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**TNO report**

**TNO 2020 R11105**

# Green Maritime Methanol
# Operation aspects and the fuel supply chain

Date 24 September 2020

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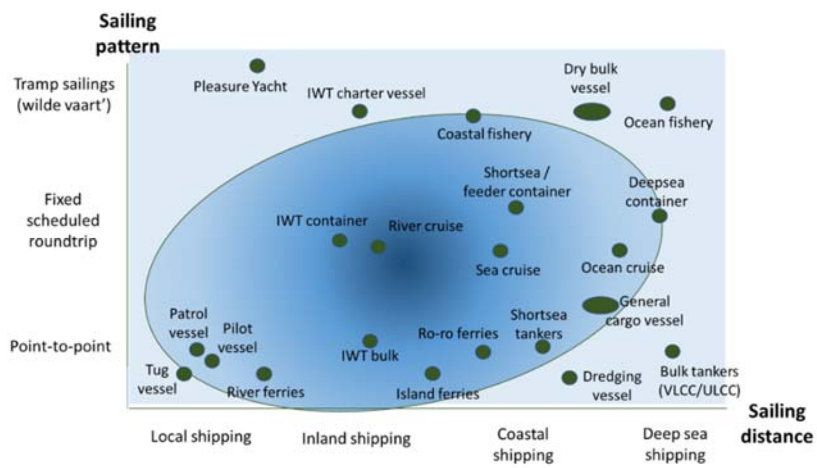
| Copy no | 2020-STL-REP-100334441 |
| Number of pages | 102 (incl. appendices) |
| Sponsor | TKI Maritime & the Netherlands Ministry of Economic Affairs |
| Project name | Green Maritime Methanol |
| Project number | 060.38323 |

# Summary


Increasing pressure on shipping to contribute to reduce GHG emissions is changing the landscape for marine fuels. In the quest for sustainable alternative fuels, methanol is one of the fuels that has a special interest in the Green Maritime Methanol project.

This report focuses on the operational aspects of using methanol, in terms of suitability to the different shipping market segments, the bunker operations and the upstream and downstream supply chain aspects of methanol as a marine fuel.

The suitability of methanol for different shipping markets depends among others on the fuel consumption patterns; what distances do these vessels sail between two subsequent ports? But also the tank capacity and the typical sailing pattern matters; point-to-point, fixed schedules or tramp sailing. With ship arrival data from the ports of Rotterdam and Amsterdam, an analysis of the suitability was made, resulting in the following 'heatmap' on the applicability of methanol.




Heatmap of methanol-applicability of shipping segments.

Most shortsea and inland shipping markets appear to be feasible in terms of their operational profiles, fuel consumption and sailing patterns. The arrival data for each vessel type show that even when using methanol, the tank capacity is still more than sufficient to execute the far majority of all trips. Only some deep sea segments, dredging and (long distance) tramp sailing segments pose challenges to the applicability in terms of tank capacity. However, newbuilt ultra large LNG container vessels show that ship design can also be adjusted to accommodate substantially larger fuel tank capacity.

Another question being answered in this report is what the adoption of methanol would imply in terms of bunker demand for methanol. The world global bunker demand is about 250-300 million metric tonnes HFO/ MGO, depending on the methodology used. Europe is responsible for one fifth of this volume. Within Europe demand is concentrated in a limited number of ports, of which Rotterdam is by far the largest European bunker port.

The ARA-region (Amsterdam-Rotterdam-Antwerp) handles around 18 million tonnes per year. Container vessels, dry bulk vessels and liquid bulk tankers are responsible for two-third of the global bunker demand.

An indicative forecast has been developed taking into consideration developments in the fleet composition and making assumptions on possible methanol shares within each shipping market: a low and a high scenario. These assumptions are based on the heatmap outcomes and expert judgement. For smaller vessels, the methanol share ranges from 10-25% in the low scenario and 25-50% in the high scenario, specified for each vessel type. For larger vessels, the low scenario assumes no share for methanol yet, only in the high scenario the share ranges from 10-20%. This results in a total methanol share ranging from 5% in the low scenario up to 22% in the high scenario. Applying this to the total bunker demand forecast for 2030, this would result in 0.6 to 2.6 million $m^3$ methanol for Rotterdam and 1.1 to 5.0 million $m^3$ methanol for the whole ARA-region.

But how does this methanol get into the vessels, how will the bunkering take place? Can it be done safely, and what does this mean for additional costs and investments, apart from the process difference of the fuel as such? These questions have been addressed in chapter 3. It starts describing the different bunker transfer methods used today, with its characteristics: ship-to-ship bunkering, truck-to-ship bunkering, shore-to-ship bunkering and bunkering at sea. In mature bunker markets, ship-to-ship bunkering is the dominant method, certainly in terms of volume. Truck-to-ship bunkering is being used for vessels with low demand and offers flexibility and control over the delivered quantity and specs. Shore-to-ship bunkering is often being applied by tugs, inland shipping vessels (floating installation), utility vessels, fishing boats, and patrol and inspection vessels (coast guard).

Since methanol is a liquid just as oil, most of these methods can and will be applied to methanol as well. Only, methanol is being treated as a hazardous liquid, so it requires some additional safety measures. However, infrastructure adjustments are marginal, contrary to LNG bunker facilities. The additional measures include among others specific safety equipment, training and certification. The IAPH audit and accreditation tool helps ports to issue a license to operate methanol bunkering in their port area. In truck-to-ship bunkering, interpretation of the safety regulations on the quay (applicability of environmental permit regimes of terminals) may differ between countries, this needs further elaboration when aiming for a European level playing field.

In the transition phase, it is expected that in the pilot phase truck-to-ship will be mainly used, but when adoption of methanol further increases the larger ports will soon facilitate ship-to-ship bunkering and shore-to-ship for the local fleet. In terms of bunker vessels, the total market will grow, the lower energy density simply requires more frequent bunkering. However, the ports do not foresee any serious capacity or safe navigation issues. Chapter 3 also includes an analysis of the price volatility of the different marine fuels used today. This analysis reveals a huge impact of the introduction of the IMO 2020 low Sulphur regulation and also shows its sensitivity for COVID-19 outbreak and corresponding market dip.
Chapter 4 further elaborates on price aspects also for the different methanol production variants.

As part of this report an upstream and downstream supply chain analysis has been performed. Global production is around 100 MT per year, whilst the production capacity is about 33% higher. The majority of both demand and supply is in Asia. Though volumes in Europe are modest, both production and demand are expected to increase rapidly in the coming years. European production is 1.5 MT in 2018, but production capacity in 2020 is 3.7 MT. Demand in Europe is with 7.5MT much higher, causing substantial import volumes from a.o. Trinidad.

The upsream supply chain of methanol distinguishes 4 different production paths: grey methanol (from fossil sources), biomethanol (from biogas), Carbon-recycled methanol, and e-methanol (from green hydrogen and a carbon source). The report describes these production paths, the production capacities, feedsyttock differences and cost-drivers of each method. The methanol demand in the short term remain being based on fossil fuels, mainly on natural gas. Price developments will be in line with the gas market price development. Biomethanol and e-methanol production are not yet mature, being reflected in the prices as summarised in the table below.

Cost range for grey, bio- and e-methanol, and their dependencies on feedstock costs.

| **Methanol type** | **Cost range** | **Cost dependent on** |
|---|---|---|
| Grey methanol | € 9-22/GJ | Policy, Natural gas price |
| Biomethanol | € 11-33/GJ | Policy, Biomass & green gas price |
| E-methanol | € 27-68/GJ | Electricity and $CO_2$ costs |

To realise GHG targets, a switch to green carbon-neutral fuels like biomethanol and e-methanol is highly desired and expected in the future. However, the ongoing transition to methanol-based maritime transport may require grey methanol as short- and medium-term solutions, as well as blends of fossil and renewable methanol.

The downstream supply chain addresses the distribution of methanol from the production location to the bunkering location and into a ship’s tank. It addresses the sustainability aspects of the distribution and the associated distruibution costs. For production locations with access to inland or seaports, short sea or inland waterway transport is a cost-efficient and rather sustainable option. For production locations without access to inland or seaports, transport by **rail** is the most sustainable option and also rather cost-effective, provided the location is connected to the rail network. Otherwise, transport by truck is a flexible option with good connectivity, also able to serve smaller ports lacking multimodal hinterland connections. Pipeline transport does not seem a feasible option for methanol supply to ports.

The main costs and emissions for the different methanol distribution options have been derived and summarized for a number of scenarios.

These distribution scenarios include:
1. From Delfzijl (BioMCN) to Port of Rotterdam,
2. From Delfzijl (BioMCN) to Port of Amsterdam,
3. From Rhine production locations (BP, Shell, BASF) to Port of Rotterdam or Amsterdam,
4. From Leuna Germany (Mider-Helm-Methanol) to Port of Rotterdam or Amsterdam,

5. From Kjørsvikbugen (Tjeldbergodden) to Port of Rotterdam or Amsterdam,
6. From several oversea production locations to Port of Rotterdam, including
   a. Middle East (Saudi Arabia East Coast, Iran, Oman),
   b. Trinidad, Venezuela (also Egypt East Coast / Saudi Arabia West Coast,
   c. Equatorial Guinea, and
   d. Russia (several locations, via St. Petersburg).

The remaining part of the downstream supply chain is the further distribution from the main hub Rotterdam to other Dutch bunkering locations. The downstream supply chain analysis demonstrates that the supply chain infrastructure for methanol distribution from European and/or oversea production locations to the Netherlands is readily available, which would position Rotterdam well as a major distribution hub for European supply of methanol as a maritime fuel.

Based on the maritime energy demand forecast and the projected share of methanol, maritime methanol demand in the Netherlands would rise to 6.5 MT or 132 PJ in 2030, which corresponds to 2.3% of total global production capacity. European demand would then comprise 8.8% of global production. Production capacity of the existing European production facilites seem to be sufficient to cope with this demand.

So taking into consideration the different analyses and corresponding conclusions, there does not seem to be any serious operational or supply chain obstacle or bottleneck that would hinder the transition towards substantial use of methanol as a maritime fuel.

# Abbreviations

| | |
|---|---|
| ADN | Accord Européen Relatif Au Transport International Des Marchandises Dangereuses Par Voies De Navigation Intérieures (ADN) |
| ARA | Amsterdam Rotterdam Antwerp |
| CAPEX | Capital Expenditure |
| ceu | car-equivalent units |
| CCNR | Central Commission for the Navigation of the Rhine (Strasburg) |
| dwt | deadweight tonnage |
| DAC | direct air capture |
| GJ | Gigajoule |
| GMM | Green Maritime Methanol |
| GHG | Greenhouse Gas |
| GT | Gross Tonnage |
| HFO | Heavy Fuel Oil |
| IFO | Intermediate fuel oil |
| IACS | International Association of Classification Societies (London) |
| IMO | International Maritime Organisation (London) |
| kW | Kilowatt |
| LNG | Liquefied natural gas |
| LSMGO | Low-sulfur Marine Gas Oil |
| MGO | Marine Gasoil |
| MARPOL | Marine Polution prevention regulation issued by IMO |
| MT | Megaton |
| MWh | Megawatthour |
| MSW | Municipal Solid Waste |
| $NO_X$ | Nitrogen Oxides |
| PJ | Petajoule |
| rfg | Recycled Carbon Fuels |
| RED II | Renewable Energy – Recast to 2030 |
| RFNBO | Renewable Fuels of Non-Biological Origin |
| Ro-Ro | Roll-on Roll-off |
| STS | Ship-to-Ship |
| SECA | Sulphur Emission Controlled Area |
| $SO_X$ | Sulphur Oxide |
| TRL | Technology readiness level |
| TTS | Truck-to-ship |
| TEU | Twenty Foot Equivalent Unit |
| ULCS | Ultra Large Container Ships |
| ULCC | Ultra Large Crude Carrier |
| ULFSO | ultra-low sulfur fuel oil |
| UN-ECE | United Nations European Council Europe (Geneva) |
| VLCC | Very Large Crude Carrier |
| VLSFO | Very-low sulfur fuel oil |

# Contents

# 1 Introduction

## 1.1 The project

IMO legislation on $NO_x$ and $SO_x$ emissions and increasing pressure on shipping to contribute to reduce GHG emissions are changing the landscape for marine fuels. In the quest for alternative fuels, methanol is one of the fuels that has a special interest. Methanol has low $NO_x$, $SO_x$ and PM emissions and methanol, is rather energy efficient in comparison to other sustainable alternatives, is liquid under atmospheric conditions, and depending on the feedstock and technology used, can also realise significant GHG reductions. Thus making methanol a fuel that could meet future sustainability requirements. In this Green Maritime Methanol project, the benefits and feasibility of application of methanol for the maritime sector are being elaborated, with a focus on short sea shipping. The project focusses both on technical development of the powertrain as well as on logistics and operational aspects. The ambition of the project is to deliver a system design of a prototype at TRL level 6 for implementation of methanol as a shipping fuel. The project will work towards an actual implementation in a pilot.

This deliverable reports the findings of WP4 in the project and elaborates on the operational aspect of using methanol as bunker fuel for shipping and the corresponding supply chain analysis of methanol. The focus is on short sea shipping, but the analysis also addresses deep sea and inland shipping market application.

## 1.2 Methodology

The analysis is built upon three main components: desk research, interviews and data analysis. The desk research includes scientific reports, scientific papers, industry papers and expert articles. Interviews have been carried out within and outside the GMM-consortium. This includes interviews with short sea operators, methanol producers, port authorities, and bunker operating companies. Finally, ship arrival data from the Port of Rotterdam and Amsterdam over the year 2018 has been analysed.

## 1.3 Report structure

The report is structured around three topics. Chapter 2 focuses on the different shipping markets, and the ease of transforming to using methanol for the typical shipping operations and corresponding fleet characteristics. Chapter 3 describes the different bunkering transfer methods and the implications of shifting towards methanol bunkering. And chapter 4 addresses the supply chain of methanol as maritime fuel. It includes an upstream analysis of the different production methods, the supply of different feedstock, production capacity, maritime demand, and the downstream analysis how the produced methanol becomes available for ship bunkering in ports. The report ends with conclusions and recommendations.

# 2 Impact of methanol on shipping operations

This chapter focuses on the implications of using methanol on daily shipping operations. What storage capacity is available in existing fleet or can be designed for in newbuilt vessels? What distances can be reached after bunkering? What does that imply for bunkering frequencies? What about availability of methanol in ports? And how does this relate to the typical market operations of carriers? In other words, what is the bunker demand? These questions should help answering the key question: which market segments are promising for methanol use as maritime fuel?

This task addresses business case aspects of methanol, such as price and cost developments but does not elaborate on the economic feasibility or business case as such. Safety aspects and corresponding legislative aspects are being highlighted, but are being addressed in more detail in WP3. Policy aspects refer to optimal storage capacity in relation to market characteristics and legislative choices about emission targets (on journey, fleet or organization level) and provide input for GMM deliverable D6.

## 2.1 Approach

In GMM WP2 operational profiles for a number of vessels representing some interesting market segments have been developed. Based on the operational profile of typical vessels, the WP2 report concludes that a number of market segments appear to be feasible for using methanol in terms of availability, tank capacity, range and shipping patterns. These include  the short sea shipping market and niche markets, such as service vessels, cruise vessels, offshore & dredging vessels. The deep-sea shipping market would pose additional challenges to the tank capacity and bunker frequency, whereas the short sea and coastal vessels sailing short port-to-port distances would also be a candidate for alternative zero-emission energy options, such as hydrogen or electricity. Here, we elaborate on those insights and extend the analysis, for instance by incorporating inland shipping and river cruise.

In this report, we have plotted the operational profiles and some additional shipping market segments along two axes:

- Sailing distance: local shipping, inland shipping, coastal/short sea shipping and deep-sea shipping.
- Sailing pattern: point-to-point, fixed scheduled roundtrip (liner service), tramp service (‘wilde vaart’).

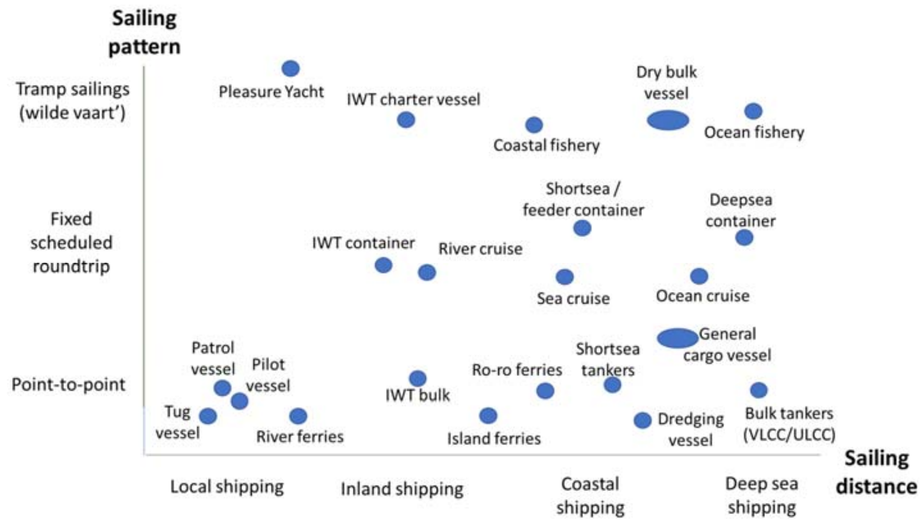



Figure 1: Portfolio of shipping segments

In this report, we use detailed data of port calls in Rotterdam and Amsterdam to elaborate operational characteristics of these categories, such as average bunker volumes, average days spent at sea and average daily consumption days. We link this with shipping market characteristics in the corresponding categories, such as bunker strategies, average bunker volumes etc. In doing so, we can better analyse what the operational impact would be to make a transition towards using methanol as maritime fuel.

## 2.2 Short sea shipping

The total gross weight of goods transported as part of EU short sea shipping is estimated at almost 1.9 billion tonnes of goods in 2017. Short sea shipping made up close to 60% of the total sea *transport* of goods to and from the main EU ports in 2017. Liquid bulk remained the dominant type of cargo in EU short sea shipping. At 823 million tonnes, liquid bulk accounted for 44 % of the total short sea shipping of goods to and from main EU ports in 2017. Liquid bulk was followed by dry bulk at 385 million tonnes (21%), containers at 271 million tonnes (15%) and roll on-roll off (Ro-Ro) units at 253 million tonnes (14%).

Short sea shipping is the key focus in our project, that's why we start describing the different shipping market segments. Subsequently, we describe Short sea/feeder container vessels, short sea liquid bulk tankers, short sea dry bulk vessels, short sea general cargo vessels, Ro-ro & Island ferries, coastal fishery vessels and dredging vessels.

### *2.2.1 Short sea container vessels*

Short sea shipping of goods in containers is concentrated around a limited number of main hub ports. In 2017, the top 5 ports for containers handled 34% of the total short sea shipped container goods in main EU ports. The top-5 consists of Rotterdam, Antwerp, Piraeus, Hamburg and Gioia Tauro.

We apply the following segmentation in short sea and feeder container vessel size:

- Container Class 1 (up to 1999 TEU)
- Container Class 2 (3000-4999 TEU)
- Container Class 3 (8000-11999 TEU)

The majority of the short sea container vessels arriving in Rotterdam (Amsterdam in does not handle maritime containers) are falling in class 1 (80%). These vessels have an average fuel consumption of 37 ton HFO/MGO per day. Short sea transport within the Sulphur Emission Control Areas would require either ULSFO or LSMGO to comply with the Sulphur requirements of <0.1% Sulphur.

These vessels were sailing on average 34 hours from the last port of call, resulting in a weighted average fuel consumption of 52 ton HFO/MGO, which is comparable with 112 ton methanol.

The vessel arrivals of Class 2 represent 12% of all short sea container arrivals in 2018. These vessels have an average fuel consumption of 86 ton HFO/MGO per day. These vessels were sailing on average 20 hours from the last port of call, resulting in a weighted average fuel consumption of 73 ton HFO/MGO, which is comparable with 157 ton methanol.

The vessel arrivals of Class represent 8% of all short sea container arrivals in 2018. These vessels have an average fuel consumption of 116 ton HFO/MGO per day. These vessels were sailing on average 31 hours from the last port of call, resulting in a weighted average fuel consumption of 148 ton HFO/MGO, which is comparable with 304 ton methanol.

Table 1: Fuel consumption pattern of short sea container vessels arriving in Rotterdam in 2018

| | Container Class 1 | Container Class 2 | Container Class 3 |
|---|---|---|---|
| | Up to 1999 TEU | 3000-4999 TEU | 8000-+ TEU |
| Vessel arrivals | 80% | 12% | 8% |
| Average daily fuel consumption HFO/MGO (in tonnes) | 37 | 86 | 116 |
| Average sailing hours from previous port (last trip, in hours) | 34 | 20 | 31 |
| Average trip consumption HFO/MGO (in tonnes) | 52 | 73 | 148 |
| Average trip consumption Methanol (in tonnes) | 112 | 157 | 304 |

A typical short sea container vessel has an engine size of 12,000 kW and consumes 7,000 ton conventional fuel per year, or 23 ton fuel per day. It has a bunker frequency of every 14 days resulting in an average bunker volume of 328 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]). This corresponds best to a large Class 1 container vessel. Taking into account a bunker safety margin of 25%, such a vessel could, therefore, sail around 75 hours on methanol, which is sufficient for almost all short sea container roundtrips.

### 2.2.2 *Short sea liquid bulk*

Rotterdam is by far the largest European port for short sea shipped liquid bulk. At 119 million tonnes, Rotterdam handled 14% of the total short sea shipped liquid bulk goods reported by the main EU ports in 2018, followed by Antwerp (43M), Marseille (33M), Trieste (26M) and Skoldvik (23M).

