A supply chain cost analysis

Green maritime methanol

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Contents

1 Introduction

1.1 Context and objective

The maritime sector must do its part to limit global climate change caused by emission of greenhouse gases. The International Maritime Organization, in its 2018 Initial IMO GHG strategy, agreed to a 40% reduction[1] of carbon intensity of international shipping by 2030 compared to 2008 levels [1]. The European Union sets ambitious greenhouse gas emission reduction targets for maritime transport under its FuelEU Maritime program, undergoing final approval by legislators at the time of writing (Q4 2022).

Shipping emissions are mainly caused by combustion of fossil fuels in ship engines. Several stakeholders are working on the development of new alternative maritime fuels in order to reduce greenhouse gas emissions. In the **Green Maritime Methanol** (GMM) program a consortium of Dutch and international maritime organizations and knowledge institutes have joined forces to investigate the application of renewable methanol as a maritime fuel.

Additional background information, the full list of active consortium partners and research results of the first phase of the program (GMM1.0, 2018-2020) and second phase (2020-2023) is (partially) available on www.greenmaritimE-Methanol.nl).

Decarbonizing the fuel usage in the maritime sector is a challenging task as there are multiple aspects that need to be considered in harmony. Amongst which, but not limited to:

- Whilst many studies are (being) conducted, 'reliable and transparent' conclusive answers on optimal fuel types, secured availability, acceptable costs and predictable price levels are not yet available.
- Trade-offs will need to be made between fuel type availability vs. price vs. emissions/environmental impacts and impact on daily operations.
- Different technologies can be deployed throughout the value chains. The desire to optimize technology selection introduces delays in the decision-making processes at stakeholders in each supply chain element.
- Decision delays can have a major impact on maritime ship operator business models: the longer investment decisions in more environmentally friendly ships are delayed, the slower the reduction of annual emissions associated with the daily operation of the ships in that organizations.

As is concluded in *WP4 report Green Maritime Vision Paper*, the availability and price of renewable methanol are two uncertainties that obstruct investment decisions. In this study a multitude of renewable hydrogen-based (synthetic) methanol fuel supply route alternatives are analyzed.

The objective of this study is to provide the maritime sector with a deepened understanding of the cost of synthetic (e-)methanol and underlying cost drivers for different supply chain designs.

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[1] Compared to the total emissions from maritime transport in 2008. For details, please refer to the IMO website [1].

1.2 The structure of this report

This report discusses the outcomes and insights regarding (imported) synthetic methanol costs for the Netherlands.

In Chapter 2 a summary of the analysis method is presented in which model logic and parameter assumptions are presented. The cost analysis yields four key findings which are discussed in Chapter 3. The recommended next steps in Chapter 4 conclude this report.

1.3 Study approach

To assess the underlying cost drivers for different synthetic methanol supply chains, the existing basis of hydrogen import cost analysis was enriched by different carbon feedstock options. A longlist of different carbon sources was inventorised. This longlist was reduced to a shortlist based on feedback of the GMM consoritum. Three different archetype supply chains were constructed to analyse various combinations of carbon feedstocks and renewable electricity sources. The methanol supply chain costs for each of these archetype supply chains were analysed with the Supply Chain Model. Based on the results of the Supply Chain Model, key insights were determined.

2 Supply chain cost analysis

2.1 What is renewable methanol?

Renewable methanol can be synthesized from different types of carbon sources via two main production processes.

The first route is the biobased route where bio-methanol can be produced through gasification of biomass or carbon rich waste streams, such as plastic waste. Alternatively, bio-methanol can be produced through reforming of biogas similarly to conventional methanol production from natural gas. Biobased processes convert the carbon feedstock (either solid biomass/waste or biogas) to a syngas, a mixture of hydrogen and carbon monoxide. This syngas is subsequently converted to methanol. However, the syngas is typically shifted to obtain the correct H_2:CO ratio.

The second route is the synthetic route where e-methanol can be produced from green hydrogen and CO_2 (Carbon dioxide). Methanol is produced by the direct hydrogenation of CO_2 instead of production based on syngas. This CO_2 is either captured from the air through Direct Air Capture, from flue gases or directly from industrial processes [2]. Hence the carbon feedstock of the e-methanol route is CO_2. This study focusses on the e-methanol route and therefore focusses on CO_2 as the main carbon feedstock. The main objective of the introduction of methanol as a maritime fuel is the decarbonization of ship operation. Given the need to pursuit the (most) effective means to decarbonize on a system level, the different routes towards decarbonized ship operation via methanol should compare the bio and synthetic supply chain performances. This comparison is placed out of scope of this study but recommended as a follow-up step.

2.2 Brief introduction of the cost analysis tool

TNO developed the hydrogen carrier import Supply Chain Model (SCM V2.2) to perform systematic comparisons of hydrogen carrier import supply chain alternatives. This model evaluates the cost of hydrogen or hydrogen carriers with the Netherlands as the importing country and archetype-level exporting countries globally. The calculations assume single project-scale supply chain sizes: all investments in the technologies required for the functioning of the supply chain are made for the sole purpose of that single supply chain to function between the exporting country, and the Netherlands. And the scales of chains are equal for all renewably produced energy carriers within the model: hydrogen (gaseous via pipeline transport, liquid and LOHC-Toluene carrier via bulk carrier ship transport), ammonia, methanol, kerosine and diesel.

The import chain of methanol is simplified by defining a sequence of supply chain elements. Figure 2.1 shows these chain elements schematically. The detailed description of the cost modelling logic and assumptions of the TNO Supply Chain Model is included in part in Appendix A and publicly available[2].

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[2] A public report [23] with extensive documentation of the TNO SCM can be downloaded at www.hydelta.nl.

Electricity generated by renewable sources (Hybrid RES) is converted to hydrogen through water electrolysis (PtH_2). The hydrogen is converted to methanol through direct CO_2 hydrogenation (H_2tCH_3OH). CO_2 is required as a feedstock for methanol production. The CO_2 is sourced either from biomass or waste conversion processes, industrial point sources or direct air captures (DAC). A compressed hydrogen (cH_2) storage is included to compensate process upsets or ramping up/down production. This compressed hydrogen buffer isn't sufficient to decouple methanol production from the variable renewable energy production. At the export terminal, produced methanol is temporarily stored in between shipments. The methanol is shipped by means of a chemical tanker to the import country. At the import terminal the methanol is temporarily stored. From the import terminal the methanol is distributed to the location of final use by barge or by truck.

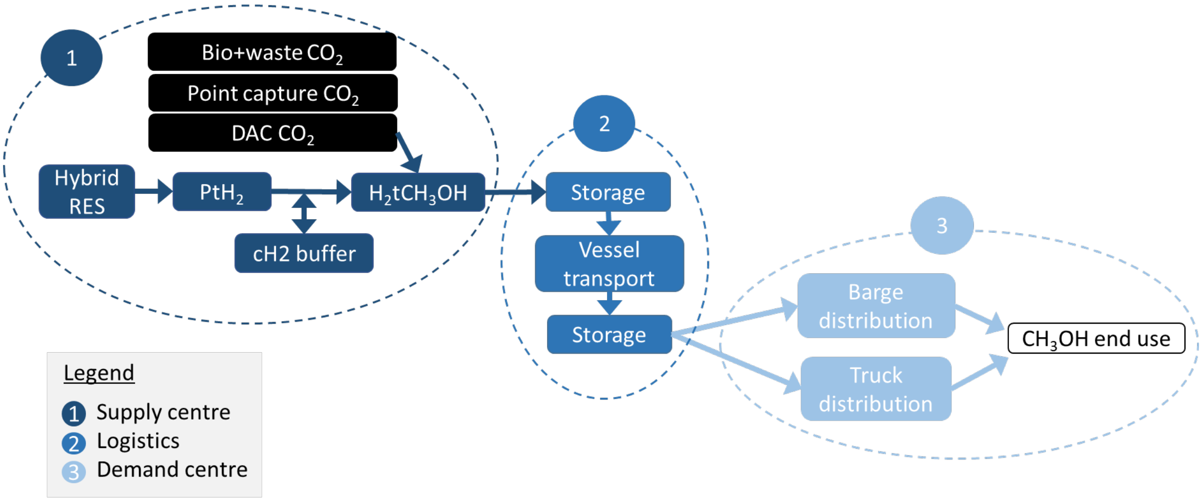

Figure 2.1: Schematic representation of a methanol supply chain in the Supply Chain Model

2.3 Defining three archetype supply chains

All around the world, countries are developing hydrogen-related strategies to explore their role in what may lead to be a global renewable hydrogen trade in the future. In this study, three archetype export countries were chosen to give an impression of the import costs for methanol from different supply chains: archetype A, C and M.

The philosophy behind the use of archetype supply chains instead of an assessment of detailed export regions/countries is the offered freedom to the reader to translate the results to supply chains with similar characteristics to those archetypes. The chosen approach allows for the comparison of different combinations of supply chain configuration choices (e.g. renewable electricity production, CO_2 sources, transport distances) in contrast to specific country characteristics and thereby gain a deepened understanding of the cost contributions per chain configuration choice.

The archetype supply chains thus provide insight into the different influencing factors on the import costs of methanol which are associated with the specific designs of that supply chain.

