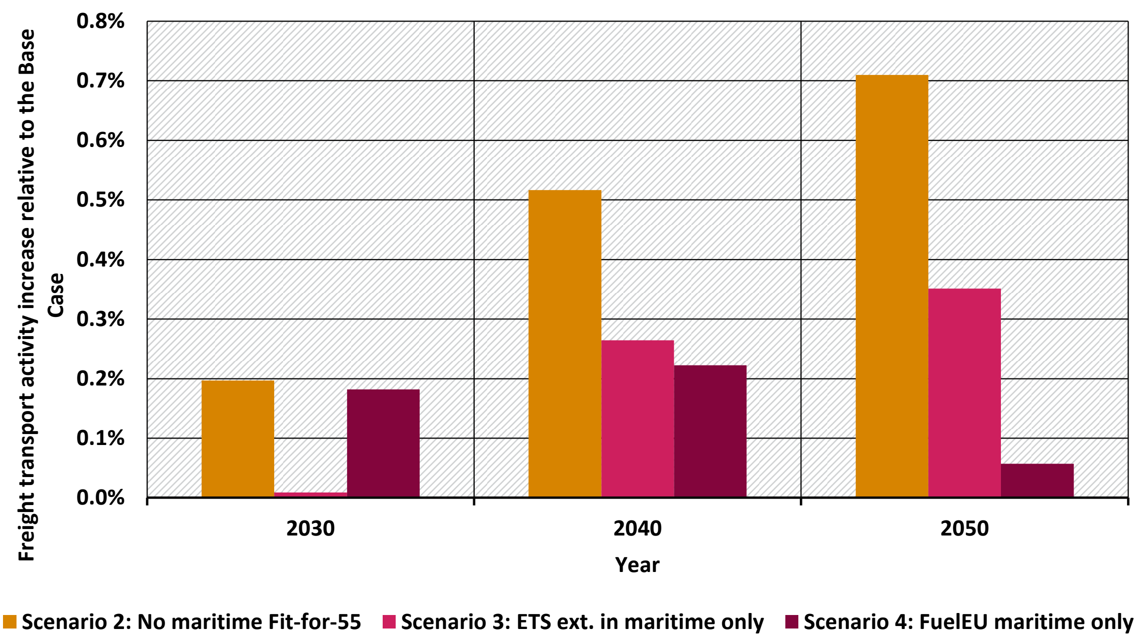
Maritime Regulation), Scenario 3 (removal of FuelEU Maritime Regulation) and Scenario 4 (removal of EU ETS 1 extension to maritime).

4.2.1 Impact on activity

The influence of the different policies on activity is presented in Figure 13 for freight maritime transport, it being responsible for more than 90 % of energy consumption of the EU maritime sector (Section 4.1.2). Changes in activity are primarily driven by differences in total cost of the maritime segment between the Scenarios and the Base Case (see also Section 4.2.4 on costs comparison with other Scenarios). The removal of both “Fit-for-55” policies (Scenario 2) is projected to lead in the highest increase in activity relative to the Base Case to a maximum 0.7 % in 2050. In the absence of regulatory drivers, the sector benefits from lower fuel costs due to the lack of carbon pricing and mandates that would otherwise promote more expensive alternative fuels. Furthermore, reduced investment needs in new technologies also lower the capital expenditures allowing for operators to grow their activity compared to the Base Case.

By contrast, the other scenarios lead to smaller changes in activity, as they maintain part of the regulatory cost burden. Between them, the introduction of FEUM alone (Scenario 4) is projected to lead to the lowest increase in activity compared to the Base Case, indicating that the regulation on its own imposes a higher share of additional costs. Nevertheless, the overall cost differences remain modest (see Section 4.2.4) and have a limited impact on maritime activity. This is because activity levels are mainly shaped by macroeconomic drivers, such as GDP, international fuel prices, and bilateral trade flows, which remain the same across scenarios.

Figure 13: Freight transport activity of the EU shipping sector by Scenario relative to the Base Case, in 2030, 2040 and 2050



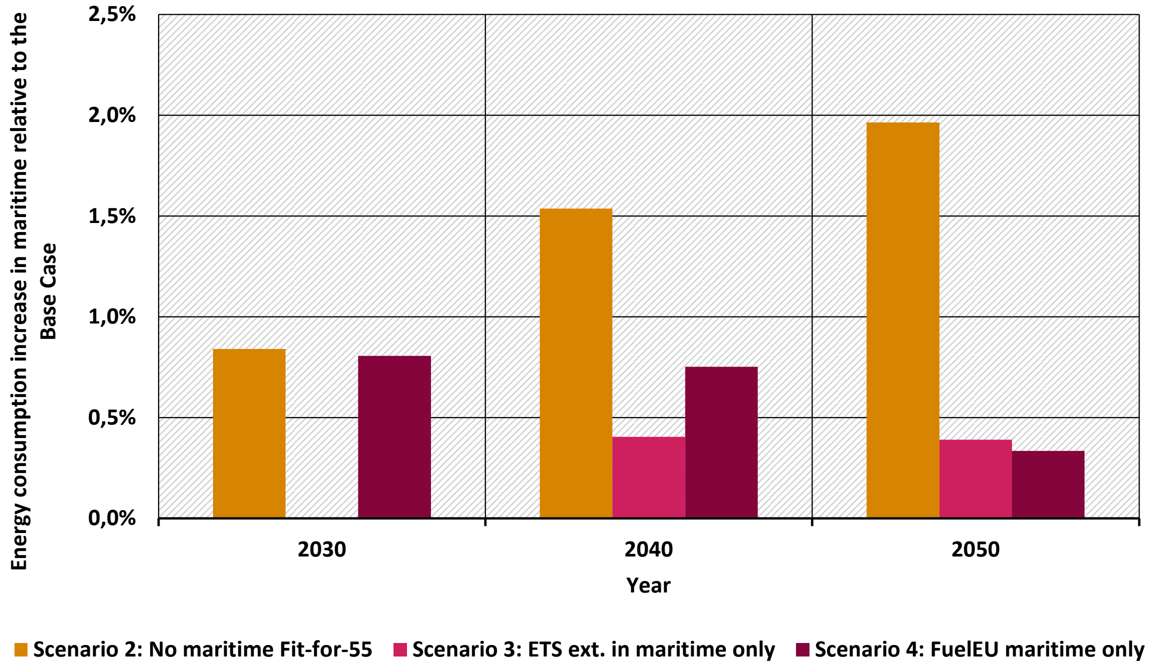
Source: PRIMES Maritime & PRIMES-TREMOVE

4.2.2 Impact on energy consumption and fuel mix

The slight increase in maritime transport activity observed in the three scenarios (Figure 13) is projected to lead to a corresponding rise in energy consumption by the sector. Compared to the

Base Case, additional energy demand reaches up to 0.4 Mtoe in 2030 and up to 1 Mtoe in 2050, depending on the scenario (Figure 14).

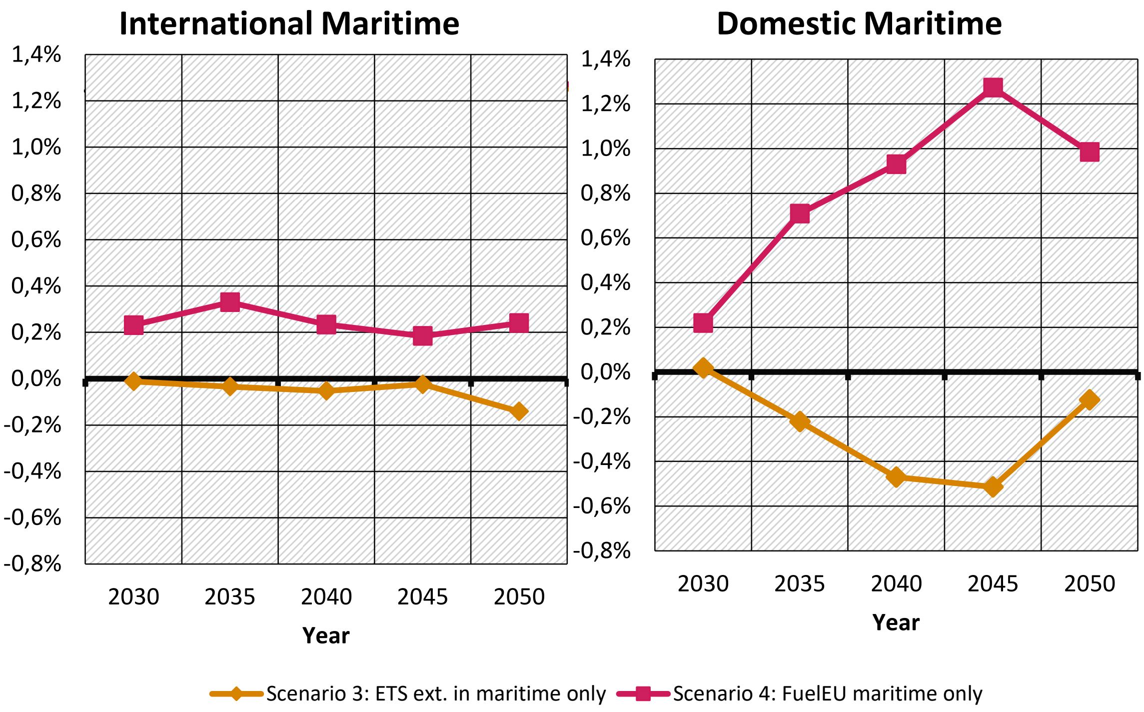
Figure 14: Energy consumption in EU maritime transport by Scenario relative to the Base Case, in 2030, 2040 and 2050



Source: PRIMES Maritime & PRIMES-TREMOVE

While the increase in energy use broadly follows the trend in transport activity, a closer comparison between Scenario 3 (removal of the FuelEU Maritime Regulation) and Scenario 4 (removal of the EU ETS 1 extension to maritime) suggests that the former is projected to lead to a slightly lower energy intensity (toe/tkm), by 0.6 % in 2030 and 0.2 % in 2050 for the overall freight maritime segment. When disaggregated, the exclusion of the EU ETS 1 from the Base Case leads to an increase in energy intensity of 0.2 % to 0.3 % for international maritime transport and 0.2 % to 1.2 % for domestic maritime transport (Figure 15). The decrease of energy intensity serves here as a key indicator of technical and operational efficiency improvements in the sector. Notably, the relative improvement would be greater in large vessels, that is, those directly impacted by the EU ETS 1. In Scenario 3, higher efficiency gains are observed compared to the Base Case, primarily driven by the EU ETS 1. Although total fuel costs are higher in the Base Case, reflecting the deeper emission reductions achieved, the share of EU ETS 1-related costs are proportionally greater in Scenario 3. This stronger cost signal incentivises the adoption of lower energy intensity options within the sector, resulting in greater technical and operational efficiency improvements. These results suggest that the inclusion of the EU ETS 1 promotes early efficiency gains in the freight maritime fleet. Although the annual improvement rates may appear modest, their cumulative impact over time contributes meaningfully to sectoral decarbonisation, also in terms of costs.

Figure 15: Energy intensity improvements in EU maritime freight transport relative to the Base Case (= 0 %)



Source: PRIMES Maritime & PRIMES-TREMOVE

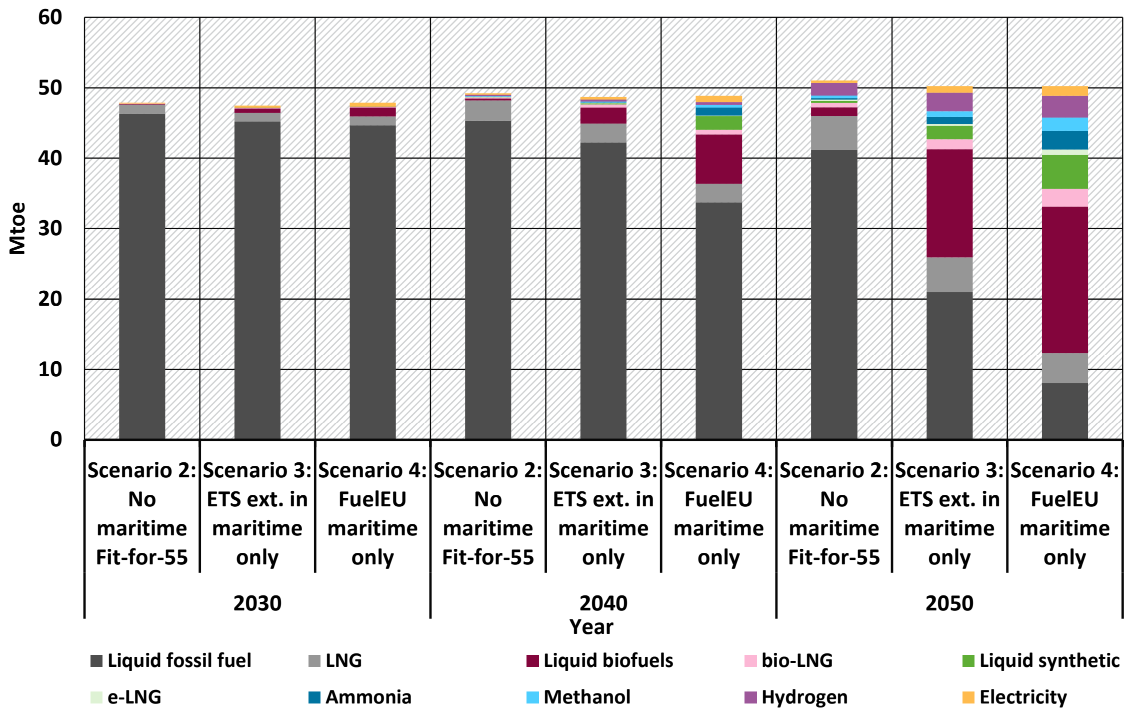
While total energy demand remains relatively close to the Base Case across all scenarios, there are marked differences in the uptake of renewable and low-carbon fuels, particularly over the long term (Figure 16). However, in Scenario 2 (removal of both “Fit-for-55” policies), these fuels do not significantly penetrate the maritime fuel mix due to the absence of regulatory drivers, as their relative cost-competitiveness with fossil fuels remains the main determining factor in the model’s fuel choice mechanism. As a result, by 2050 the maritime energy demand in Scenario 2 remains heavily reliant on conventional fossil fuels (more than 90 %, including LNG), and with only marginal uptake of renewable and low-carbon fuel alternatives (Figure 17). This outcome demonstrates the importance of targeted policy on the maritime sector in order to diversify its fuel mix and reduce its emissions.