We apply the following segmentation in short sea liquid bulk vessels:

- Bulk Class 1 (10,000–34,999 dwt)
- Bulk Class 2 (35,000–59,999 dwt)
- Bulk Class 3 (600,000–150,000 dwt)
- Bulk Class 4 (150,000–200,000 dwt)

The liquid bulk vessels of class 5,6,7 (above 200,000 dwt) sailing shortsea distances from a European port of origin to Dutch mainports were very limited (<0.2%) and were left outside this analysis, leaving us with 4 categories. The large majority of these short sea liquid bulk tankers arrived in Rotterdam, Amsterdam complements this.

With 90% of the arrivals in this category, Class 1 represent the dominant vessel type in this category. These vessels have an average fuel consumption ranging from 18 to 139 ton HFO/MGO per day. These vessels were sailing on average 33 hours from the previous port of call, resulting in a weighted average fuel consumption of 35 ton HFO/MGO, which is comparable with 76 ton methanol. The Class 2, 3 and 4 vessels complement this category, representing 2%, 5% and 2% of the total short sea liquid bulk vessel arrivals in 2018 in Rotterdam and Amsterdam. Detailed fuel consumption patterns can be found in table 2.

Table 2: Fuel consumption pattern of short sea liquid bulk vessels arriving in Rotterdam and Amsterdam in 2018.

| | Class 1 | Class 2 | Class 3 | Class 4 |
|---|---|---|---|---|
| DWT | 10-35K | 35-60K | 60-150K | 150-200K |
| Vessel arrivals (%) | 90% | 2% | 5% | 2% |
| Average daily fuel consumption HFO/MGO (in tonnes) | 18-139 | 22-139 | 50-66 | 59 |
| Average sailing hours latest trip (in hours) | 33 | 54 | 33 | 29 |
| Average trip consumption HFO/MGO (in tonnes) | 35 | 111 | 77 | 71 |
| Average trip consumption Methanol (in tonnes) | 76 | 228 | 159 | 146 |

The tank storage capacity of a typical class 1 liquid bulk tanker is large enough to facilitate the far majority of the shortsea trips, even taking into account the safety margin.

### 2.2.3 *Short sea dry bulk*

In short sea shipped dry bulk, Rotterdam leads again with 20,9M ton, closely followed by Amsterdam with 20,7M ton. Riga (17,5M), Constanta (15,6M) and Hamburg (14,2M) complement the top-5 short sea dry bulk list.

A dry bulk carrier's voyages are determined by market forces; routes and cargoes often vary. A ship may engage in the grain trade during the harvest season and later move on to carry other cargoes or work on a different route. Aboard a coastal carrier in the tramp trade, the crew will often not know the next port of call until the cargo is fully loaded. Because bulk cargo is so difficult to discharge, bulk carriers spend more time in port than other ships, the same applies to general cargo vessels.

For dedicated dry bulk vessels in shortsea, we apply the following segmentation:

- Bulk Class 1 (10,000–34,999 dwt)
- Bulk Class 2 (35,000–59,999 dwt)
- Bulk Class 3 (600,000–150,000 dwt)
- Bulk Class 4 (150,000–200,000 dwt)

Class 1 and class 2 are the dominant vessel types in this this category.
These vessels have an average fuel consumption of 21 and 32 ton HFO/MGO per day. These vessels were sailing on average 91 resp. 99 hours from the previous port of call, resulting in a weighted average fuel consumption of 81 resp 131 ton HFO/MGO, which is comparable with 174 resp 282 ton methanol. The Class 3 and 4 vessels complement this category, representing 2% and 9% of the total short sea dry bulk vessel arrivals in 2018 in Rotterdam and Amsterdam.
Detailed fuel consumption patterns can be found in table 2.

Table 3: Fuel consumption pattern of short sea dry bulk vessels arriving in Rotterdam and Amsterdam in 2018.

| | Class 1 | Class 2 | Class 3 | Class 4 |
|---|---|---|---|---|
| DWT | 10-35K | 35-60K | 60-150K | 150-200K |
| Vessel arrivals (%) | 90% | 2% | 5% | 2% |
| Average daily fuel consumption HFO/MGO (in tonnes) | 21 | 32 | 41 | 49 |
| Average sailing hours latest trip (in hours) | 91 | 99 | 96 | 56 |
| Average trip consumption HFO/MGO (in tonnes) | 81 | 131 | 162 | 114 |
| Average trip consumption Methanol (in tonnes) | 174 | 282 | 334 | 235 |

The tank storage capacity of a typical class 1 dry bulk vessel is large enough to facilitate the far majority of the shortsea trips, even taking into account the safety margin.

It is worth noting that dry bulk in shortsea shipping is not only being shipped with dedicated dry bulk carriers, moreover general cargo/multipurpose vessels are also being used to transport large volumes of dry bulk over shortsea distances. Therefore, we also include a dedicated section on general cargo vessels.

### 2.2.4 *Short sea general cargo vessels*

As stated in the previous section, general cargo vessels are frequently being used in shortsea transport, not only to move break-bulk but also dry bulk and containers.

The far majority of shortsea general cargo vessel arrivals in Rotterdam and Amsterdam consist of Class 1 vessels with 10-35K DWT capacity. Rotterdam is dominant in this market compared to Amsterdam.

These Class 1 vessels have an average fuel consumption of 10 ton HFO/MGO per day. These vessels were sailing on average 49 hours from the previous port of call, resulting in a weighted average fuel consumption of 21 ton HFO/MGO, which is comparable with 46 ton methanol. Class 2 vessels represent less than 1%.

Table 4: Fuel consumption pattern of short sea general cargo vessels arriving in Rotterdam and Amsterdam in 2018.

| | Class 1 | Class 2 |
|---|---|---|
| DWT | 10-35K | 35-60K |
| Vessel arrivals (%) | 99% | 1% |
| Average daily fuel consumption HFO/MGO (in tonnes) | 10 | 10 |
| Average sailing hours latest trip (in hours) | 53 | 96 |
| Average trip consumption HFO/MGO (in tonnes) | 23 | 42 |
| Average trip consumption Methanol (in tonnes) | 49 | 90 |

The tank storage capacity of a typical class 1 general cargo vessel is large enough to facilitate the far majority of the shortsea trips, even taking into account the safety margin.

### 2.2.5 *Ro-Ro, vehicle carriers and passenger ferries*

**Ro-Ro**

The global Ro-Ro market is exiting a long period of contraction characterized by a decreasing fleet size, an ageing fleet with few new build ships, weak charter rates and generally difficult market conditions resulting in a decrease in number of owners/operators (most Ro-Ro vessels are owned and operated by the same company) and consolidation. This is a trend that is expected to continue.
In November 2017, the Ro-Ro fleet stood at 1,014 vessels with total capacity of 1,3 M lane-metres. The Netherlands is offering strong connectivity in Ro-Ro connections, as can be seen in the picture below.

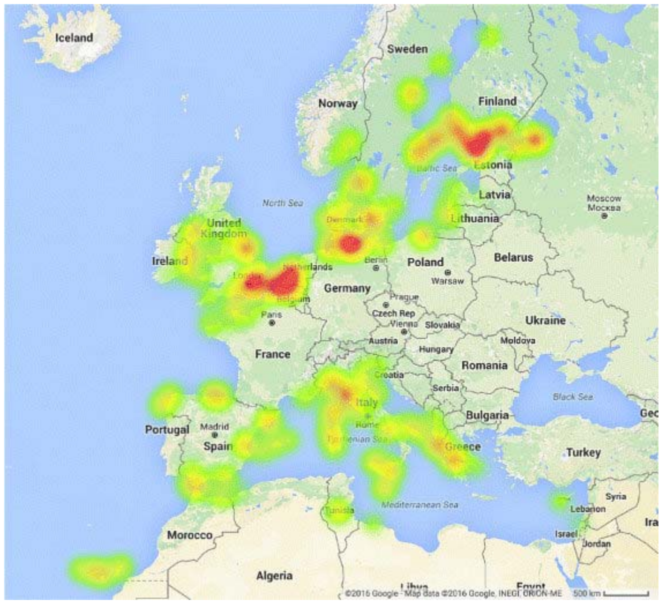



Figure 2: European Ro-Ro connectivity heatmap [5].

**Vehicle carriers**
In the global vehicle carrier fleet market there are currently 829 vessels with a total capacity of 3,9 M car-equivalent units (ceu). Between 2017 and 2021 the capacity of the 4,000+ ceu segments will expand by 2.6% each year, while the fleet of smaller carriers will shrink.

The seaborne passenger market is substantial in Europe, with 213 million seaborne passengers in 2017. Major passenger transport ports are Helsinki, Dover, Tallinn, Messina and Calais. Dominant connections are Helsinki-Tallinn and Dover-Calais. The role of the Netherlands is very modest, with 1.9 million seaborne passengers.

There are three ferry connections between The Netherlands and the UK:

- Rotterdam-Hull; seven times per week, operated by P&O Ferries;
- Hoek van Holland to Harwich; 14 times per week, operated by Stena Line;
- IJmuiden – Newcastle; seven times per week, operated by DFDS Seaways.

The Netherlands also operates national island ferries to the Waddeneilanden, which attracted almost 1.5 million visitors in 2017. The island ferry services are being operated by Wagenborg (Ameland, Schiermonnikoog), Doeksen (Terschelling, Vlieland) and TESO (Texel).

Table 5: Fuel consumption pattern of short sea of RoRo, vehicle carriers and passenger vessels arriving in Rotterdam and Amsterdam in 2018.

| | Ro-Ro | Vehicle carrier | Passenger ferries |
|---|---|---|---|
| | 63% | 5% | 33% |
| Vessel arrivals | 63% | 5% | 33% |
| Average daily fuel consumption HFO/MGO (in tonnes) | 27 | 39 | 23 /49 |
| Average sailing hours latest trip (in hours) | 29 | 35 | 16 |
| Average trip consumption HFO/MGO (in tonnes) | 33 | 58 | 12 |
| Average trip consumption Methanol ( in tonnes) | 71 | 118 | 27 |

A typical RoRo vessel has an engine size of 11,500 kW and consumes 5,500 ton conventional fuel per year, or 22 ton fuel per day. It has a bunker frequency of every 14 days resulting in an average bunker volume of 310 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]). Comparing this to the average consumption pattern of RoRo vessels arriving in Rotterdam, and taking into account a bunker safety margin of 25%, this allows for 95 hours sailing on methanol, which is largely sufficient for point-to-point roundtrips.

A typical ferry vessel has an engine size of 30,000 kW and consumes 17,500 ton conventional fuel per year, or 58 ton fuel per day. It has a bunker frequency of every 7 days resulting in an average bunker volume of 409 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]). Comparing this to the average consumption pattern of passenger ferries arriving in Rotterdam, and taking into account a bunker safety margin of 25%, this allows for 153 hours sailing on methanol, which is largely sufficient for point-to-point roundtrips.

#### 2.2.6 *Coastal fishery*

The total world fishing fleet as per IHS Fairplay currently numbers almost 25,000 vessels (above 100 GT) with a total tonnage of 11 million GT. A high level of scrapping is expected in the coming years due to the age of the fleet. Currently, more than 50% of the ships are over 30 years old . Newbuild deliveries are expected to rise from around 240 vessels in the period 2019-2030 to around 385 vessels per year in the period 2031-2035. While the latter may seem like a significant number of vessels, it is still lower than the number of vessels deleted from the fleet in that same period, resulting in a further drop of the fleet size (SeaEurope, 2018 Market Forecast report).

The future market for fishing vessels is one of the hardest markets to predict of all vessel types. This is largely due the fact that the fleet size is mostly dictated by government policies rather than market requirements. Several studies have shown that fish stocks have been seriously overfished in many areas of the world. Several countries have established targets to tackle national overcapacity of fishing fleets. A rise in fish quota restrictions is therefore to be expected. This is why the global fishery production in marine waters remains uniform between 78-83 million tonnes. Coupled to these restrictions is a likely decrease in the world fishing fleet size (SeaEurope, 2018 Market Forecast report).

The vessel arrival database from Rotterdam did not contain substantial fishing vessel arrivals. A study on alternative fuels for fishing vessels (AFFV, 2016) identifies eight representative fishery vessel types with corresponding sailing profiles, five of them are relatively large (40 meter; power ca 1.468 kW) and three relatively small (< 24 meter, power 220 kW). The sailing profile for the Pulsbokker (40 meter) assumes to be operational in 45 weeks per year (45 visweken), consuming 608,000 liter MGO per year, or 13.5 mt per fishweek. The smaller schrimpkotters or plate fishing vessels consume about 4 to 5 ton MGO per week. The study assumes a truckload of LNG to be sufficient for these bunker quantity needs. Since it would require a similar volume of methanol, this would also be sufficient for the majority of the fleet.

A typical fishery trawler has an engine size of 950 kW and consumes 456 ton conventional fuel per year, or 2 ton fuel per day. It has a bunker frequency of every seven days resulting in an average bunker volume of 13 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]). These figures lie in between the sailing patterns of the large and small fishery kotters in the AFFV-study.

### 2.2.7 *Dredging vessels*

New dredgers are expected to feature many advances in terms of reducing their environmental footprint . Already, the first LNG-fuelled maintenance dredgers are in service or under construction, and more will likely follow. LNG is not the only option though. Use of hybrid propulsion (combining diesel and batteries for example) might also be a suitable option for dredgers, as the power usage of these vessels fluctuates a lot during operations [6].

In the GMM WP2 report, the operational profile of a trailing suction hopper dredger (22,000 mt dwt; 12,000 $m^3$ hopper capacity and power 2x 5,080kW) was subject to analysis. This ship bunkers just over 1,600 $m^3$ of MGO, consumes about 40 to 50$m^3$ fuel per day, thus able to operate for 24 days without bunkering.
When bunkering methanol, it could stay at sea for about two weeks, enough for most regular projects. Allowing a safety margin of 25% of the tank capacity, the bunker quantity would be 1200 $m^3$. This would require almost 50 tank truckloads, which is not feasible when using truck-to-ship transfer. It would require ship-to-ship bunkering. Since the vessel visits many different ports, a wide network of methanol bunkering should be in place, which makes this shipping market becoming feasible if methanol bunkering is in its maturity stage. See chapter 3 for more details on the bunkering infrastructure development options.

### 2.2.8 *Motorised Yachts*

Motorised yachts can be categorized by size in yachts smaller than 30 meters, 30 to 50 meters and larger than 50 meters. Chartering a yacht can cost from 10,000 USD per week for smaller sailing yachts up to 150,000 USD per week for the most luxury motorized yachts (Alliedmarketresearch, Yacht charter market analysis 2019-2026).

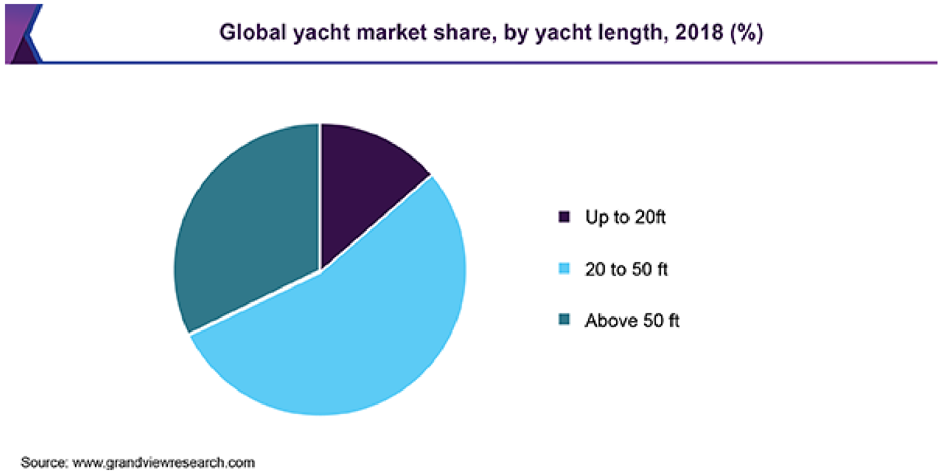



Figure 3: Global yacht market by size.

Yachts with length size ranging up to 20 ft can be used for both competitive as well as recreational purposes. Furthermore, in North America and Europe, the emerging trend of using renewable energy such as solar energy and wind energy in sea vessels is most likely to play an important role in reducing fuel usage and emissions from ships. A yacht of this length operating on renewable energy is generally compact and lightweight as it requires less energy to sail. This is also a prominent factor augmenting the growth of the up to 20 ft segment.

In 2018, a total of 19 motorised yachts, with an average fuel consumption of 14 ton HFO/MGO per day, arrived in Rotterdam from the North Sea basin. These vessels were sailing on average 6 hours sailing between Rotterdam and the previous port. That results in a weighted average fuel consumption of 3,5 ton HFO/MGO, which is comparable with 7,5 ton methanol.

In addition, 5 motorised yacht arrivals were from outside the North Sea basin, sailing on average 116 hours sailing between Rotterdam and the previous port. That results in a weighted average fuel consumption of 66 ton HFO/MGO, which is comparable with 142 ton methanol.

A typical motorized yacht has an engine size of 4,200 kW and consumes 4,234 ton conventional fuel per year, or 8 ton fuel per day. The bunker frequency varies, depending on the consumption pattern. Typical bunker quantity is 119 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]). Taking into consideration a bunker safety margin of 25%, this would allow for 11 sailing days. When using methanol instead, this would allow for 5 sailing days.

### *2.2.9 Ocean/Sea cruise*

According to the Cruise Lines International Association (CLIA, 2018), the European ocean cruise passenger numbers grew in 2018 by 3.3% against 2017, to 7.17million [6]. The average European cruise trip lasts for 8.7 days. The top destinations of Dutch cruise passengers are: Central & West Mediterranean (22.4%), Caribbean (20.6%) and Northern Europe (19.4%). The Baltics is a fast-growing destination (from 2.8% in 2016 to 4.8% in 2018).

Sea Cruise Vessels can be split into regular and large. Large sea cruises consume about 250 ton per day. These vessels are about 335 m long and have a tank capacity of 7500 $m^3$. Regular sea cruise vessels consume about 140-150 ton per day.

A typical large cruise vessel has an engine size of 117,600 kW and consumes 67,738 ton conventional fuel per year, or 226 ton fuel per day. It has a bunker frequency of every 14 days resulting in an average bunker volume of 3,161 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]). This is in line with the CLIA-report [7].

Typical ocean cruise vessel consumption patterns are listed by de Santiago [7] and include:

- The Harmony of the Seas: length xx; consuming 250 $m^3$/day.
- Queen Mary 2: 345 m long, weight 151k ton; consuming 6 ton/hour allowing them to stay at sea for 10 days.
- Norwegian Spirit: 268 m long, weight 76k ton, consuming up to 4.2 $m^3$/hr; It can stay for 12 days at sea and has a tank capacity > 1325 $m^3$.
- Freedom of the Sea class: all 339m long, consuming up to 106 $m^3$ per day
- P&O Brittania: weight 114 k ton; consuming 11.4 $m^3$ per hour.


Figure 4: Example of bunkering a cruise vessel (source: https://www.windstarcruises.com/blog/how-much-fuel-cruise-ship-uses/).

Vessels like the Queen Mary 2 and the Norwegian Spirit have a tank capacity and consumption pattern that allows them to stay for about 10-12 days at sea.
This would correspond with about five days when using methanol. Knowing that the average European cruise trip lasts for 8.7 days, this would require additional bunkering during a trip. This may be a problem if the visitors are not allowed to leave the ship during bunkering. in the meantime. Since cruises visit several ports in a trip and port in a port normally allows for rebunkering. It would also require that intermediate ports would have methanol bunkering facilities.

## 2.3 Local shipping

### 2.3.1 *Tug vessel*

We distinguish two categories of tug services: offshore anchor handling tug supply services, and regular tug services. Within these categories, we split the arrivals in Dutch mainports from the North Sea basin and from other regions.

The tugs supporting offshore anchor handling (44% of all tug arrivals in 2018) have a similar daily consumption use of 22 tonnes HFO/MGO per day. It is the previous departure port that determines the trip operating time at sea and corresponding fuel consumption. Arrivals from within the North Sea Basin have a relative short operation time of seven hours and a corresponding consumption pattern of 6 tonnes HFO/MGO, which would be similar to 13 tonnes Methanol. For trips from outside the North Sea basin, the trip duration is 69 hours, about ten times as long. Correspondingly, the fuel consumption is also 10 times bigger.

For regular tugs, representing 54% of all tug arrivals in Dutch mainports, the ones active in the North Sea basin have a daily consumption of 9 tonnes HFO/MGO and their arriving trip lasted on average 15 hours. This corresponds to 5,5 tonnes HFO/MGO or in case of methanol this would be 11,9 tonnes. The other part of the regular tug arrivals coming from outside the North Sea basin sail on average 72 hours. Based on an average daily consumption of 14 tonnes per day, this corresponds to a trip use of 27 tonnes of HFO/MGO. In case of using methanol instead, this would correspond to 58 tonnes.

Agentschap.nl, studied  harbor tugs in operation. About 30% of the time they are actually tugging, 30% they sail on slow speed, 38% of the time they are monitoring in stand-by mode, and only 2% of the time they run on full motor power. This offers room for more environmental friendly solutions (Agentschap.nl, 2011).

Table 6: Fuel consumption pattern of tug vessels arriving in Rotterdam and Amsterdam in 2018.

| | Offshore anchor handling North Sea basin | Offshore anchor handling Other regions | Regular Tugs North Sea basin | Regular tugs other regions |
|---|---|---|---|---|
| Vessel arrivals | 37% | 7% | 28% | 28% |
| Average daily fuel consumption HFO/MGO (in tonnes) | 22 | 22 | 9 | 14 |
| Average sailing hours latest trip (in hours) | 7,0 | 69 | 15 | 72 |
| Average trip consumption HFO/MGO (in tonnes) | 6,0 | 62 | 5,5 | 27 |
| Average trip consumption Methanol ( in tonnes) | 13,0 | 134 | 12 | 58 |

The average tank capacity of tug vessels operating in the North Sea basin is more than sufficient for using methanol. Using tug vessels on longer trips, it depends on the tank capacity.