The configuration design variables are:

- CO_2 source available and the associated cost (Levelized cost of CO_2)
- Type of renewable electricity generation technology with associated capacity factors (or full load hours, FLH)
- Electricity costs (Levelized Cost of Electricity, LCoE)
- Distance to be travelled per ship
- Local interest rate

Three supply chain archetype designs were chosen. All archetypes have an initial installed renewable electricity generation capacity of 3 GW_e. Archetype C uses pumped hydro-power and onshore wind as a power source, and biomass and waste as a carbon source. Archetype M uses solar PV and onshore wind power, and direct air capture to supply carbon. Archetype A also uses solar PV and onshore wind power but uses point capture at industrial plants as a carbon source. Table 2.1 and *Appendix C* provide mode detail on the supply chain details. Each archetype has a different shipping distance, depicted in the Figure below.

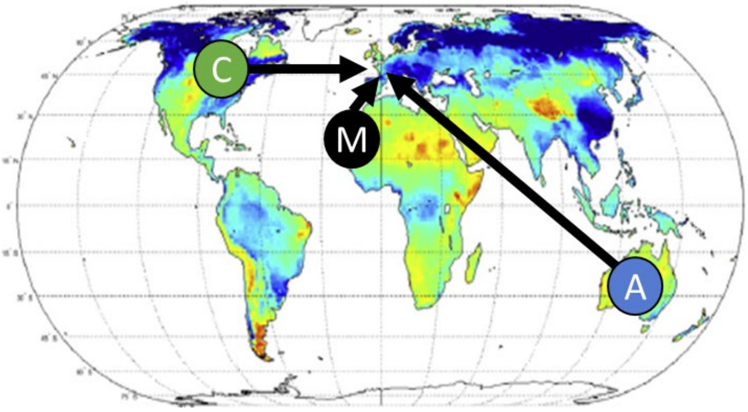

Figure 2.2: Geographical distribution of archetype countries selected in this study [3]

Table 2.1: Archetype methanol producing countries selected in this study

Archetype name	C	M	A
Example of country corresponding with archetype:	Canada	Morocco	Australia
Characteristic / parameter	Assumption		
Onshore wind power[3]	35,3 €/MWh	34,5 €/MWh	33 €/MWh
Solar PV power[3]	-	23 €/MWh	22 €/MWh
Pumped hydro power[4]	72,5 €/MWh	-	-
Combined LCoE[5]	55 €/MWh	34 €/MWh	32 €/MWh
Full load hours of electricity production per annum	77 %	60 %	62 %
CO_2 from solid biomass firing	50 %	0 %	0 %

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[3] 2030 LCoE estimates including cost reductions: [24], [3]
[4] No cost reductions expected for mature hydropower technologies. LCoE estimate taken from [12]
[5] The hybrid-technology levelized renewable power cost consists of relative cost contributions per technology based on the corresponding full load hour ratio of those technologies, taking into account an overlap factor of 10-20%.

Archetype name	C	M	A
Example of country corresponding with archetype:	Canada	Morocco	Australia
Characteristic / parameter	Assumption		
CO_2 from waste firing	50 %	0 %	0 %
CO_2 from cement production	0 %	0 %	100 %
CO_2 from direct air capture	0 %	100 %	0 %
Feedstock (CO_2) cost[6]	59,8 €/tCO_2	204,1 €/tCO_2	62,3 €/tCO_2
Annual methanol production[7]	1872 ktpa	1467 ktpa	1472 ktpa

Many different countries may have the potential to develop as methanol supply hubs. While cost minimalization may be an incentive to develop methanol trade agreements with specific countries, globalized trade experiences over the past decades have taught us to appreciate diversified supply chain portfolios from a secured supply point of view.

The annual methanol import is evenly distributed over 365 days resulting in an intermittent arrival of methanol bulk carrier ships. Sailing distance, ship travel speed, capacity and turn-around times are included in the mass flow assessment. Planning the arrival of large quantities of methanol and balancing with bunker fuel supply is expected to be crucial but is left out of scope in this study.

2.4 Carbon feedstock

The RED-II distinguishes several types of carbon feedstocks: biofuels produced from food or feed crops, waste-based biofuels, advanced biofuels and -gasses, renewable fuels of non-biological origin and recycled carbon fuels. Hence, the source of carbon is important both from a regulatory as well as an economic point of view. A detailed description of the regulatory considerations for renewable methanol can be found in *WP4 - Green Maritime Vision Paper, Annex A*.

This report mainly focuses the cost analysis of the synthetic route, where each archetype supply chain utilizes a different CO_2 feedstock.

2.4.1 Carbon feedstock costs

The cost of capturing CO_2 from any source is dependent on the CO_2 partial pressure, scale of the capture installation, technological maturity and impurities present in the feed mixture. Direct air capture is relatively cost-intensive CO_2 capturing technology due to the low partial pressure and technological immaturity. As each industrial sector or subprocess generally operates at the same conditions, a typical cost of capturing CO_2 from that sector or subprocess can be identified. In this study, the cost of capturing CO_2 from different industrial sectors has been evaluated based on several literature studies [4] [5] [6]. For each specific industry a baseline has been established by averaging out the median value of the reported range for that specific industry. The reported values are outlined in Appendix B.

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[6] Refer to Appendix B for literature sources

[7] Scale of archetype country supply chain depends on country-specific capacity factor of renewable electricity production. Annual production is calculated in the SupplyChainModel (SCM).

The low and high end of the range have been averaged out to determine the sensitivity range for each industrial sector. The CO_2 capture costs is introduced to the supply chain model OPEX related cost on a EUR/tCO_2 basis.

An overview of the CO_2 sourcing and corresponding feedstock cost for the different archetype supply chains is shown in Table 2.1.

2.4.2 Carbon feedstock availability

In this paragraph a brief introduction on carbon feedstock availability describes the challenges of assessing the availability. In Chapter 4 the recommended next steps to move forward with this important topic within the methanol supply chain development efforts are discussed.

In order to develop a scalable supply chain for renewable maritime methanol there must be sufficient raw materials available. Therefore, in addition to gaining insight into the choice of feedstock and the associated costs of different supply chains, it is important to understand the global and local availability of the different renewable carbon feedstocks that could be used for the production of methanol. To scale up e-methanol production, both the availability of a carbon source (either biobased carbon or carbon dioxide) and the potential for green hydrogen production from renewable electricity in a country is therefore preconditional.

The theoretical availability of biobased carbon can be quantified by modelling the maximum potential biomass production from agriculture and forestry, as well as the theoretical potential from their residues [7]. However, other types of biomass potentials are often more illustrative, such as the technical potential (taking into account current technical possibilities and spatial restrictions due to competition with other land use) or the ecologically sustainable potential (taking into account nature conservation and biodiversity preservation) [7]. The worldwide, EU and Dutch availability of sustainable biomass has been estimated in multiple studies, although the ranges of the results are often large (e.g. shown in the literature study by CE Delft [8]).

The available potential for carbon dioxide (CO_2) in a country can be estimated by looking at the presence of fossil and industrial point sources, such as coal and gas power plants, chemical industry, steel industry and cement industry. From a climate neutrality point of view, it is preferable to use biogenic point source CO_2, such as from biogas upgrading and bioethanol fermentation [9]. The availability of CO_2 from Direct Air Capture (DAC) is theoretically infinite, as the CO_2 is extracted from the air. DAC plants can be located anywhere, but it must be considered that large amounts of land area are required for DAC plants, as well as sufficient renewable electricity supply [10].

In addition to the technical carbon resource availability there are other important aspects that influence the geographical availability of renewable carbon and carbon dioxide for the application of methanol in the maritime sector.

Rules and regulations will influence the future supply and demand for renewable carbon and carbon-based product, such as methanol. At the time of writing, important legislation packages are still being finalized at the EU level. However, it is nearly certain the shipping sector will be subject to binding decarbonization targets at the EU level.

Another important consideration is that renewable carbon may become a scarce resource and multiple applications may start to compete for the same feedstock. The position of bio- or e-methanol in a so-called carbon “merit order” becomes significant: the carbon will likely be used first in applications with end-users that have the highest willingness to pay.

There is currently not one dataset (to the author’s knowledge) that describes the global availability of renewable carbon from the different possible resources now or in future. However, to be able make strategic decisions on which regions to import methanol from, an overview of global and/or regional renewable carbon potentials is desirable as such an overview reduces the uncertainties related to secured (long-term) feedstock availability. To that end, a detailed recommendation of a work plan can be found in Chapter 4.

3 Four findings on methanol cost in 2030

The objective of this study is to analyse the cost drivers for e-methanol. As outlined in Chapter 2, the methanol supply chain cost is determined with TNO's Supply Chain Model for three archetype countries. Each archetype country represents a different interaction between cost of electricity, capacity factor, cost of CO_2 and transportation distance. The four key findings from this analysis are discussed in this chapter. The findings are interrelated and should therefore be considered integrally.

3.1 Key finding 1: Levelized cost of e-methanol driven by both technology cost and mass flow quantity

The cost of methanol in this study is assessed for three exemplary archetype supply chains as defined in section 2.3, and is expressed as a levelized cost (LCoMeOH) to be able to easily compare different supply route options. The levelized cost is the cost per unit of methanol, either tons or gigajoules. The levelized costs per supply chain element comprise the capital expenditures (CAPEX) and operational expenditures (OPEX) of all parts of the supply chain.