Scenario 3 reflects the removal of the FuelEU Maritime Regulation from the Base Case, thereby isolating the impact of the EU ETS 1 as the primary policy driver. In this scenario, the implied carbon pricing increases the cost of fossil fuels perceived by maritime agents, enhancing the relative attractiveness of renewable, low-carbon fuel options within the model’s optimization process. Specifically, the renewable and low-carbon fuel uptake increases substantially owing to the EU ETS 1 driver in both the short-term and in the long-term.

In 2030, the introduction of the EU ETS 1 (Scenario 3) is projected to lead to a 3.6-fold increase in the uptake of renewable and low-carbon fuels (RLCFs) compared to Scenario 2. This includes an additional 0.5 Mtoe of biofuels and bio-LNG, largely displacing fossil fuels, along with a modest increase in electricity use (0.2 Mtoe). By 2050, the share of RLCFs in the maritime fuel mix rises to nearly 50 %, covered primarily by biofuels, hydrogen, liquid e-fuels, and bio-LNG; together they account for almost 90 % of the RLCF composition.

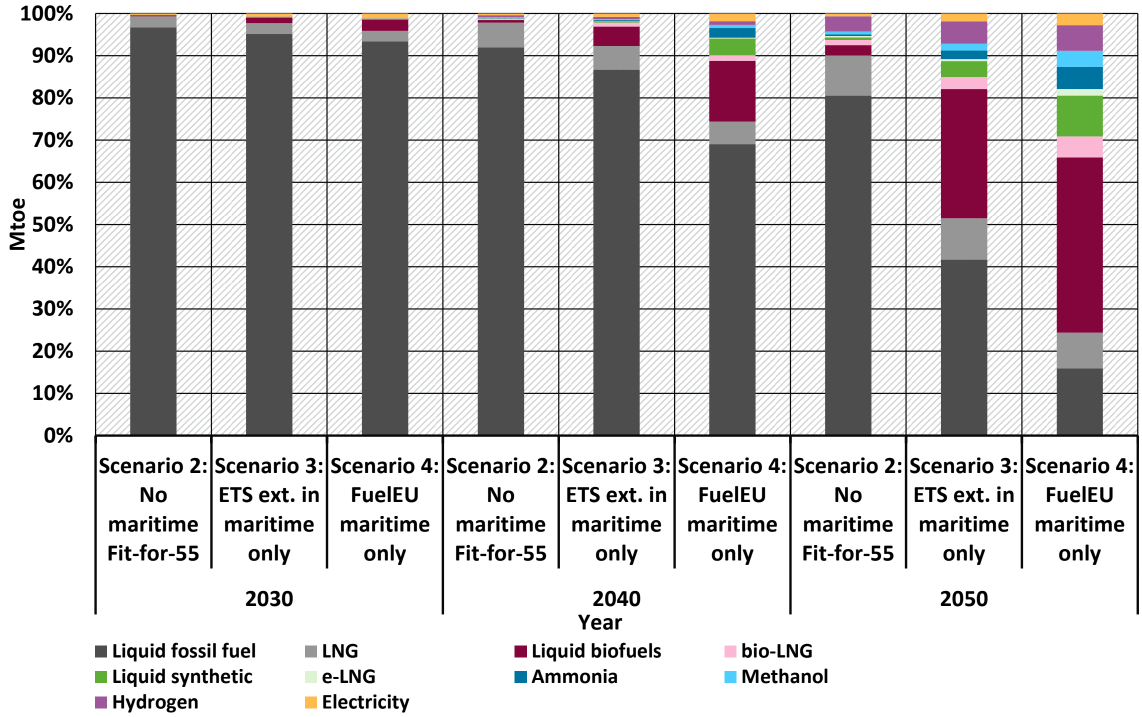
The carbon price introduced through the EU ETS 1 provides a strong market signal that supports the decarbonisation of the maritime sector. The FuelEU Maritime Regulation introduces a complementary mandate that further drives the uptake of RLCFs to meet its set GHG intensity reduction target of 80 % by 2050 (Scenario 4). In addition to the alternative fuel uptake already induced by the EU ETS 1, Scenario 4 projects approximately 56 % higher RLCF demand relative to Scenario 3, to the detriment of fossil fuels. This additional demand is equally split between RFNBOs, and biofuels (including bio-LNG), increasing by 6.6 Mtoe each in 2050. The relatively higher share of RFNBOs in Scenario 4 compared to Scenario 3 (35 % versus 27 % of the RLCF mix in 2050) is partly due to the way the compliance incentives under the FuelEU Maritime Regulation are reflected in the scenario framework. The regulation is enforced in the model by applying a penalty whenever the GHG intensity target is not met. This penalty increases gradually in each simulation round until the fuel mix complies with the target, while accounting for the full lifecycle emissions of each fuel (WtW). Since RFNBOs have no upstream emissions, they are penalized less than biofuels, which do carry upstream emissions. As a result, the model selects more RFNBOs, leading to a higher share under the FuelEU Maritime Regulation.

Figure 16: Energy consumption of the EU shipping sector of EU by fuel type and Scenario in 2030, 2040 and 2050



Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 17: EU maritime fuel mix by fuel type and scenario in 2030, 2040 and 2050



Source: PRIMES Maritime & PRIMES-TREMOVE

The carbon price sensitivity variants affect only Scenario 3, as it is the only scenario in which carbon pricing is applied. In these variants, changes in the carbon price trajectory lead to a shift in the fuel mix between fossil fuels and RLCFs, depending on whether the carbon price is lower or higher than the Base Case trajectory. For instance, in 2040, a 15 % carbon-price increase in 2040, leads to a 20 % increase of RLCFs in the mix (0.8 Mtoe) and in contrast a 38 % carbon-price reduction leads to almost 50 % reduction of RLCFs (1.8 Mtoe). In 2050, a 27 % carbon-price increase leads to an 11 % increase of RLCFs in the mix (2.8 Mtoe) compared to Scenario 3 base-carbon price trajectory projections ("see Annex – Analytical scenario results"). This illustrates the marked effect that carbon price trajectories have on the uptake of RLCFs and their corresponding impact on GHG emissions (Section 4.2.3) and fuel costs (Section 4.2.4).

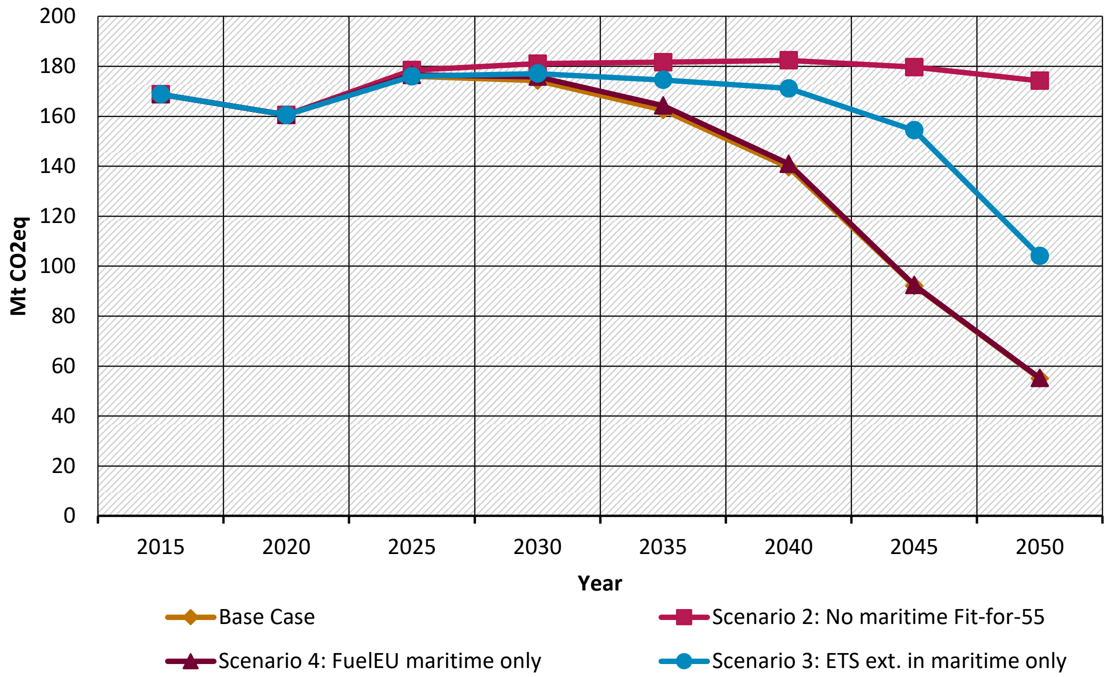
4.2.3 Impact on GHG emissions

In the following, trajectories of GHG emissions are presented for the Base Case and the different scenarios. Figure 18 presents WtW emissions (FEUM scope), whereas Figure 19 isolates TtW emissions under EU ETS 1 scope. These figures present emissions only, which are primarily driven by FEUM's binding GHG intensity targets, or in the absence of which by the EU ETS 1 only. When both measures are applied, EU ETS 1 does not alter this trajectory but influences cost structure, efficiency improvements, and revenue generation, factors not captured in emissions-only comparisons. In the Base Case, ETS incentivizes early adoption of technical and operational measures, narrowing the cost gap between fossil and renewable fuels and enabling a lower-cost decarbonisation pathway.

Scenario 2 and Scenario 3 result in distinct GHG emissions reduction trajectories compared to the Base Case, each achieving varying levels of abatement over the projection period (Figure 18). Most notably, in the absence of the "Fit-for-55" policies, Scenario 2 leads to more than triple the emissions of the Base Case by 2050, 174 $MtCO_2eq$ versus 55 $MtCO_2eq$. This outcome clearly demonstrates that, without targeted climate policies, the maritime sector falls significantly short of contributing to the EU's emissions reduction and net zero objectives.

The inclusion of maritime transport in the EU ETS 1, under the carbon price assumptions used in this study, is projected to lead to a substantial emissions reduction, ranging from 2 % in 2030 to 40 % by 2050 relative to the Base Case. This significantly narrows the gap with the GHG intensity targets set by the FuelEU Maritime Regulation. However, even at these price levels, a notable price gap remains between renewable low- and zero-carbon fuels and their fossil fuel counterparts (see also Figure 32 in Section 5). Under such price levels, the FEUM mandate plays a critical complementary role in reinforcing the carbon price signal and guiding the sector toward decarbonisation pathways consistent with the EU Green Deal targets. Within the EU ETS 1 price range applied here, FEUM's WtW intensity targets remain binding for the fuel mix, which is illustrated by the similar trajectory of Base Case and Scenario 4. Both the Base Case and Scenario 4 comply with the FEUM GHG intensity target, which is binding in both cases. As a result, the emissions trajectory remains similar, while differences arise in the fuel mix and technology choices. If the FEUM penalty were applied as an explicit cost component, the trajectory could vary more substantially. EU ETS 1, however, primarily amplifies efficiency and affects cost profiles rather than driving additional fuel switching beyond FEUM compliance.

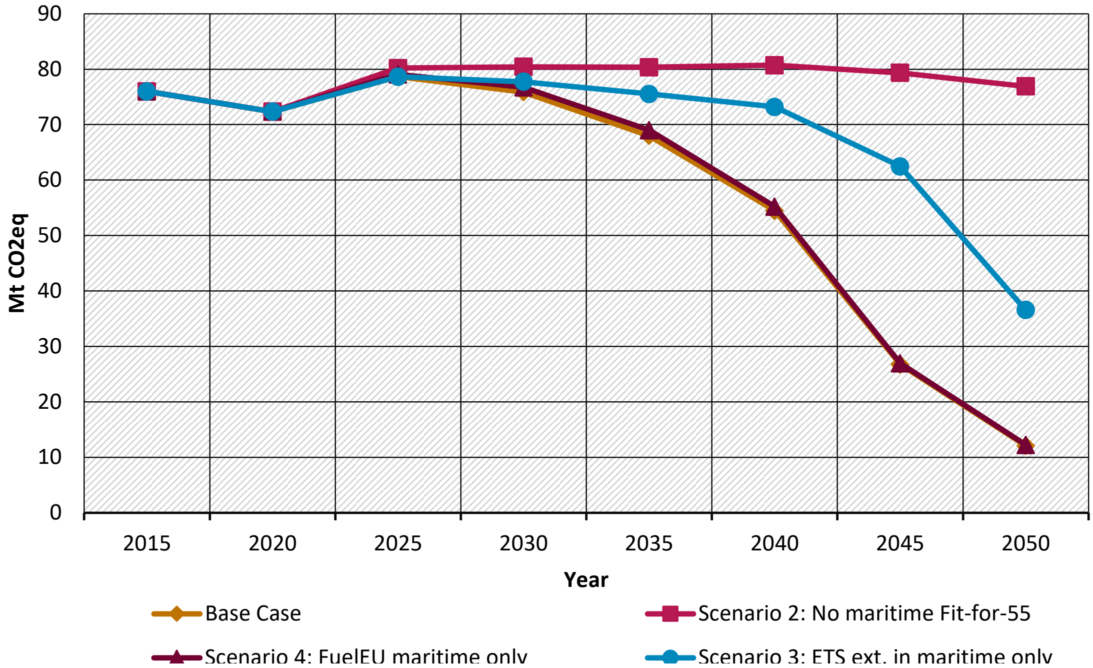
Figure 18: Well-to-Wake GHG emissions of the EU shipping sector by Scenario (WtW emissions from all EU shipping segments and sizes (large vessels, small vessels, international and national maritime transport, inland waterways) and voyage scope (100 % coverage of all voyages)



Source: PRIMES Maritime & PRIMES-TREMOVE

Similar insights emerge when focusing specifically on emissions within the scope of the EU ETS 1 (that is, TtW emissions only) (Figure 19). Scenario 3 demonstrates an even greater impact, achieving a 50 % reduction by 2050 compared to 40 % in terms of total (full scope in emissions and segments) GHG emissions. However, this pattern also holds for the Base Case and Scenario 2, where emissions under the EU ETS 1 scope are consistently higher than the total GHG emissions share, reflecting the concentration of regulatory pressure and mitigation efforts on the covered segments.

