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Supply chain and policy
Overcoming barriers towards implementation

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1 Introduction

1.1 Objective

The maritime sector aims to reduce its greenhouse gas (GHG) emissions. Therefore, shipping is transitioning to sustainable energy solutions. International and regional policy frameworks are accelerating this shift. However, the timeframe is still uncertain. For example, the International Maritime Organization (IMO) has adjourned their preliminary agreement targeting climate neutrality by 2050. At the same time the European Union has introduced ambitious decarbonisation measures under the FuelEU Maritime initiative and the Renewable Energy Directive III (RED III).

In response to these developments, the Green Maritime Methanol (GMM) project brings together a consortium of Dutch and international maritime stakeholders, including industry leaders and knowledge institutes. Supported by Top sector Knowledge and Innovation (TKI) Maritime and the Netherlands Ministry of Economic Affairs, this project investigates the feasibility and implementation of renewable methanol as a low-carbon marine fuel.

This report summarizes and outlines the GHG reduction challenge facing the maritime industry and explores the strategic role of renewable methanol in meeting these targets. Drawing on the practical insights and investment experiences of consortium members currently deploying methanol-powered vessels, the report identifies key drivers and barriers to broader adoption with a focus on supply chain development and policy alignment.

The following research objectives have been defined:

- Barrier assessment and mitigation: identification, prioritizing and strategic approach to overcoming non-technical implementation barriers.
- Benchmarking of energy carriers: comparative analysis of (bio-)methanol and selected alternative fuels, including the influence of regulatory frameworks and policy instruments.
- Identification of the bio-methanol supply chain potential: evaluation of the scalability and sustainability of bio-methanol production and distribution networks.
- Analysis of market dynamics and competitiveness: analysis of current fossil-based methanol demand versus future renewable methanol demand, with merit order modelling to assess competitiveness for maritime end-users.

Through applied research and stakeholder collaboration, the GMM project aims to provide actionable insights and policy recommendations that support the maritime sector's transition towards climate neutrality.

1.2 Structure

This report summarizes the results of the abovementioned research activities. It is structured as follows. Firstly, Chapter 2 summarizes the systemic barrier analysis related to the implementation of methanol as an energy carrier for shipping. Based on those barriers, following chapters describe a more in-depth analysis of prioritized barriers.

Chapter 3 focuses on lack of regulatory stability barrier by benchmarking methanol with other energy carriers and more in depth analysis of upcoming regulations. Chapter 4 analyses the lack of methanol availability barrier, by assessing supply chain cost and sensitivities of bio- and e-methanol. Chapter 5 studies qualitatively the lack of willingness to pay barriers for methanol in shipping. Finally, Chapter 6 concludes on the overall insights.

Note, this report provides a summary based on more detailed analysis of the aforementioned barriers. These consider the report on the barrier analysis [1], supply chain cost analysis [2], and willingness to pay analysis [3]. The first is publicly available, and the latter two analysis' can be made available upon request. Finally, in this report only supply and policy related barriers are assessed. Other (technical) barriers, are covered in complementary Green Maritime Methanol 3.0 reports.

2 Methanol implementation barrier analysis

2.1 Introduction

In previous GMM studies initial descriptions of the drivers and barriers related to green methanol use are presented [4] [5]. Drivers are its availability, emission reduction potential, relatively high energy density compared to other alternatives, similarities in operation to diesel, and availability from renewable and bio-based sources on the relative short term. However, the processes towards large scale adoption are still unclear as many investment uncertainties remain throughout the value chain. Therefore, the main objective is to qualitatively evaluate and prioritize the barriers affecting the investment decision towards sustainable methanol in the shipping industry and energy production value chain.

The approach consists of three steps. First, based upon a literature review and interviews, the initial barriers are mapped in detail. Second, these barriers are prioritized via a survey amongst the GMM partners. Finally, the barriers are mapped on the maritime stakeholder network to understand how the barriers affect the stakeholders interactions (see Figure 1). This chapter shows the summarized results of this analysis [1].

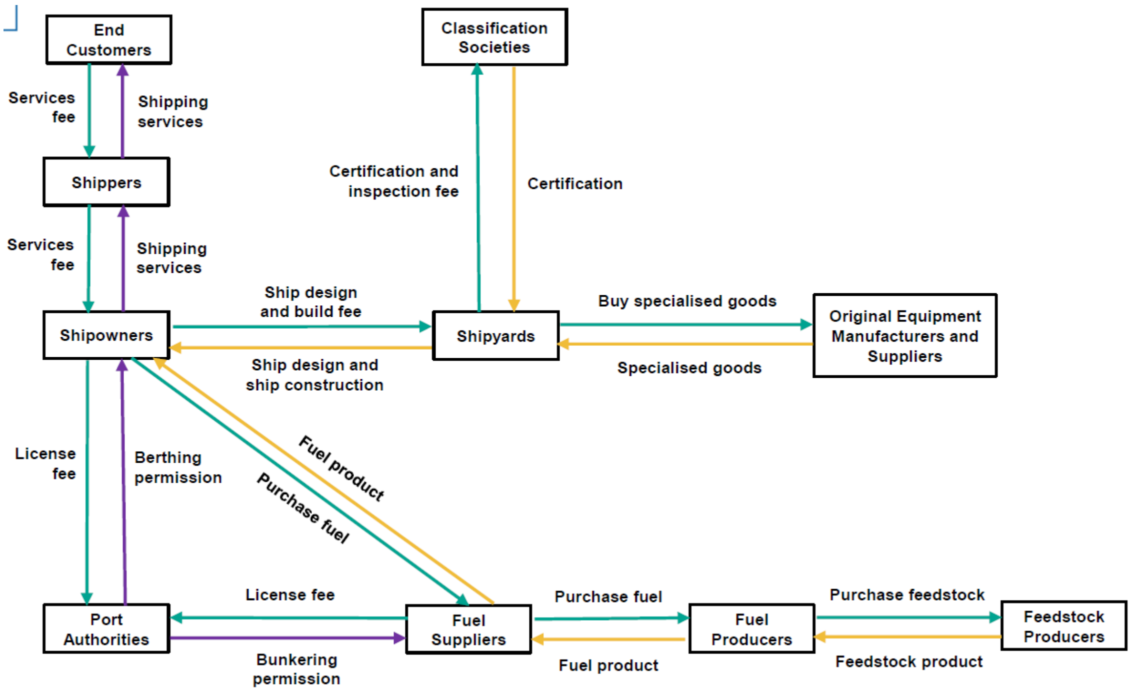

Figure 1: Exemplary stakeholder map showing the interactions between the different roles [1].

2.2 Result

2.2.1 Prioritization of the barriers

Based upon literature review, interviews and a survey within the consortium, a long list of barriers has been assembled and prioritized as can be seen in Table 1 [1]. Barriers are defined as factors that oppose the implementation of bio- or e-methanol as an energy carrier in shipping. These barriers are perceived as a risk for the stakeholders and negatively affect the economic feasibility. Therefore, barriers reduce the willingness of stakeholders to invest. We refer to [1] for detailing on the methodology towards defining and detailing the exact barriers.

The top barrier is regulatory stability, as shown in Table 1. The stakeholders perceived it as most impactful on the price of methanol. However, where the regulatory stability is considered most important for all (see Figure 1 for all types of stakeholders), methanol availability it considered more critical by shipowners. Technical readiness is rated highest by shipyards. This shows how the perceived criticality of a barrier can differ per type of stakeholder.

Table 1: Survey results of 39 respondents within GMM consortium towards prioritizing barriers on scale 1-5 (source: Socio-technical Analysis of Green Methanol in the Shipping Industry [1]).

Rank	All (n=39)	Shipowners (n = 15)	Shipyards (n = 7)
1	***Regulation stability (4.49)***	***Methanol availability (4.73)***	***Technical readiness (4.71)***
2	Technology certification (4.36)	Regulation stability (4.60)	Technology certification (4.71)
3	Technical readiness (4.33)	Infrastructural readiness (4.53)	Goals alignment (4.43)
4	Bunkering regulation (4.28)	Technical readiness (4.47)	Regulation stability (4.43)
5	Goals alignment (4.13)	Feedstock availability (4.40)	Bunkering regulation (4.43)
6	Fuel production regulation (4.05)	Bunkering regulation (4.40)	Emission reduction (4.29)
7	Infrastructural readiness (4.00)	Technology certification (4.40)	Operational expenses (4.29)
8	Operational expenses (4.00)	Level playing field (4.27)	Production regulation (4.14)
9	Enforcement capacity (3.97)	Operational expenses (4.20)	Enforce capacity (4.14)
10	Methanol availability (3.95)	Goals alignment (4.20)	Level playing field (4.00)
11	Level playing field (3.92)	Production regulation (4.13)	Infrastructural readiness (3.86)
12	Emission reduction (3.92)	Emission reduction (4.13)	Return on investment (3.86)
13	Capital intensity (3.90)	Capital intensity (4.07)	Capital intensity (3.86)
14	Return on investment (3.87)	Alternative fuel investment (4.00)	Alternative fuel investment (3.71)
15	Willingness to pay (3.87)	Enforce capacity (4.00)	Qualified staff (3.57)
16	Feedstock availability (3.85)	Return on investment (3.93)	Willingness to pay (3.57)
17	Alternative fuel investment (3.72)	Willingness to pay (3.87)	Social acceptance (3.43)
18	Subsidy availability (3.49)	Qualified staff (3.60)	Feedstock availability (3.29)
19	Social acceptance (3.33)	Social acceptance (3.47)	Methanol availability (3.29)
20	Qualified staff (3.23)	Subsidy availability (3.20)	Subsidy availability (3.00)

Using the list of Table 1 as a basis, we observe some barriers increase in their criticality when also taking into account the expert assessment of how predictable or uncertain these barriers are (low=1, high = 5). For example, the technology readiness barrier is seen as relatively certain. The technology, works and is applied, however is not yet mature for all engine types.