The scope encompasses eight chain elements, starting with a 3000 MW renewable electricity power plant and ending with the last-mile distribution up to the maritime end-user. Both costs and quantity are influencing the levelized cost: The levelized cost is an expression of the *sum of costs over the lifetime of the supply chain* divided by the *sum of methanol quantity produced over the lifetime of the supply chain*.

By designing different supply chains, the technological choice per chain element leads to substantially different costs and production volumes, and consequentially also different contributions to the total levelized cost. Trade-offs between technologies with lowest cost versus largest volume of product per year need to be made.

On the *cost* side four dominant cost drivers are represented as shown in Figure 3.1:

- Renewable hydrogen feedstock
- Renewable CO_2 feedstock
- Methanol synthesis process
- The combined import and distribution logistics as a whole

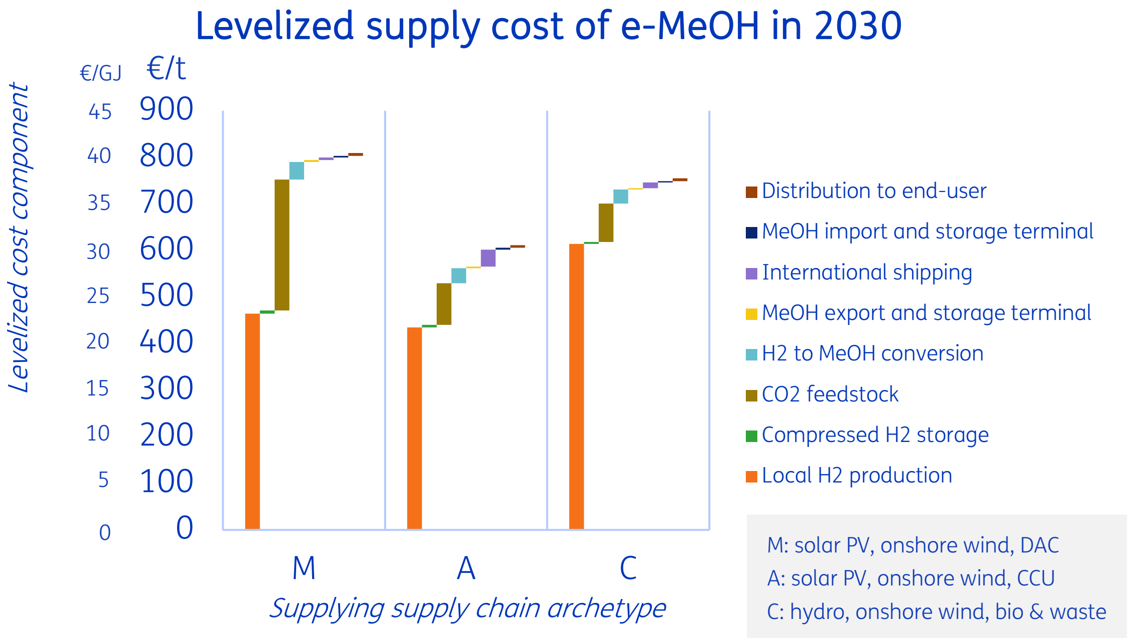

Figure 3.1: Breakdown of levelized cost of methanol for the three archetype supply chains defined in section 2.3

On the *quantity* side, the consequences of supply chain configurations and corresponding technologies on the levelized costs of methanol may be less evident. **Figure 3.2** below shows that the C archetype produces larger quantities of methanol per year. This is due to the renewable power plant technology of choice (pumped hydropower instead of solar-PV) having equal installed capacities of 3 GW_e but a higher capacity factor. The direct coupling of power to hydrogen and subsequently methanol production results in a larger mass flow of hydrogen and methanol, which leads to a lower levelized cost of methanol despite hydrogen production costs being higher in C compared to the A and M archetype and despite having technological assets at slightly larger scale from the hydrogen production chain element onwards, which also introduces higher associated costs.

All three archetype suppliers are assumed to be operating in islanded mode. The higher the annual power production hours, the higher the annual methanol quantity. And increasing the annual methanol quantity drives down the levelized cost of methanol. The absence of on-demand power sources to complement the intermittent renewable power produced implies that the maximum power availability of 8760 hours/year and respectively 2450 ktpa MeOH) is not realized in any of the three archetype supply chains.

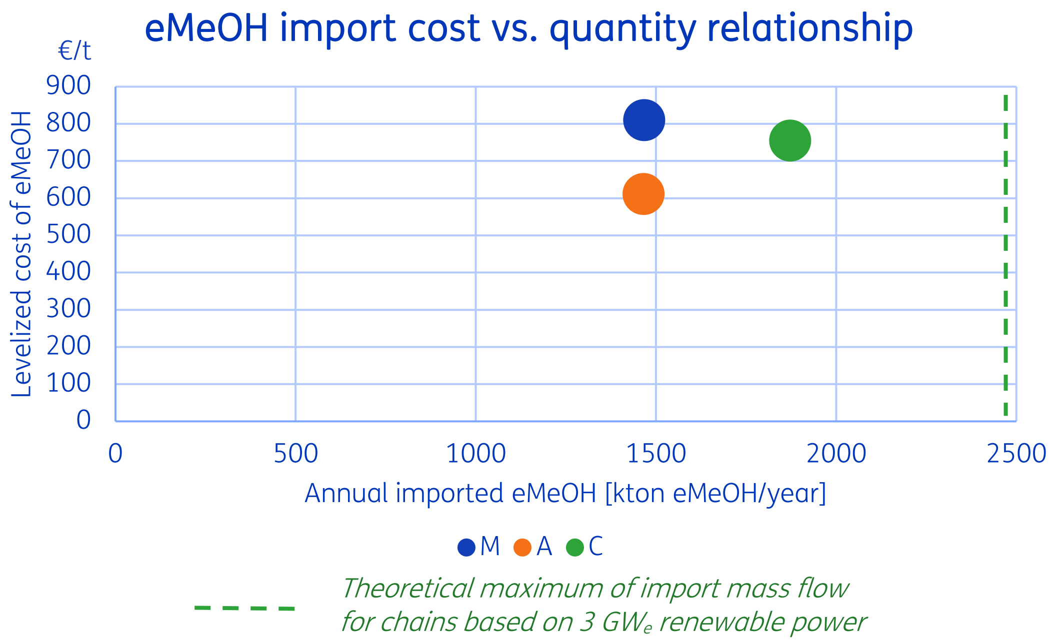

Figure 3.2: Levelized cost of methanol and annual production rate

The scale of the methanol supply chain can lead to cost reduction effects when annual asset utilization increases. The higher annual mass flow implies that the total investment and operational costs can be divided over more units of methanol supplied to its users.

Two words of caution:

1) The assessed cost of importing methanol is a built up from techno-economic performance characteristics. Costs therefore omit taxes, duties, subsidies and other factors that are to be considered when performing a *landed cost* assessment.
2) Insights related to costs are to be considered indicative at best: as methanol as a fuel enters a mature market of maritime fuels, the future *price* depends on many additional drivers. And as methanol can be considered a potential future platform (or sector integrating) commodity, price predictions, in contrast to cost assessments, are difficult and highly uncertain.

The design of the lowest-cost supply chain needs to minimize costs of each of these four drivers while maximizing the annual production mass flow through the supply chain. Key finding 2 elaborates in more detail on this trade-off.

Cost related to import and distribution logistics only makes up a small part of total MeOH supply cost. Key finding 3 discusses the low cost contribution but critical role of these supply chain elements in more detail.

3.2 Key finding 2: Trade-off needs between hydrogen-related and CO_2 related design choices emerge

A 'cost driver' is a parameter that causes a large change in the cost of methanol when its value changes. As the levelized cost of methanol is defined as the cost per mass of methanol, this cost can be reduced either by **learning effect** and innovations (reducing the cost of the production activities) or by **economies of scale** (increasing the production capacity). Knowing which supply chain elements contribute the most to the methanol supply cost is the first step to driving down methanol supply costs effectively. Cost drivers can be separated into two different categories: geographical and technology related cost drivers. Geographical cost drivers may change little over time whereas technological advancements may lead to cost reductions in technological cost drivers.

The dominant geographical cost drivers in the methanol supply chain costs are:

- Local cost of renewable electricity. The combined LCoE is the main cost driver in the methanol value chain. A decrease in LCoE lowers the e-methanol supply cost.
- Local cost of carbon. More specifically, access to point-source, biogenic CO_2 or alternatively industrial process emissions averts the use of direct air capture which is the most expensive source of CO_2 feedstock.
- Utilization of production facilities. The operational hours of renewable electricity production and subsequent production of hydrogen determine the annual methanol production volume. Higher utilization of production sites leads to lower unit cost of methanol.

The dominant technological cost drivers in the e-methanol supply chain are capital cost of electrolyzers, direct air capture and capital cost of methanol synthesis.

Figure 3.3 highlights the different cost types for every supply chain element. The three cost types presented are asset annuity, fixed and variable operational expenses. The sum of investment per supply chain are included in Appendix A.

As can be observed in Figure 3.3, the variable OPEX represents the largest share within the hydrogen production step. That cost stems from the cost of electricity and is predominantly dependent on LCoE. Feedstock cost, in the case of e-methanol the cost of CO_2, represents another large portion of the overall levelized cost. This cost is strongly dependent on the source of CO_2. As the archetype supply chain for Morocco uses direct air capture, Morocco has a relatively high feedstock cost. The levelized cost of CO_2 is represented as a variable OPEX as outlined in Chapter 2.