### 2.3.2 *Patrol & pilot vessels*

The vessel arrival database does not include patrol/pilot vessel movements. In GMM WP2, the operational profile of a typical port patrol vessel (19,64 x 7,94 x 3,39 x 2,49 meter; 896kW Power) was subject to analysis. The vessel has a bunker capacity of 14 $m^3$, on which it sails for two weeks, allowing a significant margin. When switching to methanol, the vessel therefore will require a higher bunkering frequency to sustain a significant range. The ship owner (port authority) has indicated that weekly bunkering is acceptable for the current vessel operation. Bunkering could quite easily be performed from a stationary location or by using a tank truck.

## 2.4 Deep sea shipping

### 2.4.1 *Deep sea container vessels*

The deep-sea container shipping industry is very volatile and highly competitive, resulting in tight control of costs and the preservation of sailing schedules. The size of ships serving the deep-sea container trades has grown significantly over the last decades, with ULCS's up to 400 meter and a capacity over 23,000 TEU.

The container vessel arrivals in Rotterdam with origin outside Europe over 2018 have been analysed, see the table below for the main findings.

Table 7: Fuel consumption pattern of deep-sea container vessels arriving in Rotterdam in 2018.

| Vessel class | Class 1 | Class 2 | Class 3 | Class 4 | Class 5 |
|---|---|---|---|---|---|
| TEU | Up to 1999 | 3000-4999 | 8000-11999 | 12000-14500 | 14500-+ |
| Vessel arrivals | 34% | 18% | 34% | 13% | 1% |
| Average daily fuel consumption HFO/MGO (in tonnes/day) | 37 | 86 | 116 | 122 | 130 |
| Average sailing hours latest trip (in hours) | 569 hr | 258 hr | 317 hr | 359 hr | 313 hr |
| Average trip consumption HFO/MGO (in tonnes) | 170 | 923 | 1528 | 1827 | 1691 |
| Average trip consumption Methanol (in tonnes) | 363 | 1994 | 3149 | 3765 | 3484 |

A typical Ultra Large Container Ships (ULCS) has an engine size of 110,000 kW and consumes 63,360 ton conventional fuel per year, or 211 ton fuel per day. It has a bunker frequency of every 35 days resulting in an average bunker volume of 7,392 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]).

Comparing the profile of a typical ULCS vessel to the average consumption pattern of Class 5 container vessels arriving in Rotterdam, and taking into account a bunker safety margin of 25%, this allows for 500 hours sailing on methanol, or 20 days.

Despite the huge trip fuel consumption volumes, this does not mean large container vessels cannot run on methanol. CMA-CGM recently launched the first 23,000 TEU LNG vessel from a series of 9, these vessels have a tank storage capacity of 18,600 $m^3$.

This would be sufficient to sail for 41 days with an average Class 5 container vessel (14,500+ TEU), taking into account a safety margin of 25% of the tank capacity. The volumetric energy density for LNG and methanol are similar[1].

### 2.4.2 *Deep sea liquid bulk tankers*

Oil tankers are designed for the bulk transport of oil or its products. There are two basic types of oil tankers: crude tankers and product tankers. Crude tankers move large quantities of unrefined crude oil from its point of extraction to refineries. Product tankers, generally much smaller, are designed to move refined products from refineries to points near consuming markets, corresponding to class 1 and 2 in the table below. For example, moving gasoline from refineries in Europe to consumer markets in Nigeria and other West African nations. Subclasses include Handysize, Panamax (Class 3), Aframax (Class 3), Suezmax (Class 4), Very Large Crude Carrier (VLCC, Class 6), Ultra Large Crude Carrier (ULCC, Class 7).

Table 8: Fuel consumption pattern of deep-sea liquid bulk tankers arriving in Rotterdam and Amsterdam in 2018.

| | Class 1 | Class 2 | Class 3 | Class 4 | Class 5 | Class 6 | Class 7 |
|---|---|---|---|---|---|---|---|
| DWT | 10-35K | 35-60K | 60-150K | 150-200K | 200-250K | 200K+ | 200K+ |
| Vessel arrivals | 49% | 12% | 25% | 10% | 0% | 1% | 3% |
| Average daily fuel consumption HFO/MGO (in tonnes/day) | 18-139 | 22-66 | 50-139 | 121 | | 86 | 86 |
| Average sailing hours latest trip (in hours) | 278 | 314 | 183 | 284 | | 398 | 384 |
| Average trip consumption HFO/MGO (in tonnes) | 273 | 725 | 393 | 695 | | 1424 | 1373 |
| Average trip consumption Methanol (in tonnes) | 589 | 1492 | 810 | 1431 | | 2935 | 2829 |

A typical VLCC tanker (Class 6) has a bunker capacity of 8,000 ton. When running on methanol, the average trip consumption would consume only 36% of the bunker capacity. Tank capacity would be sufficient for most deep-sea trips between origin and destination.

Methanol is already being used as maritime fuel for liquid bulk vessels, see the frame below. Waterfront Shipping is a global marine transportation company and a subsidiary of Methanex Corporation, the world's largest producer and supplier of methanol. It has an interest to boost the deployment of methanol as a maritime fuel and therefore is a frontrunner in applying dual-use methanol vessels.

[1] Methanol about 16 MJ/dm$^3$ versus LNG 22 MJ/dm$^3$. However with packaging factor for cylindrical tank, insulation and filling factor, LNG has effective energy density of about 11 MJ/dm$^3$

Table 9: Example of methanol fleet in operation

**Waterfront Shipping Dual-use Methanol Fleet**
Waterfront Shipping is a global marine transportation company and a subsidiary of Methanex Corporation. As of the end of 2019, the company operates eleven vessels capable of running on methanol. Hexter: 'Together, these ships have 70,000 operating hours running on methanol and have recorded slightly better specific equivalent fuel oil consumption when running on methanol (roughly two per cent).'

The first seven vessels are equipped with the first of its kind MAN B&W ME-LGI two-stroke dual-fuel engines. The engines can run on methanol, fuel oil, marine gas oil, and marine diesel oil. In 2019, Waterfront Shipping welcomed four new vessels built with second generation MAN dual-fuel engines. These engines achieve Tier III $NO_x$ emission compliance through a water-methanol blending process. The water vaporizes, reducing both combustion temperature and oxygen concentration, which suppresses $NO_x$ formation.

The methanol engines Waterfront uses, are based on a traditional diesel engine. The methanol component is an add-on feature. As such, the engine can always fall back on conventional fuels.
As a liquid fuel without any need for cryogenic installations, it is also easy to handle. As a low flashpoint fuel, however, it cannot be stored in the engine room and needs to be supplied to the engine through double hulled piping.

***Source: https://www.swzmaritime.nl/news/2020/03/10/waterfront-shipping-methanol-as-a-marine-fuel-works/?gdpr=accept***

### *2.4.3 Deep sea dry bulk*

A bulk carrier is a merchant ship specially designed to transport unpackaged bulk cargo, such as grains, coal, ore, steel coils and cement, in its cargo holds. Since the first specialized bulk carrier was built in 1852, economic forces have led to continued development of these ships, resulting in increased size and sophistication. Today's bulk carriers are specially designed to maximize capacity, safety, efficiency, and durability.

Today, bulk carriers make up 21% of the world's merchant fleets and range in size from single-hold mini-bulk carriers to mammoth ore ships able to carry 400,000 metric tonnes of deadweight (DWT).

Bulk carriers are segregated into six major size categories: small (Class 1), handysize (Class 1), handymax (Class 2), panamax (Class 3) , capsize (Class 4), and very large (Class 5 and 6). Capesize bulk carriers are specialized: 93% of their cargo is iron ore and coal. Though many bulk carrier's voyages are determined by market forces, the very large ships are often specifically designed for particular trade lanes. The Vale Brasil is since 2011 the biggest ore carrier in the world, with a 365,000-ton capacity, 362-meter length and 65-meter width. Vale is a Brazilian Ore mining company, they ordered 12 of these very large ore vessels for the particular trade between Brazil (mining production) and its Asian customers. Before 2011, the MS Berge Stahl was the biggest ore carrier in the world, with a 400,000-ton capacity, 342-meter length and 64-meter width.

Because of its massive size, Berge Stahl could originally only tie up, fully loaded, at two ports in the world, hauling ore from the Terminal Marítimo de Ponta da Madeira in Brazil to Rotterdam Europoort in the Netherlands. Berge Stahl made this trip about ten times each year, or a round-trip about every five weeks.

Table 10: Fuel consumption pattern of deep-sea dry bulk vessels arriving in Rotterdam and Amsterdam in 2018.

| | Class 1 | Class 2 | Class 3 | Class 4 | Class 5 | Class 6 |
|---|---|---|---|---|---|---|
| DWT | 10-35K | 35-60K | 60-150K | 150-200K | 200-250K | 200K+ |
| Vessel arrivals | 17% | 51% | 3% | 25% | 5% | |
| Average daily fuel consumption HFO/MGO (in tonnes/day) | 21 | 32 | 41 | 49 | 55 | |
| Average sailing hours latest trip (in hours) | 361 | 377 | 284 | 404 | 251 | |
| Average trip consumption HFO/MGO (in tonnes) | 322 | 501 | 479 | 816 | 1070 | |
| Average trip consumption Methanol (in tonnes) | 696 | 1081 | 988 | 1681 | 2204 | |

A typical class 1 or class 2 deep sea dry bulk vessel has an engine size of 12,100 kW and consumes 6,970 ton conventional fuel per year, or 23 ton fuel per day. It has a bunker frequency of every 30 days resulting in an average bunker volume of 690 ton per bunker transfer (Source: TNO based on [1], [2] [3] [4]).

### 2.4.4 *Deep sea general cargo vessels*

The far majority of the deep-sea general cargo vessel arrivals in Rotterdam and Amsterdam consist of Class 1 vessels with 10-35K DWT capacity, similar as for shortsea destinations. Rotterdam is dominant in this market compared to Amsterdam.

These Class 1 vessels have an average fuel consumption of 10 ton HFO/MGO per day. These vessels were sailing on average 49 hours from the previous port of call, resulting in a weighted average fuel consumption of 21 ton HFO/MGO, which is comparable with 46 ton methanol. Class 2 vessels represent less than 1%.

Table 11: Fuel consumption pattern of short sea general cargo vessels arriving in Rotterdam and Amsterdam in 2018.

| | Class 1 | Class 2 |
|---|---|---|
| DWT | 10-35K | 35-60K |
| Vessel arrivals (%) | 99% | 1% |
| Average daily fuel consumption HFO/MGO (in tonnes) | 10 | 10 |
| Average sailing hours latest trip (in hours) | 260 | 1423 |
| Average trip consumption HFO/MGO (in tonnes) | 112 | 618 |
| Average trip consumption Methanol (in tonnes) | 244 | 1335 |

These Class 1 vessels have a limited tank capacity, but would consume on average 244 ton methanol, but for trips originating from China and Korea this consumption would exceed 1,000 tonnes of methanol. Taking into account the safety margins, this would not be feasible for all trips.

## 2.5 Inland shipping

In 2017, total EU transport performance on inland waterways reached 146 billion ton-kilometres, an increase of 1% compared with 2016. This overall performance was mainly boosted by the Rhine and Western Europe, where increasing figures were observed for countries such as Belgium, Germany and the Netherlands.

Container transport on European inland waterways accounts for more than 16 billion ton-kilometres, and increased by 5% in 2017. More than 99% of this traffic takes place in Rhine countries.

In Rotterdam, inland vessels were 105,000 times loaded or unloaded in 2017. The volume of loaded cargo was 112.4 mio. tonnes, directed to the hinterland. The amount of incoming traffic amounted to 45.7 mio. tonnes. Inland waterway transport has very high shares in the hinterland traffic: 86% for dry cargo, 40% for liquid cargo and 36 % for containers. The port has the objective to increase this last share above the 40 % level.

The port of Amsterdam has over 450,000 $m^2$ of public berths for inland shipping. In 2018, the port received 22,242 port visits by inland vessels.

### *2.5.1 Fleet analysis*

For fleet analysis, we concentrate on the fleet statistics in the Rhine countries. The number of vessels in the Rhine countries (including push & tug boats) amounted to more than 9,800 units [8]. The far majority, 72% of all vessels are dry cargo vessels (self-propelled units or dumb barges). Tanker vessels account for 15% and push & tug boats for 13%. In 2017, the loading capacity of dry cargo and liquid cargo units in Rhine countries amounted to 13.5 million tonnes.

Many inland vessels (82%) are ‘overmotorised’, meaning that they have more power than needed for their sailing pattern, especially the smaller inland vessels. This allows them to sail in all conditions both upwards and downwards the rivers, to take push barges alongside the vessel if needed. Also, motor power was originally overdimensioned in order to sail fast in a time where bunker costs were a much smaller part of exploitation costs.

The majority (66%) does not comply to the CCR-2 emission norms, that entered into force in 2007 [9]. Whereas the M8 and higher classes generally comply to these CCR-2 norms, the majority of smaller vessels have CCR-1 motors or even older.

### *2.5.2 Motor vessels*

In the dry cargo segment, the number of vessels decreased further in 2017; but due to a rising newbuilding rate, and larger vessels coming on the market, the decrease in total loading capacity follows a much slower pace.

In tanker shipping, the total number of vessels continued to decrease in 2017, to a value of 1,501 units, but the decrease was quite limited when compared to the previous years. The total loading capacity was more or less stable, keeping a level at around 3.1 million tonnes. The average loading capacity per vessels surpassed the swell of 2,000 tonnes.

A motor vessel of 110 meter, with a tank capacity of 57 $m^3$ running on diesel fuel can almost sail 3 times up and down between Rotterdam and Basel with cargo on board. Using methanol, this would still be largely sufficient for a roundtrip.

### 2.5.3 *Push barges*

The push & tug fleet remained almost stable at a level of slightly more than 1,200 units over a decade, in all Rhine countries except France. At present, the Belgian fleet of push & tug boats follows a decreasing trend, while the fleet in the Netherlands is growing. Push barges operating between Antwerp-Basel (e.g. by Danser) consume around 32 $m^3$ fuel per return trip, or 1000 $m^3$ per year. This would correspond with 69 $m^3$ methanol per return trip.

### 2.5.4 *River cruises*

In the 2017 season, the river cruise fleet in Europe comprised 346 active vessels with 50,616 beds. This makes Europe having the largest river cruise fleet globally, passing the Nile fleet as of 2015. The number of active cruise vessels more than doubled between 2004 and 2017. In 2017, 1.4 million passengers took a river cruise trip in Europe, 3% more than in 2016 (1.36 million). In 2017, 17 vessels were introduced to the market with 2,558 beds. The age structure of the European fleet shows that 42% of all vessels were built after 2010. Only 13 % were built before 1990. Passenger transport is generally higher in passenger transport than in goods transport, which is reflected by the upward trend to introduce greening measures in river cruise vessels.

With 2007 river cruise visits, Amsterdam received 406.949 river cruise passengers in 2018. Another 245 river cruises were visiting Zaanstad. This is a modest growth compared to 2017 (+3.4%). The number of river cruise calls is expected to stagnate as a result of static mooring capacity (Port of Amsterdam, Annual Report 2018). Quite some European river cruises start or end in Amsterdam.

Destinations and duration include:

- Amsterdam – Strasbourg (7 days)
- Amsterdam – Basel (8 days)
- Amsterdam - Nuremberg (8 days)
- Amsterdam – Vienna (12 days)
- Amsterdam – Budapest (15 days)
- Amsterdam – Rhine – Moselle – Basel (15 days)
- Amsterdam - Black Sea – Bucharest (23 days)

Also, a number of Benelux-cruise trips include both Amsterdam and Rotterdam:

- Amsterdam – Haarlem- Den Haag – Delft – Rotterdam – Amsterdam (5 days)
- Amsterdam – Gouda – Rotterdam – Amsterdam (5 days)
- Amsterdam – Rotterdam – Antwerp (5 days)

- Amsterdam – Rotterdam – Luxembourg – Brussels (10 days)
- Paris – Brussels – Antwerp - R'dam – A'dam – Groningen - Bremen – Berlin – Dresden – Prague – Vienna (14 days)
- Amsterdam – IJsselmeer – IJssel – Rotterdam – Antwerp – Gent – Amsterdam (15 days)

Today, most of the vessels with a 110 m or 135 m length have a beam (width) of 11.4 / 11.45 m. This is the maximum width allowed to pass through locks which are 12.0 m, wide. These vessels regularly run on diesel. The Viking Longship River Cruise fleet represents this type of vessel, having the same dimensions. These vessels have a Caterpillar 2 x 1014 pk propulsion system. Let's assume these vessels have a similar tank capacity as cargo vessels of this size (around 57 $m^3$).

When assuming an average cruise trip of 10 days, operating 20 hours a day consuming 200l/h, it would consume 4000 liter diesel per day or 40 $m^3$ diesel on the whole 10-day trip. This is similar to 6 $m^3$ methanol. With a tank capacity of 57 $m^3$, this would require an additional re-bunkering along the route in one of the intermediate ports.

Table 12: Example of methanol powered river cruise vessel.

| |
|---|
| **MS Innogy – cruise vessel with the first methanol fuel cell supporting board electricity power in Germany (Lake Baldeneyesee)**<br><br>The companies innogy and SerEnergy turned a diesel-powered vessel into an electric vessel powered by environmentally friendly methanol fuel cells. It is a modular solution making it easy to adjust according to the individual energy requirements of the customer. The MS innogy fuel cell system is a 35 kW system consisting of seven 5 kW modules integrated in one rack. The energy system is a hybrid constellation consisting of a fuel cell system and a battery pack.<br><br>The MS innogy is a part of innogy's "greenfuel" project where they demonstrate the entire value chain of environmentally friendly methanol.<br>***Source: https://serenergy.com/the-first-methanol-fuel-cell-powered-vessel-in-germany-is-now-sailing-the-waters-of-lake-baldeneysee/*** |

## 2.6 Summary of methanol applicability per shipping market

The figure below highlights the attractive and feasible shipping markets for methanol use, based on the operational profiles, bunker needs and tank capacity. This does not yet say anything about the economic business case of using methanol as maritime fuel.

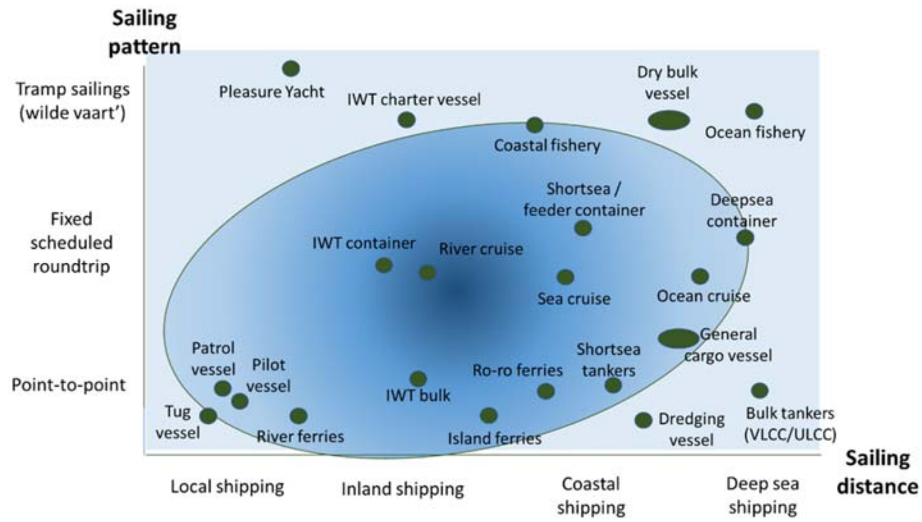



Figure 5: Heatmap of methanol-applicability of shipping segments.

Most midrange shipping markets have vessels with over-dimensioned tank capacity, which allows them to bunker methanol instead of HFO/MGO without serious adjustments to the bunker frequency, sailing pattern, or tank capacity/ship design. For shipping markets with point-to-point sailing patterns and/or short distances methanol is certainly feasible, however it may compete with other alternative green fuel options such as hydrogen. Moreover, inland shipping looks also promising for methanol, though this segment also may compete with alternative green fuels such as e-diesel, hydrogen or battery-electric propulsion.

The methanol bunker needs from the different shipping market segments provide important input for ports to establish the optimal bunker supply chain facilities in ports and facilitate the bunker transfer methods that fit to the port's role in serving these different shipping markets. That aspect is being elaborated in the next chapter, also taking into account the timing aspect, deployment pace and maturity level of methanol as maritime fuel.

## 2.7 Forecast of methanol bunker volumes

### *2.7.1 Global bunker market*

Different methods are being used to estimate global bunker demand, top-down methods and bottom-up methods. According to shipandbunker.com, the global bunker demand is estimated at around 300 million metric tonnes per year. Container vessels constitute of 6% of the world fleet but consume 22% of total yearly bunker volume. Together with dry bulk carriers and liquid bulk tankers they consume almost two-third of the global bunker demand. This bunker demand is allocated over the shipping markets according to the following table.

Table 13: Bunker demand per vessel type.

| | **Fleet** | **GT capacity (x1,000T)** | **Bunker volume (2012, in MT)** | | **Bunker per vessel** |
|---|---|---|---|---|---|
| Container vessels | 4.858 | 175.627 | 66.000.000 | 22% | 13.586 |
| Bulk carriers | 9.892 | 359.521 | 53.400.000 | 18% | 5.398 |
| *Oil & chemical tankers* | 11.730 | 281.072 | *57.200.000* | 19% | 4.876 |
| *Oil tankers* | | | *39.700.000* | *13%* | |
| *Chemical tankers* | | | *17.500.000* | *6%* | |
| General cargo | 16.061 | 57.025 | 21.700.000 | 7% | 1.351 |
| Fishery | | | 16.100.000 | 5% | |
| LNG tanker | | | 15.700.000 | 5% | |
| Cruise | 6.423 | 34.892 | 11.100.000 | 4% | 1.541 |
| Ferry ropax | | | 9.900.000 | 3% | |
| RoRo | 1.470 | 44.756 | 9.300.000 | 3% | 6.327 |
| Offshore | 7.002 | 27.968 | 8.600.000 | 3% | 1.228 |
| Vehicle carrier | | | 7.900.000 | 3% | |
| Other | | | 23.600.000 | 8% | |
| **Total** | **79.471** | **1.048.336** | **300.500.000** | | |

*Source: Equasis* [11] *and IMO* [12]

### 2.7.2 *European bunker market*

Europe handles 19% of the worlds bunker volume. This volume is rather constant the last couple of years. This can be seen in the table below.