Whereas the methanol availability is considered a highly uncertain development, as both geopolitical tensions and lack of economic feasibility create a highly uncertain outlook. The combination of impact and predictability determines the criticality of the barrier as can be seen in Figure 2.

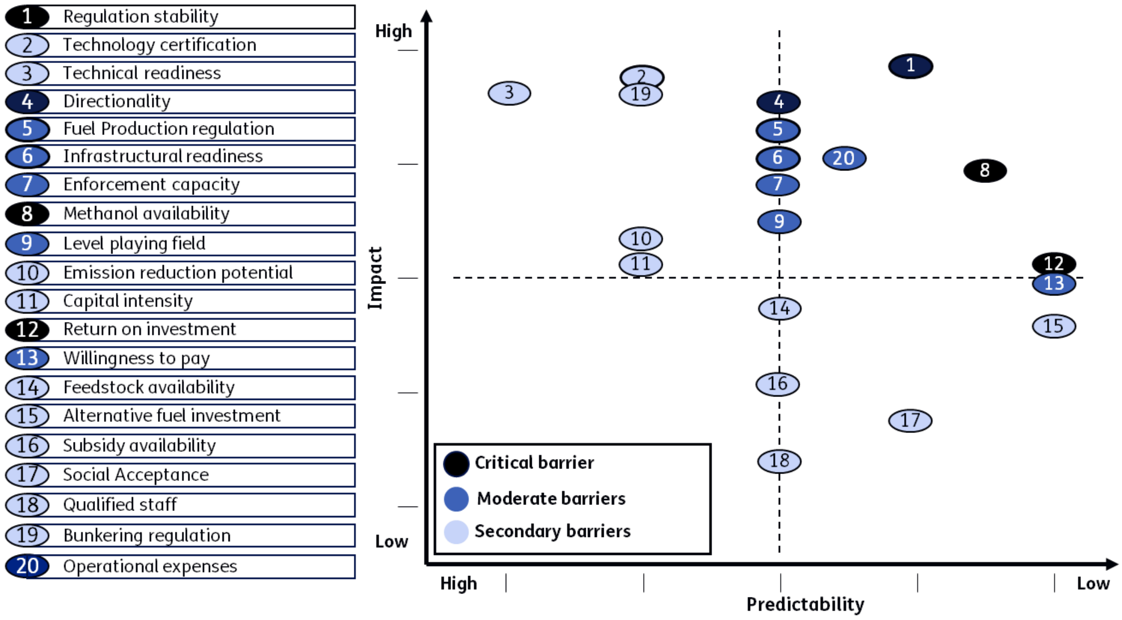

Figure 2: Criticality of listed barriers

Note, in general barriers are not considered independent variables. Barries are strongly correlated, for example the capital intensity required can directly affect the return on investment. Therefore, we place the barriers in the context of the value network, to further our understanding how they relate to the rest of the value network (see Figure 1 and Figure 3). We observe in Figure 2 that based upon the analysis the regulation stability, methanol availability, and to a lesser extent the return on investment barriers towards methanol become more critical.

The regulation stability is a barrier interacting between the government and a wider subset of maritime stakeholders (see Figure 3). The perceived impact is very high (4,49), and predictability is low-medium (2) as we experience at the IMO at the moment. In more detail, two core aspects are to be highlighted. First, the impact whether the GFI will be implemented at IMO level. Second, which feedstock for the long term are applicable for (bio-)methanol within Annex 9A/9B of the RED III on EU level. The implementation of the GFI at the IMO would create long term stability based on pricing mechanisms for GHG emissions, which positively impact the business case for sustainable solutions. Long term feedstock stability in relation to Annex 9A/9B would derisk the investments by fuel producers, also positively impact the business case towards sustainable solutions. Therefore, it is recommended to further allocate resources to align (inter)national interest and approaches on an EU and IMO level to enable a stable outlook for both GHG pricing and the use of feedstock for (bio)methanol.

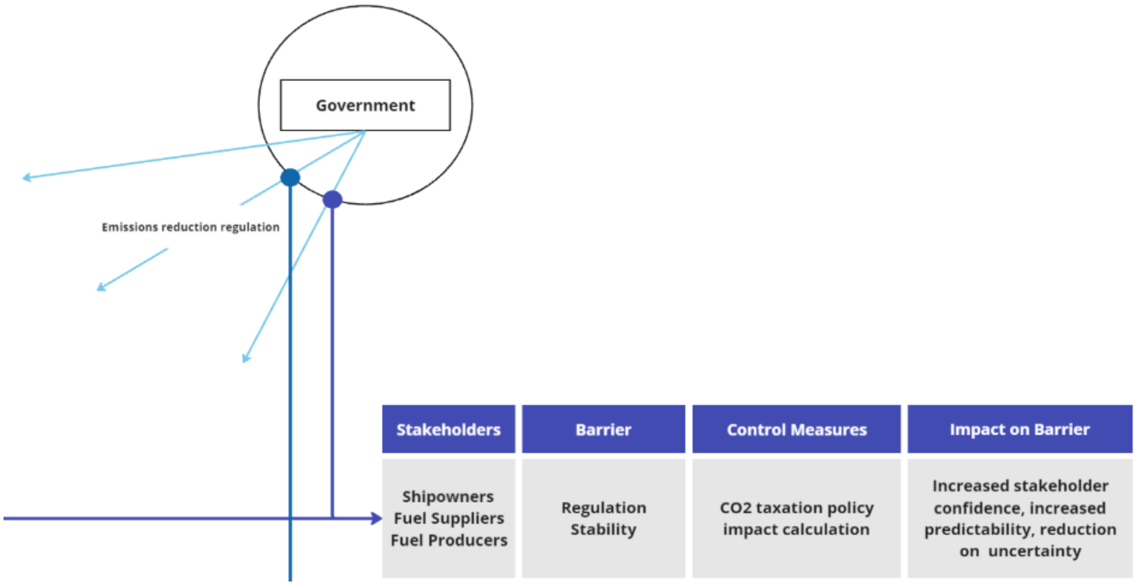

Figure 3: Regulation stability barrier example

The second highlighted and correlated critical barrier is the fuel availability. The barrier is predominantly between the fuel supplier and ship owners (see Figure 4). The perceived impact is very high (3,95), and predictability is low (1,5). This relates to the ‘chicken and egg’ challenge: lack of demands results in lack of supply, and this leads to no commitment to vessels that require sustainable fuels. This in return results in a lack of willingness to invest in production facilities. Based upon discussions with stakeholders it is recommended to explore a value at risk assessment, and perceived risk vs. willingness to invest assessment for multi stakeholder bio-methanol commodity contracting.

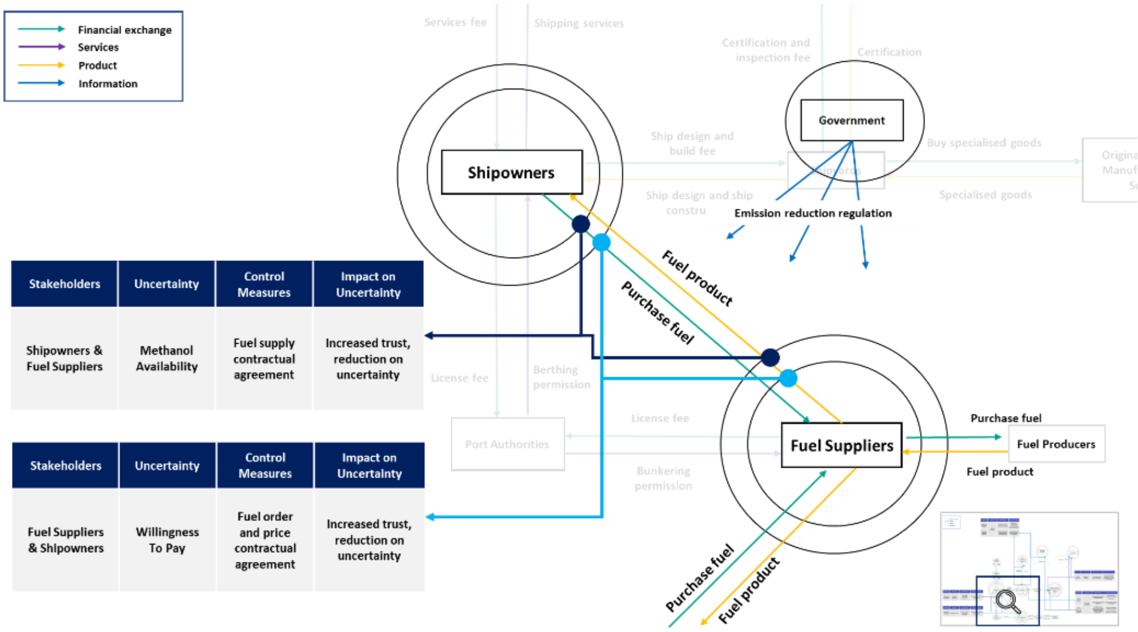

Figure 4: Methanol availability and willingness to pay barrier between shipowners and fuel suppliers.

Overall, further understanding of these barriers enable actionable insights and policy recommendations.

2.2.2 Conclusion

In conclusion, across stakeholder groups, out of 20 barriers, the regulatory stability (e.g. IMO/NZF trajectory; RED III feedstock rules) is perceived as the most critical barrier. After that, methanol availability, which suffers from the classic “chicken-and-egg” between offtake certainty and producer investment decisions. Above all, these barriers interact along the value network amplifying investment risk unless addressed jointly.