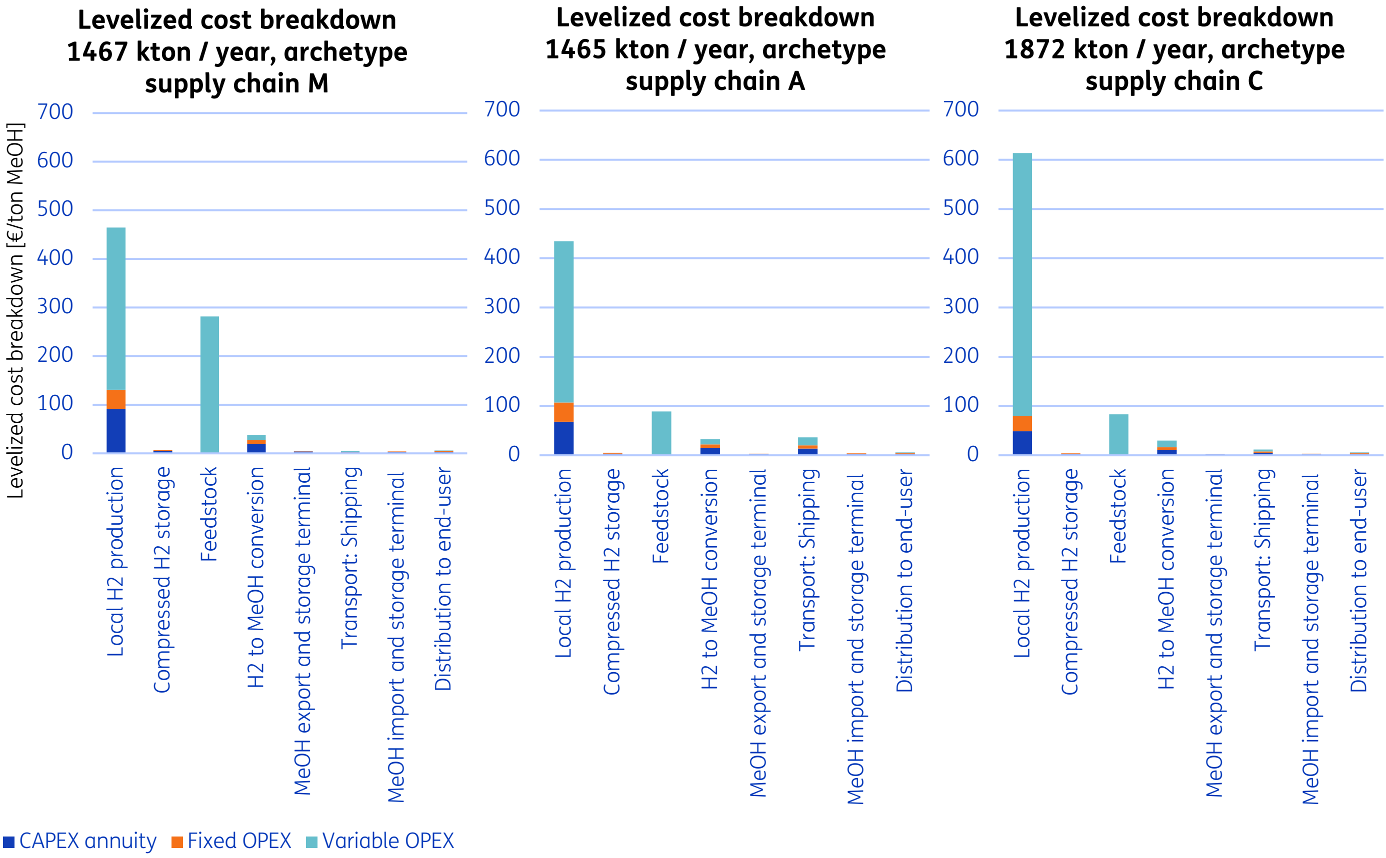

Figure 3.3: Breakdown of e-methanol levelized supply chain costs from three archetype countries: Morocco, Australia and Canada

CAPEX related costs have a smaller cost contribution throughout the methanol value chain. The most predominant CAPEX costs are associated with hydrogen and methanol production. Intermediate storage and transportation of methanol as well as regional distribution have a minor contribution to the overall supply cost of methanol.

To complement the levelized cost details with annual cost numbers, Figure 3.4 shows the annual cost breakdown in million euros per year, assuming a 20-year lifetime. Each archetype supply chain has an equal installed capacity of renewable electricity generation. As all assets are sized on peak production, all chains have hydrogen and methanol production assets of equal capacity. The annual production is dependent on the full-load hours of electricity generation. The investment costs for each asset are dependent on equipment cost, economy of scale, installation cost and interest rate. Each archetype country has the same installed capacity for the hydrogen electrolysers and methanol production facility. The annualized capex cost of these production assets is therefore equal for each archetype country. However, as the archetype-specific capacity factor of that asset depends on the hydrogen mass flow, the levelized cost contribution decreases with increased annual production.

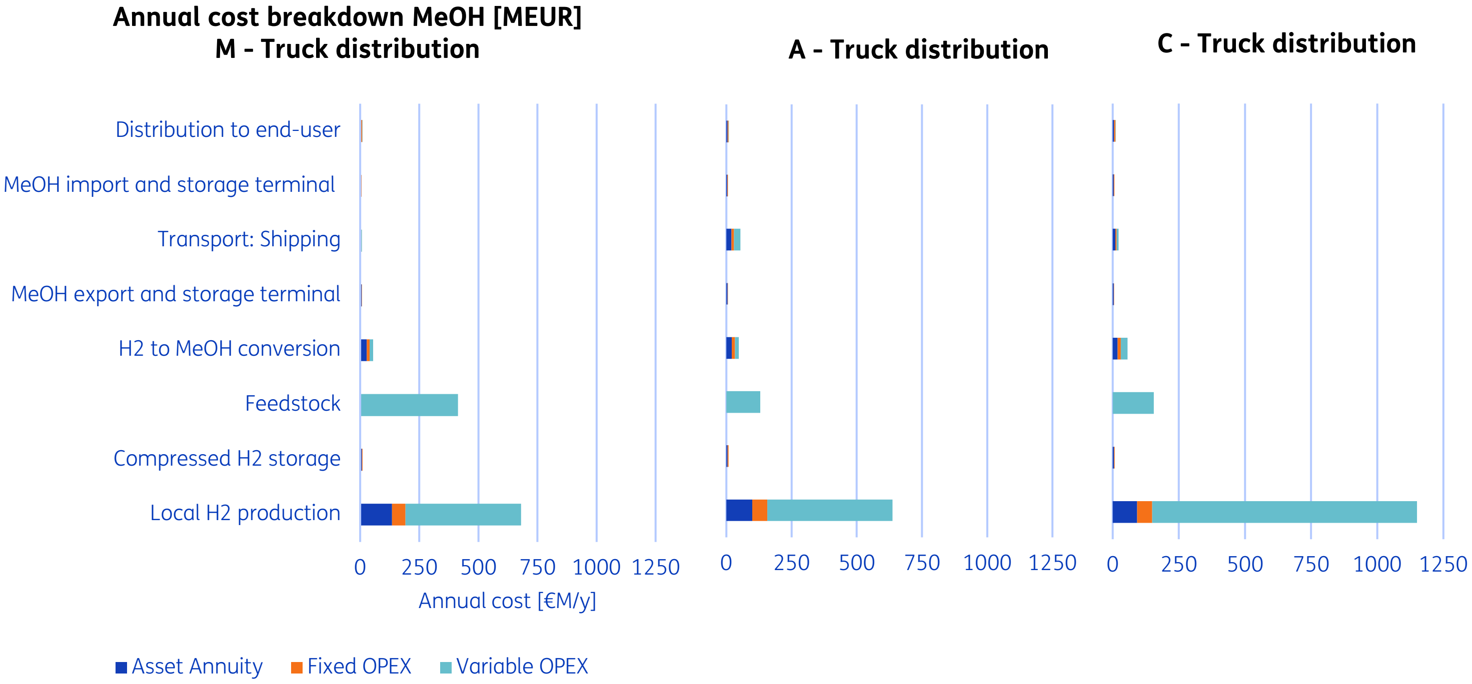

Figure 3.4: Annual cost breakdown of the methanol supply chain for 3000 MW renewable electricity converted and transported to the maritime end-user for the three archetype supply chains: M, A and C.

Supply chain design considerations show clear design decision in CO_2 feedstock costs and levelized cost of electricity. Transportation only has a minor contribution to the overall supply chain cost, key finding 3 discusses the last-mile costs.

3.3 Key finding 3: Last-mile transport costs are a small part of the supply cost of methanol

By Last-mile transport we mean the distribution of methanol from large-scale import terminals to nearby vessels for use as marine fuel. We modelled two types of delivery of methanol as a marine fuel: delivery by barge (the most common way of delivering marine fuels) and delivery by trucks (the way methanol is currently delivered to experimental ships). For both modalities the required CAPEX and OPEX is calculated, including costs for purchasing and maintenance of vehicles, wages, and fuel costs.