Table 14: Global and European bunker volume development

| **(In million tonnes)** | | **2005** | **2012** | **2.013** | **2015** | **2016** | **2017** |
|---|---|---|---|---|---|---|---|
| Marine fuel global | Total | 224 | *255* | *255* | *262* | *270* | 271 |
| | HFO | 176 | *200* | *199* | *198* | *206* | 207 |
| | MGO | 48 | *55* | *56* | *64* | *64* | 64 |
| Marine fuel EU | Total | 57 | *51* | *48* | *48* | *51* | 51 |
| | HFO | 46 | *41* | *38* | *35* | *37* | 37 |
| | MGO | 11 | *10* | *10* | *14* | *13* | 13 |

*Source: FuelsEurope* [13]

Bunkering in Europe is concentrated in a limited number of large bunker ports, not surprisingly the ports that process large volumes of containers, and or dry and liquid bulk. Draffin estimated the yearly volumes in 2015 of these major ports: Rotterdam (10 MT), Antwerp (7,5 MT), Gibraltar (4 MT), Amsterdam (3 MT), Algeciras (3 MT), Fos (3 MT), Piraeus (3 MT) and Hamburg (2,5 MT). As such, the so-called ARA-region (Amsterdam – Rotterdam – Antwerp) represents around 20 million tonnes. In 2019, the bunker volumes in the ARA region are: 9 million tonnes for Rotterdam, 6,5 million tonnes for Antwerp and 1.7 million tonnes for Amsterdam (of which 40% is to serve the inland shipping market). Most relevant shipping markets in Rotterdam include containers, liquid bulk and dry bulk, also the major consumers of bunker fuel.

### 2.7.3 *Rotterdam bunker market*

When zooming in on the Rotterdam bunker market, we see the following.

Table 15: Rotterdam bunker market statistics.

| | **2016** | **2017** | **2018** | **2019** | | **2019-Q4** | **2020-Q1** | |
|---|---|---|---|---|---|---|---|---|
| Total ($m^3$) | | 9.890.092 | 9.475.337 | 8.949.794 | | | 2.371.441 | |
| HFO | | 8.255.467 | 7.918.852 | 7.174.099 | 80% | 1.777.649 | 1.903.761 | 80% |
| - HSFO | | | | | | 693.283 | 609.203 | 32% |
| - VLSFO | | | | | | 853.272 | 989.956 | 52% |
| - ULSFO | | | | | | 231.094 | 304.602 | 16% |
| MGO | | 1.387.913 | 1.358.613 | 1.494.194 | 17% | | 381.148 | 16% |
| MDO | | 147.035 | 103.671 | 208.214 | 2% | | 65.131 | |
| Lubes | | 99.677 | 94.201 | 73.287 | 1% | | 21.401 | |
| Bio-blends (%) | | | | | | 3% | 11% | |
| | | | | | | | | |
| LNG (MT) | 100 | 1.500 | 9.483 | 31.944 | | | 15.710 | |
| | 2016 | 2017 | 2018 | 2019 | | 2019-Q4 | 2020-Q1 | |

*Source: PortofRotterdam.com*

HFO still represents 80% of total bunker volume, with VLSFO and ULSFO rapidly replacing the 3.5% sulfur HFO in the last quarters. Also, bio-blends are growing fast. Finally, we see a breakthrough in the uptake of LNG (measured in metric tonnes). Starting in 2016, the volume more than tripled last year and quadrupled in the first quarter of 2020. Nevertheless, LNG is still marginal compared with HFO and MGO.

### 2.7.4 *Outlook and possible methanol demand*

Transparency market research estimates the global bunker demand to grow by 2.5% per year in the period 2019-2027 [10]. TNO estimates an even stronger growth of the maritime freight performance over the period 2015-2030, whereas container growth is mainly absorbed by larger vessel capacity, whereas liquid bulk growth is mainly due to expansion of the fleet (no larger vessels) [11].

Assuming a 2.5% yearly increase in bunker volume until 2030 would result for Rotterdam in a total volume of 11.7 million $m^3$ in 2030. For the ARA-region, this would sum up to 22,5 million $m^3$.

In order to derive assumption of the possible market share of methanol in the ship bunker market, we use the analysis in this chapter and combine this with the bunker demand analysis and fleet development. Table 16 shows the allocation of bunker demand over the different vessel types and shows the corresponding fleet size and GT-capacity of these vessels.

By applying statistics of the fleet development for 2018, including a distinction between small/medium sized vessels (S/M) and large/very large vessels (L/VL) per category, we can simulate possible market shares of methanol in these markets, summing up to a total share of methanol in the global demand. See table 17 for more details.

Table 16: World shipping fleet statistics.

| | 2012 | 2012 | 2012 | 2015 | 2015 | 2018 | 2018 | 2018 | 2018 | 2018 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bunker consumption | Fleet | GT-capacity | Fleet | GT-Capacity | Fleet | GT capacity | Fleet Small & Medium | Fleet Large & Very Large | GT-capacity Small & Medium | GT-capacity Large & Very Large |
| Container vessels | 66,000,000 | 4,858 | 175,627 | 5,174 | 216,771 | 5,211 | 239,935 | 2,232 | 2,979 | 25,762 | 214,173 |
| Bulk carriers | 53,400,000 | 9,892 | 359,521 | 11,289 | 421,457 | 11,929 | 457,648 | 4,104 | 7,825 | 56,800 | 400,848 |
| *Oil & chem tankers* | *57,200,000* | 11,730 | 281,072 | 12721 | 307848 | 13,757 | 345,545 | 9,172 | 4,585 | 44,545 | 301,000 |
| Oil tankers | 39,700,000 | | | | | | | | | | |
| Chemical tankers | 17,500,000 | | | | | | | | | | |
| General cargo | 21,700,000 | 16,061 | 57,025 | 16,318 | 58,533 | 16,250 | 59,206 | 16,005 | 245 | 51,117 | 8,089 |
| Fishery | 16,100,000 | | | | | 24,606 | 11,412 | 24,603 | 3 | 11,298 | 114 |
| LNG tanker | 15,700,000 | | | | | | | | | | |
| Cruise | 11,100,000 | 6,423 | 34,892 | | 37,510 | 7,348 | 41,833 | 6,887 | 461 | 12,410 | 29,423 |
| Ferry ropax | 9,900,000 | | | | | | | | | | |
| RoRo | 9,300,000 | 1,470 | 44,756 | 1,489 | 48,628 | 1,471 | 49,778 | 659 | 812 | 6,275 | 43,503 |
| Offshore | 8,600,000 | 7,002 | 27,968 | 8,232 | 36,620 | 8,467 | 56,161 | 8,024 | 443 | 16,039 | 40,122 |
| Vehicle carrier | 7,900,000 | | | | | | | | | | |
| Other | 23,600,000 | | | | | 27,818 | 100,402 | 26,864 | 954 | 25,901 | 74,501 |
| | | | | | | | | | | | |
| **Total** | **300,500,000** | **79,471** | **1,048,336** | **87233** | **1,210,422** | **116,857** | **1,361,920** | **98,550** | **18,307** | **250,147** | **1,111,773** |

The simulation is based on the market segment analysis in this chapter. Market shares for small and large vessels per segment have been selected based on the data analysis outcomes of the vessel arrival data in Rotterdam and Amsterdam, and expert opinion. For simplicity it links short sea to small and medium sized vessels and deep sea to large and very large vessels. With these assumptions, we can derive a first indication of possible market shares for methanol uptake in the different markets, in line with the market segment analysis for methanol use.

Table 17: Assumptions on methanol market shares for simulation.

| | Low scenario | | High scenario | |
|---|---|---|---|---|
| | S/M share | L/VL share | S/M share | L/VL share |
| Container vessels | 25% | 0% | 50% | 20% |
| Bulk carriers | 25% | 0% | 50% | 10% |
| Oil & *chem tankers* | 25% | 0% | 50% | 10% |
| General cargo | 25% | 0% | 50% | 10% |
| Fishery | 10% | 0% | 50% | 10% |
| LNG tanker | 0% | 0% | 0% | 0% |
| Cruise | 25% | 0% | 50% | 10% |
| Ferry ropax | 25% | 0% | 50% | 10% |
| RoRo | 25% | 0% | 50% | 20% |
| Offshore | 10% | 0% | 25% | 0% |
| Vehicle carrier | 25% | 0% | 50% | 20% |
| Other | 10% | 0% | 50% | 20% |

This would result in an overall methanol market share of 22% in the high scenario and 5% in the low scenario. Applying this methanol share to the forecasted bunker market in 2030 results in a methanol demand in the range of 0.6 to 2.6 million m3 for Rotterdam and 1.1 to 5.0 million $m^3$ for the whole ARA-region. Chapter 4 shows us that this demand can easily be met by the global methanol production capacity.

# 3 Bunkering of methanol

In this chapter the possible procedures for bunkerage of methanol are described and subsequently analyzed for feasibility. We start describing the bunkering operation procedures and the different bunker transfer options, also highlighting what implications methanol bunkering would have and bunker fleet implications. Then we discuss bunker price s and price volatility, and sensitivity for the IMO 2020 regulation and impact of COVID-19 on the market prices. Then we report on the safety aspects of methanol bunkering. Finally, we describe how ports could facilitate methanol bunkering using a maturity model.

## 3.1 Bunkering operation procedures

Firstly, we describe the existing bunkering operation processes. Bunkering usually takes place in a port. There are more than 400 ports around the world that have marine fuel bunkering operations. The majority of bunker fuels include HFO and MGO; LNG bunker volumes are still very small. Fuel oil gets transported to the ports by tankers. It will be collected in a storage place in the ports. Before the ship receives the bunkers, an engineer calculates the volume of supplies needed. After that, a pre-bunker checklist is followed. This checklist is important to prevent oil spills. Poor quality bunker fuels can cause serious damage to the engines caused by contaminations, therefore it is common practice among prudent ship operators to first test the fuel. This can be done either in a laboratory, but this happens more and more on board. The Person-In-Charge (PIC) - often a Chief Engineer - is always responsible for safe bunkering operations, the pre-loading plan, communication procedures and emergency shutdown procedures.

The bunkering procedure on a ship can be divided into three important stages (Source: https://www.marineinsight.com/guidelines/bunkering-is-dangerous-procedure-for-bunkering-operation-on-a-ship/):

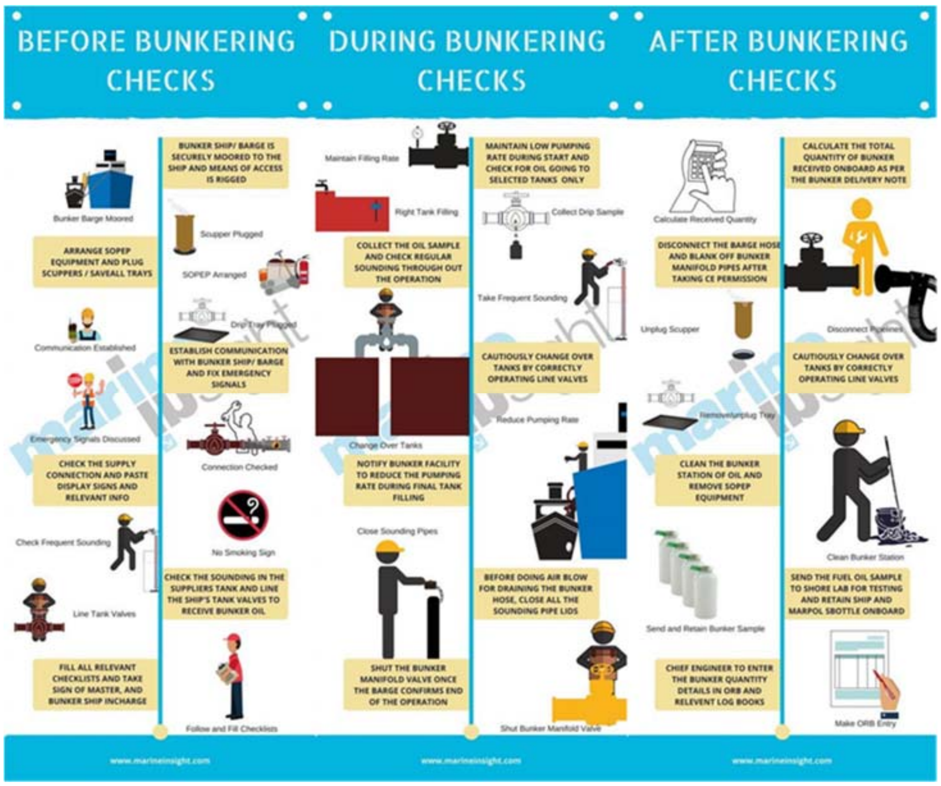
1. Preparatory phase– Preparing for the bunkering operation which will involve the readiness of bunkering equipment, storage tanks and bunkering safety;

    a) Make sure the bunker barge is securely moored to the ship;
    b) Arrange the Ship Oil Pollution Emergency Plan (SOPEP) equipment, such as oil absorbent pads, sawdust bags, booms etc.
    c) Establish communication with the bunker barge;
    d) Check the bunker supply connection;
    e) Check the sounding in the supplier tank (to determine leakages) and check the tank valves in the receiving ship;
    f) Fill in all the checklists.

2. Execution phase– Performing the bunkering operation in real time as per the pre-decided procedure and receiving the marine fuel according to the bunker plan;
    a) Maintain low pumping rate during start and check for bunker fuel going to the selected tanks only;
    b) Collect an oil sample and check regular sounding;
    c) Cautiously change over tanks by correctly operating the line valves;

   d) Notify bunker facility to reduce the pumping rate during final tank filling;
   e) Close all the sounding pipes;
   f) Shut the bunker manifold valve.

3. Wrap-up phase – Ensuring the correct amount and quality of bunker fuel has been received onboard and wrap up;
   a) Calculate the total received quantity and check against the bunker delivery note;
   b) Disconnect the barge hose and blank off the bunker manifold pipes;
   c) Cautiously change over tanks by correctly operating the line valves;
   d) Clean the bunker station and remove the SOPEP equipment.




*Source: https://www.marineinsight.com/guidelines/bunkering-is-dangerous-procedure-for-bunkering-operation-on-a-ship/)*

Figure 6: Bunker procedures in the three phases

Though there are some differences, these processes will be quite similar in case of methanol bunkering. The differences are elaborated in the next section.

## 3.2 Bunker transfer modes

Both Rotterdam and Amsterdam are bunker hubs and process considerable bunker volumes. The ARA-range (Antwerp, Rotterdam -Amsterdam) as a whole process around 20 million m$^3$ per year. Rotterdam is even one of the worlds few major bunker hubs.

Rotterdam transships around 10 million $m^3$, of which 80% HFO, LNG bunker volume in Rotterdam is very small but growing: from about 0.1% in 2018 to 0.8% in Q1 2020 (Rotterdam bunker sales). Amsterdam transships around 1.7 million $m^3$, of which 1 million for maritime purpose and 0.7 million $m^3$ for inland shipping purposes. In Amsterdam, LNG volume is very marginal. Antwerp transships around 6.5 million $m^3$.

### 3.2.1 *Bunker transfer modes*

Current maritime operations use these types of bunker transfer:

1. Ship-to-ship (common way for maritime vessels);
2. Shore-to-ship(common for barges and local fleet, inland waterway vessels often use a floating pontoon connected to the shore);
3. Truck-to-ship (common for small volumes and in pilot stage); and
4. Bunkering at sea (hardly being applied in merchandised shipping);

The first three are the mainstream bunker options applied in port areas. In addition we consider for completeness a 4th option: Bunkering at sea. This option is hardly used in practice today, but this might become a serious option if also deep-sea transport needs to comply to stricter emission requirements.

Which bunker transfer method is being used depends on a combination of the following factors:

1. Location of bunkerage, defining:
    a. availability of infrastructure and
    b. rules and regulations per fuel and procedure;
2. Amount of fuel to be bunkered;
3. Operating costs of vessel to be fueled;

For elaboration of the different bunker transfer options in the next sections, we made use of the IAPH's WPCI LNG working group descriptions on www.lngbunkering.org.

### 3.2.2 *Ship-to-ship bunkering*

Ship-to-Ship (STS) indicates the transfer of bunker fuel from one ship to another. A small (typical 110 – 130 m length) ship filled with the fuel or other supplies will go alongside the ship that needs to be bunkered. Then, a hose will be connected between the two vessels. A pump, aboard the bunker barge, will force the liquid to be transferred via the hose. At first, the liquid will be pumped through the hose slowly, so the receiving ship can make sure it gets in the right tanks. When this is going correctly, the liquid will be pumped into the tanks at full speed.

Ship-to-ship bunkering can take place at different locations: along the quayside, at anchor or at sea. It is the most common bunkering method used for bunkering seagoing vessels with HFO and MGO. The capacity of bunkering vessels can range from 1,000 to 10,000 $m^3$. Compared with other bunkering methods, the flexibility of ship-to-ship bunkering is high with respect to capacity and bunkering location. Because the bunker vessels are moored alongside the fueled ships, this bunker method could permit simultaneous cargo handling if approved by the relevant authorities, such as the port authority. This also applies to Ship-to-Ship bunkering of LNG.

Ship-to-ship bunkering in the most common method of bunkering in main ports, such as Rotterdam, Amsterdam and Antwerp. Large volume requirements of deep-sea vessels in combination with simultaneous bunkering and (un)loading makes ship-to-ship bunkering common practice in these ports.

**Methanol STS-bunkering**; According to several stakeholders, using methanol as maritime fuel would only require small adjustments to the existing bunkering infrastructure (e.g. storage locations, bunker installations, bunkering vessels). If regulations allow it, this process could easily be done with methanol due to comparable properties to current fuels (both liquid).

Nevertheless, there are some considerations:

- First, a vessel consumes more than twice as much bunker volume. This means that either bunker frequency needs to be increased, or bunker volume needs to be increased, or a combination of both.
- Second, methanol is classified as a dangerous liquid/substance requiring additional safety measures for inland shipping (2-kegelschip). This implies with berthing to respect a distance of 50 meter of other vessels, 100 meters from installations (e.g. bunker stations), and 300 meters from living areas. Alternatively, the port harbor master can give operators an exemption if the procedure is responsibly safe according to the harbor master.

The bunkering cost for ship-to-ship bunkering mainly depends on the bunker quantity. Small bunker vessels used to serve IWT vessels are assumed to cost € 2,200/day and deliver around 6 deliveries of 40 tonnes per day, resulting in average bunker cost of €14/ton. For maritime vessels the bunker quantity can vary. A typical bunker vessel that can deliver 8,000 tonnes methanol, would cost around €10,000/day. This would result in bunkering cost of €4/ton. For smaller deliveries up to 100 tonnes, the cost per ton would be around €6/ton. These ship-to-ship bunker costs are higher than for bunkering HFO or MGO. The bunker vessel has to invest in safe equipment for the transfer, emergency stop system, flame taming elements in grids, vapor return hoses, vapor manifolds, specific tank coatings, and it is a chemical substance that requires some additional precautions (SOPAP). This results in slightly higher bunker costs per ton. In Rotterdam, the average bunker costs for large bunker volumes HFO/MGO lie around €2 to €3 per ton. For calculations and assumptions, we refer to section 4.4.4.

Briefly summarised, the table below highlights the strengths and other applicability aspects of ship-to-ship bunkering.

Table 18: Applicability aspects of ship-to-ship bunkering.

| **Procedure** | **Applicability aspects** |
|---|---|
| Ship-to-ship<br>*Bunker ship – to –ship* | • Bunker volumes should be of significant volume, above 100 $m^3$ – more than 3 tank truck loads<br>• Possibility of simultaneous bunkering and (un)loading-operations. This would result in optimizing the sailing time of vessels compared to shore-to-ship bunkering.<br>• Port reachable for bunker ship – from methanol storage or plant.;<br>• Policy and regulations that allow bunkering of methanol from ship – to – ship<br>• Higher bunkering costs |

| | |
|---|---|
| | • Permission procedure for methanol bunkering supported by The IAPH Working Group on Clean Marine Fuels<br>• Optional to bunker ship-to-ship at open sea, requires further study for environmental risks. |

### 3.2.3 *Truck-to-ship (TTS) bunkering*

An alternative bunkering method is truck-to-truck bunkering. The truck is connected to the ship on the quayside, generally using a flexible hose. This is a common bunkering method for vessels requiring limited amount of fuel. Moreover, some smaller ports do not have suitable (storage) facilities and scale to facilitate ship-to-ship bunkering. Especially for LNG-bunkering, this method requires limited investments.

The main drawback of TTS bunkering for large consumers is the limited capacity of trucks: approximately 40-80 $m^3$. This bunkering method is only suitable for bunkering quantities up to 50 tonnes and is therefore only suited to smaller-sized vessels. Owing to the limited flow rate, bunkering takes about an hour (around 1,000 l/min).

The presence of truck and bunker processes also impacts other quayside activities like cargo and passenger handling. Furthermore, a road connection with the preferred bunkering position is required, and local safety requirements need to be met, as with any bunker operation.

There are regulatory differences between countries in safeguarding TTS-bunkering. In the Netherlands, TTS-bunkering is subject to the Environmental Code (Omgevingswet), which prescribes under what conditions dangerous goods have to be transshipped and how it impacts the Environmental Permit of the terminal.
In Germany, this is similar, but Germany applies other methods to safeguard External Safety (risk-oriented versus impact-oriented). However, this difference in approach is not expected to have significant impact on the ‘minimum distance’ implications in case of methanol bunkering.