3 Methanol status quo

3.1 Introduction

To further understand the context of the highlighted barriers in Chapter 2 we describe the status quo of methanol and other alternative energy carriers. Currently, a variety of alternative energy carriers is under consideration for shipowners (e.g., bio- or e-methanol, biodiesel, ammonia, etc). The variety of choices increases the complexity of strategic decision making in relation to fleet development. The complexity can be reduced by focusing on the topics that are of most importance in the current timeframe. As analysed in Chapter 2, a highly prioritized barrier is the regulation stability of alternative energy carriers such as methanol in shipping.

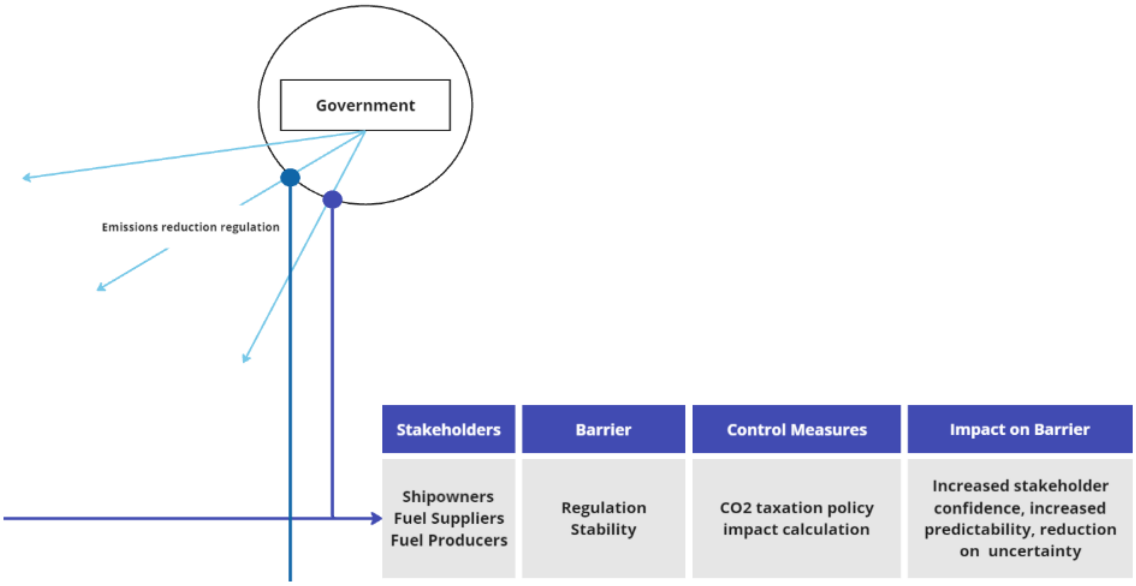

Figure 5: Systemic barrier on regulatory stability between government and various stakeholders.

Therefore, the objective is to compare alternative green fuels options with bio- and e-methanol on both technology, and policy and regulation to determine the relevant considerations in the current timeframe. The approach consists of two steps. First, a comparison of the technology readiness level (TRL) and the emission reduction potential per energy carriers. Second, a description of the impact of upcoming aforementioned regulation such as the Renewable Energy Directive III and the Net Zero Framework (NZF).

3.2 Results

3.2.1 Technology

3.2.1.1 Technology readiness level (TRL)

Bio- or e-methanol is one of many energy carriers that can be used for low-emission ship propulsion. In this chapter, we will compare methanol to those alternatives. There are several types of 'green' ship propulsion methods with a high TRL [6]. Methanol engines are already used by around 30 ships worldwide.

Bio-diesel and bio-LNG can be, and are, used in normal diesel and LNG marine engines, often blended with fossil fuels. Battery-powered ships exist in many places, although they are mainly used for short voyages due to the limited energy storage capacity of current-generation batteries. Ammonia and hydrogen are still considered in the pilot phase.

*Table 2: Readiness levels (TRL1-9) for propulsion technology and production and distribution technology [7] [8] [9]. *Note, TRL does depend on the power requirements.*

	Readiness propulsion technology*	Readiness production + distribution	Phase - propulsion	Phase - production + distribution
bio-methanol	7-9	7-9	implementation	implementation
e-methanol	7-9	5-6	implementation	pilot
e-ammonia	4-6	5-6	pilot	pilot
biodiesel	9	9	implementation	implementation
e-diesel	9	5-6	implementation	pilot
bio-LNG	9	9	implementation	implementation
e-LNG	9	5-6	implementation	pilot
e-hydrogen	6-8	5-6	pilot	pilot
battery-electric	7-9	9	implementation	implementation

Marine engines using ammonia and hydrogen are being developed, and several engines and fuel supply systems have received case-specific approval from classification societies. They are likely to reach the ‘deployment’ phase in a few years. In summary: bio and e-methanol combustion is a low-emission way of powering ships with a medium level of technology readiness. There are alternatives with high TRLs, both in terms of fuel stock as energy conversion technology. Furthermore, there are many developments regarding fuel and energy conversion technologies that are technologically less developed. When considering different vessel types, it shows that methanol is relatively widely applicable. The energy density is less than diesel, but better than ammonia and hydrogen [7].

3.2.1.2 Well-to-wake greenhouse gas emissions

As illustrated in Figure 6, there are many alternative maritime fuels that cause very low net emissions of greenhouse gases into the atmosphere. The figure also shows that the feedstock choice greatly influences the net emissions for bio-based fuels. This chart shows pathways that represent upper and lower values for bio-diesel and bio-methanol according to the 5th version of the JEC well-to-tank study [10].

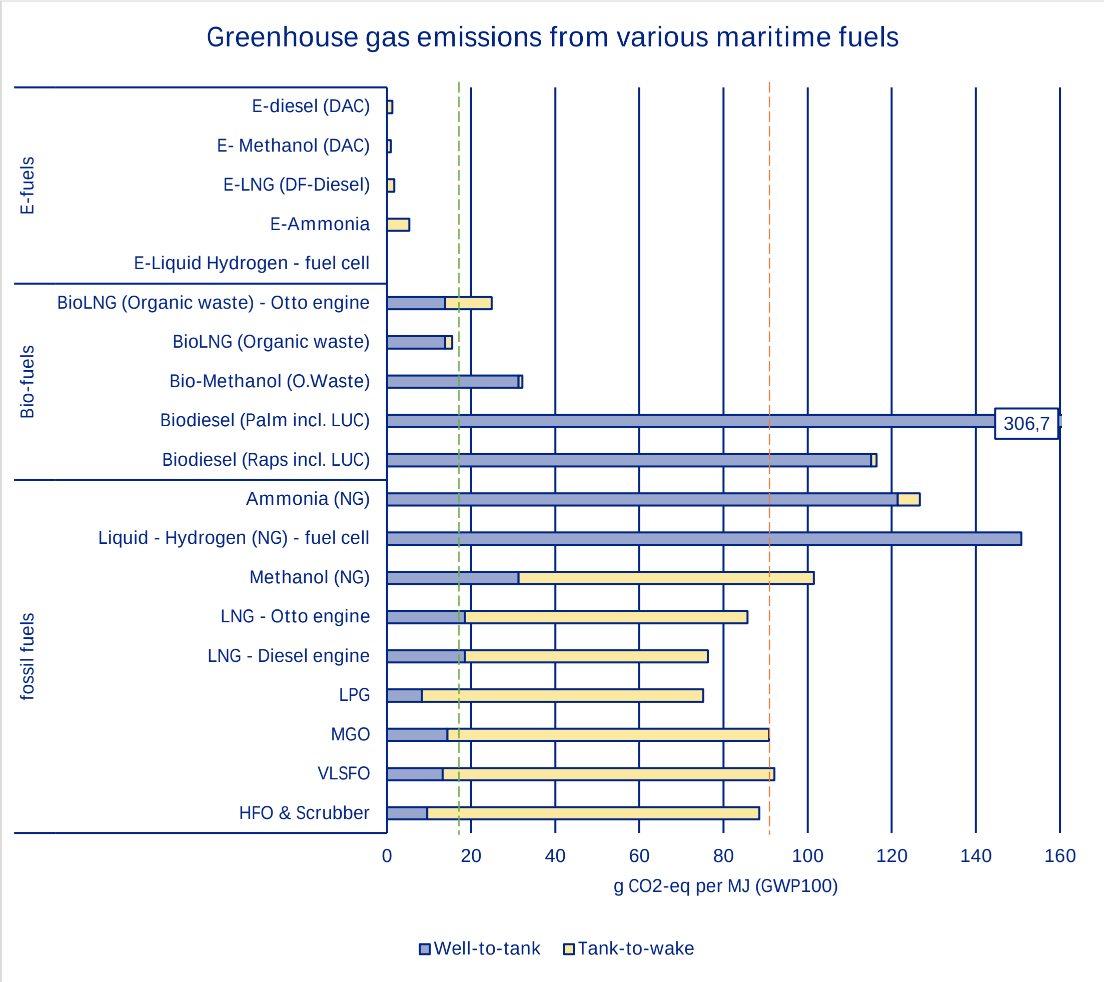

Figure 6: Greenhouse gas emission from various maritime fuels [11]. The green dashed line – 80% reduction (FuelEu Maritime 2050 target) orange dashed line are MGO emissions for reference.

E-fuels are assumed to be produced using emission-free electricity from wind power. 'Blue' variants of methanol, hydrogen and ammonia are not included in this chart as emissions during transportation and storage of captured carbon are not yet known. For a more extensive explanation and source data, please refer to [5]. Depending on the feedstock used, bio-methanol leads to roughly 80% - 90% reduction in greenhouse gas emissions compared to marine gas oil. E-methanol can even lead to a reduction of about 99% of greenhouse gas emissions compared to MGO, if 100% renewable energy is used for its creation.