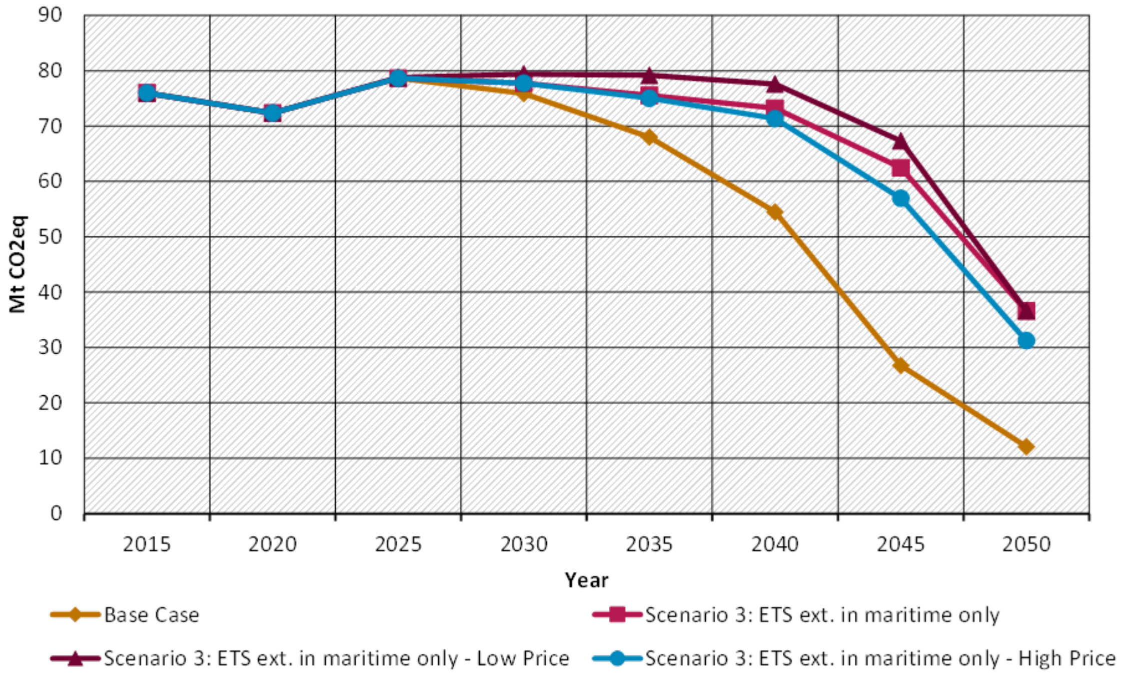
Figure 19: Tank-to-Wake GHG emissions in the scope of the EU ETS 1 extension to maritime by Scenario (TtW emissions of EU shipping segments and sizes covered under EU ETS 1 – that is, large vessels in international and national maritime transport, and voyage scope – 100 % domestic and intra-EU voyages and 50 % extra-EU voyages)



Source: PRIMES Maritime & PRIMES-TREMOVE

The influence of the carbon price trajectory in Scenario 3, is evident as due to the price signal the RLCFs relative competitiveness to fossil fuels is affected, ultimately driving the uptake of clean energy and the resulting emissions (Figure 20). For instance, using the high-carbon price trajectory prices, for a 27 % carbon price increase in 2050, the TtW emission reduction increases by 14 %. The low-carbon price trajectory converges with that of Scenario 3 in 2050, however, owing to the lower carbon price in the preceding period (20 % - 50 % depending on the period) the emissions trajectory is different, affecting cumulative savings.

Figure 20: Tank-to-Wake GHG emissions in the scope of the EU ETS 1 extension to maritime in the carbon-price sensitivity variants

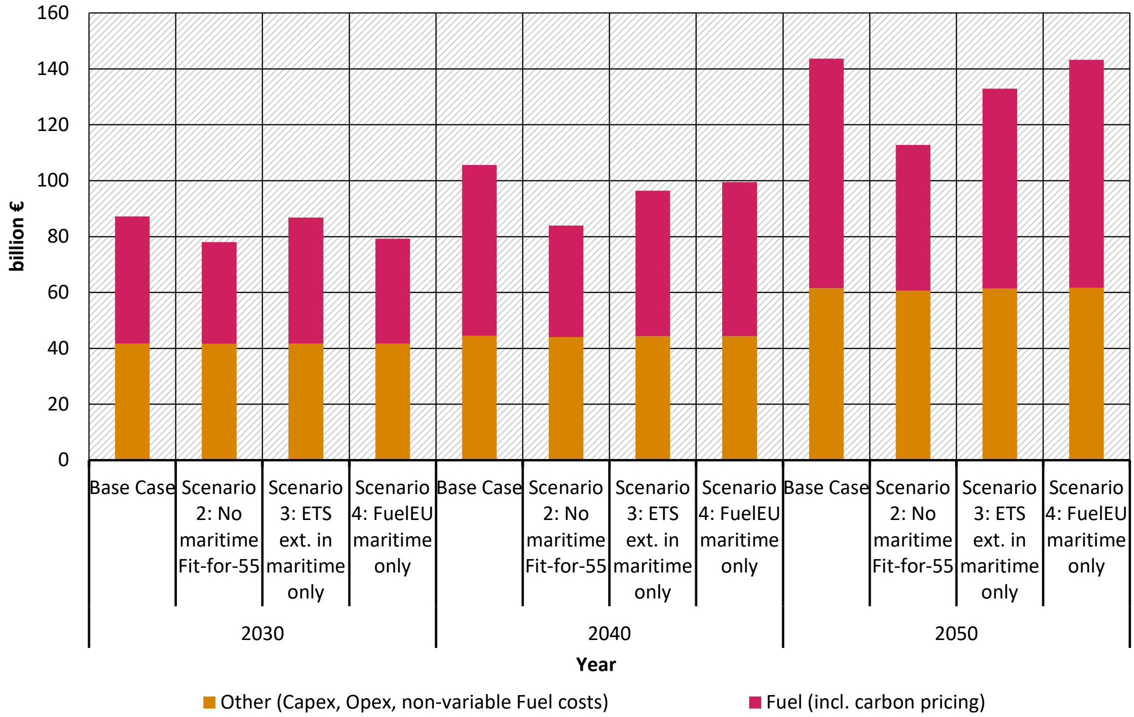


Source: PRIMES Maritime & PRIMES-TREMOVE

4.2.4 Impact on costs

The analysis presented below (Figure 21) reflects the total system costs of the EU international maritime transport sector for key milestone years over the projection period. Depending on the scenario, total system costs range from 78 to 87 billion euro (bn EUR) in 2030, 83 to 105 bnEUR in 2040, and 112 to 143 bnEUR in 2050. As discussed in Section 4.2.3 the emission reduction trajectories differ across scenarios (with only the Base Case and Scenario 4 achieving similar levels of reduction, as per scenario design), which largely explains the variation in total costs. These differences are primarily driven by the degree of uptake of alternative fuels in the maritime fuel mix. Scenario 2, which excludes both “Fit-for-55” policies, is projected to lead to the lowest total system costs, with the share of RLCFs ranging from just 0.5 % to 9.5 % over 2030–2050. In contrast, the Base Case and Scenario 4 show the highest total costs, with RLCFs accounting for 4 % in 2030 to 75 % in 2050 of the fuel mix. Across scenarios and years, fuel-related costs, including EU ETS 1 payments, where applicable, make up between 46 % and 58 % of total system costs.

Figure 21: Total system costs of the EU maritime sector by Scenario



Source: PRIMES Maritime & PRIMES-TREMOVE

Scenario 4 (which includes only the FuelEU Maritime Regulation) presents lower total costs than the Base Case in the initial period, despite achieving the same emission reduction target. This outcome is primarily explained by the fact that the Base Case includes EU ETS 1 payments as an explicit fuel cost component, whereas in Scenario 4, compliance costs are modelled implicitly. In Scenario 4, the effort required to meet the GHG intensity target is captured through a penalty factor that represents indirect costs, rather than actual monetary payments by the maritime segment. With pre-tax fuel prices being the same between scenarios, these shadow costs reflect the policy effort needed to drive the uptake of RLCFs and are part of the model's internal compliance mechanism (see also Section 2.2.2). While both the Base Case and Scenario 4 include such implicit costs, they are notably higher in Scenario 4, ranging from 30 % to more than 60 %, depending on the time period.

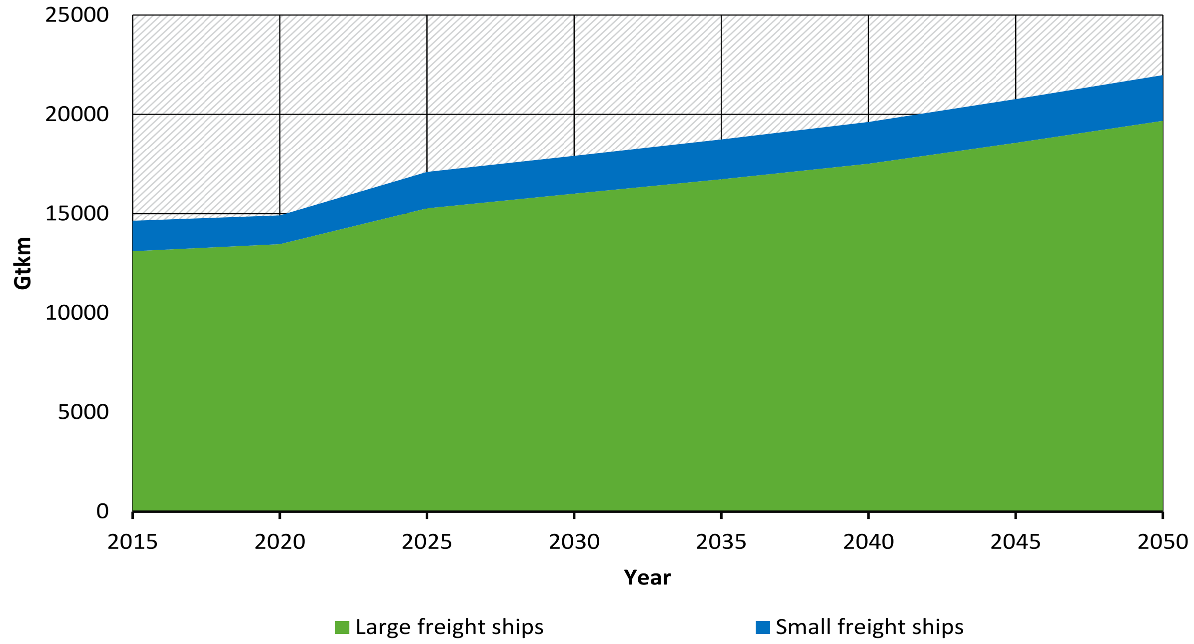
When both direct (EU ETS 1 payments) and indirect (penalty-based) compliance costs are considered, the modelling suggests that up to 2035 the carbon price applied under the EU ETS 1 is aligned with the shadow cost of FEUM. This is projected to lead to a similar fuel mix and level of technology uptake across the two scenarios. However, beyond 2035, the EU ETS 1 drives further improvements in fleet efficiency by incentivizing the adoption of technical and operational measures (see Section 4.2.2), setting the sector on a lower-cost decarbonisation pathway. These efficiency gains, combined with both direct and indirect cost savings, have compounding effects over time, further reinforcing the cost-effectiveness of the trajectory.

4.3 Extending EU ETS 1 coverage to additional maritime segments

4.3.1 Extending EU ETS 1 coverage to small vessels (< 5,000 GT)

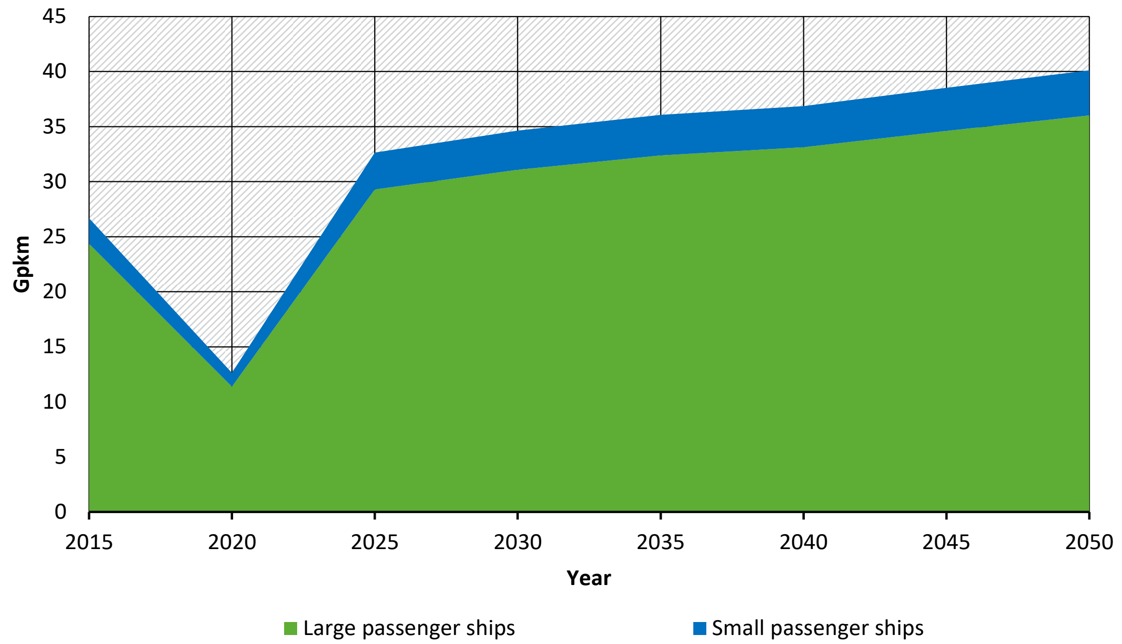
The majority of freight and passenger transport activity (approximately 90 % throughout the projection period), is carried out by large ships (Figure 22 and Figure 23). This nonetheless leaves a significant share of emissions unaddressed by the current policy framework. According to projections from the Base Case scenario (Figure 24), emissions from small vessels are estimated at 25 $MtCO_2eq$ in 2020, declining to 18 $MtCO_2eq$ by 2050. Although small vessels benefit indirectly from spillover effects driven by decarbonisation policies targeting large vessels, their relative contribution to sectoral emissions increases over time. By 2050, small vessels are projected to account for roughly one-third of total emissions from the EU maritime sector, from about 15 % today.