The situation in Belgium is different. In Belgium, operations on a terminal are split into terminal operations (until the backdoors of warehouses) and quay-related operations. The terminal operations fall under the Environmental Code and Permit of the company, the quay-related operations fall under the Port Rules and Regulations (‘Havenverordening’). In the compliance and enforcement policies of Port Rules and Regulations, the Harbour Master has more flexibility to assess compliance to the Regulations. Truck-to-ship bunkering falls under the ‘quay-related operations. We identify differences in regulatory regimes, and recommend to further research possible consequences of this lack of harmonization and implications for the level playing field of TTS-bunkering in the different European Ports.

**Methanol TTS-bunkering**:
In smaller seaports, where no ship-to-ship bunkering takes place, bunkering of short-sea cargo vessels is done by truck–to–ship. This is today the most widely used bunkering method for methanol, because of the still limited demand in combination with the lack of infrastructure and the relatively low investment costs. The bunkering cost for truck-to-ship bunkering is assumed to be around € 14/ton.

This assumes a daily cost of €2300 per tank truck, and 4 tank deliveries of 35 ton per day, see section 4.4.4 for more details. This makes it quite an expensive bunker transfer method, only feasible for small volumes or in ports where no alternative bunker transfer methods are available.

Briefly summarised, the table below highlights the strengths and other applicability aspects of truck-to-ship bunkering.

Table 19: Applicability aspects of truck-to-ship bunkering.

| **Procedure** | **Applicability aspects** |
|---|---|
| Truck-to-ship | • Bunker volumes can vary in size from 1 to several full truck loads.<br>• Ship hourly asset costs should be too high for ship to bunker at a fixed site(shore-to-ship)<br>• Port reachable for bunker truck – from methanol storage or plant.<br>• Policy and regulations that allow bunkering of methanol from truck – to – ship<br>• Possibility of simultaneous bunkering and (un)loading -operations.<br>• Lack of European harmonization in regulatory framework for Truck-to-Ship bunkering .<br>• Lowest investment costs of the 3 different procedures and therefore most suitable on short term in pilot phase. |

### 3.2.4 *Shore-to-ship bunkering*

Sometimes, the receiving ship can bunker directly at the storage places. This called shore-ship bunkering, whereby the fuel is either bunkered directly from an (intermediary) storage tank or station, or like with LNG from an import or export terminal. Pipelines from the terminal to the quay are needed if the LNG-terminal is not directly situated at the berth.

Shore-ship bunkering is generally a good option for ports with stable, long-term bunkering demand. Because the pipeline and the loading arm arrangement are fixed, a larger hose can be installed to increase the bunkering rate (up to 3,000 l/min), leading to significantly shorter bunkering times. Shore-ship bunkering is especially suitable for shipping services with a high frequency, limited demand, less strict timetables and limited vessel draft. Examples include bunkering vessels, tugs, inland shipping vessels, utility vessels, fishing boats, and patrol and inspection vessels (coast guard).

Shore-ship bunkering could be a good option for inland shipping, because inland vessels have the flexibility to visit fixed stations, whereas seagoing vessels do not. In Cologne, there is a fixed shore-ship bunker installation for LNG.

One of the major drawbacks of this type of bunkering is the effort it takes a ship to get to the location of the bunker terminal (or pipeline). In case of LNG, limited berth access for larger LNG-fueled vessels can also be a barrier for shore-ship bunkering. Given the scale of import terminals, as well as for efficiency reasons, most ports will not be equipped with an LNG import terminal.

Shore-to-ship bunkering is mostly being used by smaller vessels, such as inland waterway barges, the coast guard and tugboats. As said before methanol can be pumped through current bunker infrastructure and this procedure could therefore be adapted to also provide methanol as a fuel.

A variant to shore-to-ship is regularly being applied for replenishment of bunker vessels. Instead of using a berth for loading bunker fuel, these vessels make use of a kind of floating bunker installation, a kind of push barge can be replenished when empty for a full one, and a vessel can take the push barges to a storage place (e.g. in Rotterdam) to reload new bunker fuel.

The bunkering cost for shore-to-ship bunkering depend on the investment and operating cost of the bunker facility. Based on an average investment of xx and average delivery quantity of xx ton and 4 deliveries per day, the bunker cost would be around €6/ton. This makes it an attractive option for deliveries between 40 and 100 ton. For detailed calculations and assumptions, we refer to section 4.4.4.

**Methanol Shore-ship bunkering**

The high pump capacity makes shore-ship bunkering of methanol an interesting option for large ports with a stable volume of methanol-demand for serving the promising markets: bunkering vessels, tugs, inland shipping vessels, utility vessels, fishing boats, and patrol and inspection vessels (coast guard).

Briefly summarised, the table below highlights the strengths and other applicability aspects of shore-to-ship bunkering.

Table 20: Applicability aspects of shore-to-ship bunkering.

| Procedure | Applicability aspects |
|---|---|
| Shore-to-ship | • Bunker volumes can be any size, given shore location can deliver.<br>• Ship hourly asset costs should not be too high, visiting shore site takes time and can therefore be costly.<br>• Shore site should be able to deliver methanol<br>• Policy and regulations that allow bunkering of methanol from shore – to – ship<br>• Not possible to bunker simultaneous with (un)loading operations (due to regulations in Dutch main ports). |

### 3.2.5 *Bunkering at sea*

Today, bunkering at sea is hardly being used, despite some advantages such as avoiding port fee, avoiding congested berths and waiting times, and avoiding diverting if bunker berth is not on the route towards destinations. The main reason for that is maritime safety. Oil spillage in case of incidents have a higher probability to happen on open sea. Moreover, it would also require more expensive seagoing bunker vessels - a seaworthy hull and a large bunker beam -, whereas today often inland waterway vessels are being used. In addition, the receiving bunker vessels also need slight adjustments. However, it is worth further analysis this way of bunkering, since it might be a suitable method to enable the adoption of methanol use in deep sea shipping.

The Port of Rotterdam commissioned an internal study on bunkering at sea to explore its potential to combat port congestion [12]. Below, we summarise some the most relevant findings from this study. If bunkering at sea is being applied, it is often at sheltered waters nearby anchorage locations or behind jetty's, such as in Singapore, Gibraltar and nearby the Panama Canal.

Bunkering operations at sea are subject to MARPOL regulations, particularly Annex 1 describing the regulations for the prevention of pollution by oil Annex 6 describing the prevention of air pollution from ships. These prescribe strict filing of oil records and having emergency plans.

In Particularly Sensitive Sea Areas (PSSA) there are very strict MARPOL requirements (MARPOL 73/78, minimizing pollution of the seas), this includes among others the Wadden Sea and the Baltic Sea. Fuel that is being supplied here must meet MARPOL regulations 14 and 18 of annex 6.

Systems and methods for bunkering at sea include:

- Ship-to-ship bunkering, by sea-going bunkering vessels. This is similar as the ship-to-ship transfer method by bunker barges as described in section see section xx. The difference is that instead of bunker barges, the vessels are sea-going and this implies additional requirements for the vessel (stronger construction, stability requirements, and equipped with a beam) and the crew (training, education). It can only be applied in good weather and calm sea conditions.

Figure 7: Ship-to-ship bunkering at open sea by seagoing bunker vessel [12].

- Stern line bunkering; The stern bunkering operation is used to deliver on open sea in rough weather conditions, whereas both vessels are in motion during delivery. When the towing line (up to 200 meters long) has been secured, the vessels will proceed together at a manoeuvring speed of a minimum of two knots.

Figure 8: Stern line bunkering at sea [12].

- Line transfer bunkering; This is a way of bunkering while sailing, being used by the navy. They shoot a line from the supplying vessel to the receiving vessel. When the receiving vessel pulls in that line, a thicker line is attached to it. When the line has been attached, the fuel hose is put on the gliding rail underneath that line.

Figure 9: Line transfer bunkering at sea [12]

Some technology systems used in offshore industry support safe bunkering at open sea, such as the dynamic positioning system keeping the two vessels stationary, the Ampelmann system (transfer of people, to be adjusted with a beam for fuel transfer), the turrent mooring system and the offshore bunkering tower.

Although bunkering at sea is today hardly being used, this way of bunkering could make it attractive to apply methanol also for deep sea shipping. The fact that methanol spills on open sea cause much less environmental impact and the safety improvement potential of further developing the above safety techniques, make it a feasible option for methanol bunkering for deep sea vessels with limited tank capacity. Another option to overcome this challenge would be to enlarge the tank capacity. . Newbuilt LNG-ULCS vessels with substantially larger tank capacities also entering the market. With this tank capacity, deep sea shipping can also shift to methanol without having to bunker halfway far destinations. So there are more options to facilitate methanol bunkering for deep sea vessels.

Nevertheless, this market segment is not expected to be one of the first movers shifting to methanol, which follows from the analysis in chapter 2.

## 3.3 Bunker barges

Around 99% of the total bunker volume in Rotterdam is transferred by ship-to-ship, in amount of bunker transfers this percentage is obviously lower. The typical bunker barges active in the ARA-region have a dwt-capacity varying between 2,800 and 6,000 tonnes and a pump capacity ranging from 500 to 1,500 $m^3$ per hour. Exceptions include the 147-meter MTS Vorstenbosch, with a dwt of 13,300 ton, a bunker capacity of 13.500 $m^3$ divided over 20 tanks.
This is similar to 533 tanktrucks.


Figure 10: MTS Vorstenbosch bunkering an ultra large container vessel (Photo: Joost Roeland)

Generally, the larger bunker vessels serve the deep-sea shipping market and the smaller bunker vessels serve the short sea shipping market. Normally, the bunker vessels have only one particular grade or blend in their tanks. Multi-fuel bunkering where bunker vessels carry multiple fuels or grades and can serve several vessels with different spec requirements in one milkrun hardly ever occurs in practice. These operators prefer to deliver at once the full volume to one customer and return to their base for refilling. A milkrun-concept would result in less efficient asset utilization.

Only very few bunker barges are equipped with a mass flow meter, it does not measure the volume, but the mass passing through the tube. This is important, since the density of the fluid may change with temperature, pressure, or composition. However, this equipment is rather expensive.

The larger bunker vessels all have multiple tanks enabling them to carry multiple grades of marine fuel cargo. This may look promising to use the bunker vessels to also include a number of tanks with methanol, but it is not that easy. The ‘double cone’ safety requirement of shipping methanol demands for additional construction, equipment and personnel requirements compared to bunker vessels carrying fossil fuels.

A growing adoption of sea vessels running on methanol might result in fleet enlargement of the bunker fleet; a growing share of large bunker vessels with substantial dwt-capacity. Inland chemical tankers (double-walled) that are currently being used for shipping methanol between refineries/ports and chemical plants at inland locations (e.g. along the Rhine corridor or between Rotterdam and Antwerp) could easily be used for bunkering methanol. They already comply to the ADN-requirements for safe transfer and shipping of dangerous liquids, and its crew has followed the correct education. As such, we do not expect any serious short-term availability issues in applying ship-to-ship bunkering of methanol if the market demand rises.

## 3.4 Bunker fuel prices

This section concentrates on current bunker fuels and price developments. Bunker fuel constitutes around 50% of ships operating cost, so bunker prices have a huge impact on ship owners, operators, and charterers. High bunker prices encourage the use of alternative energy for the shipping industry such as gas, biofuels and also methanol. The fuel price for shipping (Free on Board (FOB)) does not only consist of the production costs but also distribution costs and a margin for the seller. Levies are not accounted for since bunkering of international marine fuels (e.g. HFO, MGO) is free of duty and VAT [13].

We describe here the price development of the different bunkers, using the Rotterdam bunker index prices. Bunker fuel is a derivative of crude and therefore there is some correlation between crude oil prices and bunker fuel prices.
Bunker prices also depend on the availability of the product in the market. Bunker prices also depend on the schedule of barges (logistics) of the supplier, for example if the supplier has already taken bunker supply orders for particular dates than prices are expected to be higher. Bunker prices would generally be higher if bunker purchaser fixes the bunker closer to the delivery date, generally it is recommended to fix bunkers at least seven days prior to vessel Estimated Time of Arrival.

There are also other factors such as speculation in the crude market, refining priorities and capacity constraints, inherent difficulties for vessel operators in either storing or hedging fuel – create pricing distortions that may have an impact on bunker oil prices. Bunker suppliers determine the price for their bunker fuel depending on their cost, product availability and logistics availability.
Russian ports (e.g. St Petersburg) are the lowest bunker price ports in the world. the ports with highest bunker volume are Singapore, Fujairah, Rotterdam, Houston, Gibraltar. Rotterdam processes 11 million $m^3$ per year. Two aspects are crucial in the analysis of bunker prices: the introduction of the IMO 2020 low sulfur requirements and the COVID-19 impact on global trade, fuel prices and maritime transport.

### 3.4.1 *IMO 2020 low sulfur implementation and COVID-19*

The International Maritime Organisation (IMO) has ruled that from 1 January 2020, marine sector emissions in international waters be slashed. The marine sector will have to reduce sulphur emissions by over 80% by switching to lower sulphur fuels. The current maximum fuel oil sulphur limit of 3.5 weight percent (wt%) will fall to 0.5 wt%. This does not impact the strict sulphur cap of 0.10% in so called SECA Sulphur Emission Controlled Areas. The SECA areas include the Baltic Sea area, the North Sea area, and the North American area as well as the United States Caribbean Sea area. We see these new Sulphur requirements reflected in the bunker products.

We distinguish the following fuels, that describe the ignition quality and viscosity of residual fuel:

- IFO 380; Intermediate fuel oil with a maximum viscosity of 380 centistokes (<3.5% sulfur). IFO is a blend of gasoil and heavy fuel oil, with less gasoil than marine diesel oil. This fuel is no longer compliant to the new IMO 2020 regulation, but can be blended with alternative low-sulphur products or can be used in combination with open-loop or closed-loop scrubbers in order to comply to the IMO 2020 regulation.
- IFO 180; Intermediate fuel oil with a maximum viscosity of 180 centistokes (<3.5% sulfur). This fuel is no longer compliant to the new IMO 2020 regulation, but can be blended with alternative low-sulphur products.
- MGO; Marine Gas Oil with a Max 1.50% Sulfur "Clear and Bright" Distillate (DMA, DMZ, etc). This fuel is no longer compliant to the new IMO 2020 regulation, but can be blended with alternative low-sulphur products, such as LSMGO.
- LSMGO; Low-sulfur (<0.1%) Marine Gas Oil - The fuel is to be used in EU Ports and Anchorages in accordance to the EU Sulfur directive 2005/33/EC and SECA requirements.
- VLSFO; Very-Low Sulphur Fuel Oil, containing < 0,5% sulfur. This is used to comply to the new IMO 2020 requirements. It used to fit some regional requirements, such as in China, which were less strict then most SECA requirements.
- ULSFO; Ultra-Low Sulphur Fuel Oil, containing < 0,1% sulfur, which is used to comply to the strict SECA requirements as well as the EU Sulfur directive 2005/33/EC.

Also relevant to mention is the impact of COVID-19 on bunker process. Commodity markets for energy products are closely interconnected with global trade and economic growth predictions. Obviously, COVID-19 has huge impact on the demand side and in transparent markets like the Rotterdam Bunker Index we see this directly reflected in the price development. Nevertheless, we present here the development of some key bunker fuels, with the ‘Rotterdam’ prices.

### 3.4.2 *Rotterdam bunker price indices*

**IFO 380**

This is the cheapest maritime fuel in the list, a residual fuel with a high viscosity level (380 $mm^2/s$ at 50˚C). Modern engines are designed to burn IFO 380, which is considerably cheaper than IFO 180, the lower viscosity residual fuel. On May 27, 2020, the market price was $201 per mt.

On September 17, 2019, the price was $421 per mt whereas the lowest point was reached on April 28 this year, being $123 per mt. This enormous volatility was primarily caused by the IMO 2020 regulation, resulting in a huge demand drop for non-compliant IFO 380 fuel.

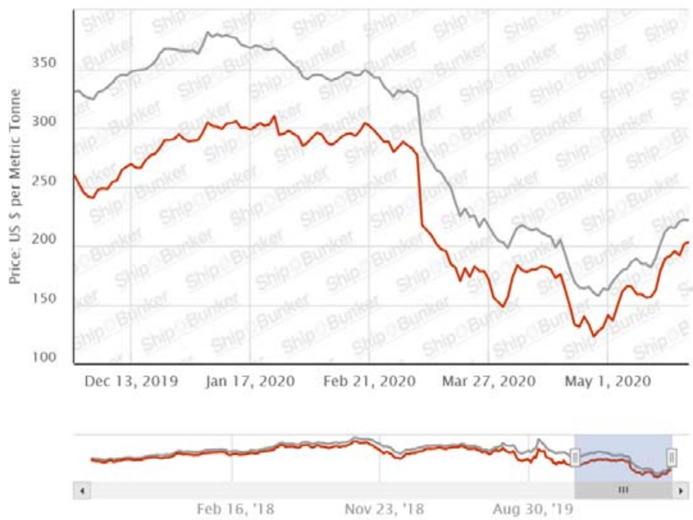



Figure 11: Bunker price development of Rotterdam IFO 380 (source: www.shipandbunker.com).

**IFO 180**

Similar story for IFO 180 bunker fuel, with lower viscosity than IFO 380 (180 $mm^2/s$ at 50˚C). On February 20, 2020, the market price was $320 per mt, this was the last day the IFO 180 was included in the Rotterdam Bunker Index.
On September 17, 2019, the price was $451 per mt whereas the lowest point was reached on December 2, 2019, being $271 per mt.

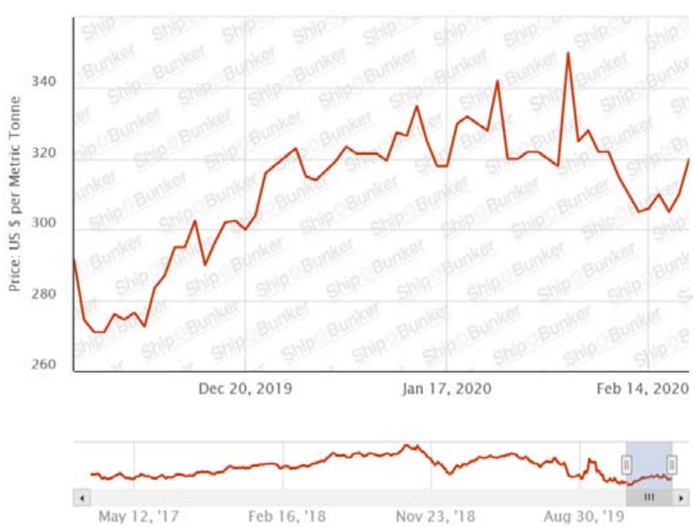



Figure 12: Bunker price development of Rotterdam IFO 180 (source: www.shipandbunker.com).

**MGO**
Standard Marine Gas Oil (MGO) is made from distillate only. On May 27, 2020, the market price was $287 per mt. On January 6, 2020, the price was $611 per mt whereas the lowest point was reached on April 28, 2020, being $176,50 per mt. Price erosion was mainly caused in the last couple of months, assuming that the COVID-crisis was primarily responsible for the huge price drop.


Figure 13: Bunker price development of Rotterdam MGO (source: www.shipandbunker.com)

**LSMGO**
Low Sulfur Marine Gas Oil (LSMGO) follows a different pattern. LSMGO moves in price towards regular MGO. On May 27, 2020, the market price was $286 per mt. On September 17, 2019, the price was $619,50 per mt whereas the lowest point was reached on April 28, 2020, being $182,50 per mt. The highest price was just after the regulation came into practice. Price erosion was mainly caused in the last couple of months, assuming that the COVID-crisis was primarily responsible for the huge price drop.

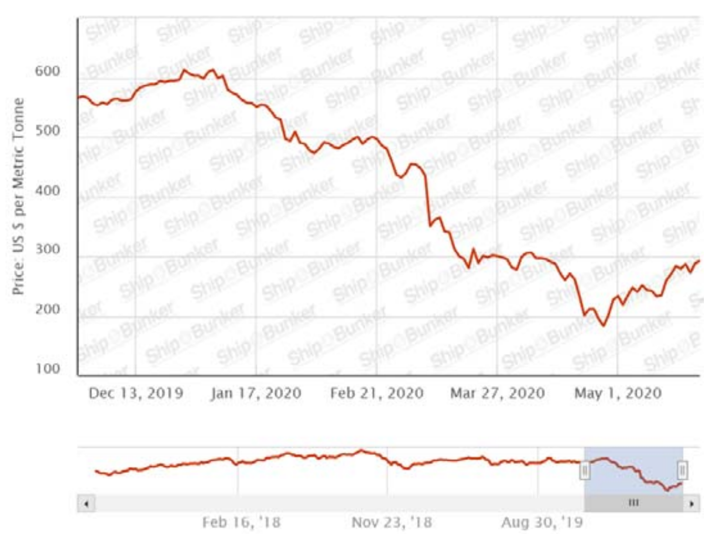



Figure 14: Bunker price development of Rotterdam IFO LSMGO
(source: www.shipandbunker.com)

**VLSFO**
Very-Low Sulphur Fuel Oil (< 0,5% sulfur) shows a similar pattern as LSMGO, both compliant to the new IMO 2020 Sulpur directive. On May 27, 2020, the market price was $254,50 per mt. On January 6, 2020, the price was $598 per mt whereas the lowest point was reached on April 28, 2020, being $149,50 per mt. The highest price was just after the regulation came into practice. Price erosion was mainly caused in the last couple of months, assuming that the COVID-crisis was primarily responsible for the huge price drop.