Overall, the TRL level and the well2wake comparison shows that the use of methanol is feasible, yet highly dependent on which feedstock is used, to determine how sustainable it actually is. This is heavily related to how it is perceived in upcoming regulation.

3.2.2 Regulation

In this section we go in more depth regarding two specific developments. The RED III and IMO Net Zero Framework. RED III is a key instrument to meet EU climate targets for 2030 and beyond. It shifts from energy-based to GHG-based accounting and introduces sector specific obligations. Both frameworks are in principle energy carrier agnostic, although lower TRL technologies such as nuclear propulsion are not yet embedded.

Overall, both the RED III and the NZF aim to enable, if implemented, a strong and clear long term outlook enabling the use of sustainable energy carriers.

3.2.2.1 RED II towards RED III

The evolution from the Renewable Energy Directive II (RED II) to RED III marks a change in the European Union's strategy to decarbonize the transport sector. Under RED II, the focus was primarily on road and rail transport, with a target of 14% renewable energy by 2030. Currently, the maritime sector has an opt-in role under RED II, meaning there is no binding obligation to use renewable fuels. However, voluntary use of such fuels generates tradeable certificates called Renewable Fuel Units (RFU). In practice, this has led to widespread use of FAME (Fatty Acid Methyl Esters) as a cost effective way to meet RED II targets in shipping.

One of the reasons of this cost effectiveness of RFU was due to a 'double count' incentive for advanced biofuels resulting in twice the amount of Renewable Fuel Units (RFU) for the same fuel quantity. One RFU represents 1 gigajoule (GJ) of renewable energy delivered on the market, which can be used to meet the organizations climate goals or to be sold to other more fossil based organisations that require carbon offsetting. Which feedstocks can be used for advanced biofuels is defined on RED II Annex IX A as mentioned in Chapter 2. In this context maritime and aviation received an additional incentive through an energy contribution multiplier of 1.2. This dynamic has created a competitive imbalance, as sustainable fuels in the road sector struggle to compete (see Figure 7). This is phased out towards RED III.

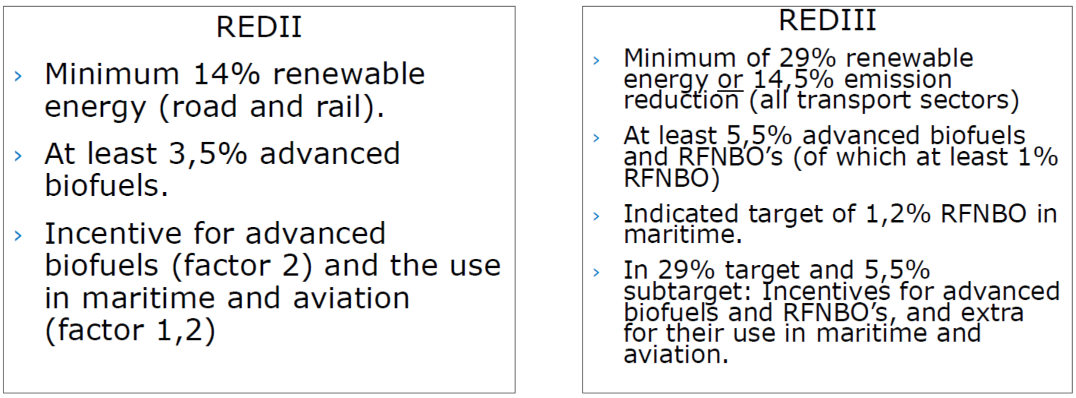

Figure 7: Changes from RED II towards RED III [12].

In contrast, RED III introduces a more ambitious and comprehensive framework. By 2030, member states must achieve either 29% renewable energy in transport or a 14.5% reduction in greenhouse gas (GHG) intensity. The scope now includes all transport modes. Another change in RED III is the mandatory inclusion of Renewable Fuels of Non-Biological Origin (RFNBOs), such as e-methanol, within the 5.5% target for advanced fuels, with at least 1% specifically from RFNBOs [13]. For maritime transport, RED III sets an indicative RFNBO target of 1.2%, reinforcing the sector's role in the EU's climate ambitions. The sustainable fuel obligation over time can be seen in Table 4. In total in 2030 the maritime sector has an obligation of 8.2% renewable fuels share. However, 2.5% of 'free space' can be attained via the 'new' RFU's called Emission Reduction Units (ERU's) via other sectors.

Table 2: Sustainable fuel obligation in RED III over time. Note, RFNBO share grows towards 0.32% towards 2030 [12] (RVO, 2025).

Year	Seagoing shipping renewable fuel obligation (excluding free space)	Total renewable fuel obligation incl. free space (e.g. via Emission reduction Unit's (ERU's)
2026	2.5%	3.6%
2027	3.3%	4.8%
2028	4.1%	5.9%
2029	4.9%	7.1%
2030	5.7%	8.2%

Based upon this obligation, fuel suppliers have certainty towards market demand of renewable fuels and RFNBO's, which then enables investments into fuel production. As result, by 2030, the expected methanol use includes approximately 1,500 kton of bio-methanol and 70 kton of e-methanol [12]. A limitation is, that the annual obligation after 2030 is not yet fully clear.

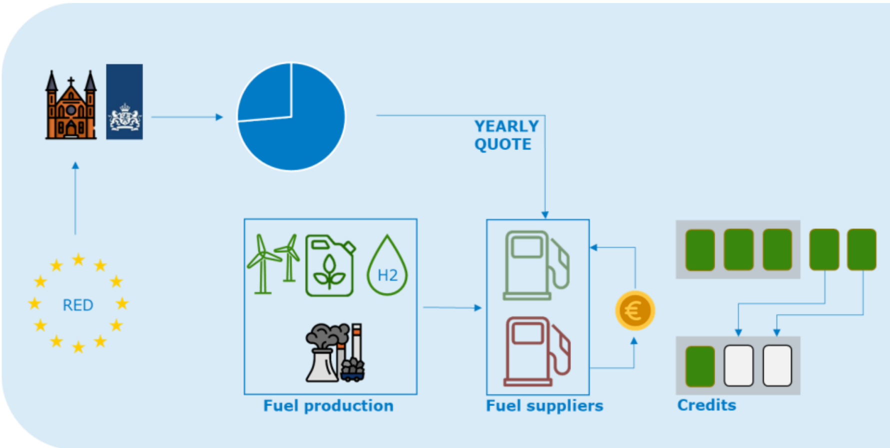

Figure 8: Flow of activities intended by RED III.

3.2.2.2 IMO Net-Zero Framework

The International Maritime Organization (IMO) has introduced the Net-Zero Framework (NZF) as a cornerstone of its strategy to decarbonize global shipping by 2050. This framework was agreed upon at MEPC 83 in April 2025 and was expected to be formally adopted in October 2025. Despite its current adjournment, it still represents a significant regulatory milestone aimed at creating a global level playing field for sustainable shipping.

If implemented, then from 2028 onwards, ships will be required to [14]:

- Monitor the Greenhouse Gas Fuel Intensity (GFI) of the energy they use, expressed in gCO_2e/MJ on a well-to-wake basis.
- Reduce their GFI progressively, with targets of 17% reduction by 2029 and 43% by 2034, compared to the baseline.
- The GFI calculation considers all energy sources, including fuel oil, electricity from shore power, and zero-emission energy such as wind and solar propulsion. This holistic approach ensures that all energy inputs are accounted for in compliance assessments.

Ships that fail to meet GFI targets must purchase Remedial Units (RUs):

- First 13% of excess emissions: USD 100 per tonne CO_2e.
- Beyond 13%: USD 380 per tonne CO_2e.

Ships that outperform targets earn Surplus Units (SUs), which can be traded. However, the supply of SUs is expected to be limited, keeping their price close to the higher RU cost.

The NZF will significantly alter fuel economics:

- Fossil fuels become less competitive due to compliance costs. For example, the additional cost of using VLSFO is projected to rise by USD 163 per tonne in 2028 and USD 631 per tonne by 2035.
- Renewable fuels, such as bio-methanol and UCO FAME, generate financial benefits through SUs. For instance, using UCO FAME could benefit by of USD 919 per tonne in 2028, decreasing to USD 549 per tonne by 2035.

Furthermore, the framework introduces Sustainable Fuel Certification Schemes (SFCS), recognized by IMO and subject to five-year renewals. From March 2027, a Fuel Life Cycle Label (FLL) will be mandatory on Bunker Delivery Notes, detailing certified emission factors and sustainability criteria. These measures aim to ensure transparency and credibility in the certification of low-carbon fuels, reinforcing trust in the system and supporting global adoption.

Overall, the regulatory assessment shows that enabling frameworks are between implementation and commitment phase. The core uncertainty that remains is the (inter)national commitment and thereby long term stability required to enable investments.

3.2.3 Conclusion

In conclusion, methanol is technically deployable now, but sustainability and scale depend on feedstock choices. Methanol propulsion and handling have medium-to-high TRLs, with early commercial deployment underway. Well-to-wake benefits are substantial when using advanced bio-feedstocks or RFNBO. In addition, regulatory trajectories are enabling, but investment confidence hinges on clarity and timing. RED III broadens transport coverage and codifies RFNBO shares, while the IMO Net-Zero Framework (with GFI targets and unit pricing) can make fossil fuels less competitive and reward low-carbon fuels. Yet timing, international alignment, and long-term feedstock eligibility remain uncertain. Policy coherence across sectors is pivotal to avoid cross-sector bottlenecks and to anchor price signals for investment decisions.

4 MeOH (supply chain) cost analysis

4.1 Introduction

Cost and availability of methanol are intertwined issues, resulting a ‘chicken and egg’ challenge. In this section we report the supply cost analysis along the production chain, with the aim to identify the main risks and drivers for lowering the investment barrier. Thereby increasing our understanding of the lack of methanol availability barrier.