Figure 22: Freight transport shipping activity of the EU by ship size category, in the Base Case



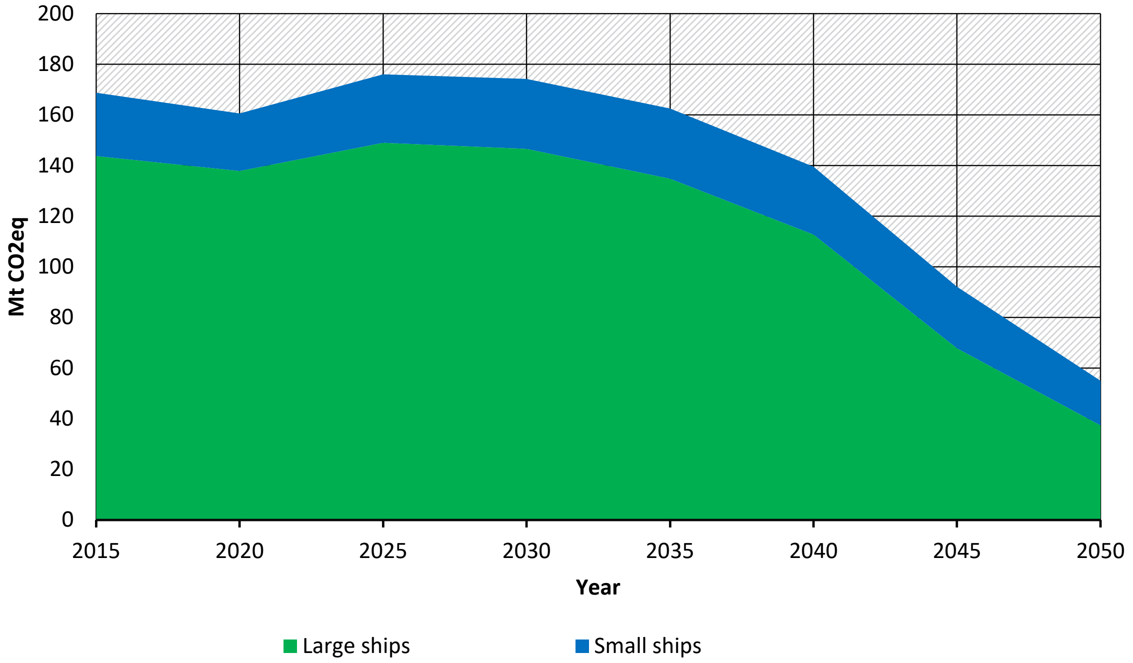
Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 23: Passenger transport shipping activity of the EU by ship size category, in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 24: GHG emissions of the EU shipping sector by size segment in the Base Case



Source: PRIMES Maritime & PRIMES-TREMOVE

Extending the coverage of the EU ETS 1 to include the small vessel segment of the EU international and domestic maritime transport sector, while keeping it outside the scope of the FuelEU Maritime Regulation (quantified in Scenario 5), can be expected to generate price-induced effects that incentivise cleaner fuel choices and promote technical and operational efficiency improvements among ship operators.

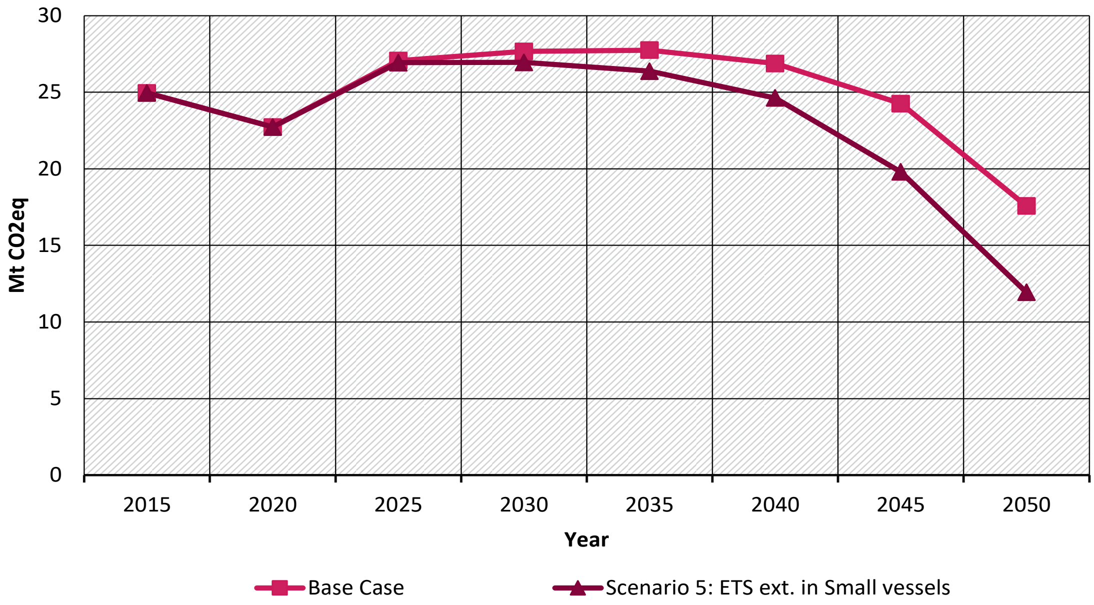
Due to the relatively small contribution of the segment to total maritime activity, the inclusion of small vessels in the EU ETS 1 leads to a limited reduction in overall activity compared to the Base Case (that is, less than 0.2 %). In relative terms, the impact on activity from including small vessels in the EU ETS 1 is smaller than the effects observed in Scenario 2, which removes the "Fit-for-55" policies from the Base Case. This is because the small vessel segment is already partially decarbonized due to spillover effects from the decarbonisation of the large vessel segment. As a result, carbon pricing has a comparatively lower influence on the total cost structure for small vessels, resulting in a more limited impact on their activity levels.

In Scenario 5, the additional uptake of renewable and low-carbon fuels compared to the Base Case amounts to 0.18 Mtoe in 2030 and 1.6 Mtoe in 2050 (Figure 25). This increase is primarily composed of biofuels (0.8 Mtoe), RFNBOs (0.5 Mtoe, used as e-fuels, methanol, or hydrogen), and electricity (0.2 Mtoe), all in 2050. Gaseous fuels and ammonia are not further adopted as decarbonisation options by small vessel operators EU ETS 1 due to their limited cost-effectiveness and technological suitability for this segment.

Although the additional uptake of RLCFs in Scenario 5 is small in absolute terms relative to total maritime fuel consumption, it is not negligible for the small vessels segment. By 2050, this additional uptake represents approximately 25 % of the energy demand of small vessels. In other words, the extension of the EU ETS 1 to this segment triggers a significant shift, with RLCFs accounting for one-quarter of their total energy use. The overall share of biofuels, RFNBOs and electricity increases by 0.4 % percentage points in 2030 and 3.6 % percentage points in 2050 (Figure 27). The sensitivity scenarios on carbon price trajectories do not impact the fuel mix of the overall EU maritime sector (Figure 26), yet they lead to a higher RLCF uptake of 0.09 Mtoe in 2040 or 0.13 Mtoe in 2050 when carbon price increases by 15 % and 27 %, respectively, or conversely, it reduces by 0.4 Mtoe in 2040 and 0.02 Mtoe in 2050, when carbon price is lower by 39 % in 2040.

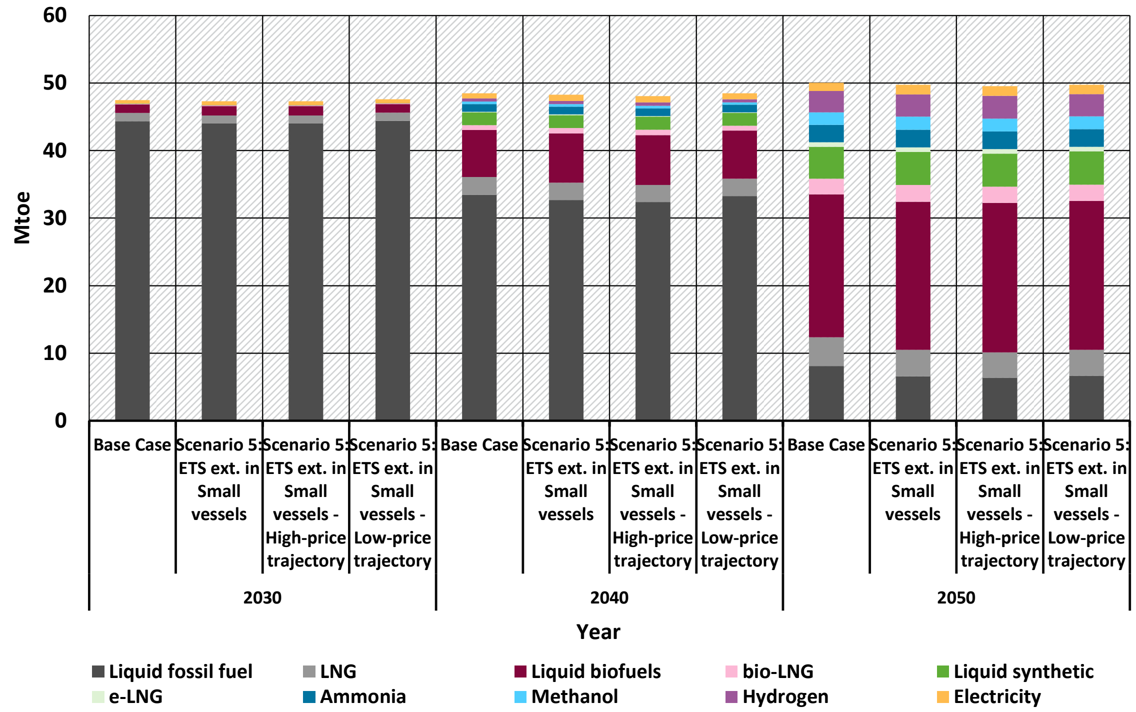
As a result of the penetration of RLCFs in the energy mix of small vessels due to the extension of EU ETS 1 also to small vessels, the segment embarks on a lower emissions trajectory from 2030 onwards (Figure 25). In Scenario 5, GHG emissions are lower by 2.5 % in 2030 to 32 % in 2050. This translates to about 0.7 $MtCO_2eq$ lower in 2030 and 5.5 $MtCO_2eq$ lower in 2050. In 2050, this represents 10 % of the residual emissions in the Base Case.

Figure 25: Well-to-Wake GHG emissions of the EU shipping sector in the Base Case and Scenario 5 (extension of EU ETS 1 to small vessels)



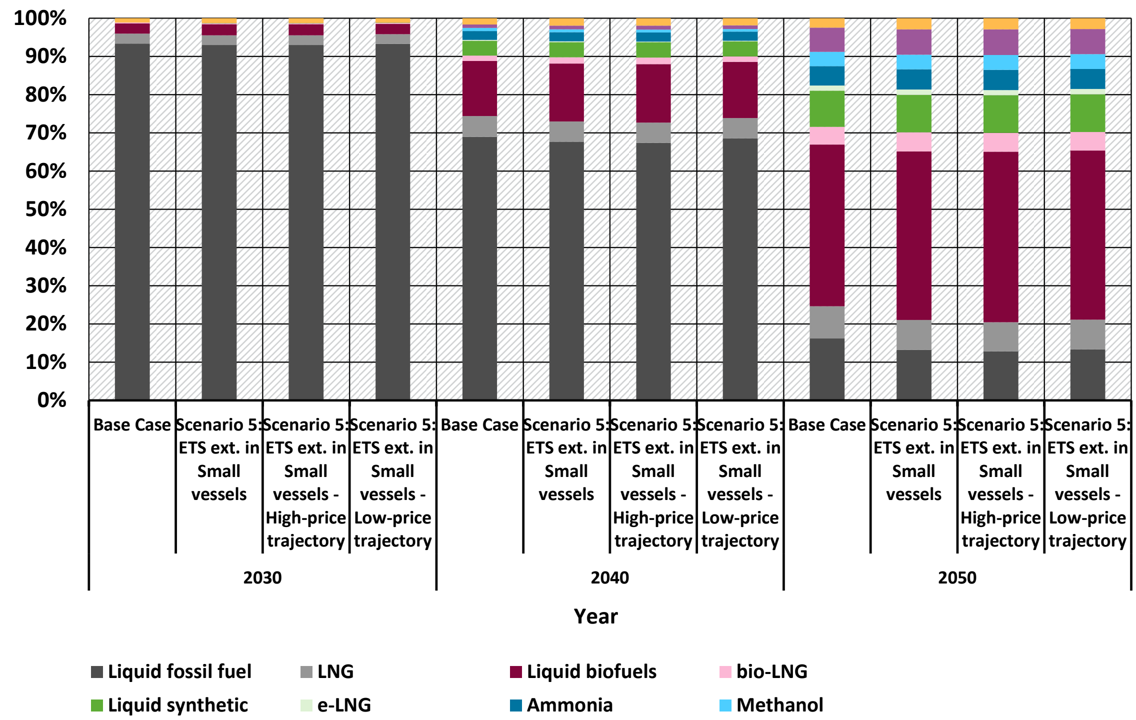
Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 26: Energy demand of the EU shipping sector by fuel type in the Base Case and Scenario 5 (extension of EU ETS 1 to small vessels)



Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 27: Fuel mix of the EU shipping sector by fuel type in the Base Case and Scenario 5 (extension of EU ETS 1 to small vessels)



Source: PRIMES Maritime & PRIMES-TREMOVE

4.3.2 Extending EU ETS 1 coverage to inland waterway vessels (> 5,000 GT)

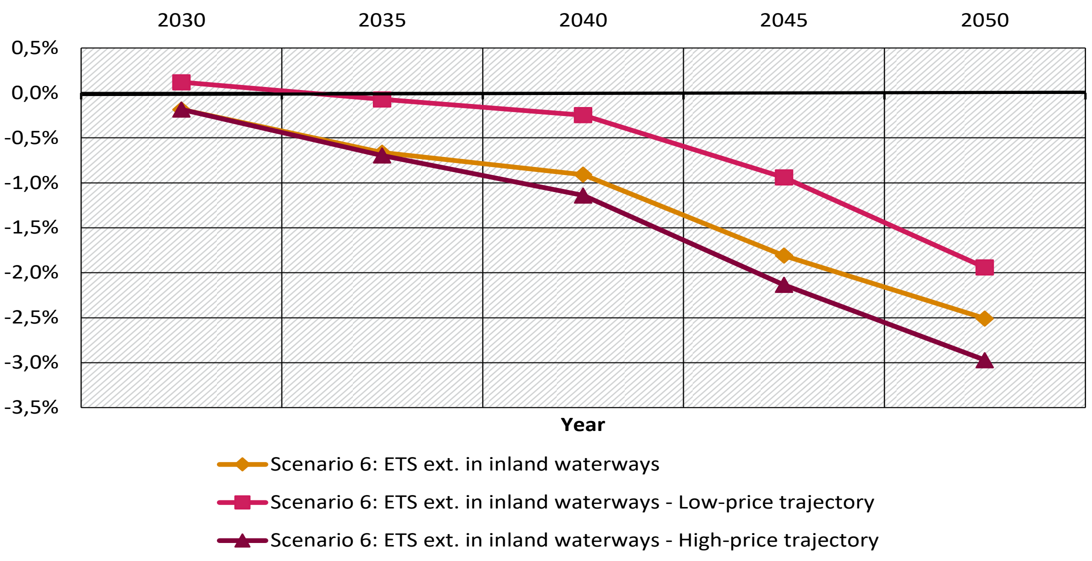
The EU inland waterways segment is relatively small compared to the freight (tonne-kilometres) and passenger (passenger-kilometres) activity of the overall EU maritime transport sector. In 2015, it accounted for approximately 1 % of freight activity (Figure 3) and 2 % of passenger (Figure 4) activity within the maritime sector. The segment also consumes about 2 % of maritime energy demand (Figure 5), which corresponds to roughly 2 – 4 % of maritime GHG emissions (Figure 10) throughout the projection period in the Base Case.