Figure 3.5: Methanol being delivered by barge (left) and truck (right)

The cost of bunkering methanol is assessed to be between 1.8 and 2.2 euros per ton when delivered by barge, and between 5.8 and 6.1 euros per ton when delivered by truck. Unit costs for barge bunkering are much lower than those for bunkering from trucks, because bulk transport by barge is more efficient. Of course, CAPEX and OPEX for bunkering companies are strongly dependent on details of their operations and exact costs will be different for each company. A comparison between last-mile delivery costs for each modality and archetype supply chain is included in Appendix C.

Because methanol is liquid at ambient conditions and not especially corrosive or hazardous, existing tanker trucks or barges can be used to transport methanol with no or minimal adaptations [11]. This means last-mile distribution of methanol for use as a fuel will be comparable in cost to the distribution of traditional deep-sea maritime fuels when costs are expressed as euros per ton.

Regardless of the distribution method and supply chain configuration, last-mile distribution costs are negligible compared to feedstock and production costs, as can be seen in Figure 3.4. However, this does not imply these costs do not matter. For buyers and sellers of methanol as a marine fuel, they are an important factor in methanol bunker prices and the business case of methanol fuel suppliers.

3.4 Key finding 4: Uncertainties lead to very large spread in cost estimates

The cost of renewable methanol depends on many elements, e.g. CAPEX, efficiencies and the cost of electricity. To analyse which parameter affects the end result – being the cost of methanol production and import – the most, a sensitivity analysis has been performed. This analysis shows how the different factors affect the output and gives a range of possible costs.

The combined uncertainty range for the cost of methanol cost is between 241-1241 €/ton.

For this sensitivity analysis, we distinguish two types of uncertainties: technical and fundamental. Examples of technical uncertainties are CAPEX and efficiency, whereas an example of fundamental uncertainties are the number of Full Load Hours (FLHs) for an asset. Technical uncertainties can be influenced, e.g. by stimulating innovation the efficiency can be improved. Fundamental uncertainties cannot be influenced, e.g. the FLHs of wind can be higher or lower in a year. Such weather-induced performance differences affect the marginal production costs of that year and may be averaged out over the asset lifecycle.

Figure 3.6 shows the results of the sensitivity analysis. It can be concluded that for all regions, both the uncertainty in LCoE and FLH input data results in the largest uncertainty.

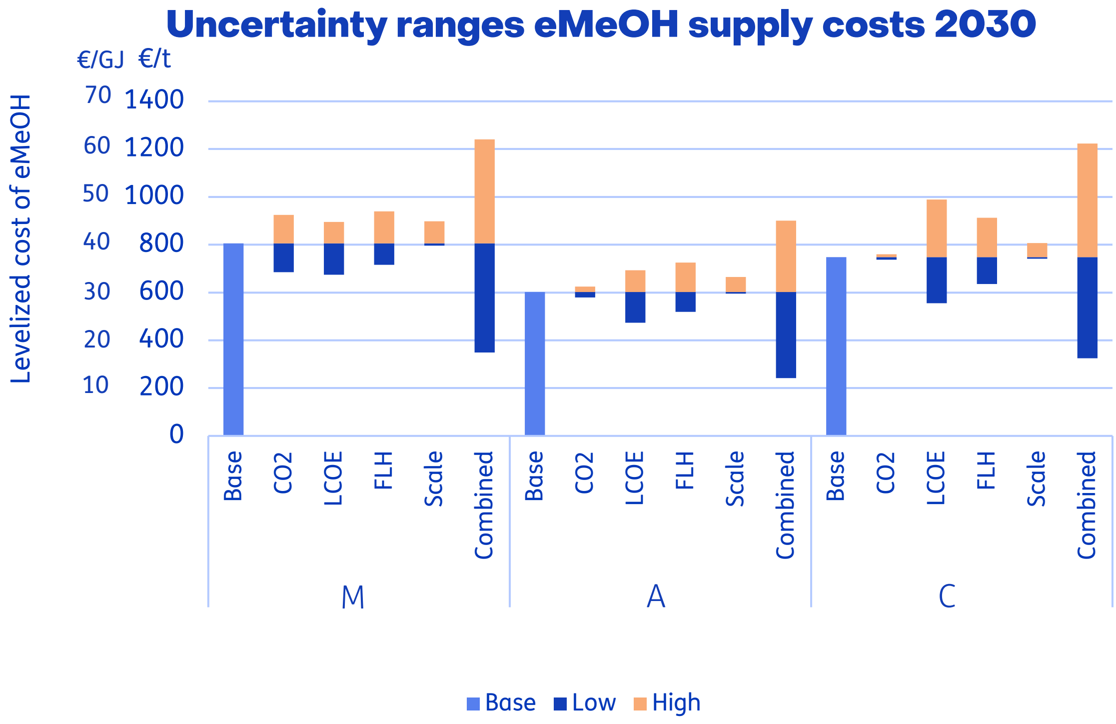

Figure 3.6: Uncertainty ranges of methanol supply costs for supply chain archetypes C, M and A.

The following parameters were varied:

- **Cost of CO_2** (based on range reported in literature).
  Specific carbon supply routes may have higher or lower cost implications, depending on the technologies of choice and regional opportunities/limitations and proceeding technological advancements.
- **LCoE** renewable electricity supply (RES) (based on range reported in literature) (e.g. different wind or solar yield at specific location, varying metrological patterns, proceeding technological advances, higher raw material prices).
- Changes in supply chain mass flow, triggered by variances in the combined **FLH of the RES** (80% - 120%). Can vary based on power supply optimization (e.g. adding battery, different wind or solar yield at specific location, varying metrological patterns).
- RES production **scale** (600 MW – 4 GW). Supply chain specific scale differentiating from the chosen 3 GW scale.
- The **combined effect** of all four parameters.

The uncertainty range for capturing CO_2 has been taken by averaging out the lowest and highest reported cost per industrial sector as outlined in Appendix B. Likewise, for each RES source, the lowest and highest reported cost for 2021 in [12] has been used to determine the uncertainty range. And as uncertainties do not exist in isolation, they are assessed at the same time to indicate their cumulative influence on the methanol cost.

For supply chain archetype M, the uncertainty in CO_2 capture costs is significantly larger than for chain A and chain C. In the M case, this is due to the use of DAC and the large uncertainty is related to the relative technical immaturity. For the other archetypes the uncertainty in CO_2 capture costs does not have a large impact on the overall supply cost of methanol. Economy of scale gives a cost benefit especially in scaling up from the MW range to several GW. Lowering the project scale from 3 GW to 600 MW leads to a levelized cost increase and increasing the project scale from 3 GW to 4 GW shows minor levelized cost decrease. Hence, economy of scale starts to level out after several GW of scale.

More detailed techno-economic assessments of methanol supply chains are recommended to be done at project-level in contrast to this archetype level to explore more detailed uncertainties and sensitivities in promising supply chain configurations to import e-methanol.

4 Recommended next steps

Three steps are recommended as a follow-up of the cost analysis as presented in this report. This chapter discusses these recommendations in unprioritized order.

Recommended next steps:

- Assess carbon availability
- Transit from a cost to a price perspective
- Compare the performance of alternative fuels to bio- and e-methanol under equal circumstances, including regional impact for onboard application

4.1 Recommendation 1: Assess carbon availability

It is important to take into account the perspective of global (methanol a-specific) resource availability when analysing possible future supply chains for renewable methanol production (see Section 2.4.2). As indicated in Key Finding 2, the feedstock costs of CO_2 have a significant impact on the overall methanol supply chain cost when no point-source CO_2 is available. However, point-sources have a limited and declining availability which is currently not reflected in this analysis. Therefore, this section recommends to proceed with a carbon availability analysis for methanol feedstock purposes. A preliminary work plan for the estimation of country-level renewable carbon availability and the derived methanol production potential is proposed below.

Additional context: The topic of carbon resource availability is complex, especially looking towards the (long-term) future. Due to the required emissions reduction and energy transition, carbon flows in our energy and industrial systems are expected to change drastically, both on the supply and demand side. For instance, the carbon demand and carbon emissions from industry will be partly determined by the degree of process electrification in industry, the choice between the hydrogen or CCS-route for steelmaking or the reduction of concrete production, due to decreased use in buildings. The available biobased carbon supply is dependent amongst others on improvements of agricultural management, choice of crops and future food demand [7]. Furthermore, the availability of carbon from waste is dependent on implementation of recycling systems, the composition of different waste streams and possible yield from these streams. National and internal policy will partly determine the availability of CO_2 from point sources for reuse to chemicals. In short, the carbon cycle of the future and the associated availability of carbon is a complex system of interactions with many uncertainties. The key objective of those carbon cycles remains to minimize global emissions, where possible focus on negative emissions and re-use carbon molecules continuously to prevent carbon resource and emission inefficiencies.

Next steps: Fortunately, many studies, models and databases exist that can contribute pieces of the puzzle.

Combining different sources of information can provide an (albeit imperfect) indication of the theoretically available potentials of carbon from biomass, waste and point sources on a country level. A schematic of a potential research methodology is provided in Figure 4.1.