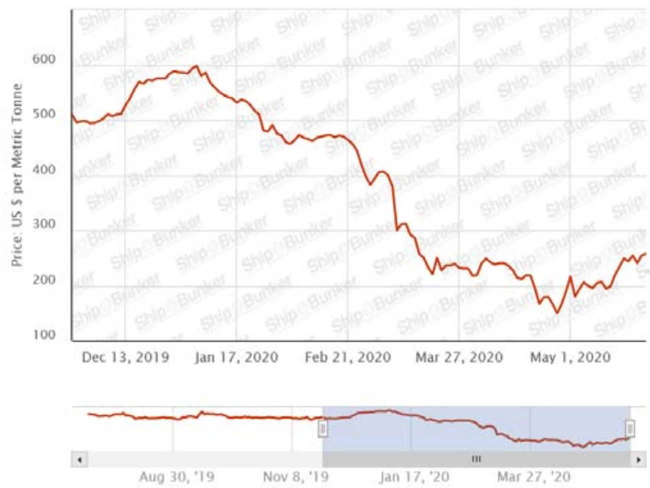



Figure 15: Bunker price development of Rotterdam VLSFO (source: www.shipandbunker.com)

**ULSFO**
Ultra-Low Sulphur Fuel Oil (< 0,1% sulfur) shows a similar pattern as VLSFO, except for the period around the IMO2020 implementation date. On 27 May 2020, the market price was $257,50 per mt, only slightly more expensive than VLSFO. On 7 January 2020, the price was $580 per mt whereas the lowest point was reached on 22 April 2020, being $166,50 per mt. The price is generally a fraction higher than VLSFO, except for the period around the IMO2020 implementing date. This can be explained by the demand peak for VLSFO, resulting in a price peak. Continuing high demand for VLSFO resulted in small price difference of just 1.2%.

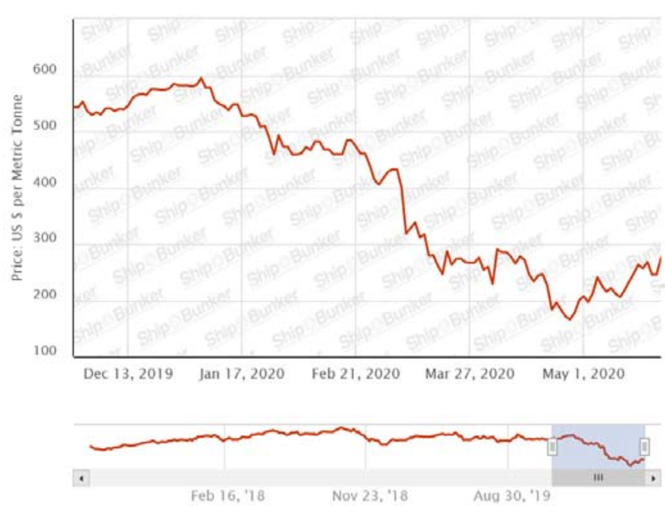



Figure 16: Bunker price development of Rotterdam ULSFO (source: www.shipandbunker.com)

When summarized in a table, we can compare the price spread between the different bunker fuels and the volatility.

Table 21: Rotterdam Index prices summarized (source www.shipandbunker.com)

| Per mt | Latest price (27/05/20) | Lowest 12 months | Highest 12 months |
|---|---|---|---|
| IFO 380 | $ 201 | $ 123 (02/12/19) | $ 421 (17/09/19) |
| IFO 180 | $ 320 | $ 271 (28/04/20) | $ 451 (17/09/19) |
| MGO | $ 287 | $ 176,50 (28/04/20) | $ 611 (06/01/20) |
| LSMGO | $ 286 | $ 182,50 (28/04/20) | $ 619,50 (17/09/19) |
| VLSFO | $ 254,50 | $ 149,50 (28/04/20) | $ 598 (06/01/20) |
| ULSFO | $ 257,50 | $ 166,50 (22/04/20) | $ 580 (07/01/20) |

So, all bunker fuel prices dropped considerably since September 2019. HFO (IFO 380) is the cheapest fuel per mt with a current price of $ 201 per mt. The low sulfur MGO (<0,1% sulfur) is with $287 per mt around 43% more expensive. The ULSFO (also <0,1% sulfur) is slightly (+1.2%) more expensive than the VLSFO (<0.5% sulfur), but considerably more expensive as standard HFO: +28%.

A relevant point to make here is that companies can use the daily market prices but some market players have entered into long term price agreements. With these type of contracts, they cannot benefit from the advantage of the sharp price drop since September 2019.

Chapter 4 elaborates on the cost and price developments of the different production variants of methanol. The price per volume is substantially higher, the Methanex European contract price varies this year between € 260 and €275 per metric ton, which is quite in line with but slightly higher than the VLSFO and LSMGO prices. Those prices have shown huge volatility last year, but seem to stabilize. Remains the fact that it consumes more than twice as much, it can be expected that the fuel cost would more than double and assuming fuel contributing to 50% of the ship operating costs in the HFO-era, the ship operating cost would increase by more than 50%. So widescale adoption of methanol in shipping would not come naturally under these circumstances. A detailed business case analysis is projected in WP6.

## 3.5 Facilitating methanol bunkering in ports

### *3.5.1 Carrier Bunker strategies*

From interviews with short sea carriers, we distinguish two dominant carrier bunker strategies in short sea shipping:

1. ***Load optimized bunkering***; Assign vessels to specific shipping market segments in such a way that the vessel optimizes its load carrying capacity whilst tank capacity is sufficient for the majority of its return trips. This is done by carriers that choose to load as much cargo as possible and minimize the load of bunker fuel to reach the next destination.
2. ***Fuel price opportunistic bunkering***; Allocate vessels to shipping markets with substantial reserve tank capacity, and bunker full tanks if the price is attractive. It requires having a bunker trader who continuously monitors price developments and make suggestions where and how much to bunker.

If existing vessels will be adjusted to use methanol, tank capacity may become a problem when vessels remain being assigned to the same shipping market, especially in case of load optimized bunkering. In case of fuel price opportunistic bunkering, the spare tank capacity may no longer remain.

In general, the fuel price opportunistic bunker strategy will no longer allow for bunkering substantially more volume, however, bunker timing and location choices may still depend on the local (future) price developments of methanol.

### 3.5.2 *Maturity model for facilitating methanol bunkering in ports*

If methanol will be used as an alternative maritime fuel, ports have to facilitate the corresponding bunker transfer methods that suit the pace of methanol use. Initially, methanol use will be limited to pilot projects and ‘first movers’. Demand for methanol in ports will be low and in this phase, tank truck to ship is a flexible way to facilitate this. However, accessibility may be an issue. Quays in use do not prefer to have their quay be occupied by vessels that need to be bunkered by trucks on their premises. This because of their environmental permit space and its limited availability for lading/unloading activities. Port of Amsterdam reserves a public quay for this kind of (pilot) purposes, called ‘De Groene Kade’ in de Americahaven, that can be used for safe bunkering, e.g. LNG bunkering by truck or methanol bunkering by truck.

As soon as the market uptake grows, ship-to-ship transfer becomes attractive for vessels with a demand of 200 mt or more (> 4 tank trucks). Ports with substantial short sea destinations and connected to an inland waterway hinterland network are positioned well to facilitate methanol bunkering. These ports often already facilitate LNG-bunkering, which requires much more complex bunker adjustments. Ports with mainly bulk transports and trunk sailing are less obvious to start facilitating methanol bunkering.

Bunkering methanol at sea would only become an option if the ship-to-ship market has entered into a maturity state. Only then. This option would complement (deep sea) shipping markets that cannot be served with bunkering at origin and destination.

Section 4.4 discusses in detail the downstream supply chain options for methanol used as a bunker fuel. If the port would have its own methanol production facilities, supply for bunkering is straightforward. Alternatively, fast and efficient truck transport is a flexible option for truck-to-ship transfer, and inland shipping vessels carrying methanol used for ship-to-ship bunkering would be even more preferable. The latter is similar to the introduction of LNG bunkering. Apparently, these ‘LNG-ports’ already operate with LNG bunkering within the physical and environmental space.

### 3.5.3 *Support audit and accreditation tooling for methanol bunker facilities*

IAPH announced in 2018 the launch of an audit and accreditation tool to recognize good LNG bunker facility operators and to have a deterrent effect on possible malpractice in the industry. The tool aims at supporting ports in making the transition from conventional HFO bunkers to low-sulphur offerings.
Any bunker facility operator’s quality management system may be audited on eight safety criteria.

Once audited and accredited, ports may issue a license to operate in their port area. Participating ports may share their audit results and information on the safety performance of a bunker facility operator with each other.

The IAPH Working Group on Clean Marine Fuels decided in April 2018 in Bremen to expand the scheme so that it becomes a blueprint not only for LNG bunker suppliers but also for suppliers of upcoming new clean marine fuels such as hydrogen and methanol.

## 3.6 Safety aspects of methanol bunkering

For the safety aspects of methanol bunkering, reference is made to GMM WP3, dealing with safety aspects of methanol. Furthermore, Lloyds Register recently published a technical reference for Methanol bunkering in assignment for methanol Institute [6].

Methanol must be considered as a hazardous substance, because of its volatility, flammability, toxicity and vapour density,. In fact the authority for transport of hazardous cargo on European waterways categorises methanol as a ‘two blue cones’ cargo, i.e. as hazardous as ammonia (ADN 2019 [7]). It therefore is substantially more risky than HFO or MGO. The main risks are leaked vapours mixing with air and consecutively catching fire and intoxication of people handling the fuel. Methanol is not considered an acute danger to the (aquatic) environment. Fortunately, the chemical industry is familiar with methanol and ample knowledge and experience are available regarding safe storage and handling. These are currently being consolidated in the IGF-code (IMO 2019 [7]) .

Also, some ships already use methanol as a fuel and experience gained with those ships is likely to be shared with the maritime community through additions to and amendments of the IGF code. The most important implications are that the ship design must be modified in order to ensure a strict separation between to location/ area on board where bunkering takes place and any other spaces or areas on board. So, for example loading/ unloading the ship must not interfere with the bunkering and vice versa. The most desirable approach to authorities in allowing methanol, or in fact any hazardous fuel, is demonstrating a safety level which is equivalent to levels attained with conventional fuels. For the ship side there is consensus amongst regulators that this must be done through conducting a risk assessment [IMO, IGF-Code, https://puc.overheid.nl/nsi/doc/PUC_80736_14/1/]. Classification societies have issued a recommended practice on how to conduct such an analysis [Risk assessment as required by the IGF Code - Aug 2016, Rec 146, http://www.iacs.org.uk/publications/recommendations/141-160/]. The essence of such analysis boils down to determining where the intended hazardous activity, e.g. bunkering sits in the so-called risk matrix (Figure 17).

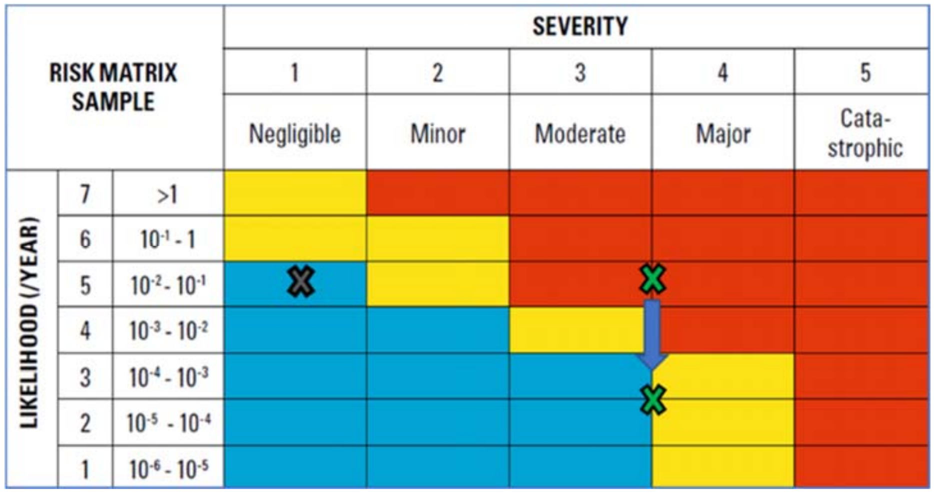



Figure 17: A typical risk matrix (NEN, [20]).

MGO would be at the row 5 column 1 location (purple cross) and since it is in the blue region, tolerable from a safety point of view. Methanol might initially be located at row 5 column 3/4 and therefore unacceptable. However, by taking measures which reduce the probability of leakage the methanol bunkering activity would move downwards to row 3/2 (green crosses), which would be (just) tolerable because it has entered the blue zone again. Further details may be found in ref. [TNO report 2020 R10502 Unconventional bunker fuels, a safety comparison].

The supply side of the bunkering process is more complicated. In case of truck to ship bunkering local authorities must grant permission. Obtaining permission tends to be a cumbersome process because in general quay locations where trucks can unload into a ship are numerous and usually not intended for handling hazardous substances. So, locations must be considered on a case by case basis. When a bunkering location is located on a permanent location the permission granting process needs to be run only once which simplifies matters considerable. Moreover, fixed locations allow for establishing safety distances. Fixed bunkering locations are quite feasible for ships like ferries which berth at fixed locations anyway. For other ships, being forced to go to a bunker station for refuelling is usually not an attractive prospect. It is noted however that in inland water way shipping fixed bunker stations are in operation. The most common way of bunkering is from a bunker boat to a ship. Both vessels are in principle subject to river authority and shipping inspectorate regulations only, which simplifies the permission granting process substantially. These authorities follow the regulations issued by IMO, CCNR and UN-ECE ADN committee. Local authorities tend to consider complying with requirements issued by these parties as sufficient.

## 3.7 Conclusions

The use of methanol as a maritime fuel would require modest adjustments to the bunkering infrastructure. But these adjustments can easily be overcome.

The IAPH audit and accreditation tool helps ports to issue a license to operate methanol bunkering in their port area. In contrast to LNG bunkering, the existing bunkering infrastructure for HFO/MGO bunkering can largely be used, and the bunkering and distribution cost of methanol (not the fuel cost) are not expected to be substantially higher than bunkering HFO/MGO. However, methanol consumption is more than twice as high, so bunker frequency and/or bunker quantity is considerably higher and therefore also the total distribution costs.

Obviously, the energy value is more than twice as low, thus it would require more volume or a higher bunker frequency. Even if the price of ‘grey’ methanol per metric ton is slightly higher than low Sulphur HFO, the fuel cost would more than double. And ship operating cost would increase by at least 50%, let alone the use of green methanol. So widescale adoption would not come naturally. Nevertheless, some vessels, shipping patterns and market requirements would make methanol better applicable then others.

Supply would follow the demand and ports will most probably facilitate the different bunker transfer options. This starts with facilitating truck-to-ship bunkering for pilot initiatives and facilitating the ‘first movers’, quickly followed by facilitating ship-to-ship bunkering of methanol. The larger bunker vessels have multiple bunker tanks on board, which can even be used for I bunkering of different fuels. Widescale adoption of methanol would lead to a capacity increase of the bunker fleet in ports, both in number (because of  higher bunker frequency of maritime vessels) and in size (because of larger bunker volumes). In addition to the large multi-fuel multi-tank bunker vessels, double-walled inland chemical tankers being used to ship methanol between ports, refineries and inland industrial sites can easily be used for methanol bunkering. Shore-to-ship bunkering would be an attractive option for ferry terminals. Bunkering at sea does not seem a realistic option for widescale use.

Some regulatory issues require a more in-depth analysis to facilitate a smooth transition towards methanol as a sustainable maritime fuel. These include the European level playing field in facilitating truck-to-ship bunkering of methanol (for inland and small maritime vessels) on quays that do not transship dangerous goods (e.g. container terminals), and the reconsideration of the ADN 2019 regulation categorizing methanol as a ‘double blue cone’ commodity.

# 4 Fuel supply chain of methanol

## 4.1 The methanol supply chain: upstream and downstream

Methanol is one of the most widely used and produced industrial chemicals since the 1800s. Due to its key role for material synthesis in the chemical industry, its production and transport, including safety aspects, are very well-known. In fact, more than 95 billion liters of methanol are produced globally every year, and methanol is the most commonly shipped chemical worldwide [8]. In principle, the production, storage and transportation infrastructure of methanol are therefore well-established, efficient and safe.

In contrast, the use of methanol as a *shipping fuel* is currently in a development stage and has gained momentum in the recent years. It is not yet established how the end product methanol should be efficiently stored and bunkered as a fuel, and in what way the production and infrastructure may need to be adapted to meet the increasing demand. Our analysis of the methanol fuel supply chain is therefore split up into two parts (see Figure 18):

1. The **upstream** chain analysis, focusing on methanol production from different (fossil or renewable) feedstocks with different production methods.
2. The **downstream** chain analysis, addressing the transportation and storage logistics of the final 'methanol fuel' product to the end customer, *i.e.*, into a ship's tank.

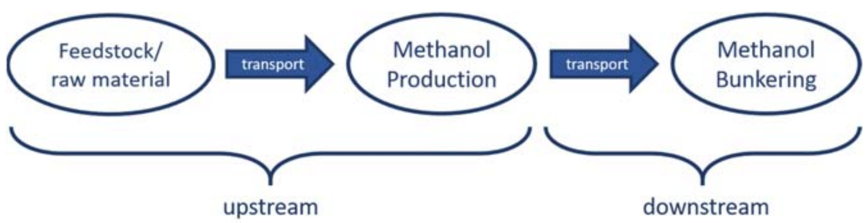



Figure 18: Methanol supply chain.

In the upstream analysis, we describe the most important methanol feedstocks and production methods, identified in the WP2 report of this project, in more detail. Additionally, we analyze the logistical steps arising specifically for *renewable sources* in the production of green methanol, and their impact on the sustainability of the process. The price, energy-efficiency and sustainability of the renewable supply chains is then compared to those including fossil fuels.

Relevant stakeholder in the **upstream** supply chain are typically:

- **Suppliers of feedstock for Methanol Production; Methanol Feedstock producers,**
  - natural gas and coal,
  - biomass,
  - fossil waste, and
  - (green) Hydrogen and $CO_2$.
- **Transport companies, and**
- **Methanol producers**

For the **downstream** part of the supply chain, we determined the logistical steps and infrastructure required for the distribution of methanol as a maritime fuel, regardless of whether the methanol has been produced from renewable or fossil feedstocks.

The most relevant market players involved in the downstream chain are:
- **Commodity Traders / Brokers**
- **Transport companies**
- **Oil Blending & Storage Companies**
- **Bunker operators**

For the downstream analysis, we mainly consider maritime ports the end of the methanol fuel supply chain. In the upstream chain, however, source locations of raw material, processing location(s) as well as the transport distances and methods may vary for different scenarios.

The goal of our supply chain analysis is to compare several scenarios and answer the following questions:
1. What could the supply chain for methanol as a maritime fuel look like and what type of feedstock can be used?
2. How does the maximum production potential of different feedstocks and supply chains of methanol compare to the maritime fuel demand?
3. What are the costs of different supply chain scenarios?
4. How will these costs develop in the future?

As the details of the supply chain have a great impact on the sustainability and price of methanol as a shipping fuel, these questions are not only relevant to the parties involved in the process, but also to the end consumer.

In the following section, we describe the current global production, price and demand of methanol. The upstream and downstream supply chains are subsequently analyzed in the sections 4.3 and 4.4, respectively. In section 4.5, we focus on the current and future maritime fuel usage and methanol demand. At the end of this chapter, we summarize our findings and conclude the main implications of a transition to methanol for the Dutch shipping sector.

## 4.2 Methanol production volumes, price and demand

*Global production volumes and demand*

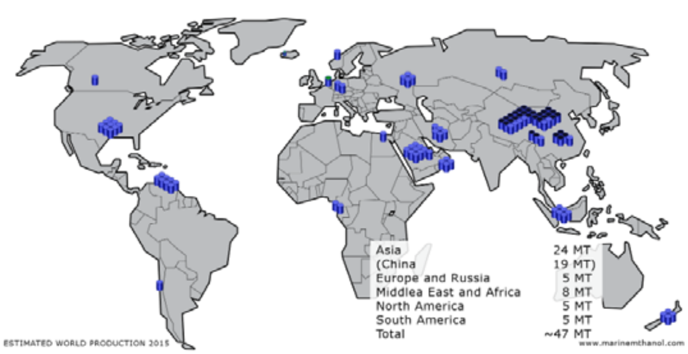



Figure 19: Global spread of the methanol production in 2015. [9]

According to the IHS and MMSA, the global methanol supply in the year 2015 amounted to 76 – 79 million metric tons (MT) and has grown to nearly 100MT/ year in 2020. The total production capacity has grown from 122Mt to 152Mt in the same period, meaning that methanol plants on average operate at roughly 65% of their nameplate capacity. As can be seen in Figure 19, methanol is predominantly produced near fossil feedstock sources like natural gas fields or coal supplies. Production takes place mainly in China, the Middle East, the US, Venezuela, Trinidad & Tobago and Russia [9]. Note that Figure 19 assumes a methanol production of 47MT in 2015, much lower than the estimates by IHS and MMSA. Roughly 40% of the global methanol supply has an energy or fuel purpose, while 60% are used as a feedstock in the chemical industry.

Figure 20 demonstrates the spread of global methanol production as well as the demand per region. With roughly 70% of the worldwide methanol consumption, Asia had the largest methanol demand in 2019, followed by Europe and the US. The Figure also shows that the methanol demand in Asia, Europe and North America is higher than the respective production capacity. A significant amount of methanol in these regions is therefore imported. Japan, for instance, relies entirely on methanol imports. In contrast, the Middle East, Africa and Middle America are major methanol export regions.

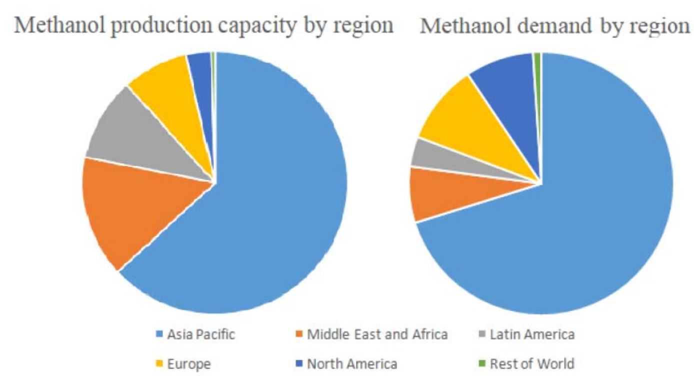



Figure 20: Spread of global methanol production and demand. Source: https://www.aimspress.com/article/10.3934/energy.2018.6.1074

Polaris market research estimates that the market for methanol might increase significantly in the coming years. The development and outlook of the European and global methanol demand is shown in more detail in Figure 21.