In the Base Case, the inland waterways segment is projected to undergo transformation, driven by improvements in energy efficiency and a gradual decarbonisation of the fuel mix. Energy efficiency improves over time as more advanced technologies become commercially mature and are increasingly selected by the model's discrete choice mechanism. As a result, the segment's energy intensity decreases by 20 % in 2050 compared to 2030 (Figure 7). The fuel mix also shifts towards cleaner options: the share of RLCFs increases from 3.8 % in 2020 to 4.4 % in 2030 (alongside a 13 % share of LNG) and reaches 52 % RLCFs by 2050 (Figure 9).

However, despite the shift toward a cleaner energy mix and more efficient technologies, driven by the broader decarbonisation context of the maritime sector and the energy system, inland waterways are still projected to consume around 0.5 Mtoe of liquid fossil fuels in 2050, representing 6 % of total maritime fuel consumption. This is projected to lead to approximately 2 $MtCO_2eq$ emissions. Extending the EU ETS 1 to this segment presents an opportunity to further incentivise decarbonisation and accelerate the uptake of cleaner alternatives. This opportunity is explored with Scenario 6, that applies the EU ETS 1 to the large vessels (5,000 GT) of the EU inland waterways segment.

As shown in Figure 28, the EU ETS 1 may drive further efficiency improvements of the sector by up to 3 % percentage points in 2050 (in the High-price trajectory variant). The inclusion of EU ETS 1 in the segment, results in higher fuel cost savings by improved vessel efficiency and thus, the discrete choice model opts for even more efficient technologies than in the Base Case.

Figure 28: Energy intensity improvement in the EU inland waterway segment in Scenario 6 (extension of EU ETS 1 to inland waterways) compared to the Base Case (= 0 %)

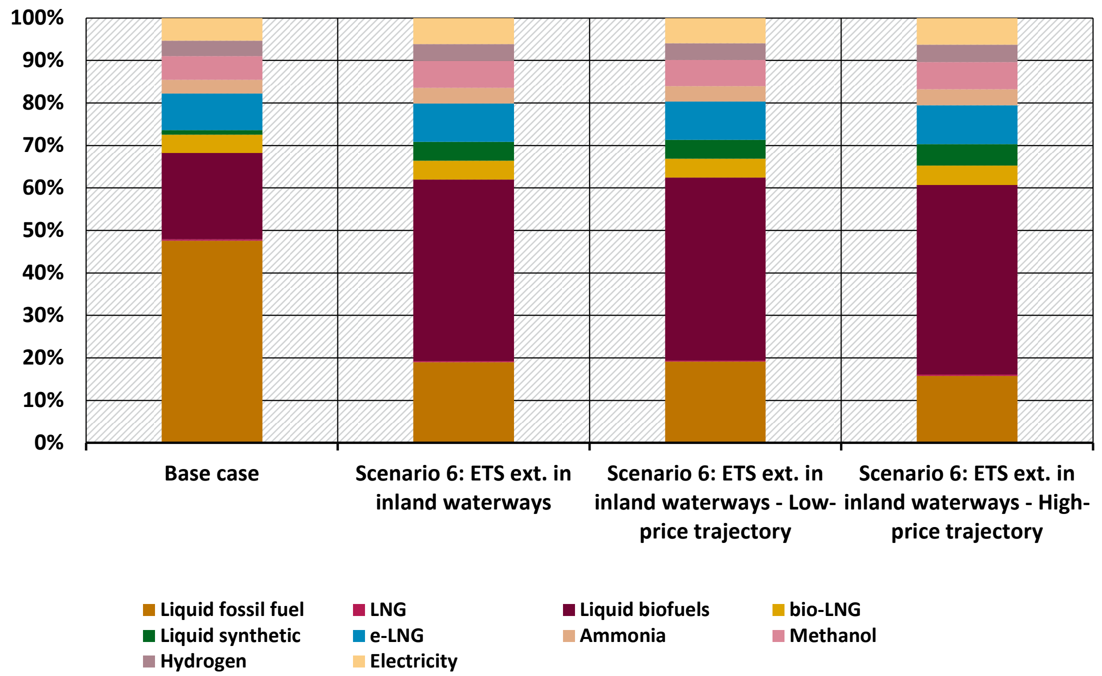


Source: PRIMES Maritime & PRIMES-TREMOVE

The resulting improvements in energy efficiency lead to savings of approximately 0.04 Mtoe in 2050, about 4 % compared to the Base Case (Figure 29) partly driven by a slight reduction in activity due to higher total costs. Variations in the carbon price trajectory do not substantially change this outcome. Under the High-price trajectory, the share of renewable and low-carbon fuels (RLCFs) increases by 3 percentage points relative to Scenario 6, while energy intensity improves by an additional 0.5 percentage points. Overall, the RLCF share in the fuel mix grows significantly, from 52 % in the Base Case to 81% in Scenario 6, and further to 84 % under its high-price variant. Within this segment, biofuels remain the dominant decarbonisation option; combined with bio-LNG, they account for roughly half of the RLCF mix. As a result, the GHG emissions from the segment are practically halved by 2050 compared to the Base Case, from about 2 MtCO2eq to about 1 MtCO2eq (Figure 30). Whilst the different price sensitivity variants have a similar endpoint in 2050, the trajectory differs, something that impacts the cumulative emissions.

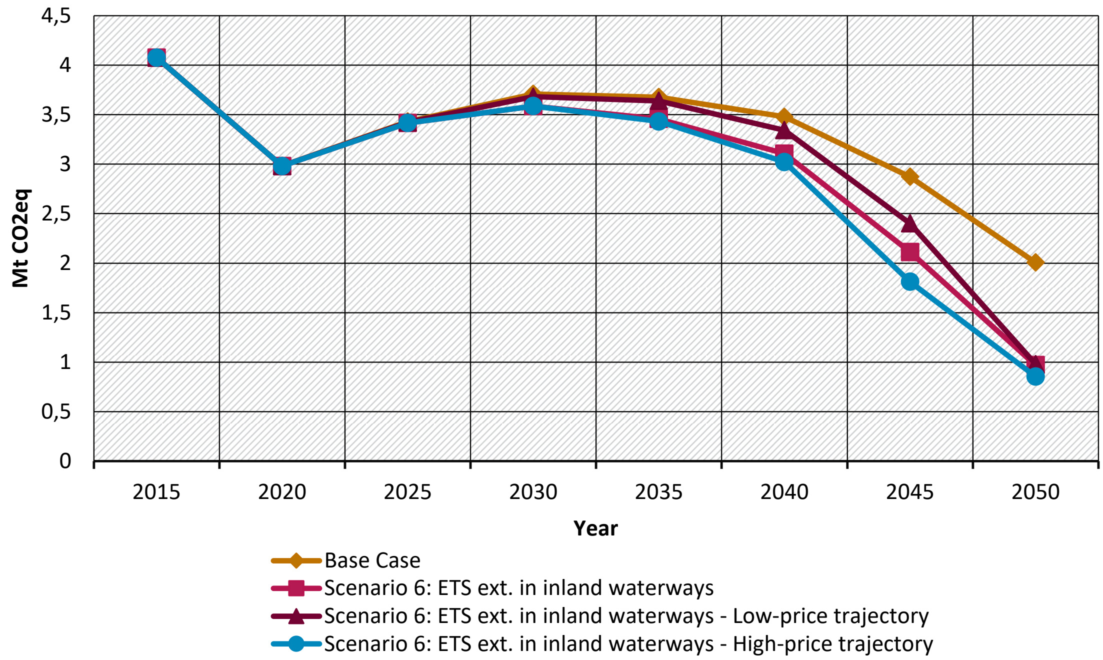
The sensitivity variants have a marginal impact on the segment owing to the high RLCF share already in the Base Case.

Figure 29: Fuel mix of the EU inland waterways segment by fuel type in 2050 in the Base Case and Scenario 6 (extension of EU ETS 1 to inland waterways)



Source: PRIMES Maritime & PRIMES-TREMOVE

Figure 30: Well-to-Wake GHG emissions from inland waterways in the Base Case and Scenario 6 (extension of EU ETS 1 to inland waterways)



Source: PRIMES Maritime & PRIMES-TREMOVE

5 Discussion

Summary of results and conclusions

This study assessed the impact of the extension of the EU Emissions Trading System (EU ETS 1) to maritime transport and the introduction of the FEUM Regulation to incentivize the decarbonisation of the European maritime sector, within the framework of the EU Green Deal targets, their operationalization through the implementation of the "Fit-for-55" policy package and the intermediate target trajectories set by the 2040 Climate Target Plan. First and foremost, the study evaluated the combined contribution of these two key policies in reducing emissions, explored their complementarity, and analysed the potential effects of further extending the EU ETS 1 to currently uncovered maritime segments. It also explored the individual influence of the EU ETS 1 and FEUM.

It therefore shed light on answering the following research questions:

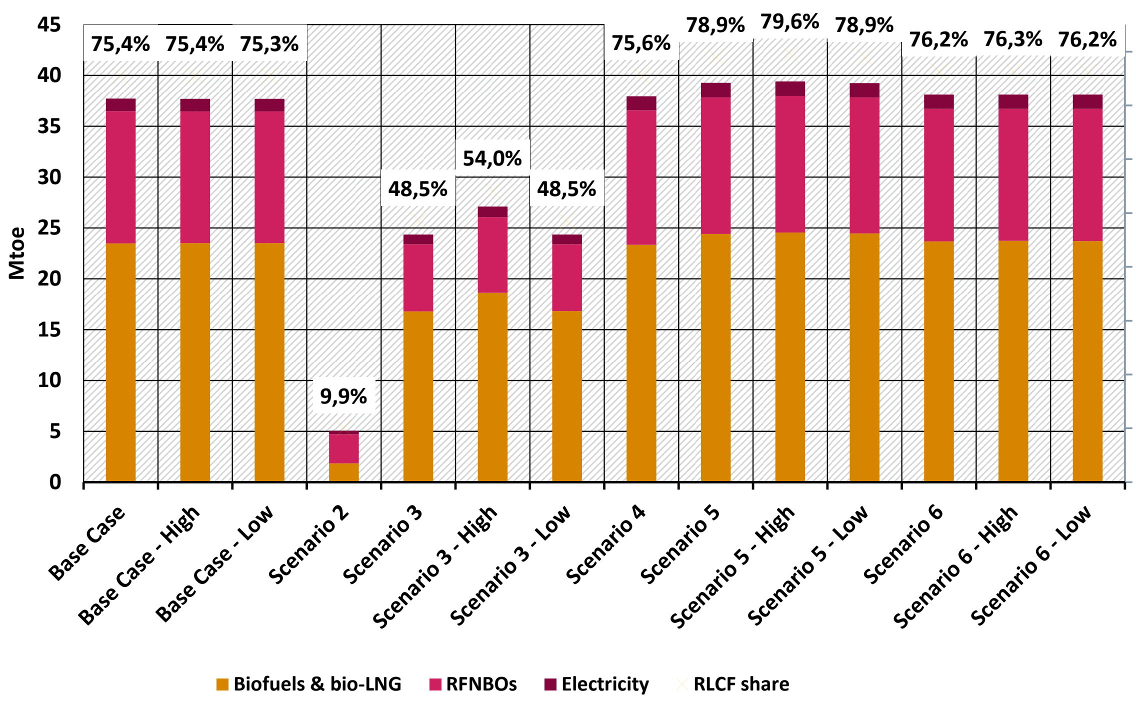
- To what extent do the EU ETS 1 extension to maritime and the FuelEU Maritime Regulation contribute to the decarbonisation of the European maritime transport sector, and
- how do they interact in shaping the decarbonisation trajectory across covered and non-covered segments, as assessed through scenario-based modelling?

decarbonisationThe intuitive expectation examined in this study is confirmed. **The combined implementation of the EU ETS 1 extension to maritime transport and the FuelEU Maritime Regulation accelerates the decarbonisation of the European maritime transport sector, with their joint implementation yielding more benefits than either policy would achieve in isolation.** To support this finding, the study used the PRIMES Maritime and PRIMES-TREMOVE model frameworks under a scenario-based approach. This anticipation stems also from earlier studies, as for example, the impact assessment accompanying the ETS, that attests a positive interaction between the two policies by stating that *"adoption of carbon pricing measures for the maritime sector, in conjunction with other measures such as the FEUM initiative, is expected to promote energy efficiency measures and a higher uptake of sustainable fuels"* (Budaragina et al 2021). Compared to earlier work, the present study takes stock of updates with more recent policy, technical and economic developments since.