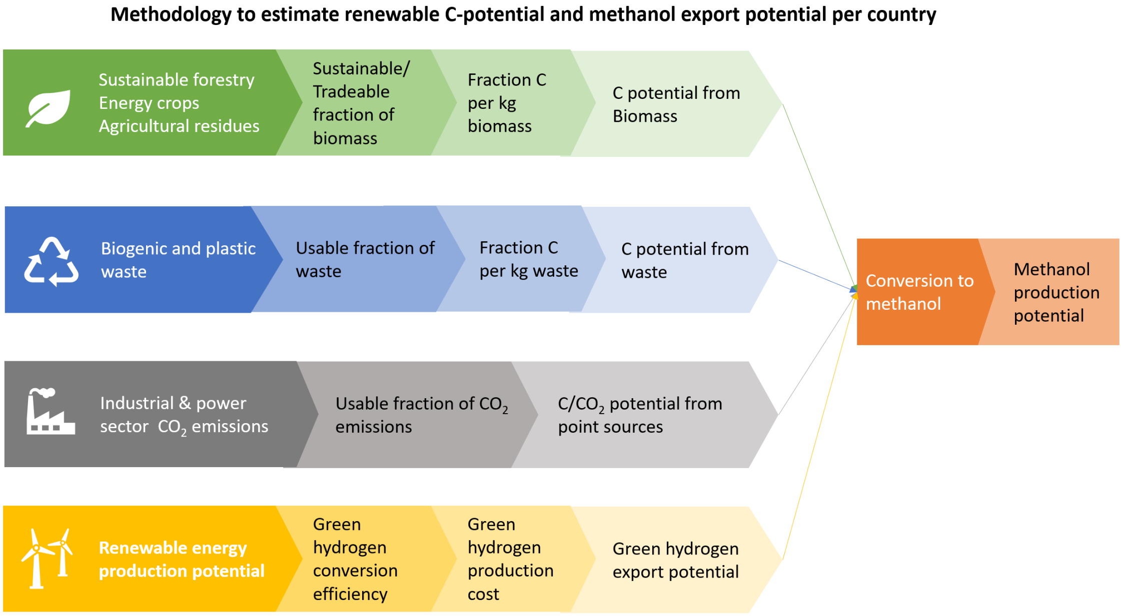

Figure 4.1: Schematic of a methodology for methanol production potential

Merging global country level estimations of carbon potential is required to assess the plausible future carbon availability and its uncertainty ranges in regions and the corresponding abundance or lack of feedstock. The first three rows of the schematic scheme in Figure 4.1 show a stepwise approach to calculate the carbon or carbon dioxide potentials for each different carbon source. The fourth row includes the steps to convert renewable energy production potential to green hydrogen export potential (total minus own use). Since hydrogen is required to produce e-methanol, the estimations of green hydrogen export potential per country need to be merged with the CO_2 availability to estimate the e-methanol production potential per location. Finally, using conversion efficiencies of the required biogenic and e-methanol production processes, the potential methanol production can be assessed.

A preliminary assessment of existing data sources indicated that for each type of renewable carbon resource, multiple databases and models already exist. Note that this is not an exhaustive list.

Firstly, for the availability of carbon from biomass, the potentials from Daioglou, et. al. [13] could be used, which have been modelled using the IMAGE integrated assessment model, which projects the global and long-term interactions of the land-use, agricultural, energy, and climate systems under different scenarios. Other relevant sources of information are the FAO's agricultural production, food balances, forestry and land use databases. [14]

Secondly, the current carbon fraction from solid waste could be estimated from data on carbon rich waste streams such as biogenic and plastic waste. The World Bank and the Organization for Economic Cooperation and Development have public country-level datasets on waste generation per sector [15].

Thirdly, global CO_2 emissions from point sources can be found in the EDGAR database [16]. Fourthly, many overviews and databases of H_2 export potential per country exist, amongst which a variety of IRENA and IEA publications as well as publications from [17] [18] and [3].

In future work on carbon availability assessments for renewable methanol production, commodity trade dynamics (e.g. willingness-to-pay) and the effective decarbonization potential (e.g. demand merit orders) from a systems perspective need to be incorporated.

4.2 Recommendation 2: Transit from a cost to a price perspective

We recommend further research to increase the understanding of the (dominant) market forces and mechanisms that will determine the marginal price per unit of renewable methanol in the future. A qualitative approach is recommended as future price quantification is considered indicative at best, and plainly wrong at worst.

Ultimately, methanol prices will depend on many factors including, but not limited to,

- The gap between methanol supply and demand (including other sectors)
- The (in)elasticity of supply and demand capacity ramp-up and down.
- Feedstock and CO_2 emission pricing
- Norms and regulations on decarbonization of maritime fuels
- Fiscal regimes and policy measures.

Future projections of methanol prices are difficult and uncertain (if not impossible). However, price drivers and lower bound values may be predicted with some level of confidence. Which provides a deeper level of understanding for decision-makers and analysts and indications which drivers can be monitored to better understand price trends and future outlooks.

Two follow-up questions are recommended to address:

1. What are qualitative factors that determine the price of renewable methanol?
2. How does willingness-to-pay for renewable methanol in the maritime sector relate to other current and future competing end-users of renewable methanol in the short (2023-2035) and long (2035-2060) term?

4.3 Recommendation 3: Compare the performance of alternative fuels to bio- and e-methanol under equal circumstances, including regional impact for onboard application.

For the production of e-methanol, the costs of hydrogen and to a lesser extent CO_2 are the most important cost drivers. Alternatively biomass could be used to produce bio-methanol, averting the need for hydrogen and CO_2 sourcing.

Studies on fuel alternatives tend to continuously iterate from high-level to more detailed analysis. This relatively detailed methanol analysis in GMM2.0 provides additional insight, such as the most important cost drivers, in the feasibility of e-methanol. In addition to different methanol production routes, other decarbonisation pathways are available for maritime shipping.

To understand the impact of the obtained additional insight on methanol, comparison to other alternatives based upon the available information is yet again required, leading to advancing the understanding on relative performances of fuels in the sector yet again.

In addition to generic fuel performance differences, the specific designs of supply chains, starting in the production region, shows to be relevant for the performance of the fuel(s) of interest. The economics of the different fuels considered in these pathways differ in utilisation efficiency of feedstocks, feedstock type (hydrogen, nitrogen, biomass, CO_2, syngas) and costs associated with feedstock, production assets, storage, transportation and distribution. The (dis)advantages of regional characteristics per fuel type is to be recognized. For example, a lack of CO_2 in a region could result in a stronger focus on ammonia production, and therefore a higher probability of application of that alternative in that region. Other elements, such as population density, available space and societal acceptance, can also affect the feasibility of an energy carrier in a region. These multidisciplinary KPIs are critical to understand the pathway towards upscaling specific fuels and their applications.

We recommend therefore to increase the understanding of supply chain costs at supply chain archetype level not only for renewable methanol but to also expand to other renewable fuels with the expansion of multiple performance criteria beyond costs to add to the insight towards maritime application.

The supply chain costs represent only a portion of the KPI's which ultimately drive the selection of feasible fuel decarbonisation pathways. The KPI's can be differentiated into three categories: practical application and safety, environmental impact and economics. The dominant underlying KPI's, as recommended in previous fuel comparison study by TNO [19]:

Practical application and safety	Environmental effects	Economics
–Vessel modification –Impact on bunkering infrastructure –Impact on operations –Safety	–Pollutant emissions: NOx, SOx, PM –GHG emissions –Carbon utilization effectiveness of methanol fuel	–Production cost –Storage and distribution cost –Powertrain cost and efficiency –Availability

Figure 4.2: Key performance indicators proposed to assess fuel alternatives systematically

The WP4 – Green Maritime Methanol Vision Paper [20] has made an overall comparison of the well-to-wake greenhouse gas emissions. This comparison highlights the large differences between well-to-wake emissions of different marine fuels. Adding existing environmental performance studies, such as [21] and [22], to the conducted study on costs requires the alignment of scopes and assumptions of the different research activities.

The authors recommend to add the environmental performance of each MeOH supply chain configuration to any conversation that compares fuel costs to keep the objective of decarbonized maritime ship operation central to the discussions.

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6 Signature

TNO Mobility & Built Environment, The Hague, 24 July 2023

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Appendix A - Supply chain cost modelling logic and assumptions

Introducing the generic model structure

The Supply Chain Model is developed in MS Excel and has a modular design. Four key model elements are connected as such that repetitive calculations can be done effectively while maintaining a transparent view on the calculations: Generic input and chain specific input are directed to the various supply chain calculation sheets. And the outcomes of the calculation sheets are collected in the dashboard (Figure A.1).