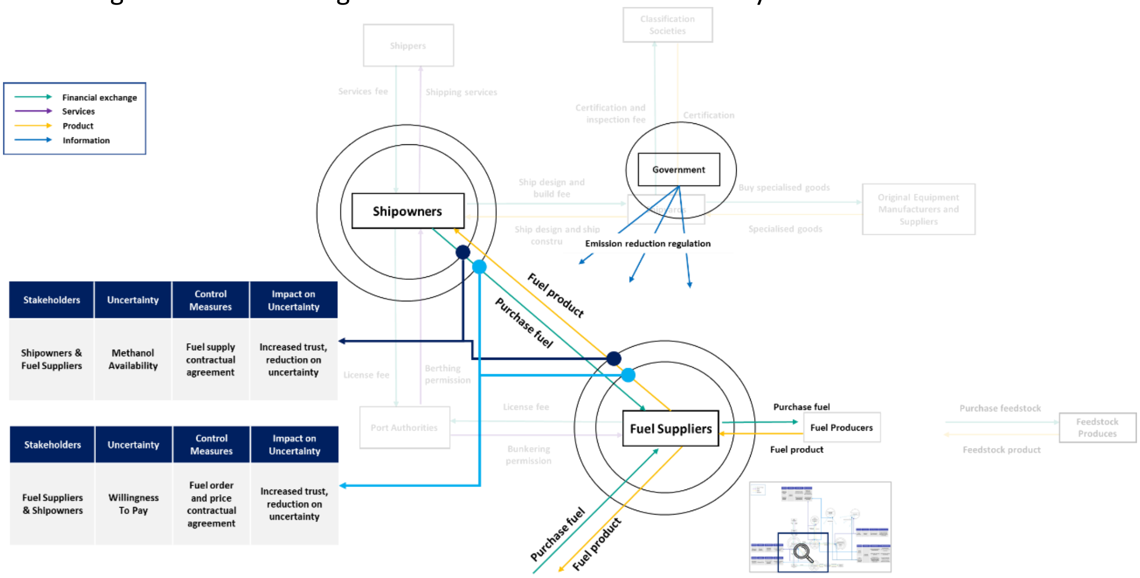

Figure 9: Barrier visualisation showing the relation between fuel suppliers and shipowners. Note, the value chain extends much further beyond, however this is the core interaction to focus methanol availability and willingness to pay for green methanol.

The approach consists of two steps. First, we model the bio- and e-methanol supply chain cost based on the cost breakdown of all production and transportation steps. This provides insight on both the cost drivers, and the potential cost sensitivity. To enable fair comparison three different supply chain routes have been analysed. Secondly, we assess together with consortium stakeholders the perceived cost sensitivity. This chapter shows the summarized results of this analysis [2].

4.2 Result

4.2.1 Comparison between bio-methanol and e-methanol costs

To model the bio- and e-methanol supply chain we must first understand the cost drivers. For example, the main cost driver for the bio-methanol is the biomass feedstock cost and the transportation cost of the raw biomass. In total eight cost components have been assessed for the e-methanol supply chain, and six cost components for the bio-methanol supply chain. These cost components have been compared between three high level archetype supply chains. The resulting cost comparison between e-methanol (GMM2) and bio-methanol (GMM3) is shown in Figure 10.

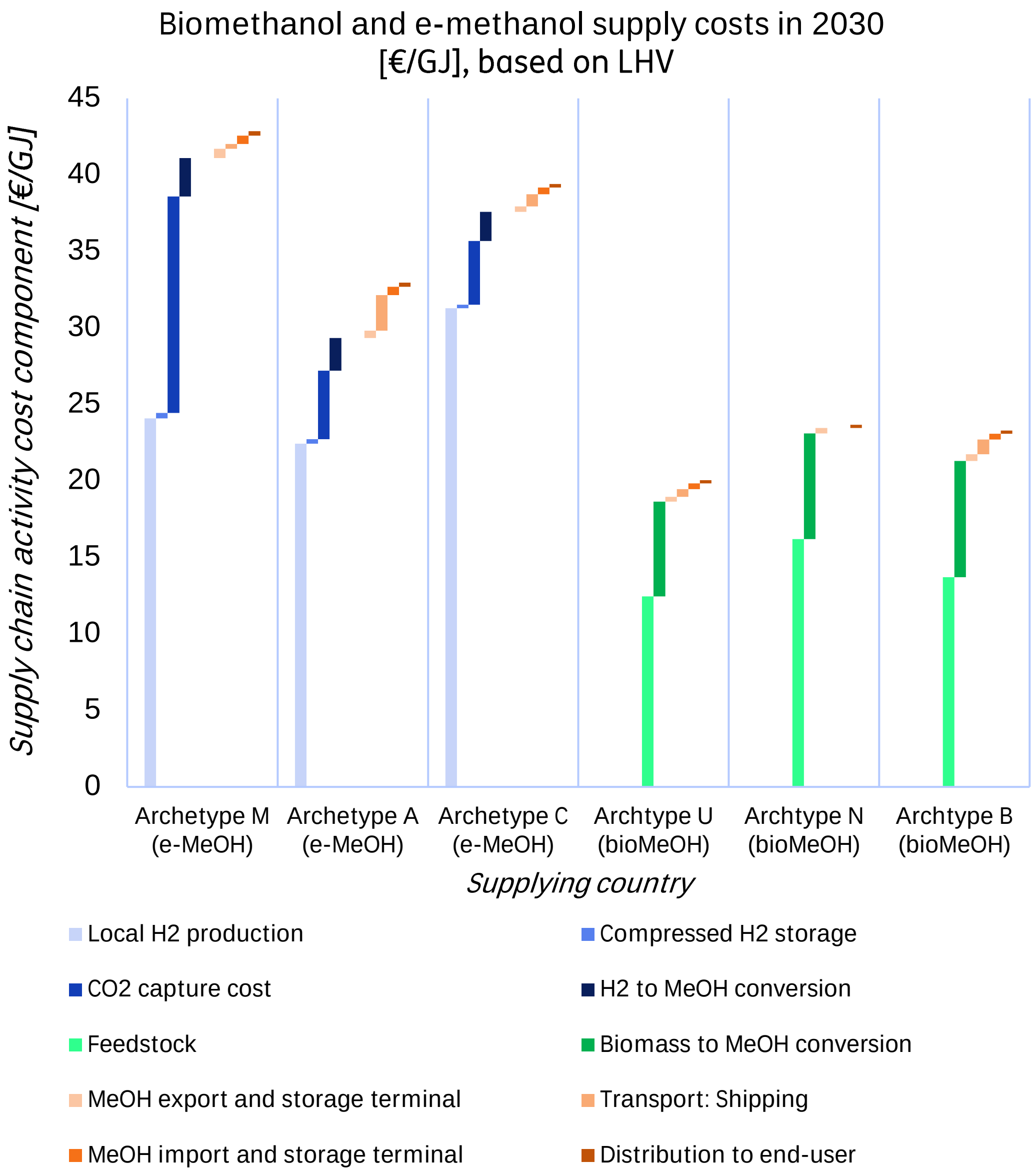

Figure 10: Levelized cost breakdown comparison of bio-methanol and e-methanol for six archetype supply chains (M = Marocco, A = Australia, C = Canada, U = USA, N = Netherlands, B = Brazil). Source: memo: Cost analysis of bio-methanol supply chains [2].

The cost of e-methanol is about 50% higher than of bio-methanol. In both cases the feedstock related costs are the primary cost driver for supply cost of methanol. And the feedstock costs for e-methanol (hydrogen, carbon dioxide) are more dominant than the biomass feedstock for bio-methanol. There also is a major difference in the cost for conversion to methanol: The cost for conversion of bio-methanol is significantly higher than that of e-methanol since more equipment is required such as the gasification section, air separation unit and a gas-cleaning section.

4.2.2 Sensitivity analysis of bio-methanol and e-methanol costs

Many uncertainties exist regarding the cost components within renewable methanol supply chains. Therefore, performing a sensitivity analysis on the cost components increase our understanding on their impact on the methanol availability barrier. In this section, the results of the sensitivity analysis for both bio and e-methanol are described.

The scope of the sensitivity analysis is limited to quantitative input variables that relate to the costs of producing, transporting and distributing renewable methanol to the end user. The uncertainties and qualitative cost drivers, required to produce estimated bandwidth of the future market price of renewable methanol, are part of the market dynamics and willingness-to-pay analysis in chapter 5.

The following parameters were varied to explore which factors affect the bio-methanol cost most:

- CAPEX (general): The CAPEX of all assets within the supply chain (MeOH plant, import terminal, etc.).
- CAPEX (bio-MeOH conversion): The CAPEX of the conversion plant, which consists of the following process steps: feedstock pre-treatment, gasification, syngas cleaning, water gas shift and CO_2 removal, methanol synthesis and purification.
- CAPEX (terminal): The CAPEX of the import terminal and storage assets.
- Scale of bio-MeOH conversion plant: The capacity of the methanol conversion plant within one bio-MeOH supply chain.
- Transport distance: As the cost analysis uses archetype supply countries, other countries with similar characteristics that are more close/farther away may exist. Deep-sea transport distances are therefore varied.
- Biomass feedstock cost: The 'at-the-gate' cost of biomass feedstock.
- Interest rate: The interest rate within the country under consideration. The depreciation rate is assumed equal to the interest rate.

The ranges were determined based on input from the GMM community involvement in March 2024 and feedback through bilateral expert consultation. The results of the sensitivity analysis are displayed in below Figure 11.