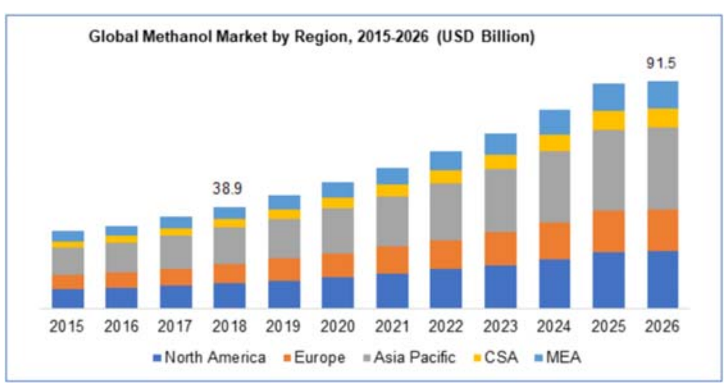



Figure 21: Expected development of the Global Methanol market by region between 2015 and 2026 [10].

Methanol plants are only operating at a fraction of their nameplate capacity. Globally, this fraction is estimated at approx. 65%. Reasons for the globally low average utilization include large methanol price fluctuations, a low or fluctuating global methanol demand, maintenance works or scheduled closures due to national laws.

Due to the overall low utilization of methanol production facilities, we expect that production at existing facilities may easily be scaled up by at least 40 – 50% in order to meet the increasing demand arising from the transition to methanol as a maritime fuel.

*Methanol production, trade and demand in the European Union*
Focusing on the European methanol market, we note that the theoretical nameplate capacity of EU27 methanol plants in 2020 is estimated to be approx. 3.7 million tons[2], and has not significantly changed since then. In section 4.3.2 an overview of current production facilities is presented [11]. Not all capacity is currently utilized. According to production statistics by the European Commission, total production in the European Union (EU27) amounted to 1.5 million metric tons of methanol in 2018, with main production taking place in Germany and the Netherlands. Statistics between 2010 and 2018 show that production has been stable. Production in 2019 in the Netherlands is estimated to ramp up  to ca 1.0 Mt due to increased production capacity.

In contrast, the *demand* of methanol in Europe is much higher than the quoted production volumes. The European methanol demand has grown from 5.7MT in the year 2015 to approx. 7.5MT in 2018 [12].  A large share of this demand is imported from outside of the EU. Important import countries are Russia (1.6 Mton in 2019), Trinidad (1.4 Mton), United States (0.6 Mton), Norway (0.6 Mton) Venezuela (0.5 Mton), Equatorial Guinea (0.5 Mton) and Egypt (0.4 Mton) [13]. High imports to Europe may be attributed to higher natural gas prices in comparison with Russia, the Caribbean and the Middle East, which offer more affordable methanol prices due to abundant natural gas supply.

The Netherlands is an important trade hub for methanol in Europe. Around 35% of the extra EU imports are transferred in the Netherlands and distributed to other European countries. This role is similar for other chemical products.

[2] Estimation of methanol producers in the consortium

Table 22: Production, trade and apparent consumption of methanol in EU27 in 2018 (Mton).

| Country | Production | Import | Export | Apparent consumption[1] |
|---|---|---|---|---|
| Belgium | 0.0 | 0.8 | 0.2 | 0.6 |
| France | 0.0 | 0.7 | 0.0 | 0.7 |
| Germany | 1.1 | 1.5 | 0.3 | 2.3 |
| Italy | 0.0 | 0.6 | 0.0 | 0.6 |
| Netherlands | *0.5*[e] | 2.5 | 2.2 | *0.8*[e] |
| Poland | 0.0 | 0.7 | 0.2 | 0.6 |
| Spain | 0.0 | 0.7 | 0.0 | 0.6 |
| Other EU27 | 0.0 | 1.8 | 0.3 | 1.4 |
| ***EU27 total*** | ***1.5*** | ***9.2*** | ***3.2*** | ***7.5*** |

[1] *Consumption was calculated using production and trade statistics*

[e] *Production values for the Netherlands are confidential for 2018. Estimations were made based on the available production values presented between 2009 and 2017.*

Source: TNO based on Eurostat Comext and Prodcom [13] and [14]

*Price*

The market price of methanol is rather volatile and closely related to crude oil and natural gas prices. Figure 22 shows the price development of natural gas in the US and Europe between 2012 and 2019, while the Figure 23 and Figure 24 below visualize the respective price development of methanol.

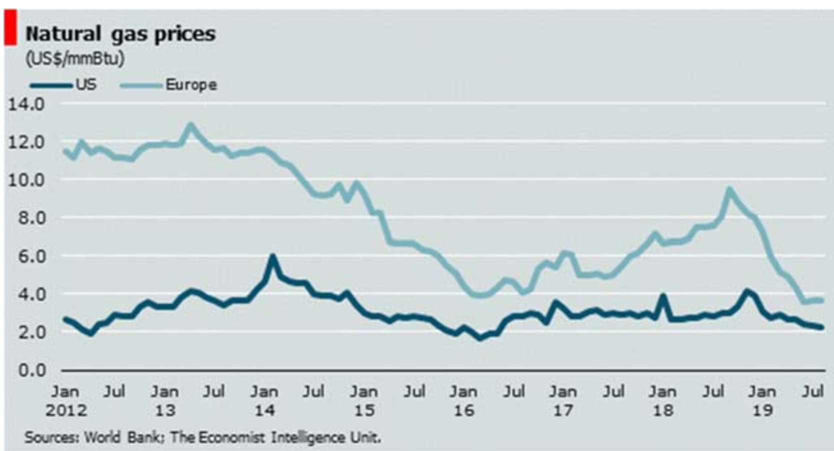



Figure 22: Natural Gas Price between 2012 and 2019 Source: EIU (2019) [7].

It can be seen that, in the period from 2007-2020, the methanol price fluctuated significantly. European peak prices crossed 540€/ton in 2008 [15]. Very recently, in April 2020, the methanol price in Rotterdam was again at a four-year-low, with spot prices in the range of 150-185€/ton, partly due to the economic impact of the corona crisis [16].

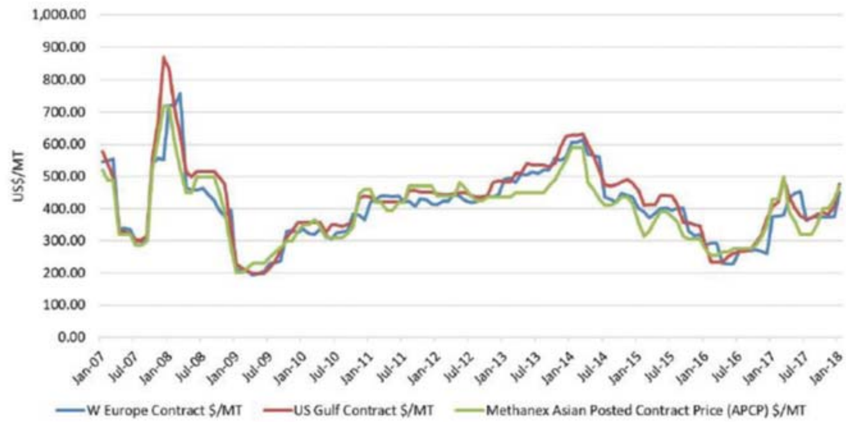



Figure 23: Methanol price development between January 2007 and January 2018 (USD per ton) Source: WTC (2019) [17].

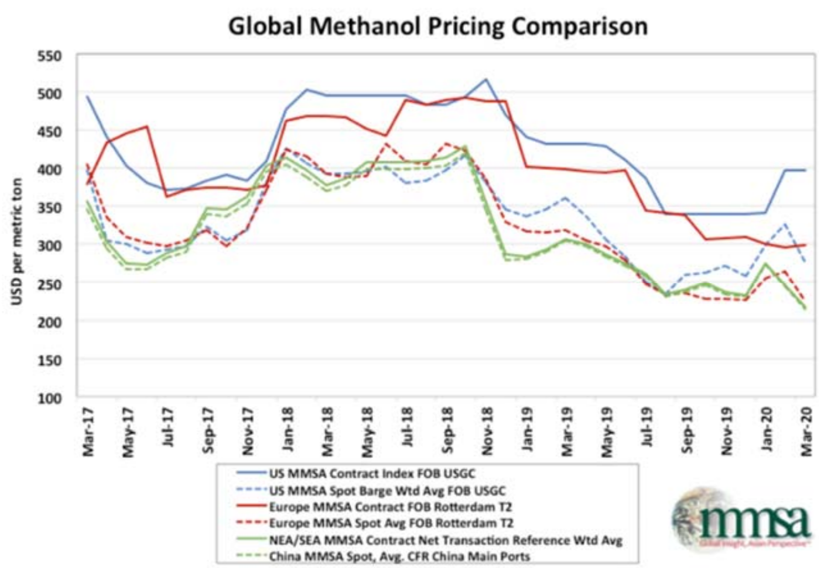



Figure 24: Methanol price development between March 2017 and March 2020 (USD per ton) Source: MMSA (2020) [18].

Vitiello (2020) argues that in times of low methanol prices (around or below 200€/ton) in combination with high natural gas prices, the economic feasibility of methanol production becomes questionable. As a result, methanol plants may run at only 50 or 60% of their capacity or be entirely idled. An example is the Romanian Doljchim methanol plant, which was shut down during the price drop in 2009.
In the fourth quarter of 2019, when the methanol price dropped to approx. 205€/t in combination with curtailed feedstock, methanol producers in the Asia-Pacific region have started to shut down production facilities [19].

## 4.3 Upstream fuel supply chain

### *4.3.1 Production methods*

Methanol can be produced from a large variety of feedstocks via different production routes. If fossil feedstocks like coal or natural gas are used, the resulting product is often called grey methanol. Biomethanol is methanol produced from dry or wet biomass feedstocks, while e-methanol is produced from the abundant feedstocks water and air by using electrical power. Carbon-recycled methanol refers to methanol that is obtained via gasification of fossil-based municipal solid waste (MSW) such as plastics. A summary of different production routes of methanol is visualized in Figure 25.

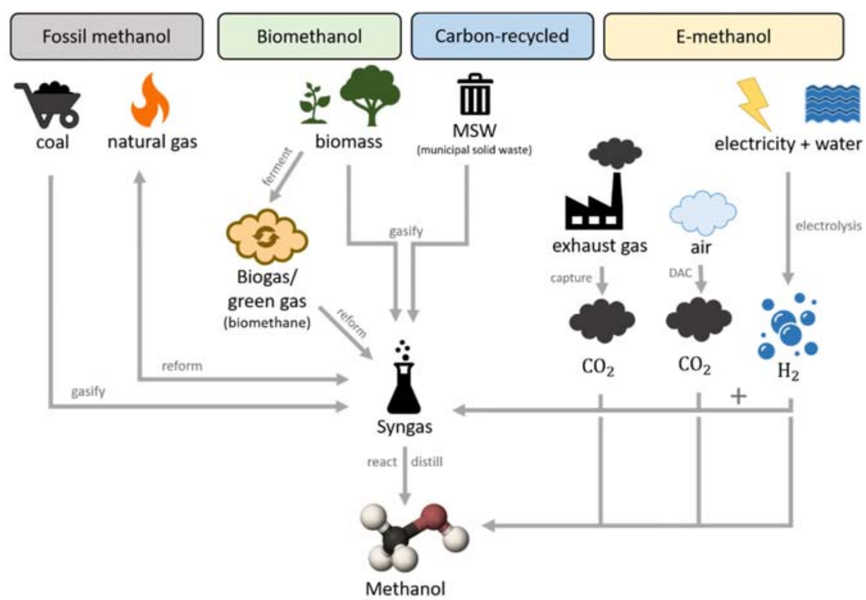



Figure 25: Production Methods of Methanol from different feedstocks.

Typically, the production of methanol uses fossil fuels (**grey/fossil methanol**). It takes place by reforming of natural gas to produce synthesis gas (syngas), or from coal gasification to produce syngas (predominant in China). From syngas ($H_2$ + CO or $H_2$ + CO + $CO_2$), methanol can be produced by CO or $CO_2$ hydrogenation with an energy efficiency of roughly 80%.

This process consists of the reactions:

- CO Hydrogenation: $CO + 2 H_2 \rightarrow CH_3OH$
- $CO_2$ Hydrogenation: $CO_2 + 3 H_2 \rightarrow CH_3OH + H_2O$

and subsequent distillation. [20]

**Biomethanol** is a renewable energy source. Its feedstock is biomass, which includes agricultural and forestry products such as wood pellets, black liquor (a waste product from paper production or sugar beet processing waste), animal waste products (manure) and organic fraction of municipal solid waste and sewage sludge. Biomass can directly be gasified to syngas or fermented to biogas in a process called anaerobic digestion. The biogas can then act as a precursor to produce either syngas or biomethane. Biomethane is biogas that is purified to natural gas quality. It has the advantage that it can be fed into the existing natural gas network, which greatly facilitates its distribution as a feedstock for methanol production. The two options of fermentation and gasification allow for very heterogeneous types of biomass. If produced from biogenic waste as listed in the Renewable Energy – Recast to 2030 (RED II), biomethanol qualifies as an advanced biofuel.

The production of **carbon-recycled methanol** makes use of a similar gasification technology as dry biomass. Waste streams that are otherwise non-recyclable can be gasified and thereby used as a feedstock for methanol production.
For the production of **e-methanol or power-to-fuel methanol**, hydrogen ($H_2$) is produced by water electrolysis, either with electricity from fossil fuels or by using renewable electricity. Carbon dioxide ($CO_2$) can be captured from industrial exhaust gases, from biomass, or by direct air capture (DAC). Together, hydrogen and $CO_2$ can be combined to either produce syngas, or to directly react to form methanol [20].

The sustainability of methanol is determined by the feedstock used and the GHG emissions from the production and use of the methanol.
Under the definition of a circular economy, the main determining factor for the qualification ‘circular’ is that no newly mined fossil carbons are being brought into the production system. Under this approach, biomass, recycled carbons, air captured $CO_2$ and hydrogen from non-fossil sources (including green electricity) qualify as circular feedstock.

Besides the feedstock, GHG emissions of the final fuel are important in determining the sustainability. In the Renewable Energy Directive (RED) that regulates the methodology for calculating the GHG emissions for (primarily) road transport, a well to wheel (well to wake) approach is chosen. Under the methodology of the RED the net emissions of combustion of biofuels is considered zero (in line with the IPCC methodology). For determining the GHG emissions of ‘new alternative fuels’ such as Renewable Fuels of Non-Biological Origin (RFNBO’s) and Recycled Carbon Fuels (RFG’s) the European Commission is currently in the process of establishing the GHG method in so called EU delegated acts. The European Commission has recently proposed to include shipping under the ETS system. An ETS system, different from the RED approach, would imply a ‘tank to wake’ approach determining the GHG emissions of the fuel, however also in this approach the emission of (combustion of) biofuels would be considered zero.

According to the Methanol Institute, the global methanol feedstock in 2019 consisted of 65% natural gas, 35% coal (China) and less than 1% biomass or other renewable origin. While a complete switch to green carbon-neutral fuels like sustainable methanol is highly desired and expected in the future, the ongoing transition to methanol-based maritime transport does require fossil (or grey) methanol as short-term solution. For the medium term (5 year onward) a shift should be made to blue and green methanol only.

During the transition from grey to sustainable methanol production in the near future, also blends of fossil and sustainable methanol may be used. One option for blending is the increased production of green gas, which has similar properties as fossil natural gas and can be fed into the existing pipeline infrastructure[3].

In Table 23, we summarize the most likely and feasible production scenarios of methanol as a maritime fuel in the short and long term. The table distinguishes grey, recycled and (renewable) green routes. In the following sections, we analyze the supply chains of different methanol production routes in detail, focusing on their financial costs, energy efficiency and sustainability. For existing methanol plants co-production of (increasing shares of) sustainable methanol alongside grey methanol production is a likely transition pathway.

Table 23: Most feasible production scenarios of methanol in the short and long term.

| **Short term:** | **Long term:** |
|---|---|
| • NG to methanol<br>• Coal to methanol (China) | • Steam methane reforming with biomethane as a feedstock (acquired through fermentation or gasification) (Biomethanol).<br>• Use of syngas (gasificiation of biomass or of fossil waste ) (Carbon Recycled Methanol or bio-methanol).<br>• Production of methanol from of Green hydrogen and $CO_2$ (E-Methanol). |

### 4.3.2 *Grey (fossil) Methanol*

As mentioned in the previous section, approx. 99% of the current worldwide methanol production uses fossil feedstock. Typical feedstocks are coal (mainly in China) and natural gas (rest of the world). With natural gas being a major feedstock of grey methanol in most countries, the supply chain of grey methanol is very similar to the supply chains of the fossil feedstocks oil and gas. Also, the methanol price is strongly correlated with the corresponding natural gas price. This has already been demonstrated in section 4.2 above. The Figure 23 and Figure 24 visualize the global and European price development of grey methanol from 2007 – 2018 and from 2017 – 2020, respectively. It can be seen that the grey methanol price strongly fluctuates, and typically lies between 200 and 500€/ton. The current price (April 2020) lies at about 150 to 185€/ton.

The production capacity of grey methanol depends solely on coal or natural gas supply and is therefore, in principle, not limited in the short and medium term. From natural gas, methanol can be produced with an energy efficiency of up to 66% [21]. In Europe, the average efficiency lies at approx. 37.2% [22]. Production emissions from natural gas-based methanol lie between 0.5 and 0.85 ton $CO_2$ per ton methanol and are significantly higher if coal is used as a feedstock [11].

Focusing on the availability of grey methanol in Europe, and in particular in the Netherlands, we list the largest EU production facilities of grey methanol in the year 2011 in Table 24: Production grey (fossil) methanol in below:

[3] This can be blends of fossil methanol with all of the different types of methanol distinguished earlier: (Advanced) bio-methanol, Recycled Carbon methanol based on gassification of fossil waste or E-methanol based on green hydrogen from renewable electricity and $CO_2$. Since the chemical structure of all methanol is identical they can all be used replacing grey methanol or alongside grey methanol (drop in).

Table 24: Production grey (fossil) methanol in EU27.

| Company | Location | Capacity in kt/year |
|---|---|---|
| BioMCN | Delfzijl, The Netherlands | 1,000 |
| Mider-Helm Methanol | Leuna, Germany | 660 |
| BASF | Ludwigshafen, Germany | 480 |
| Shell & DEA Oil | Wesseling, Germany | 400 |
| BP Refining & Petrochemicals | Gelsenkirchen, Germany | 300 |
| Viromet | Victoria, Romania | 225 |
| MSK | Kikinda, Serbia | 200 |
| Achema | Jonava, Lithuania | 130 |
| Zaklady Azotowe Kedzierzyn | Chorzow, Poland | 100 |

Source: ICIS, Europe Chemical Profile Methanol (2012) [11]

As already mentioned in section 4.2, the European methanol demand is not exclusively met by European production facilities. Significant amounts of methanol get regularly imported from Trinidad & Tobago, Venezuela, Equatorial Guinea, and Russia. In fact, Saudi Arabia and Trinidad are among the largest grey methanol producers in the world, with a total production of 7 and 6.6 million metric tons per year, respectively.

### Future development

The future supply and price of grey methanol depends by and large on the price and production capacities of the feedstock natural gas. Focusing on methanol production in Europe, it needs to be noted that historically, Russia has been Europe's main import source of natural gas. In 2018, Russia supplied 201 billion cubic meters, equivalent to 38% of the European demand. However, the increased shale gas production in the US and investments in gas liquefaction facilities resulted in export competition between the US and Russia. As a result of the growing export volumes, European natural gas prices faced a historic low in June 2019. The recent development of the natural gas price with a forecast to 2021 is shown in Figure 26 [23].

While the European demand of natural gas is expected to remain rather flat, domestic production is expected to fall by roughly 3.5% per year due to shrinking production in the North Sea area as well as the Groningen natural gas phase-out. As a result, the natural gas price in Europe is expected to rise again in the near future. Also, in the US, price forecasts expect a slight increase of natural gas prices. An exception is the scenario of high oil and gas supply, in which case the natural gas price remains roughly constant. The exact price development will depend on several factors like economic growth especially in upcoming Asian economies, the oil and gas supply as well as environmental policy measures such as $CO_2$ allowance fees. This is demonstrated in Figure 27, in which the expected natural gas price development tor several scenarios is shown until the year 2050.

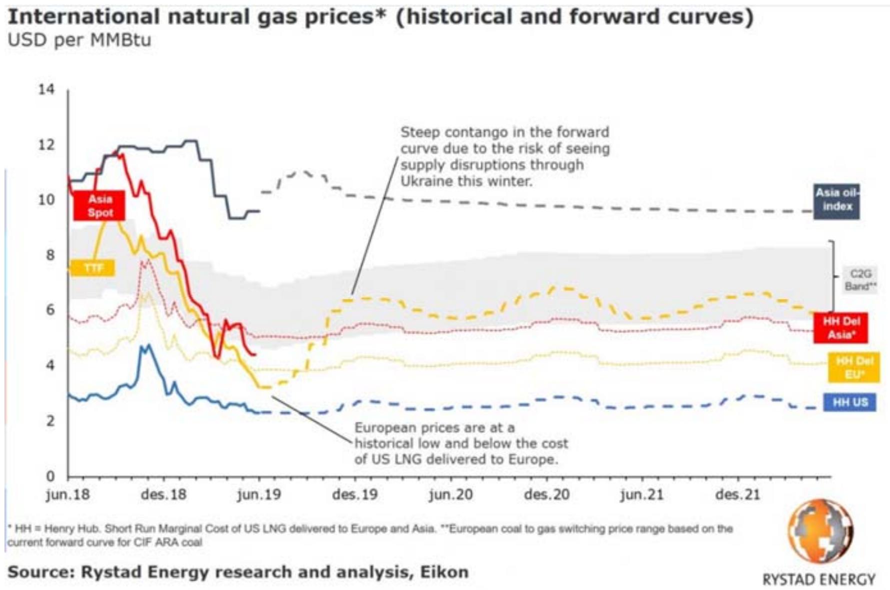



Figure 26: Natural Gas price history and forecast. Source: European Gas Hub (EGH) 2019 [23].