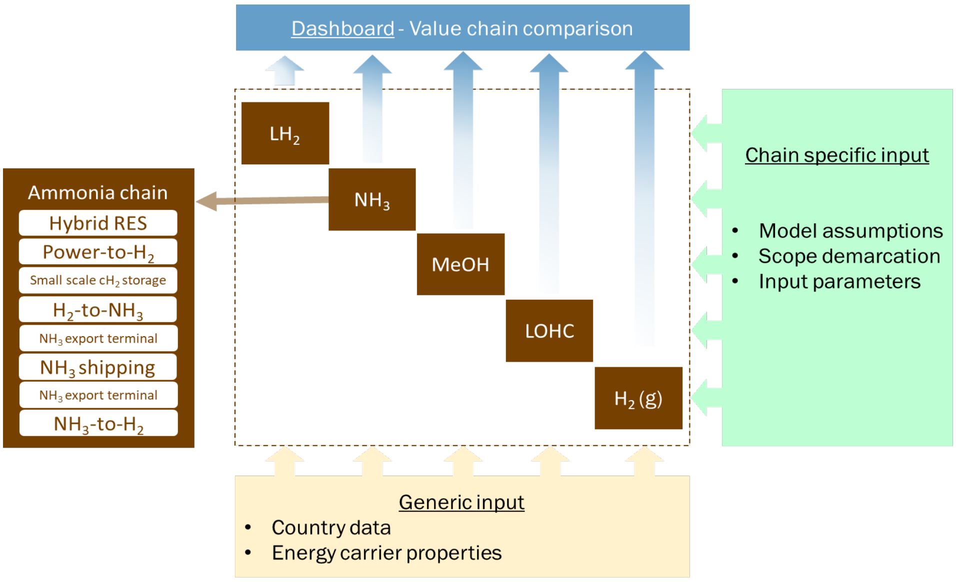

Figure A.1: Schematic representation of Supply Chain Model

“All models are wrong, but some are useful”. This famous saying of statistician George Box articulates the challenges that we face when creating an accurate representation of our world. To create a useful hydrogen carrier import supply chain model, many assumptions are made in the modelling process to mimic those supply chains from a techno-economic perspective. The considerations that were made that apply to all the different supply chains within the scope of this study are transparently discussed in this paragraph.

Firstly, the topics are briefly introduced and subsequently, their implications and mutual relations are described in more detail.

A. Arguably the most important factor is **time**. The time stamp of the study affects forecasted (specific) cost estimates for the most costly chain elements, for example the LCoE for renewable power, CAPEX for H_2 and carrier conversion plants. We use the time stamp of 2030 in this analysis.

B. The second most important factor for the cost estimates is the **scale** of the technologies utilized in each chain element, influencing production costs as well as logistics (shipping and export/import terminal costs). The supply chain scales are based on one single point of reference: the installed renewable electricity supply capacity. The minimal scale of the supply chain analysis that yields acceptable results based on underlying logic and input parameters is 600 MWe. The maximal scale is 4 GWe. For this study, we assume 3 GWe installed renewable electricity supply capacity. An appropriate scaling factor is used for each technology to benefit from economies-of-scale effects that reduces the specific cost of assets once deployed on a larger scale.

C. The number of full-load hours (FLH) per year for the H_2 production and the conversion plants has an impact on production volume, and thus the cost per unit produced. Hydrogen is only produced from renewable power, and thus the FLH depends on the region and the capacity factor of the selected power producing technology.

D. The operating flexibility of the methanol synthesis plant is also an important factor. Typically, such processes would need to keep running, or be maintained in hot stand-by when there is no renewable power or hydrogen available to operate. Following from (C), we assume that hydrogen carriers are only produced when hydrogen is available. Intermediate small-scale hydrogen storage to facilitate operational flexibility is discussed in more detail below.

E. Related to the previous two considerations C and D, carrier production plants are assumed to be stand-alone, or ‘islanded’ plants that are not connected to a local power grid. This implies that back-up power generation is needed to keep the show (partially) running when there is no wind or sunshine. While this power could be generated from the locally produced hydrogen, we assume an independent source of electricity as this would eat away some of the freshly produced H_2. The use of back-up power for the hot stand-by mode is discussed in more detail below.

F. The decision is made to evade large-scale H_2 (g) storage and simplify the modelling logic by over-dimensioning the Hydrogen-to-Methanol system element. All hydrogen-to-methanol conversion thus happens during the hours in which that hydrogen is produced from renewable power.

G. In the analysis, either a RES-project based lifetime (e.g. 40 years for solar PV utility scale) could be chosen, or the lifetime equal to the Hydrogen-to-methanol conversion plant (i.e. 20 years) could be taken. We decided to use 20 years as the operational lifetime of the supply chain elements up to distribution, and 5 years of operational lifetime for the distribution assets. Potential exploitation beyond this time horizon is thus excluded from the analysis.

H. In this analysis we assume that the investment comes from a bank loan and the discount rate (DR) is set to the interest rate of the country under consideration.

I. The asset annuity method is applied to integrate investment costs in the levelized cost of hydrogen.

J. No taxes, levies, profit margins, raw material or equipment market dynamics and commodity market dynamics are included in cost calculations.

Economic results are thus bare technical costs with discounted investment costs (H) over the lifetime of the project (G), and not the estimates of end-user prices of hydrogen in the future.

The following approach was used to calculate the landed cost of methanol:

- To arrive at a specific cost per unit of hydrogen, we will ultimately calculate the levelized cost of hydrogen by dividing the total amount of hydrogen produced by an asset by the total cost of that asset. For both of the values, the lifespan of the assets is of importance. The longer the asset operates, the more hydrogen can be produced and the longer the (investment) costs can be discounted over the years. Discounting these investment (or Capital Expenditure, CAPEX) costs over time requires a discount rate. This discount rate is used in the asset annuity method.

- The annuity method is a shortcut method commonly used as an alternative to more elaborate NPV calculations, in early phase project studies when the uncertainty of CAPEX estimates is still very high. Using a given interest rate (i), a lifetime (n) and the total capital investment (TCI), the annual cost of capital (ACC) is approximated as follows:

$$\mathrm{ACC} = \mathrm{TCI}\frac{(1+i)^n i}{(1+i)^n - i}$$

- This annual cost of capital is subsequently incorporated in the calculations. The example for $LCoH_2$ is given below:

$$LCoH_2\left[\frac{€}{ton}\right] = \frac{\sum \frac{annual\ cost\ of\ capital + fixed\ OPEX + variable\ OPEX}{(1+i)^n}}{\sum \frac{hydrogen\ produced}{(1+i)^n}}.$$

Logic and assumptions per chain element

In the supply chain cost model uses three groups of supply chain elements. The model logic and assumptions for each chain element in those groups are discussed in more detail below and/or in previous public reports[8].

- Supply-focussed chain elements
- Import logistics-focused chain elements:
- Distribution and end-use-focussed chain elements

Detailed elaboration and source data of the cost modelling can be found in [23].

<u>Supply-focussed chain elements</u>

Chain elements included:

- Renewable power production (e.g. [24], [3] [12])
- Electrolysis process
- Small gaseous hydrogen storage
- Methanol synthesis process

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[8] [23]**Invalid source specified.**

The hydrogen gas is produced by converting renewable power from a combined renewable power plant of 3 GW in combination with a load-following 2.9 GW Alkaline electrolyser system. Renewable energy can be generated by solar PV, onshore wind, hydropower or a combination of two options dependent on the archetype country. Every type of renewable electricity generation has a geographically distinct LCoE and a specific number of full-load hours. The overall renewable electricity generation is a combination of different assets. When combining the different generation assets, the model accounts for a critical overlap. This critical overlap reduces the number of full-load hours as the production profile overlaps.

Table A.1: Renewable electricity supply assumptions of the archetype countries in this study

Parameter	Unit	Canada	Morocco	Australia
LCoE for onshore wind in 2030	€/MWh	35.3	34.5	33
LCoE for offshore wind in 2030	€/MWh			
LCoE for solar PV in 2030	€/MWh		23	22
LCoE for geothermal in 2030	€/MWh			
LCoE for hydro power in 2030	€/MWh	51.8		
LCoE for combined RES in 2030	€/MWh	55	34	32
Cost of back-up power in 2030	€/MWh	120	120	120
Full-load hours for onshore wind	%	46	43	43
Full-load hours for utility PV	%		23	25
Full-load hours for pumped hydro	%	50		
Combined Full-load hours (including critical overlap in production)	%	77	60	62

When there is no renewable electricity available the electrolyser and downstream production processes, assets are assumed to operate on hot stand-by. To maintain these assets in hot stand-by, back-up electricity is required. It is assumed that 1% of the installed capacity is required to maintain the system in hot stand-by. This power is provided by a not-defined type of back-up power supply source.

The model assumes that the majority of electricity is directly converted to hydrogen. Hence both the electrolyser and methanol production operate in a load-following mode. A 12-hour intermediate hydrogen buffer is included to cover ramp-up/ramp-down or process upsets. It is assumed that the methanol production is operated with 2 trains to offer more operational flexibility. To offer more flexibility in decoupling hydrogen and methanol production, large-scale underground storage would be required.

A variety of import methanol supply chains can be established. Potentially interesting exporting countries are characterized by low electricity costs, high capacity factors of renewable electricity plants, little limitations on land use, an excess of renewable energy production compared to local consumption, an available renewable carbon feedstock reservoir and a stable (political) investment climate.

A diverse range of exporting countries or regions become of interest. Amongst others: Kingdom of Saudi Arabia, Oman, Morocco, Algeria, Egypt, Namibia, Australia, Chili, Argentina, Norway, Iceland and the United Kingdom. In this feasibility study, Morocco, Australia and Canada are chosen as MeOH exporters.

These three countries show a variety of 'unique selling points' and can therefore be considered as 'archetype' countries of which other similar countries exist that may be (more) competitive globally.

Import logistics-focused chain elements:

Chain elements included:

- Export terminal
- Vessel
- Import terminal

The total amount of imported methanol is based on the sum of annual hydrogen produced and the corresponding amount of carbon feedstock fed into the methanol synthesis process. The ship size and number of ships required is determined based on vessel cargo capacity, sailing speed, on/offloading time and sailing distances. The export terminal is assumed to be a copy of the import terminal. The terminal is sized according to the transportation volume of the ship with an additional 25% buffer. The number of tanks required is based on the maximum allowable design capacity for a single tank.