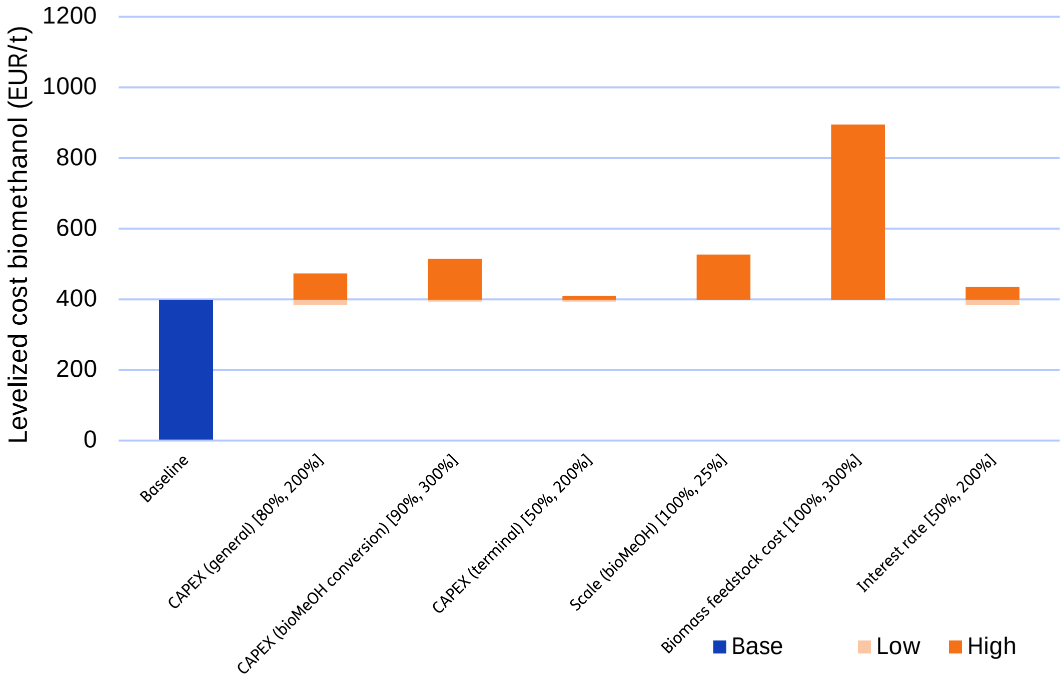

Figure 11: Uncertainty ranges of bio-MeOH supply chain costs per parameter, with ranges based upon GMM consortium member and expert input.

The largest uncertainty lies in the cost of biomass feedstock. The levelized cost of bio-methanol is highly sensitive to fluctuations in feedstock cost, making it the most significant cost driver of bio-methanol costs. In addition to the uncertainty in feedstock costs, there is considerable uncertainty regarding the CAPEX of the bio-methanol production plant. Since the CAPEX significantly influences the overall levelized cost, it is the second major cost driver. The third sensitive cost driver is the scale of deployment: the smaller the annual production scale, the higher the levelized cost due to the large impact of scale via the scaling factor of investment costs (CAPEX) as well as the annual volumes of methanol over which the supply chain costs can be spread. Based on the seven sensitivities analysis, the cost estimate for bio-methanol in this study ranges between about 400 to 900 EUR/t when sensitivities are considered in isolation. To be able to more accurately calculate the levelized cost of methanol, a more narrow estimate of the cost of feedstock, CAPEX of the bio-methanol production plant and the scale of deployment are required to determine a smaller bandwidth in future cost analysis.

Applying the same approach covering ten parameters, the cost estimate for e-MeOH in this study ranges between about 680 to 1200 EUR/t (see Figure 12) when sensitivities are considered in isolation, and 400 up to 1600 EUR/t when sensitivity ranges are merged. Note that these sensitivities are not analysed in relation to each other – all parameters are varied individually while correlations and causalities amongst them can be expected.

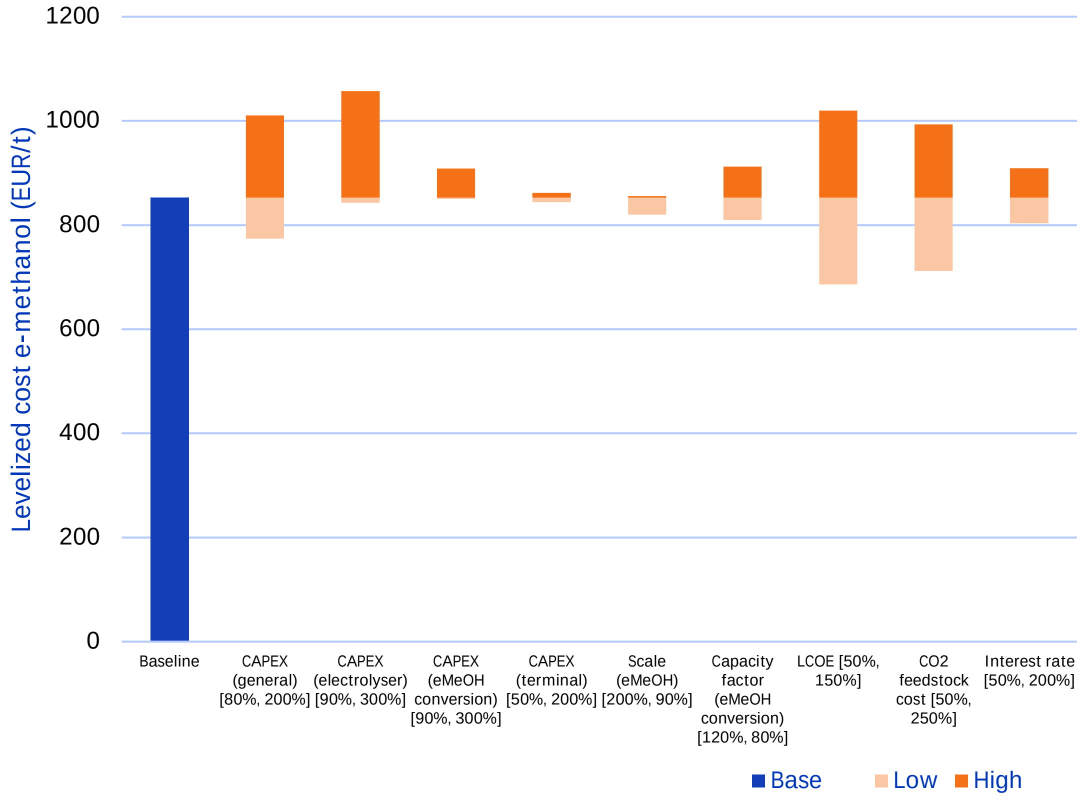

Figure 12: Uncertainty ranges of e-MeOH supply costs for supply chain archetypes M, A and C

Overall, the costs of both bio-methanol and e-methanol have substantial uncertainty drivers. Bio-methanol relies on a diverse range of feedstock supply chains and suppliers, making feedstock uncertainty exogenous to the cost analysis, with uncertainty concentrated at the front end (feedstock cost, OPEX). E-methanol is almost always more expensive, even when considering positive ranges for e-methanol and negative ranges for bio-methanol.

E-methanol internalizes more CAPEX supply chain elements, implying a larger set of uncertainties is endogenous to the cost analysis and more spread throughout the supply chain, affecting both CAPEX and OPEX. This extensive range in supply chain cost, further clarifies an uncertainty for those requiring methanol and those producing. It is recommended to focus on the drivers with the highest impact on the cost.

4.2.3 Conclusion

In conclusion, supply chain costs are uncertain as feedstock prices and scale dominate the economics. In this context, bio-methanol shows cost ranges primarily driven by biomass price and conversion CAPEX, whereas e-methanol costs are generally higher and more sensitive to electricity, CO_2 supply, and electrolyser pathways. Across supply chain archetypes throughout the word, levelized costs exhibit wide bands, underscoring the need for demand aggregation and risk-sharing mechanisms to unlock economies of scale and lower financing costs.

5 Exploring methanol fuel pricing

5.1 Introduction

The transition barrier analysis in chapter 2 highlights that methanol availability for maritime use is the highest priority barrier for shipowners (4.74). This strongly correlates with the willingness to pay barrier (3.87) of those shipowners and their competitors. Therefore, we aim to understand the maritime sector's positioning relative to other industries regarding methanol availability, as part of the broader 'chicken and egg' systemic challenge.

The systemic challenge of methanol availability for shipping is complex, because market dynamics of any emerging renewable fuel are dependent on many factors. Furthermore, both demand- and supply-side uncertainties make it difficult to predict future market prices. Therefore, instead of predicting market prices, the best approach is to analyse the key mechanisms driving the willingness to pay (WTP) across competing sectors. Based upon the key mechanisms, we can further understand the position of shipping. Figure 13 illustrates the interactions between stakeholders within the larger value network, as analysed in chapter 2.

The approach consists of three steps. First, we characterize the current state of the renewable methanol supply and demand. Next, we develop a comparative framework for willingness to pay between sectors. Finally, we perform a (sub)sectoral willingness to pay analysis. Here we qualitatively assess the demand from the maritime sector alongside other sectors such as aviation and chemical industry. We aim to construct a renewable demand merit ranking to better understand how different sectors compete for methanol under varying market conditions. Thereby increasing our understanding to what extent the methanol demand across other sectors functions as an enabler or as a barrier [3].