The study showed that **both the EU ETS 1 extension to maritime transport and the FuelEU Maritime Regulation are instrumental for the sector to embark on a decarbonisation trajectory.** The modelling results demonstrated that the EU ETS 1 and the FuelEU Maritime Regulation are essential and complementary. The Base Case scenario, which includes both instruments, results in nearly 70 % lower emissions by 2050 compared to a counterfactual without them, supported by a maritime fuel mix reaching 75 % renewable and low-carbon fuels. In contrast, the absence of both policies leaves the sector heavily fossil-dependent, with marginal alternative fuel penetration and system-wide emissions more than tripling. Considering the effect of FEUM alone lacks the additional incentives for efficiency and cost-effectiveness provided by carbon pricing but also results in the lowest increase in activity compared to the Base Case, indicating that the regulation on its own imposes a higher share of additional costs. Considering the effect of the EU ETS 1 alone leads to improved energy intensity of the maritime transport sector. In addition, the Base Case benefits from EU ETS 1 replacing internal shadow penalties with explicit carbon pricing, which improves economic efficiency over time. The apparent similarity between Base Case and FEUM-only scenarios in emissions terms should not be interpreted as marginal EU ETS 1 impact. EU ETS 1 plays a decisive role in improving cost-effectiveness, accelerating early efficiency gains, and generating auction revenues that can be reinvested in the sector. These contributions are not reflected in emissions charts but are essential for policy sequencing and economic viability. Some elements, such as direct revenue recycling are not captured in the analysis presented in the study. The combined implementation of EU ETS 1 and FEUM achieves outcomes neither policy can deliver alone. EU ETS 1 provides market-based incentives and transparency, while FEUM ensures deep decarbonisation through binding targets. The joint implementation of FEUM and the EU ETS 1 provides complementary benefits: FEUM ensures compliance with GHG intensity targets through technology and fuel choices, while the EU ETS 1 introduces a market-based price signal that reinforces these decarbonisation incentives and supports the uptake of near-zero carbon fuels and efficiency improvements. These findings make clear that only through the combined effect of these instruments can the sector effectively embark on, and sustain, a decarbonisation trajectory aligned with EU climate objectives.

The primary decarbonisation lever for the sector is Renewable and Low-Carbon fuels. This holds across all scenarios featuring the EU ETS 1 extension and/or the FuelEU Maritime Regulation (Figure 31). Among RLCFs, the modelling highlights the key role of biofuels, including drop-in biofuels and bio-LNG, as the dominant contributors to near- and medium-term decarbonisation. They make up roughly 50 % of the RLCF mix by 2050, particularly in segments and vessel types for which operational compatibility and availability of supply make them cost-effective options. At the same time, RFNBOs (such as e-liquids, e-methanol, and e-ammonia) gain increasing relevance over the longer term, notably under the FuelEU Maritime Regulation.

Figure 31: Renewable and low-carbon fuel consumption and shares in the EU maritime sector by scenario, in 2050



Source: PRIMES Maritime & PRIMES-TREMOVE

Note: S1: Base Case, S2: Absence of Fit-for-55 maritime policies, S3: Absence of FEUM, S4: Absence of EU ETS 1 extension in Maritime, S5: EU ETS 1 extension to smaller ships, and S6: EU ETS 1 extension to inland waterways

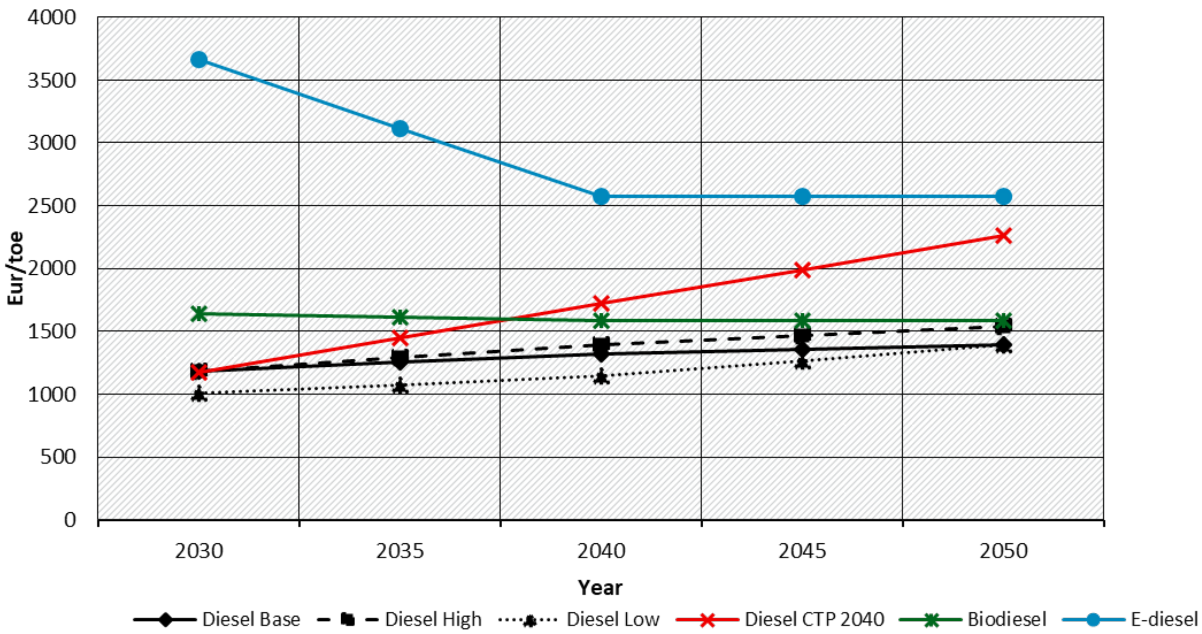
The EU ETS 1 stimulates Renewable and Low-Carbon Fuel (RLCF) uptake since it increases the cost of fossil fuel use and thus narrows the price gap with RLCFs and making them more attractive in operators' fuel mix decisions. In Scenario 3 (ETS-only), this leads to a 3.6 times higher uptake of RLCFs in 2030 and nearly 50 % share by 2050, compared to only 0.5 - 9.5 % when no carbon pricing or blending obligations are applied. The EU ETS 1 thus creates an economic pull for clean fuels, complementing the regulatory push from FEUM in other scenarios.

While fuel switching is the main driver of emissions reduction, the study also showed that technical and operational efficiency improvements contribute meaningfully, especially in the short-to-medium term. It was shown that **the EU ETS 1 incentivizes energy efficiency improvements** through the cost signal sent to vessel operators, and especially of large vessels. The operators act by adopting technical and operational efficiency measures resulting in measurable improvements in energy intensity. These gains, while modest annually, accumulate over time and help reduce emissions and compliance costs.

The EU ETS 1 also enhances the economic efficiency of decarbonisation by replacing internal compliance penalties with market-based signals. In scenarios without the EU ETS 1, such as the FEUM-only case, the model forces compliance through internal shadow costs that simulate the effort required to meet GHG intensity targets. These penalties do not generate revenues and lack direct feedback to the energy system. By contrast, the EU ETS 1 imposes an explicit carbon cost on fossil fuel use, which directly affects operator decisions and generates auction revenues, as opposed to, for instance influencing supplier decisions. These revenues could be reinvested into decarbonisation, directly for the maritime sector, for example, supporting infrastructure, clean fuel supply, or fleet renewal or indirectly through investments in the rest of the energy system (for example on fuel supply technologies) and thereby reduce the cost of compliance with FEUM targets. The EU ETS 1 thus provides a transparent, economy-wide mechanism that reinforces regulatory mandates while enabling a more cost-effective and equitable decarbonisation pathway, as demonstrated by the lower costs of the Base Case scenario. The revenues in the Base Case reach 8-9 bn EUR annually in the decade 2030-2040, whereas they drop to about an average 4 bn EUR annually in 2040-2050 due to the emission reductions achieved.

The gap owing to the fuel price differential covered by the EU ETS 1 is critical. The cost differential applied in this study, as expressed through the carbon price is more conservative than other trajectories. For comparison, in the 2040 CTP the carbon price applied to emissions in ETS-covered energy and industry sectors ranges from 290 EUR '23/tCO_2 in 2040 to 470 EUR '23/tCO_2 in 2050. Similarly, according to IMO (2020), the marginal abatement costs for a complete decarbonisation of maritime transport amount to more than 400 EUR/tCO2, mainly due to the high RFNBO prices (Wissner et al. 2024). These values are considerably higher than the EU ETS 1 carbon price trajectories used in the present study and its sensitivity cases. As shown in Figure 32, this price difference significantly influences fuel competitiveness: under the lower EU ETS 1 price applied in the study, including the sensitivity scenarios, fossil marine diesel remains cost-competitive with biodiesel and substantially cheaper than e-diesel across most of the projection period, only converging with biodiesel around 2040-2050. In contrast, higher carbon prices, such as those used in the 2040 CTP, result in fossil diesel reaching cost parity with biodiesel already by 2040 and converging with e-diesel by 2050. This price differential gap is translated to a cost difference that should be covered by blending mandates or regulatory penalties. It should be pointed out that the abatement in the maritime sector is not driven by carbon pricing alone. Sector-specific measures, such as the FuelEU Maritime Regulation, energy efficiency standards (EEDI/SEEMP), and RFNBO quotas under RED III, play a critical role in shaping decarbonisation pathways. The high marginal abatement costs (above 400 EUR/tCO_2) reflect the current high prices of RFNBOs required for full decarbonisation, rather than an implied carbon price level. In practice, compliance may likely involve a combination of allowance purchases and targeted regulatory instruments rather than relying solely on EU ETS 1 pricing.

Figure 32: Comparative fuel prices for conventional and alternative fuels, 2030-2050



Source: PRIMES Maritime & PRIMES-TREMOVE

Extending the EU ETS 1 to small vessels and inland waterways could present an opportunity to broaden the scope of carbon pricing and ensure that all emitting segments contribute to the EU's climate goals. These segments, while currently outside the EU ETS 1, represent a growing share of maritime emissions, as regulated segments are projected to reduce their contribution, and their inclusion would close existing coverage gaps. Although these segments are projected to benefit from spillover effects, such as increased availability of RCLFs and infrastructure driven by regulations on larger vessels, their direct inclusion in the EU ETS 1 provides additional incentives for operators to adopt RCLFs, and to improve energy efficiency. In the absence of a price signal, these transitions may remain slower or partial. The revenues generated through carbon payments could reach about 1.8 bn EUR annually in the decade 2030-2040, whereas they drop to about an average 1.3 bn EUR annually in 2040-2050.

Final considerations

The conclusions of this study are grounded in a robust scenario-based modelling approach. However, to appropriately interpret the findings, several limitations and contextual considerations should be acknowledged.

First, the scenarios imply a more relaxed Linear Reduction Factor (LRF) for the EU ETS 1 than currently defined in the legal framework. This reflects a balanced effort-sharing approach across the EU economy in line with achieving long-term climate targets, but it may underestimate the market stringency and carbon price signals that would emerge under the current full legal compliance.

Second, the modelling applied in this study does not simulate the feedback from carbon pricing or regulatory mandates into fuel prices within each scenario. In the case of the FEUM-only scenario, this could imply a higher cost for clean fuels, since the uptake is not driven by market payments. Moreover, while fuel prices used in all scenarios are derived from the Base Case, reflecting opportunity costs across the entire energy system, this approach does not capture scenario-specific effects. For instance, lower uptake of RLCFs in one scenario could result in lower marginal biofuel prices, while high uptake under the EU ETS 1 could push up marginal supply costs. These mechanisms are part of the broader PRIMES modelling suite which would need to be used. Moreover, a dedicated sensitivity analysis on fuel prices would be required to fully assess their interaction with the EU ETS 1 price signal. Variations in fossil fuel and alternative fuel prices can significantly influence the relative contribution of different renewable and low-carbon fuels (for example biofuels versus RFNBOs) and affect total system costs. However, as the Base Case and other scenarios are normative, designed to meet the FEUM emissions trajectory, the overall emissions outcome would remain broadly similar. Lower fossil fuel prices would likely reduce the relative impact of the EU ETS 1, whereas higher prices could amplify it.

Third, the modelling does not assess the full potential for carbon leakage or behavioural responses such as evasive routing or fuel bunkering outside the EU. This is partly due to the lack of dynamic allocation of vessels to origin-destination pairs or adjustment of routing strategies in response to policy-induced cost changes that are out of the model's scope. Consequently, the potential for emissions shifting outside the EU regulatory scope remains unquantified.

Finally, the modelling does not include the wider international context, in particular recent developments at IMO. These measures, once implemented, are expected to complement EU policies by setting a global direction for maritime decarbonisation. Their inclusion could strengthen the availability and uptake of clean fuels, reduce the risk of carbon leakage, and increase the overall effectiveness of EU action. As such, the scenarios presented here reflect only the impact of EU-level policies in isolation and may underestimate the future evolution of the sector under a more globally coordinated policy environment. These findings also underscore the importance of maintaining coordinated EU-level action while considering the potential synergies and risks of global policy alignment under the IMO.

These limitations do not undermine the overall findings of the study but highlight important caveats in interpreting the cost-effectiveness and emissions performance of different policy pathways. Furthermore, one can draw inspiration for further research and possible avenues for future investigations and model adaptations.