Distribution and end-use-focussed chain elements:
Chain elements included:

- Distribution via barge
- Distribution via truck

Function: The function of this supply chain element is to distribute methanol from large-scale storage in seaports to ships that use it as a fuel ('bunkering').
For use as a marine fuel, methanol must be delivered to ships. This study calculated the cost of doing so by barge (the most common way to distribute marine fuels) or by tanker truck (the easiest way to start with small-scale deliveries). It is assumed that the tanker trucks distributing the methanol run on batteries and the bunker barges run on methanol as a fuel.

Logic & assumptions: Bunkering is assumed to be done either by 3,000 ton barge or by 44,5 ton tanker truck. The total volume of methanol is assumed to be distributed in full load parcels. The total volume of methanol distributed is assumed to be equal to the imported volume described in the previous paragraph.
Demand for methanol as a marine fuel is assumed to be constant during the year, so the barges or trucks used for bunkering have a constant utilization rate. The average last mile distribution distance is assumed to be 60 km for barges and 100 km for trucks. Because of travel and transfer times, barges and trucks are assumed to deliver at most 3 parcels per day. Trucks and barges are assumed to have an 'uptime' of 96%, equalling approximately 350 days per year. The number of vessels / trucks required is calculated as follows:

$$n_{vessels} = \frac{V_{import}}{V_{vessel} * 3 * 96\%}$$

Techno-economic input data: The techno-economic input parameters are reported as datasheets i5 (trucks) and SH5 (barges).

Variance over time: Both barge and tanker truck technology are mature. No significant improvement in efficiency is foreseen in the model.

Appendix B - Carbon feedstock cost

	IEA [6]			IRENA [5]		
	LOW [USD/tCO_2]	MID [USD/tCO_2]	HIGH [USD/tCO_2]	LOW [USD/tCO_2]	MID [USD/tCO_2]	HIGH [USD/tCO_2]
Ethanol fermentation	25	**31,5**	38	10	**15**	20
Solid biomass firing	55	**60**	65	-	-	-
Waste firing	-	-	-	-	-	-
Natural gas firing (NGCC)	50	**75**	100	90	**100**	110
Cement	58	**89**	120	55	**69**	84
Kiln	-	-	-	-	-	-
Pre-calciner	-	-	-	-	-	-
MEA	-	-	-	63	91,5	120
Calcium looping	-	-	-	56	73	90
Full-oxidation	-	-	-	45	53	61
Partial oxidation	-	-	-	55	59	63
Iron and steel	58	**79**	100	61	**110**	159
COREX plant	-	-	-	-	-	-
Blast furnace	-	-	-	-	-	-
Lime calcining	-	-	-	-	-	-
Sinter plant	-	-	-	-	-	-
Ammonia	25	**31,5**	38	14	**26,5**	39
Natural gas processing	16	**22**	28			
Hydrogen production unit (SMR)	50	**65**	80	50	**63**	76
Direct air capture	134	**233**	332	-	-	-

	CCS INSTITUTE [4]			AVERAGE		
	LOW [USD/tCO_2]	MID [USD/tCO_2]	HIGH [USD/tCO_2]	LOW [USD/tCO_2]	MID [USD/tCO_2]	HIGH [USD/tCO_2]
Ethanol fermentation	0	**5**	10	10,3	15,0	19,8
Solid biomass firing	60	**71**	82	50,4	57,4	64,4
Waste firing	60	**71**	82	52,6	62,2	71,9
Natural gas firing (NGCC)	69	**93**	117	61,1	78,3	95,5
Cement	46	**55**	64	46,4	62,3	78,1
Kiln	49	56,5	64	-	-	-
Pre-calciner	43	53,5	64	-	-	-
MEA	-	-	-	-	-	-
Calcium looping	-	-	-	-	-	-
Full-oxidation	-	-	-	-	-	-
Partial oxidation	-	-	-	-	-	-
Iron and steel	-	**67,9**	-	52,2	75,0	113,4
COREX plant	43	48,5	54	-	-	-
Blast furnace	46	51,5	57	-	-	-
Lime calcining	59	73,5	88	-	-	-
Sinter plant	72	98	124	-	-	-
Ammonia	0	**5**	10	11,4	18,4	25,4
Natural gas processing	0	**5**	10	7,1	11,9	16,7
Hydrogen production unit (SMR)	50	**62,5**	75	43,8	55,7	67,5
Direct air capture	-	-	-	117,4	204,1	290,8

Appendix C - Cost of last-mile distribution per archetype country and modality

Below is an overview of the costs per ton of last-mile distribution of methanol for each of the three archetype countries. For all countries, last-mile delivery by barge is significantly cheaper than last-mile delivery by truck.

Table C.1: Cost of last-mile delivery of methanol as a marine fuel

Distribution mode	unit	Chain M	Chain A	Chain C
Distribution to end-user - barge	€/t MeOH	2,23	2,11	1,82
Distribution to end-user - truck	€/t MeOH	6,07	5,82	5,91

The annual costs for methanol delivery companies are calculated to be as follows:

Table C.2: Annual cost breakdown last mile distribution

	unit	Chain M			Chain A			Chain C		
		Asset Annuity	Fixed OPEX	Variable OPEX	Asset Annuity	Fixed OPEX	Variable OPEX	Asset Annuity	Fixed OPEX	Variable OPEX
Barge	M€/year	0,81	1,75	0,70	0,81	1,75	0,53	0,81	1,75	0,84
Truck	M€/year	4,48	3,70	0,74	4,38	3,62	0,53	5,60	4,63	0,84

Appendix D - Overview of methanol mass flow and investment throughout the supply chain

Table D.1: Supply chain asset capacities of M archetype

Supply chain element	# assets	Installed capacity of single asset, mass flow	Investment
Renewable electricity supply	n/a	3000 MW_e	n/a
Hydrogen production	n/a	2700 MW_e	1145 MEUR
Hydrogen gas storage	n/a	102 ton H_2	59 MEUR
Feedstock	n/a	2025 kton/year	n/a
Methanol production	2	1048 kton/year (1473 kton/year)	237 MEUR
Methanol export storage	4	114 kton, 50.000m^3	49 MEUR
Methanol shipping	1	44,6 kton	29 MEUR
Methanol import storage	3	31,6 kton	41 MEUR
Methanol distribution by truck	44	0,04 kton	44 MEUR
Methanol distribution by barge	1	2,26 kton	8 MEUR

Table D.2: Supply chain asset capacities of A archetype

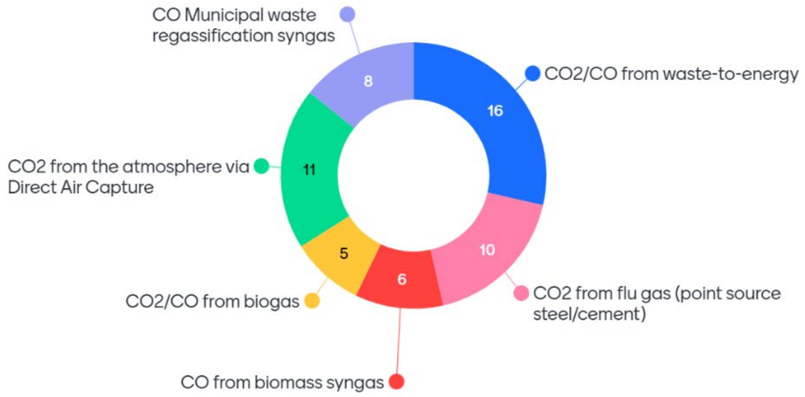
Supply chain element	# assets	Installed capacity of single asset, mass flow	Investment
Renewable electricity supply	n/a	3000 MW_e	n/a
Hydrogen production	n/a	2700 MW_e	1145 MEUR
Hydrogen gas storage	n/a	102 ton H_2	59 MEUR
Feedstock	n/a	2025 kton/year	n/a
Methanol production	2	1048 kton/year (1523 kton/year)	237 MEUR
Methanol export storage	4	114 kton, 50.000m^3	49 MEUR
Methanol shipping	4	95 kton	196 MEUR
Methanol import storage	3	30,5 kton	41 MEUR
Methanol distribution by truck	43	0,04 kton	43 MEUR
Methanol distribution by barge	1	2,26 kton	8 MEUR

Table D.3: Supply chain asset capacities of C archetype

Supply chain element	# assets	Installed capacity of single asset, mass flow	Investment
Renewable electricity supply	n/a	3000 MW_e	n/a
Hydrogen production	n/a	2700 MW_e	1145 MEUR
Hydrogen gas storage	n/a	102 ton H_2	59 MEUR
Feedstock	n/a	2025 kton/year	n/a
Methanol production	2	1048 kton/year (1891 kton/year)	237 MEUR
Methanol export storage	4	114 kton, 50.000m^3	51 MEUR
Methanol shipping	2	95 kton	98 MEUR
Methanol import storage	3	31,4 kton	43 MEUR
Methanol distribution by truck	55	0,04 kton	55 MEUR
Methanol distribution by barge	1	2,26 kton	8 MEUR

Appendix E - GMM2.0 consortium input 27 October 2022

What is the renewable carbon feedstock source in 2030?



Which variable is a cost driver of interest to you?

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