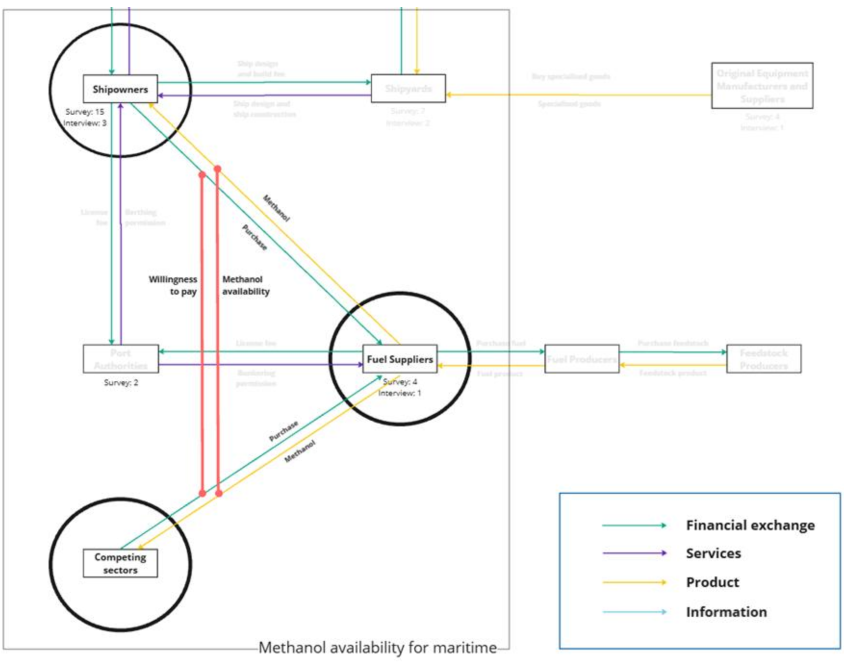

Figure 13: Barrier visualisation highlighting the relation between fuel suppliers, shipping and competing sectors considering the willingness to pay barriers.

5.2 Result

5.2.1 Methanol supply and demand

The current conventional (natural gas or coal based) methanol demand has been growing significantly in the past decade, from 40 Mt in 2010 to 100 Mt today [15]. Two demand sectors have been mainly responsible for this growth: methanol-to-olefines and gasoline blending. However, renewable methanol currently accounts for only a small share annually. Looking further ahead, scenarios by the International Renewable Energy Agency (IRENA) and industry analysts foresee a dramatic scale-up: global methanol consumption could rise to about 500 Mt per year by 2050, with the vast majority of that growth coming from renewable methanol. Estimates suggest up to 400 Mt of the 2050 volume could be bio- or e-methanol) [16].

On the supply side, there is a pipeline of many projects in various levels of maturity aiming to produce renewable methanol. By 2024, over 130 new bio-methanol and e-methanol projects have been announced globally. The total pipeline of renewable and low-carbon methanol projects adds up to 41.2 Mt in 2030, of which 34 Mt is renewable (bio- and e-methanol). While not all announced projects will the trend is clear: supply is ramping up in response to anticipated demand. However, several green methanol projects have been cancelled or paused due to high energy costs and lack of demand. In February 2024, the Power to Methanol project at the Port of Antwerp, which aimed to produce 8,000 tonnes per annum (tpa), was cancelled because no customers were willing to sign long-term contracts. This results in the wide supply and demand range projections in Figure 14.

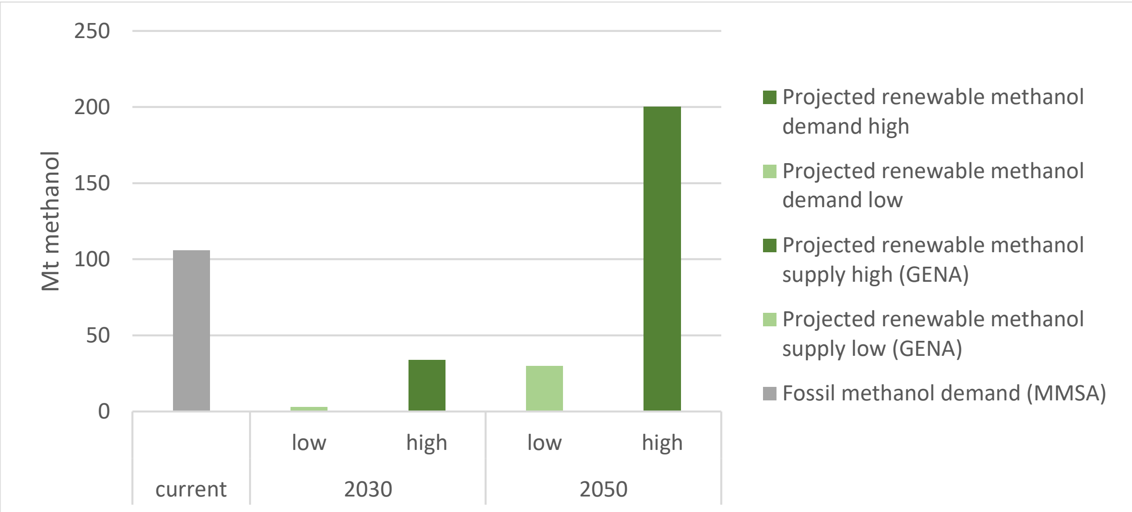

Figure 14: Supply and demand projections of renewable methanol (2030-2050) [17]

Right now, renewable methanol projects only move forward if offtakers commit to long-term agreements, which derisks the projects by ensuring revenue certainty for renewable methanol producers. This combined with the projections above, could result in a supply shortage is likely in the late 2020s if renewable methanol demand increases. Especially when large shipping companies start operating methanol ships which may outpace the increase of supply. Such a shortage can be expected to drive up price levels and makes securing offtake agreements crucial.

To understand the mechanics, it is key to grasp that the evolution of markets for a new commodity like renewable methanol typically follows three phases (see Figure 15) [18]. Each phase reflects increasing maturity, economies of scale, and price convergence.

The renewable methanol market is in an early-stage (Phase 1) of development, characterized by the aforementioned opaque pricing and bilateral contracts. Presently, most green methanol deals are dedicating offtake agreements. For example, a shipping company contracting directly with a producer for a guaranteed volume at an agreed price. Trade activities are limited and not yet transparent, much like the renewable ammonia market's infancy where contracts are long-term and confidential [18]. Moving to phase 2, a more established spot market, can mitigate much of the uncertainty related to the willingness to pay. An ongoing first step could be for major ports where many buyers and sellers trade, and methanol is bunkered, could create reference prices. Phase 3 is currently less of a priority, but would increase broader market participation (e.g. financial hedgers) thereby increasing the overall willingness to pay for renewable methanol.

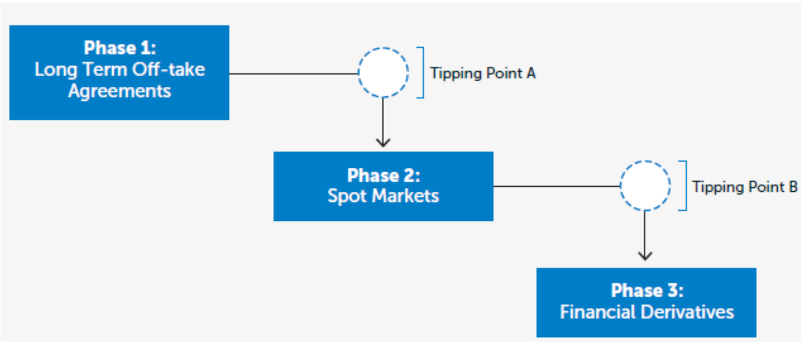

Figure 15: Commodification pathway [18]

5.2.2 Willingness to pay

In economic theory, willingness-to-pay (WTP) refers to the maximum price a buyer is prepared to pay for a good or service [19] or avoid an undesirable outcome. In the context of methanol trade, a WTP thus reflects a perceived value it provides to the buyer. This concept is highly relevant to fuel procurement in the context of decarbonization. Understanding WTP helps to understand who may buy (more) expensive renewable fuels and feedstock voluntarily and who will only buy if compelled by regulations or incentives.

In renewable methanol markets, WTP can vary significantly across demand sectors (e.g., shipping, chemicals, and fuel blending) due to differences in perceived benefits, regulatory pressure, and competitive alternatives.

For instance:

- Shipping companies may use methanol as a decarbonizing option and may have a higher WTP due to the stringent decarbonization mandates they need to comply with.
- Chemical producers produce higher value products from the methanol feedstock and may have a moderate WTP, driven by customer preferences for sustainable products, but low WTP for base products where costs cannot be passed on as readily.
- For fuel producers methanol also is a feedstock and this sector may have a moderate WTP due to regulatory requirements, but lower WTP if cheaper substitutes like bioethanol are viable.

Broadly speaking, we've defined four factors shape a stakeholder's competitiveness as an offtaker by balancing compliance, market dynamics and economic viability. Regulatory pressures mandate sustainable practices, forcing stakeholders to internalize compliance costs or risk penalties, thereby influencing their market positioning and pricing flexibility.

Availability of alternatives determines bargaining power: limited substitutes enable a higher WTP whereas abundant viable alternatives lower WTP. Total Cost of Ownership shifts focus from upfront costs to long-term value, where stakeholders offering lower lifetime expenses gain preference despite higher initial costs. Cost pass-through capability reflects market structure: in concentrated or specialized markets, stakeholders can pass costs on to consumers whereas competitive markets or low margin products may compel cost absorption to retain customers.

5.2.3 Sectoral analysis

The current maritime market shows a total orderbook of several hundreds of methanol capable vessels in the coming five years. This is huge expansion with a total share of 8-14% of global GT between 2022 and today [20]. When the 2026 delivered fleet would sail full capacity on methanol, this would exceed the total global capacity for sustainable green methanol. However, there are major differences per maritime subsector, and other sectors. Based upon the four factors defining willingness to pay Table 3 provides insight on how different (sub)sectors compare. The analysis is based on 10 interviews held with parties within the Green Maritime Methanol consortium and available data per type of (sub)sector. The results of the analysis are shown in Table 3. In this analysis we differentiate between four shipping subsectors (general cargo, luxury yachts, offshore service vessels, fishing vessels), and consider competing sectors from a more generic perspective.