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A Appendix

A.1 Detailed segment representation in the modelling

Table 7: Detailed segmentation of the international maritime transport sector in the modelling

International Maritime – PRIMES Maritime	
Trip types	Passenger transport Freight transport

Vessel types & sizes	Freight transport
	- Containers – 7 size groups (each group: DWT & GT)
	  ○ < 999 TEUs
	  ○ 1000 – 1999 TEUs
	  ○ 2000 – 2999 TEUs
	  ○ 3000 – 4999 TEUs
	  ○ 5000 – 7999 TEUs
	  ○ 8000 – 11999 TEUs
	  ○ 12000 TEUs
	• Dry bulk carriers – 5 size groups (each group: DWT & GT)
	  ○ Handysize
	  ○ Handymax / Supramax
	  ○ Panamax
	  ○ Post-Panamax
	  ○ Capesize
	• Tankers – 4 size groups (each group: DWT & GT)
	  ○ 10000 – 69000 DWT
	  ○ 70000 – 119000 DWT
	  ○ 120000 – 199000 DWT
	  ○ 200000 DWT
	• General cargo – 1 size (DWT & GT)
	Passenger transport
	• Ro-Ro & Cruise – 1 size (DWT & GT)

Engine types (technology)	ICE engine (Diesel, RFO) LNG engine Electric engine H_2 Fuel cell engine Dual-fuel engines (NH_3, MeOH)
Fuel types	RFO, Bio-RFO, e-RFO Diesel, Biodiesel, e-diesel Fossil LNG, Bio-LNG, e-LNG H_2 Electricity Methanol (MeOH) Ammonia (NH_3)
Destination	Short Sea Shipping Deep Sea Shipping Intra-EU Extra-EU Berth

International Maritime – PRIMES Maritime	
Emissions / Pollutants	Well-to-Tank CO_2 Tank-to-Wake CO_2 Well-to-Wake CO_2 CH_4 (slippage) N_2O (slippage) NO_X CO NMVOC PM10 SO_X

Source: PRIMES Maritime

Table 8: Detailed segmentation of the domestic maritime transport sector in the modelling

Domestic Maritime - PRIMES-TREMOVE	
Trip types	Passenger transport Freight transport
Vessel types & sizes	<u>Freight transport</u> - Bulk carriers (dry and liquid) – Small (below 5000 GT) & Large (above 5000 GT) - Containers – Small (below 5000 GT) & Large (above 5000 GT) - General cargo – Small (below 5000 GT) & Large (above 5000 GT) <u>Passenger transport</u> - Small (below 5000 GT) & Large (above 5000 GT)
Engine types (technology)	ICE engine (Diesel, RFO) LNG engine Gasoline engine Electric engine H_2 Fuel cell engine Methanol (MeOH) Ammonia (NH_3)
Fuel types	RFO, Bio-RFO Diesel, Biodiesel, e-diesel Gasoline, Bio-Gasoline, e-gasoline Fossil LNG, Bio-LNG, e-LNG H_2 Electricity Methanol (MeOH) Ammonia (NH_3)
Emissions / Pollutants	Well-to-Tank CO_2 Tank-to-Wake CO_2 Well-to-Wake CO_2 NO_X CO NMVOC PM10 SO_X

Source: PRIMES-TREMOVE

Table 9: Detailed segmentation of the Inland Waterways sector in the modelling

Inland Waterways - PRIMES-TREMOVE	
Trip types	Passenger transport Freight transport
Vessel types & sizes	Freight transport - Containers – Small (below 5000 GT) & Large (above 5000 GT) - Bulk carriers (dry and liquid) – Small (below 5000 GT) & Large (above 5000 GT) - General cargo – Small (below 5000 GT) & Large (above 5000 GT) Passenger transport - Small (below 5000 GT) & Large (above 5000 GT)
Engine types (technology)	ICE engine (Diesel, RFO) LNG engine Gasoline engine Electric engine H_2 Fuel cell engine Methanol (MeOH) Ammonia (NH_3)
Fuel types	RFO, Bio-RFO Diesel, Biodiesel, e-diesel Gasoline, Bio-Gasoline, e-gasoline Fossil LNG, Bio-LNG, e-LNG H_2 Electricity Methanol (MeOH) Ammonia (NH_3)
Emissions / Pollutants	Well-to-Tank CO_2 Tank-to-Wake CO_2 Well-to-Wake CO_2 NO_X CO NMVOC PM10 SO_X

Source: PRIMES-TREMOVE

A.2 Endogenous fuel price estimates

This section provides a high-level description of how fuel prices that are used in this study are derived.

The modelling exercise is considered to take place within the broader decarbonisation context of the 2040 Climate Target Plan and is in line with a net GHG reduction target of at least 90 % in 2040 compared to 1990. This entails the scenarios in the present study contain the same assumptions on policy context, for sectors beyond maritime. This assumes that the overall EU economy is projected to decarbonize in accordance with the CTP 2040 targets and the 2050 net carbon neutrality goal. Overall, fuel demand and supply as well as resulting fuel prices are developed within this context.

PRIMES simulates a well-functioning market where supply meets demand, and the prices of bioenergy products, synthetically produced fuels and electricity per sector are calculated in order that total system costs are recovered. Different energy product prices are derived from different modules within PRIMES. Based on international fuel prices, the prices for energy products are derived from PRIMES, as projected within the aforementioned decarbonisation context set by the Climate Target Plan.

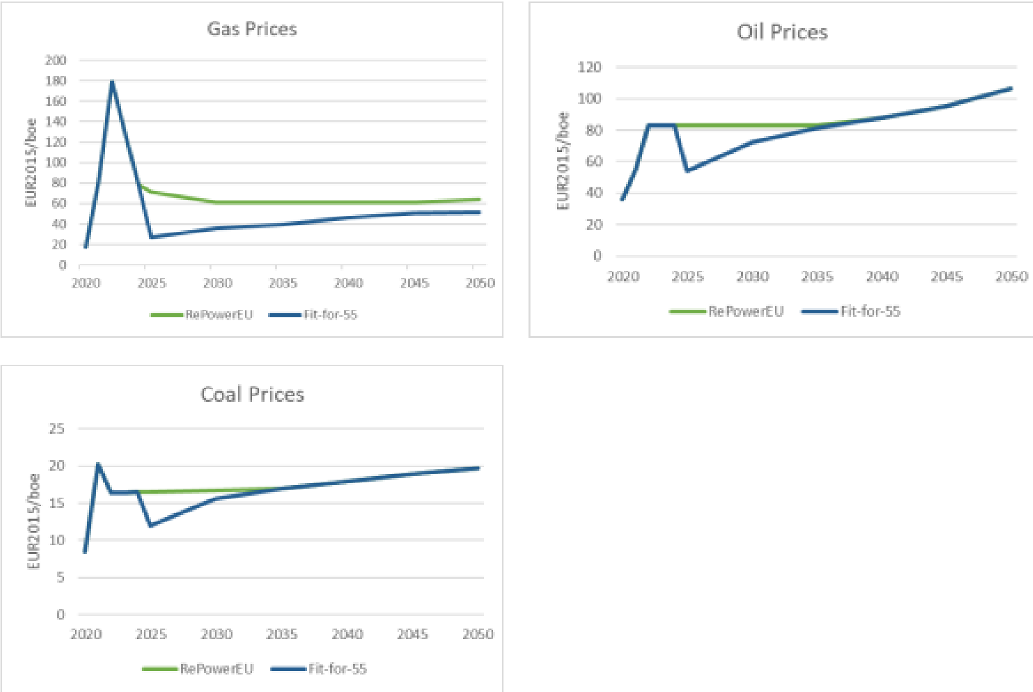
For the different scenarios explored in this study, a single fuel price scenario is used, which is an input in PRIMES Maritime and PRIMES-TREMOVE considering the said decarbonisation context. The working assumption is that fuel prices are not responding to isolated changes in specific maritime policies (for example, due to demand change for a specific fuel).

This fuel prices scenario is derived from the following inputs methods.

International fossil fuel prices

The international energy context and related fossil fuel prices (oil, gas and coal products) follow global market developments and have been derived from the POLES-JRC model projections as described in the CTP 2040 impact assessment publication (EC, 2022).

Figure 33: International fossil fuel price trajectory used in the modelling



Source: EC (2024a)

Fossil fuel prices

International fossil fuel price projections apply uniformly on all EU MS, differentiated by country taking into account transport costs and systematic differences of country prices from average EU import prices due to market reasons, as calculated using observed time series of prices on which an econometric function, extrapolating the differences to the future and avoiding market distortions.

The model projects fossil fuel prices in the domestic markets by sector of consumption, to take into account price differentiation by sector. Pre-tax fossil fuel prices by sector are calculated by adding three components, as follows. After-tax prices add excise taxes and VAT rates as exogenous parameters. a) cost corresponding to the primary energy price of the fuel, b) cost of fuel processing (for example refinery) which is specific to each fossil fuel type, c) cost of transportation and distribution which is specific to the customer (sector) type. This component includes cost of refuelling at service stations for conventional transport sector fuels. Transport and distribution regulated tariffs differ by type of system hence sector (for example high vs low pressure pipelines). Similarly the requirements for gas balancing are different by sector, thus prices of gas differ by sector, also because of weighting pipeline and LNG gas or services from storage. Gas balancing costs are estimated using shares of LNG and gas storage in gas supply. The regulated tariffs are calculated and projected by the model, based on costs of regulated asset basis and on a levelized costing method using a regulated discount rate. The tariff computation is compared and validated with information collected for past years (E3Modelling, 2018, p. 206).

Electricity prices

The prices of electricity are derived from the PRIMES Power and steam generation and supply model. Electricity (and steam/heat) fuel prices are determined by category of customer (sectors and sub-sectors of demand). The aim is to allocate variable, fixed, and capital costs as well as grid and other costs to each category of customers as would be the case in a well-functioning market in which suppliers would conclude efficient and stable bilateral contracts with each customer category, based, for example, on the specific load profile of the customer (E3Modelling, 2018, p. 131).

Biofuel prices

The prices of bioenergy commodities are projected using the PRIMES biomass model which includes a pricing model, that meets a given demand for bioenergy commodities, which is derived from the rest of PRIMES model demand modules (including demand from the specific transport sectors, maritime transport included. The minimization is subject to equilibrium constraints, which represent the cost structure of various feedstock supplying possibilities, as well as the cost functions of technology suppliers, including policy-related restrictions and requirements, that are represented as overall constraints such as the sustainability criteria posed in the Renewable Energy Directive or the fuel standard from the FuelEU Maritime Regulation (E3Modelling, 2018, p. 172). The model also determines bioenergy commodity prices because of maximizing social surplus by Member State subject to recovering all types of fixed and variable costs of biomass supply.

Synthetic fuel prices

The prices of synthetic fuels are derived from the PRIMES New Fuels model. This includes alternative pathways for the production of numerous low or zero-carbon energy carriers, such as hydrogen, synthetic methane and synthetic liquid hydrocarbons produced via Power to X (PtX) routes as used throughout the energy system. This module of PRIMES is operating at an hourly resolution and can capture effectively the operation of large-scale power storage systems. For example, the module determines the hours of the day with excess renewables generation in order to produce energy carriers (for example hydrogen) that can be used for the production of electricity later when renewable generation is limited (storage). However, at the same time, this module is also able to decide whether economics favour the production of synthetic hydrocarbons (using, for example, hydrogen as feedstock) instead of providing storage services. It does so considering the demand for useful energy derived from the specific PRIMES demand modules such a PRIMES Maritime and PRIMES-TREMOVE. In this way, it captures competition for carriers that can serve different purposes (storage vs. feedstock) for different customers (power generator vs. synthetic fuel factories). The module solves for all countries of Europe simultaneously in order to capture trade of the carriers, location of new factories and infrastructure (power grids, gas, H2 network and distributed heat). It optimizes the investments and operation of the system under perfect foresight assumptions (E3Modelling, 2018, p. 198).

A.3 Data tabels

Table 10: Freight and passenger transport shipping activity of the EU, by shipping segment, in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

Activity	2015	2020	2025	2030	2040	2050
Freight transport - Gtkm	**14,646**	**14,918**	**17,108**	**17,917**	**19,614**	**21,980**
International maritime	14,350	14,629	16,819	17,590	19,248	21,587
National maritime	148	158	158	178	196	206
Inland waterways	147	132	131	148	170	187
Passenger transport - Gpkm	**26.7**	**12.6**	**32.6**	**34.6**	**36.9**	**40.1**
International maritime	14.4	5.2	19.6	20.2	21.7	23.8
National maritime	11.8	7.4	12.7	14.0	14.7	15.9
Inland waterways	0.50	0.04	0.35	0.40	0.43	0.47

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 11: Energy consumption of the EU shipping sector, by shipping segment, in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

Energy demand (Mtoe)	2015	2020	2025	2030	2040	2050
Total Shipping	**44**	**42**	**47**	**47**	**48**	**50**
International maritime	40	39	43	43	44	46
Domestic maritime	2.8	2.7	2.9	3.1	3.0	2.9
Inland waterways	1.09	0.82	0.94	1.02	1.07	1.03

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 12: Energy intensity of the shipping sector of the EU, by shipping segment, in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

Energy intensity (toe/tkm)	2015	2020	2025	2030	2040	2050
International maritime	2.6	2.6	2.4	2.3	2.2	2.0
National maritime	10.4	10.7	10.2	9.8	9.0	8.3
Inland waterways	7.0	6.2	6.8	6.6	6.0	5.3

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 13: Energy consumption of the shipping sector of the EU, by fuel type, in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

Energy consumption (Mtoe)	2015	2020	2025	2030	2040	2050
Total Energy demand	**44.2**	**42.3**	**46.8**	**47.5**	**48.6**	**50.1**
Liquid fossil fuel	44.2	41.9	45.2	44.3	33.4	8.1
LNG	0.0	0.2	0.9	1.2	2.7	4.2
Liquid biofuels	0.0	0.3	0.6	1.3	7.0	21.2
bio-LNG	0.0	0.0	0.0	0.1	0.7	2.3
Liquid synthetic	0.0	0.0	0.0	0.0	1.9	4.7
e-LNG	0.0	0.0	0.0	0.0	0.1	0.7
Ammonia	0.0	0.0	0.0	0.0	1.1	2.6
Methanol	0.0	0.0	0.0	0.0	0.4	1.9
Hydrogen	0.0	0.0	0.0	0.0	0.5	3.2
Electricity	0.0	0.0	0.1	0.5	0.8	1.2

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 14: Fuel mix by EU maritime segment in 2030 in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

Fuel type (Mtoe)	2030			2050		
	International Maritime	Domestic Maritime	Inland waterways	International Maritime	Domestic Maritime	Inland waterways
Total energy demand	43.4	3.1	1.0	46.1	2.9	1.0
Liquid fossil fuel	40.7	2.8	0.8	6.9	0.7	0.5
LNG	1.0	0.1	0.1	4.2	0.0	0.0
Liquid biofuels	1.2	0.1	0.0	19.6	1.3	0.2
bio-LNG	0.1	0.0	0.0	2.2	0.0	0.0
Liquid synthetic	0.0	0.0	0.0	4.5	0.2	0.0
e-LNG	0.0	0.0	0.0	0.5	0.1	0.1
Ammonia	0.0	0.0	0.0	2.4	0.1	0.0
Methanol	0.0	0.0	0.0	1.7	0.2	0.1
Hydrogen	0.0	0.0	0.0	3.0	0.1	0.0
Electricity	0.4	0.1	0.0	1.0	0.2	0.1

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 15: GHG emissions of the EU shipping sector by segment in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

WtW GHG emissions ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Total shipping	169	161	176	174	140	55
International maritime	154	147	162	160	128	50
Intra-EU	36	34	41	37	26	7
Extra-EU	118	113	121	122	102	42
Domestic maritime	11	10	11	11	8	3
Inland waterways	4	3	3	4	3	2

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 16: Decomposition of emission intensity reduction in EU maritime transport in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