Table 3: Sectoral WTP analysis based on interviews and available data per (sub)sector (green is high WTP, orange medium and red low).

Sector	Subsector	Regulatory incentives to use green methanol	Methanol lock-in (lack of alternatives)	TCO impact	Cost pass through (market elasticity)	Score
Maritime	General Cargo Vessels					Medium
Maritime	Luxury Yachts					Low-Medium
Maritime	Offshore Service Vessels					Low-Medium
Maritime	Fishing Vessels					Low-Medium
Aviation	Airlines					Medium-High
Chemical industry	Methanol-to-Olefins, formaldehyde and base products					Medium
Road transport	Fuel blending					Medium

In short, general cargo vessels show **medium** WTP, driven by regulatory pressure from FuelEU Maritime and upcoming GHG Fuel Intensity rules. Compliance mandates and penalties push adoption, though cost constraints remain. Operators like Maersk are piloting dual-fuel vessels, reflecting a balance between regulation and commercial realities. In comparison, luxury yachts rank **low-medium**. Exempt from major regulations and facing minimal client demand, WTP is limited. However, some builders invest in methanol-ready designs for strategic positioning and brand image. Owners' financial capacity suggests cost is not the main barrier; rather, small market size and bunkering logistics hinder uptake. Furthermore, Offshore service vessels (OSVs) also score **low-medium**. With no current regulatory obligations, charterers resist higher fuel costs.

Still, some operators invest in methanol capability to future-proof fleets, viewing it as more practical than ammonia or hydrogen. WTP could rise if policy incentives or tender requirements emerge. Finally, fishing vessels show **low-medium** WTP due to exclusion from FuelEU Maritime and tight margins. Price-sensitive markets and limited consumer demand for sustainable seafood constrain adoption. Unless regulations or buyer preferences shift, WTP will remain low.

The aviation sector shows the highest (**medium-high**) WTP for green methanol, though indirectly. RefuelEU Aviation mandates rising shares of sustainable aviation fuel (SAF), and e-methanol is a key feedstock for the Methanol-to-Jet (MTJ) pathway. SAF's drop-in nature avoids aircraft or infrastructure modifications, eliminating CAPEX barriers. Cost pass-through is feasible: ticket prices will rise, but demand for long-haul routes remains strong. The main challenge lies upstream in methanol and MTJ production capacity. With few alternatives and strong regulation, aviation demonstrates the strongest WTP.

The chemical industry's WTP is **medium** and varies by segment. While no direct mandates exist today, anticipated EU recycled-content requirements create forward-looking incentives. Renewable methanol can replace fossil methanol in Methanol-to-Olefins (MTO) and formaldehyde production without major CAPEX, though shifting from naphtha-based olefins requires high investment. WTP is highest in segments serving high-value or consumer-facing markets, such as plastics (PE, PP, PVC), specialty chemicals, adhesives, and coatings, where sustainability claims justify premiums. Commodity chemicals remain cost-sensitive and slower to transition. Cluster-level optimization and space constraints add complexity and delay, increasing costs.

Road transport shows **medium** WTP, driven by blending mandates. Bio-methanol is already used in fuel blending, though challenged by lower energy density compared to ethanol or biodiesel. Regulatory frameworks are advanced, but blending limits vary globally: EU and North America allow low percentages, while China permits M5–M100. Small blends require minimal infrastructure changes, but dedicated methanol vehicles need high investment and face competition from EVs and hydrogen. Cost pass-through to end-users is difficult without mandates, as fuel price increases are borne directly by consumers.

Overall, aviation, road transport, and parts of the chemical industry exhibit higher WTP than maritime sectors. Aviation leads due to SAF mandates and limited alternatives. Road transport benefits from blending regulations, while chemicals show selective WTP in high-value applications. Maritime sectors, despite regulatory pressure, have limited ability to absorb high fuel costs. In consumer goods, raw material price increases have minimal impact on final prices, unlike shipping where fuel significantly affects cost. However, the share in cost does highly differ per subsector. The rate in which regulation is implemented per sector is confirmed as a key driver towards the WTP.

5.2.4 Conclusion

In conclusion, sectoral willingness-to-pay (WTP) shows that aviation exhibits the highest effective WTP (via SAF mandates and drop-in advantages). Road transport blending and selected chemical segments (e.g., MTO/formaldehyde for high-value products) show medium WTP. Maritime subsectors vary, but in aggregate have constrained cost pass-through and face tighter commercial margins. However, green methanol's dual origin (bio and e-fuel) and compatibility with existing infrastructure make it a strong candidate for decarbonization, but competition from other sectors may limit financial feasibility in a short to medium timeframe for shipping.

6 Conclusions

Methanol is one of the most implementable low-carbon options for shipping today, but near-term volumes will flow to the highest-WTP sectors unless maritime demand is aggregated, de-risked, and supported by coherent, durable regulation. Coordinated action on policy clarity, offtake structuring, and cost-gap instruments can help overcoming the barriers that enable the chicken-and-egg cycle and make green methanol a scalable pillar of maritime decarbonization. However, at the moment the transition to green methanol in the maritime sector still faces several critical barriers.

In that context we can state the following:

- Across stakeholder groups, regulatory stability (e.g. IMO/NZF trajectory; RED III feedstock rules) is perceived as the most critical barrier out of 20. After that, methanol availability, which suffers from the classic "chicken-and-egg" between offtake certainty and producer investment decisions. Above all, these barriers interact along the value network amplifying investment risk unless addressed jointly.

- Methanol is technically deployable now, but sustainability and scale depend on feedstock choices. Methanol propulsion and handling have medium-to-high TRLs, with early commercial deployment underway. Well-to-wake benefits are substantial when using advanced bio-feedstocks or RFNBO.

- Regulatory trajectories are enabling, but investment confidence hinges on clarity and timing. Renewable Energy Directive (RED) III broadens transport coverage and codifies RFNBO shares, while the IMO Net-Zero Framework (with GFI targets and unit pricing) can make fossil fuels less competitive and reward low-carbon fuels. Yet timing, international alignment, and long-term feedstock eligibility remain uncertain. Policy coherence across sectors is pivotal to avoid cross-sector bottlenecks and to anchor price signals for investment decisions.

- Supply chain costs are uncertain as feedstock prices and scale dominate the economics. In this context, bio-methanol shows cost ranges primarily driven by biomass price and conversion CAPEX, whereas e-methanol costs are generally higher and more sensitive to electricity, CO_2 supply, and electrolyser pathways. Across supply chain archetypes throughout the word, levelized costs exhibit wide bands, underscoring the need for demand aggregation and risk-sharing mechanisms to unlock economies of scale and lower financing costs.

- Sectoral willingness-to-pay (WTP) shows that aviation exhibits the highest effective WTP (via SAF mandates and drop-in advantages). Road transport blending and selected chemical segments (e.g., MTO/formaldehyde for high-value products) show medium WTP. Maritime subsectors vary, but in aggregate have constrained cost pass-through and face tighter commercial margins. However, green methanol's dual origin (bio and e-fuel) and compatibility with existing infrastructure make it a strong candidate for decarbonization, but competition from other sectors may limit financial feasibility in a short to medium timeframe for shipping.

As aforementioned, with the upcoming potential regulatory frameworks green methanol, especially bio-methanol, would come into the range of economic feasibility. However, major barriers are currently still in place. Therefore, we recommend stakeholders to consider the following actions to mitigate the most critical barriers:

For shipping companies:

- Pool demand and standardize offtake: Form buyer consortia to aggregate volumes, negotiate longer-tenor, indexed contracts, and enable producers investment decisions.
- Embed certification clauses to ensure well-to-wake performance.
- Stage fleet conversion with supply commitments: align newbuild/retrofit timelines with secured methanol supply and bunkering, prioritizing routes/ports with early availability.
- Use hedging and flexibility: adopt contracts for difference like structures with suppliers.
- Include multi-pathway clauses (bio/RFNBO) to mitigate feedstock risk.

For methanol producers and fuel suppliers:

- Target first-mover niches, then scale: start with aviation SAF pathways, high-value chemicals, and leading container lines to anchor initial volumes
- Design modular plants to scale with contracted demand.
- Share risk and increase transparency: offer indexed pricing to GHG unit costs, publish certified lifecycle factors, and co-invest with offtakers in logistics/bunkering.

For governments and regulators:

- Lock in long-term signals: finalize and harmonize Net Zero Framework (NZF) with EU policy as much as possible or vice versa, and provide cross-sector consistency on feedstocks (Annex IX) to reduce investor uncertainty.
- Bridge the cost gap: Deploy Contracts for Difference, investment tax credits, and green CAPEX guarantees focused on advanced bio-feedstocks and RFNBOs; extend incentives to currently exempt maritime niches (yachts, OSV, fishing) to broaden demand.
- Ensure certification integrity: Operationalize Sustainable Fuel Certification Scheme and Fuel Lifecycle Label on bunker notes, with robust verification and five-year reviews to maintain market trust.

For financiers:

- Demonstrate bankable templates and or best practices: Publish standard offtake frameworks, certification checklists, and port-bunkering readiness scores to reduce transaction friction and accelerate investment decisions.

For knowledge institutes:

- Quantify Willingness To Pay (WTP) and risk across sectors: Develop comparative WTP models tied to regulatory exposure, cost pass-through, and margin structures; integrate value-at-risk/Monte Carlo on feedstock and CAPEX to narrow cost bands.
- Bi-annually monitor the status of the barriers, and perform the required analysis for prioritized barrier to further sectoral understanding or mitigation.

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