Index 2015 = 100	2015	2020	2025	2030	2040	2050
Emission intensity (tCO_2eq/tkm or pkm)	100 %	94 %	90 %	85 %	62 %	21 %
Energy intensity (toe/tkm or pkm)	100 %	98 %	89 %	87 %	82 %	76 %
GHG emission intensity of fuel mix (tCO_2eq/toe)	100 %	99 %	99 %	96 %	75 %	29 %

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 17: Lifecycle emissions by component (WtT, TtW and slippage) and ETS emissions of the EU shipping sector in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

WtW GHG emissions ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Well-to-Wake (WtW)	**169**	**161**	**176**	**174**	**140**	**55**
Well-to-Tank (WtT)	25	24	27	27	24	16
Tank-to-Wake (TtW)	142	134	146	144	113	36
Slippage	2	2	3	3	3	3
ETS maritime	76	72	79	76	54	12

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 18: Freight transport activity increase of the EU shipping sector by scenario, relative to the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

% increase relative to the Base Case	2030	2040	2050
Scenario 2: No maritime Fit-for-55	0.2 %	0.5 %	0.7 %
Scenario 3: ETS ext. in maritime only	0.0 %	0.3 %	0.4 %
Scenario 4: FEUM only	0.2 %	0.2 %	0.1 %

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 19: Energy intensity improvements in international and domestic freight maritime transport (relative to the Base Case = 0 %), over the projection period

Projections for 2030-2050

	2030	2035	2040	2045	2050
International maritime					
Scenario 3: ETS ext. in maritime only	0,0 %	0,0 %	-0,1 %	0,0 %	-0,1 %
Scenario 4: FEUM only	0,2 %	0,3 %	0,2 %	0,2 %	0,2%
National maritime					
Scenario 3: ETS ext. in maritime only	0,0 %	-0,2 %	-0,5 %	-0,5 %	-0,1 %
Scenario 4: FEUM only	0,2 %	0,7 %	0,9 %	1,3 %	1,0 %

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 20: Energy demand of the shipping sector, of EU, by energy carrier and scenario

Projections for 2030

Fuel type (Mtoe)	2030			
	Base Case	**Scenario 2**	**Scenario 3**	**Scenario 4**
Total Energy demand	**47.5**	**47.9**	**47.5**	**47.9**
Liquid fossil fuel	44.3	46.3	45.2	44.7
LNG	1.21	1.26	1.22	1.22
Liquid biofuels	1.29	0.11	0.65	1.27
bio-LNG	0.10	0.05	0.09	0.10
Liquid synthetic	0.02	0.00	0.01	0.02
e-LNG	0.00	0.00	0.00	0.00
Ammonia	0.01	0.00	0.00	0.01
Methanol	0.00	0.00	0.00	0.00
Hydrogen	0.00	0.00	0.00	0.00
Electricity	0.52	0.14	0.34	0.55

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 21: Energy demand of the shipping sector, of EU, by energy carrier and scenario

Projections for 2050

Fuel type (Mtoe)	2050			
	Base Case	Scenario 2	Scenario 3	Scenario 4
Total Energy demand	50.1	51.0	50.3	50.2
Liquid fossil fuel	8.1	41.1	21.0	8.0
LNG	4.23	4.85	4.94	4.27
Liquid biofuels	21.19	1.25	15.38	20.83
bio-LNG	2.30	0.61	1.41	2.52
Liquid synthetic	4.74	0.31	1.91	4.86
e-LNG	0.68	0.19	0.23	0.76
Ammonia	2.56	0.22	1.01	2.64
Methanol	1.87	0.33	0.82	1.90
Hydrogen	3.15	1.82	2.64	3.07
Electricity	1.24	0.35	0.95	1.37

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 22: WtW GHG emissions of the shipping sector, of EU, by scenario

Statistical data for 2015-2020, and projections for the period 2025-2050

WtW GHG emissions ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Base Case	169	161	176	174.3	140	55
Scenario 2: No maritime Fit-for-55	169	161	179	181.0	182	174
Scenario 3: ETS ext. in maritime only	169	161	176	177	171	104
Scenario 4: FEUM only	169	161	177	176	141	55

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 23: ETS maritime emissions of the shipping sector, of EU, by scenario

Statistical data for 2015-2020, and projections for the period 2025-2050

ETS maritime emissions ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Base Case	76	72	79	75.9	54	12
Scenario 2: No maritime Fit-for-55	76	72	80	80.4	81	77
Scenario 3: ETS ext. in maritime only	76	72	79	78	73	37
Scenario 4: FEUM only	76	72	79	77	55	12

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 24: ETS maritime emissions of the shipping sector, of EU, in the Base Case and in ETS price variants of Scenario 3

Statistical data for 2015-2020, and projections for the period 2025-2050

ETS maritime emissions ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Base Case	76	72	79	75.9	54	12
Scenario 3: ETS ext. in maritime only	76	72	79	77.7	73	37
Scenario 3: ETS ext. in maritime only - High price	76	72	79	78	71	31
Scenario 3: ETS ext. in maritime only - Low price	76	72	79	79	78	37

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 25: Total system costs of international maritime transport of the EU, by scenario

Statistical data for 2015-2020, and projections for the period 2025-2050

System costs (billion Euro)	2015	2020	2025	2030	2040	2050
Base Case	48	45	67	87	106	144
Scenario 2: No maritime Fit-for-55	48	45	65	78	84	113
Scenario 3: ETS ext. in maritime only	48	45	67	87	96	133
Scenario 4: FEUM only	48	45	66	79	99	143

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 26: Freight and passenger transport shipping activity of the EU, by ship size, in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

Shipping segment/Ship size	2015	2020	2025	2030	2040	2050
Freight transport - Gtkm	**14,646**	**14,918**	**17,108**	**17,917**	**19,614**	**21,980**
Large vessels	13,112	13,470	15,264	16,004	17,522	19,681
Small vessels	1,534	1,448	1,843	1,913	2,092	2,299
Passenger transport - Gpkm	**27**	**13**	**33**	**35**	**37**	**40**
Large vessels	24	11	29	31	33	36
Small vessels	2	1	3	4	4	4

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 27: WtW GHG emissions of the shipping sector of the EU, by ship size, in the Base Case

Statistical data for 2015-2020, and projections for the period 2025-2050

WtW emissions ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Total Shipping	**169**	**161**	**176**	**174**	**140**	**55**
Large vessels	144	138	149	147	113	37
Small vessels	25	23	27	28	27	18

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 28: WtW GHG emissions of small ships of the EU, in the Base Case and scenario 5

Statistical data for 2015-2020, and projections for the period 2025-2050

WtW emissions ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Base Case	25	23	27	27.7	27	18
Scenario 5: ETS ext. in Small vessels	25	23	27	26.9	25	12

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 29: Energy demand of the EU shipping sector by fuel type, in 2030, in the Base Case and in Scenario 5 (extension of EU ETS 1 to small vessels)

Projections for 2030

Fuel type (Mtoe)	2030			
	Base Case	**Scenario 5**	**Scenario 5 - High price**	**Scenario 5 - Low price**
Total Energy demand	**47.5**	**47.3**	**47.3**	**47.6**
Liquid fossil fuel	44.3	44.0	44.0	44.4
LNG	1.2	1.2	1.2	1.2
Liquid biofuels	1.3	1.4	1.4	1.3
bio-LNG	0.1	0.1	0.1	0.1
Liquid synthetic	0.0	0.0	0.0	0.0
e-LNG	0.0	0.0	0.0	0.0
Ammonia	0.0	0.0	0.0	0.0
Methanol	0.0	0.0	0.0	0.0
Hydrogen	0.0	0.0	0.0	0.0
Electricity	0.5	0.6	0.6	0.6

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 30: Energy demand of the EU shipping sector by fuel type, in 2050, in the Base Case and in Scenario 5 (extension of EU ETS 1 to small vessels)

Projections for 2030

Fuel type (Mtoe)	2050			
	Base Case	**Scenario 5**	**Scenario 5 - High price**	**Scenario 5 - Low price**
Total Energy demand	**50.1**	**49.8**	**49.5**	**49.8**
Liquid fossil fuel	8.1	6.6	6.4	6.7
LNG	4.2	3.9	3.7	3.8
Liquid biofuels	21.2	21.9	22.1	22.0
bio-LNG	2.3	2.5	2.4	2.4
Liquid synthetic	4.7	4.9	4.9	4.9
e-LNG	0.7	0.7	0.7	0.7
Ammonia	2.6	2.6	2.6	2.6
Methanol	1.9	1.9	1.9	1.9
Hydrogen	3.2	3.3	3.3	3.3
Electricity	1.2	1.4	1.4	1.4

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 31: Energy intensity improvement in the EU inland waterways segment in Scenario 6 compared to the Base Case (=0 %)

Projections for 2030

	2030	2035	2040	2045	2050
Scenario 6: ETS ext. in inland waterways	-0,2 %	-0,7 %	-0,9 %	-1,8 %	-2,5 %
Scenario 6: ETS ext. in inland waterways - Low-price trajectory	0,1 %	-0,1 %	-0,2 %	-0,9 %	-1,9 %
Scenario 6: ETS ext. in inland waterways - High-price trajectory	-0,2 %	-0,7 %	-1,1 %	-2,1 %	-3,0 %

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 32: Fuel mix by EU inland waterways segment in 2030 in the Base Case and Scenario 6

Projections for 2030

Fuel type (Mtoe)	2030			
	Base Case	Scenario 6	Scenario 6 - High price	Scenario 6 - Low price
Total Energy demand	**1.03**	**0.99**	**0.98**	**1.00**
Liquid fossil fuel	0.49	0.19	0.16	0.19
LNG	0.00	0.00	0.00	0.00
Liquid biofuels	0.21	0.42	0.44	0.43
bio-LNG	0.04	0.04	0.04	0.04
Liquid synthetic	0.01	0.04	0.05	0.04
e-LNG	0.09	0.09	0.09	0.09
Ammonia	0.03	0.04	0.04	0.04
Methanol	0.06	0.06	0.06	0.06
Hydrogen	0.04	0.04	0.04	0.04
Electricity	0.06	0.06	0.06	0.06

Source: PRIMES-TREMOVE

Table 33: WtW GHG emissions of inland waterways sector of EU, by scenario

Statistical data for 2015-2020, and projections for the period 2025-2050

WtW GHG emissions of inland waterways ($MtCO_2$)	2015	2020	2025	2030	2040	2050
Base Case	4.08	2.98	3.43	3.71	3.48	2.01
Scenario 6: ETS ext. in inland waterways	4.08	2.98	3.42	3.59	3.11	0.97
Scenario 6: ETS ext. in inland waterways – High	4.08	2.98	3.42	3.59	3.02	0.85
Scenario 6: ETS ext. in inland waterways – Low	4.08	2.98	3.42	3.68	3.34	0.98

Source: PRIMES-TREMOVE

Table 34: Renewable and Low Carbon fuels and share in the EU maritime sector in the Base Case and the Scenarios in 2050

Projections for 2050

Mtoe	Base Case	Base Case - High	Base Case - Low	Scenario 2
Biofuels & bio-LNG	23,48	23,53	23,51	1,85
RFNBOs	13,00	12,94	12,97	2,86
Electricity	1,24	1,24	1,23	0,35
RLCF share (%)	0,75	0,75	0,75	0,10
Mtoe	**Scenario 3**	**Scenario 3 - High**	**Scenario 3 - Low**	**Scenario 4**
Biofuels & bio-LNG	16,79	18,63	16,83	23,35
RFNBOs	6,62	7,45	6,57	13,23
Electricity	0,95	1,03	0,94	1,37
RLCF share (%)	0,48	0,54	0,48	0,76
Mtoe	**Scenario 5**	**Scenario 5 - High**	**Scenario 5 - Low**	
Biofuels & bio-LNG	24,41	24,55	24,46	
RFNBOs	13,43	13,42	13,38	
Electricity	1,43	1,43	1,42	
RLCF share (%)	0,79	0,80	0,79	
Mtoe	**Scenario 6**	**Scenario 6 - High**	**Scenario 6 - Low**	
Biofuels & bio-LNG	23,69	23,75	23,72	
RFNBOs	13,04	12,98	13,01	
Electricity	1,39	1,39	1,38	
RLCF share (%)	0,76	0,76	0,76	

Source: PRIMES Maritime & PRIMES-TREMOVE

Table 35: Marine diesel fuel price including carbon price based across different scenarios and studies in comparison with biodiesel and e-diesel

Projections for 2050

EUR/tCO_2	Carbon price	2030	2035	2040	2045	2050
Diesel	Base (this study)	1.181	1.253	1.324	1.359	1.393
Diesel	High (this study)	1.181	1.289	1.396	1.468	1.540
Diesel	Low (this study)	1.007	1.076	1.144	1.269	1.393
Diesel	CTP 2040 (EC, 2024c)	1.175	1.448	1.720	1.990	2.260
Biodiesel	-	1.640	1.615	1.590	1.590	1.590
E-diesel	-	3.660	3.115	2.570	2.570	2.570

Source: PRIMES Maritime & PRIMES-TREMOVE

A.4 Analytical scenario results

A detailed set of results is provided as electronic supplementary material.

Specifically, the indicators included collectively describe the evolution of the maritime transport sector under different policy scenarios. The indicators broadly cover maritime activity, energy demand, fuel mix, GHG emissions, and overall system costs, and other parameters (for example intensity indicators).

- Maritime activity, for both freight and passenger transport and by vessel type, is reported by shipping segment: international maritime transport, domestic maritime transport, and inland waterways transport;
- Energy demand is shown as total consumption per shipping segment and further disaggregated by fuel type;
- The energy demand is disaggregated to the following fuel types: including liquid fossil fuels, LNG, liquid biofuels, bio-LNG, synthetic liquids, e-LNG, ammonia, methanol, hydrogen, and electricity;
- GHG emissions are provided per shipping segment, and for international maritime transport also by operational area (intra-EU and extra-EU). Emissions are also disaggregated into WtT, Tank-to-Wake TtW, and methane slippage components;
- In addition, the study reports on the energy and emissions intensity of maritime activity and its projected evolution;
- The total system costs associated with international maritime transport in the EU are also quantified, and broken down to fuel cost breakdown to total costs, fuel costs, operational and non-fuel variable costs, and capital costs;
- External costs associated with air pollutants.

All indicators are projected through to 2050, where relevant, results are also presented by vessel size category, distinguishing ships above and below 5,000 GT.