The price development for the long term will depend on several factors like economic growth especially in upcoming Asian economies, the oil and gas supply as well as environmental policy measures such as $CO_2$ allowance fees.
This is demonstrated in Figure 27, in which the expected natural gas price development in the US for several scenarios is shown until the year 2050.
The figure shows that the economic growth hardly has an impact on the expected price level (maroon and green lines), while differences in availability (yellow and red line) have a considerate impact (-50% to +100% compared to the reference case).
Introduction of carbon taxes (light blue and green lines) have considerable impact on the price level (+200% in 2050), making alternative feedstock options economically viable (see the next sections).

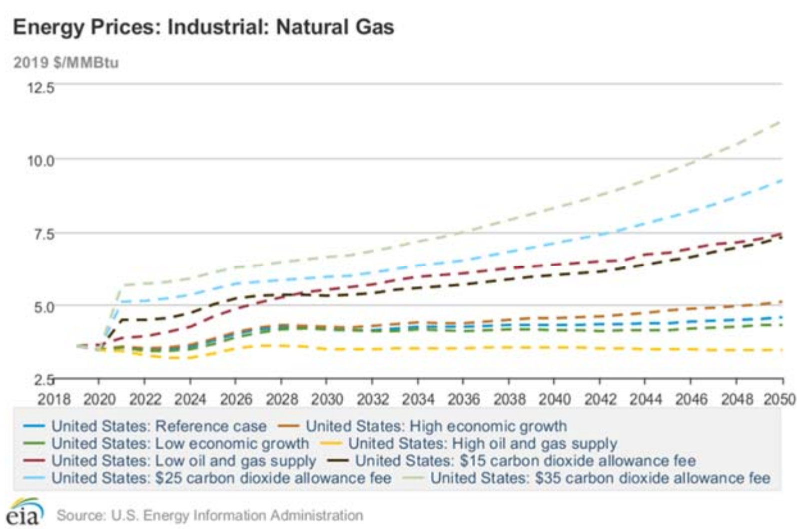



Figure 27: US price forecast for natural gas in several scenarios. Source: EIA 2020 [24].

As a result of the natural gas price developments, we expect also the price of grey methanol from natural gas to remain in its typical range between 185€/ton and 500€/ton until the year 2030, and below approx. 650€/ton until 2050. However, this only holds in the absence of carbon dioxide allowance fees and if the oil and natural gas supply is sufficiently large (see Figure 27). If $CO_2$-fees are imposed on natural gas production or the supply of fossil fuels strongly limited, the grey methanol price may increase further, possible making its price competitive with carbon-recycled or green methanol.

### 4.3.3 *Biomethanol and methanol from MSW (municipal solid waste)*

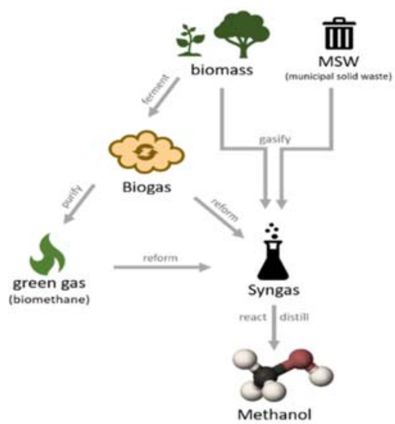



Figure 28: Schematic visualization of the production methods of biomethanol and carbon-recycled methanol. Production can take place by fermentation (biochemical route) or gasification (thermochemical route), with or without a purification step to green gas (biomethane).

Biomethanol is considered to be a viable long-term production route. This section will elaborate two production routes that can be sourced from a wide range of biomass feedstocks: the *biochemical* and the *thermochemical* route. Figure 28 schematically visualizes both routes.

The biochemical route uses fermentation or “anaerobic digestion” of wet biomass to the so-called *biogas.* Biogas can be reformed to syngas as a feedstock for methanol production, or be purified to biomethane (green gas), which can be directly fed into the existing natural gas network. The energy-efficiency of biomethanol production depends strongly on the process and the type of biomass used. Methanol is typically produced to meet the specifications of the International Methanol Producers and Consumers Association (IMPCA), in which a 99% purity is required (IMPCA 2015 [25]).

In principle, all wet biomass sources can be fermented to biogas and further processed for methanol production. Organic waste, manure and sewage sludge, for instance, are commonly used fermentation feedstocks. With more than 18,000 biogas plants in Europe, anaerobic digestion of biomass is a mature, proven and widely applied technology.

95% of European plants are decentralized small-scale Combined Heat and Power plants (CHP) with an average capacity of 0.5MW [26].While the current production facilities mainly produce heat, electricity or green gas, in principle also biomethanol could be produced.

The thermochemical route relates to the *gasification* of dry biomass to syngas (see Figure 28 above). Low-moisture materials like wood pellets are the most energy-effective biofeedstock and provide methanol production efficiencies of up to 55% [20] [27]. A downside of the gasification technology is that it is slightly less mature and more expensive than the fermentation method.

However, it can in some cases have higher energy efficiencies and exhibits a larger feedstock potential than fermentation. In addition, it can also be applied to recycle non-biological feedstocks like plastic waste. Gasification is therefore a promising methanol production method.

*Biomethanol via green gas injected to the NG grid*

An attractive option is to purify biogas to the quality of natural gas by removing excess $CO_2$ and other impurities. The resulting *biomethane* or *green gas* can be added to the natural gas network, while the scrubbed $CO_2$ may be used for farming or cooling applications. In 2017, 500 out of the 18,000 European biogas plants upgraded their product to natural gas quality. 200 of these plants were located in Germany, nearly 100 in the UK and 65 in Sweden [26].

Besides biogas, also syngas produced by gasification can be reformed to biomethane with natural gas quality. The convenience step of reforming biogas or syngas to green gas for distribution via the natural gas network, however, comes at the cost of reducing the overall energy-efficiency of the methanol production process.

At this point in time, the production of biomethanol from green gas depends by and large on the availability of biomethane production facilities and the green gas price. The methanol plant of BioMCN in Delfzijl, for instance, uses biomethane fed into the existing natural gas network as a feedstock for the production of approx. 60 kilotonnes or 1.2 PJ of biomethanol per year, but biomethanol production can be scaled up with increasing demand. However, the price of green gas is currently estimated at 22-33€/GJ, roughly 70 – 170% higher than that of natural gas [28] [29]. A premium price is paid for the biomethane, covering the higher costs of the production of biomethane, compared to regular natural gas.

Also, other methanol plants that rely on natural gas as a feedstock and are well-connected to the network could switch to green gas with very little effort, given that customers are willing to pay an extra premium for sustainable methanol and that the overall green gas supply is sufficiently large.

In fact, the Dutch production capacities for green gas are currently being scaled up. In 2018, 115 million cubic metres (4.5PJ) of green gas were produced. This volume increased by 25% to 144 million $m^3$ (5.6PJ) in 2019, with expectations of 180 million $m^3$ for the year 2020 [30].

Until 2030, the Dutch government in the Dutch Climate Agreement is aiming to further increase the production capacity to 70PJ, equivalent to 1.8 billion $m^3$ [30]. The injection of green gas into the natural gas grid is subsidized by the Dutch scheme SDE++.

The main market for scaling up green gas production is to replace natural gas with green gas for heating purposes in industry. Biomethane can be used for several applications. This may lead to competition with the biomethanol sector in the future, with unknown consequences which makes availability for biomass for maritime biofuels uncertain. It should be noted that the availability of biomethane and the biomass needed for production is not only a biomethanol issue but is relevant to all types of biofuel (biodiesel, bio-LNG etc).

To scale up the green gas production capacity, fermentation and gasification locations with access to biomass and to the natural gas network are required. Also, the feedstock availability can be a bottleneck for green gas production. In the short term, a feasible option for feedstock supply is the use of local biomass waste-streams such as biogenic fraction municipal solid waste (MSW), biogenic industrial waste and manure. Since biomass is not available on very large scales in the Netherlands, however, large import volumes may be necessary in the medium to long term in order to meet the growing green gas demand.

A viable alternative to *biomass* import is the import/ trade of *green gas* from countries with larger biomass production capacity. The producer acquires green gas certificates from locations where green gas from biomass is locally fed into the NG network. Also, as is the case with other (marine) biofuels, the direct import of the end-product biomethanol could be a feasible option in the future.

There is discussion on the compliance of this route with the RED II guidelines. The use of biomethane transported through the national gasgrid may be in compliance with the mass balance approach as set out in the RED. The gasgrid does allow for physically tracing biomethane. This has been the outcome of the ruling of European Court of Justice (Eon-Biofor case, C-549/15). In line with the EU Court Ruling, the reporting methodology for reporting shares of renewable energy towards the commission allows for reporting shares of biomethane from the gasgrid for use in transport. The use of biomethane from the grid for use in transport is applied by several EU Member States, such as Denmark, Germany, Italy and Austria.

Due to the biodiesel fraude case in the Netherlands (biodiesel Kampen see (ILenT 2019 [31]), the Ministry of I&W has strong concerns on the legitimacy of biofuels claimed for use in the Netherlands. As a result of this, not only biodiesel but all biofuel production chains have been investigated. As a result, NL is looking into requiring by law the presence of biomolecules in the biofuels used for fulfilling the blending mandate. This would affect several biofuel chains of custody, including chains of custody where biomethane from the grid is used. (bio-LNG, biomethanol).

*Biomethanol and MSW-to-methanol <u>without</u> gas purification*

An alternative to the abovementioned green gas route is to produce syngas by fermentation and subsequent reformation of biogas.

Additionally, if gasification technology is used, syngas can be directly produced by gasification of several types of biomass or by gasification of otherwise non fossil waste-recyclable MSW (see also Figure 28). If the feedstock is waste originally made from fossil fuels, then the product is carbon-recycled methanol. An example of the direct methanol production method is a waste-to-chemicals plant, which is currently being developed and built in Rotterdam. It will produce methanol from otherwise non-recyclable dry waste such as plastics. This project is a cooperation between Nouryon, Air Liquide, Enerkem, Port of Rotterdam and Shell, with an estimated yearly capacity of approx. 60kt of carbon recycle methanol and 60kt of biomethanol. The plant is expected to be finished in the year 2020 or 2021.

An advantage of direct methanol production from syngas is that the purification step to natural gas quality is omitted, with the downside that the existing natural gas network cannot be used for distribution of the intermediate product, thus requiring the syngas production (and possibly feedstock) to be close to the methanol production facility.

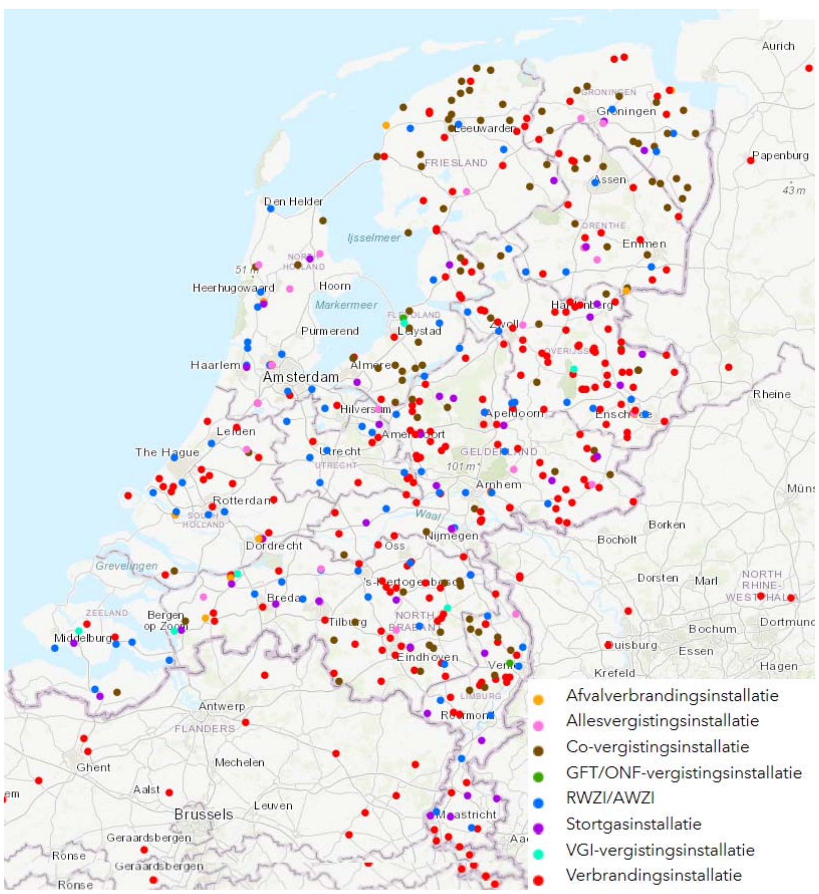



Figure 29: Dutch biogas and biomethane network. Red and orange dots represent gas and waste combustion locations, respectively. Blue dots are wastewater treatment facilities. The remaining dots represent production locations of biogas or biomethane. Source: RVO (2020) [32].

Due to the increased logistical effort of distributing biomass, MSW, biogas or syngas compared to biomethane, methanol production without the gas purification step may be more locally restricted to the feedstock supply location.

Figure 29 shows the current Dutch infrastructure for the production of biogas and green gas, as well as the current locations of biogas consumption (combustion). Small-scale (bio-) gas production locations rely on the local biomass and waste supply, and are rather scattered across the Netherlands. Also, in the future, we expect the development of a number of small-scale plants processing wet biomass and local municipal waste instead of a large scale-up of existing facilities. An exception are gasification plants for dry biomass such as wood-pellets, which may be built and scaled up in the future. The reason is that the import of large volumes of dry biomass can remain economically feasible despite increased transport costs. Whether or not large amounts of dry biomass will get imported and the biomethanol industry settles in the Netherlands, however, is challenging to foresee. In the end, it will largely depend on industrial investment policies and the position of the Dutch government.

### Cost of biomethanol and waste-based methanol

The production costs of several kinds of biofuels depend, among others, on the feedstock prices, and the capital expenditures  While fossil fuel prices currently range from approx. 8 – 14 €/GJ [26], the production costs of alternative (bio-)fuels are estimated between 17 and 44 €/GJ if the fuel is produced from solid biomass feedstocks, and between 13 and 29 €/GJ for production based on waste streams, according to the IEA [26]. This demonstrates the cost advantage of using wet biomass suitable for anaerobic digestion and other waste feedstocks for fuel production. Nevertheless, a significant cost gap of 3-36 €/GJ remains between fossil fuels and low-carbon biofuels.

Focusing on **methanol** as a biofuel, several different but similar cost predictions exist by the IEA [26] and the Maritime Knowledge Centre, TNO and TU Delft [33]. Production costs via anaerobic digestion are typically estimated to lie between 40 and 120 €/MWh, equivalent to 11-33 €/GJ. For thermal gasification of biomass or waste, costs are estimated to lie between 13 €/GJ and 33 €/GJ, and costs for MSW-to-methanol are typically lower than for dedicated gasification feedstocks. This is shown in Figure 30 below [26] [34]. In contrast, the price of grey methanol usually lies between 9-22€/GJ (see Figure 23). It is therefore expected that biomethanol and carbon-recycled methanol require a premium of up to 45% in order to be cost-competitive with the grey variant. [33]

Green gas as an intermediate product for biomethanol production also exhibits a price difference with its fossil equivalent. The green gas price is currently estimated at 22-33€/GJ. This is approx. 70% – 170% higher than the price of fossil natural gas [29].

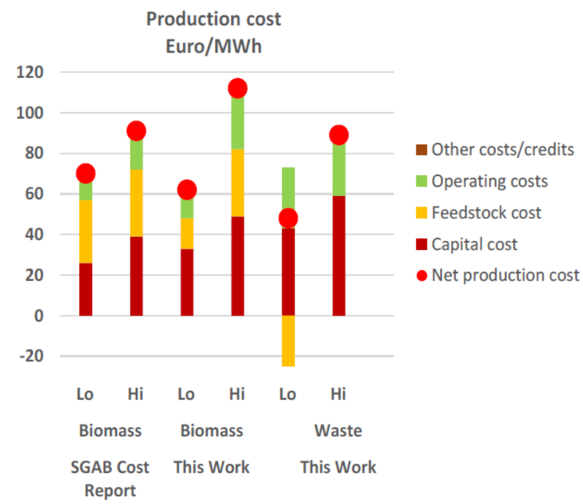



Figure 30: Estimated cost of biomethanol and biomethane production from thermal gasification. Source: IEA [26].

As a result of the growing national and international interest in biogas, fermentation, gasification and purification technologies are likely to become more efficient in the future. Cost reductions are anticipated in capital and operating costs.
The development of biofeedstock costs are uncertain and are influenced by market factors such as national and global competition on feedstock availability [35].
For the anaerobic digestion route, for instance, mass production may turn out more expensive than small-scale production due to the limited availability of wet local waste streams. While it is challenging to exactly predict feedstock costs and price trends in a situation with increasing demand and competition, biomethanol and other biofuels may not experience such drastic cost reductions as, for instance, the wind- and solar energy sector faced in the past.

According to the IEA, both in biomethanol production and in the production of other biofuels, increasing experience and R&D may offer cost reductions between 5%-27% [26]. Capital costs could even be further reduced by 5 to 16% if advanced technology is combined with more favorable financing terms for biofuel plants (e.g. lower interest on capital). As a result, the total biomethanol costs in the future may decrease to 12-28€/GJ if based on lignocellulosic biomass feedstocks, and to 10-22€/GJ for fuel production based on waste streams. [26]. Still, a cost gap between fossil and biological fuels is expected to remain. The uptake of biomethanol (as for all sustainable fuel alternatives) for marine applications therefore requires continuing policy support in the future, either in subsidies for low-carbon fuels or substantial $CO_2$ costs associated with emissions for fossil fuels. Currently, a carbon price of 49€-525€ per ton $CO_2$-equivalent is needed to bridge this gap. With cost reductions implemented in the future, this fee may be reduced to 0-365€/ton $CO_{2eq}$. Also, due to the increasing importance of air quality and GHG reduction and pressure to introduce legislative measures such as RED, Fuel Quality Directive, Emissions Trading System, Taxation of fossil fuels, users may be sensitized for the sustainability of their fuel and prepared to pay a slightly higher premium for renewable methanol. In the future, biomethanol prices will be influenced by many factors, including the supply, the demand from different sectors, as well as national and international policies.

Next to the demand of the maritime sector, biomethanol will also serve to the chemical industry and may in addition be blended to common road transport fuels. Important aspect for the Dutch Maritime case is that the Dutch government is considering phasing out marine shipping out of the blending mandate, thus out or the RED.

### Production potential of biomethanol and waste-based methanol

Currently, biomethanol  and carbon-recycled methanol supply is mainly restricted by the availability of fermentation/ gasification and production facilities. At this point in time, this type of methanol is only produced in a few facilities worldwide (i.e BioMCN in the Netherlands, Enerkem in Canada, OCI Beaumont in the USA). However, many installations are either in construction or in planning, such as the Enerkem plant in Rotterdam, Ecoplant Molecular Recycling Solutions in Spain, Vaermlandsmetanol Hagfors in Sweden, or the Södra cell pulp mill in Monsteras, Sweden. With the increasing amount of facilities, the biomethanol production capacity will largely depend on the availability of its feedstocks: wet and dry biomass and municipal solid waste (MSW) in the future.
According to the PBL, the current biomass availability in the Netherlands amounts to about 340PJ. [36] In the future, biomass production in the Netherlands can potentially be scaled up to 342-390 PJ in 2030 and 372-454 PJ in 2050 [36]. These numbers include the current biomass use, and it is assumed that existing flows may be utilized differently in the future, i.e. in biorefineries [36]. The PBL numbers for biomass availability in the Netherlands are in line with an earlier study by Wageningen University of Research [37]. A large potential of biomass in Europe and globally lies in the agricultural sector, both in the dedicated energy crops and in agricultural waste streams. Due to its long coastline, additional biomass sources for the Netherlands may include microalgae or seaweed.
Internationally, Shell predicts in its long term scenarios (2070) a potential of 6.2EJ/year energy from biomass in the European Union, 19EJ in Europe, and nearly 100EJ worldwide [38].

Not only the biomass supply, but also the Dutch and global biomass demand is rapidly growing. According to a recent study by PBL, the Netherlands is not going to be able to supply its own biomass requirements in any of the investigated scenarios [36]. As a result, biomass will always need to be imported to cover Dutch demands. Depending on the underlying assumptions, the Dutch biomass demand constitutes up to 6.5% of the total European production potential. This means that it is indeed physically possible to import the required biomass volumes. Whether or not it turns out desirable and economically/politically feasible to import such large amounts of biomass will strongly depend on Dutch sustainability policies, biomass prices and international fair-share agreements for biomass supply. Fair-share policies, however, are challenging to apply from the perspective of national sustainability frameworks and must be agreed upon on an international level [36]. In a recent advice to the Dutch Government, the Social and Economic Council (SER) recommended recommends using biomass primarily as a feedstock for the chemical industry and for materials. The use of biomass in heavy transport, including maritime shipping, is seen as a temporary solution to synthetic fuel (SER 2020 [39]. This issue is not exclusive for biomethanol, but affects all biofuels (including biodiesel and LBG). Turning to the availability of municipal solid waste, we note that in the year 2017, 1,650 kilotonnes of plastic waste were available in the Netherlands. Assuming an average heating value of 26.4GJ/t, this is equivalent to approx. 43.5PJ of energy. However, the energy density of plastic waste varies strongly (13.7GJ/t for PVC vs. 41.8 GJ/t for PE), which complicates estimations of energy availability [40].

The *global* plastic production and plastic waste amounts to approx. 360 million metric tons in 2018, of which 62 million were produced in Europe. [41]This is equivalent to an energy availability of approx. 9.50EJ and 1.64EJ, respectively.

In the Netherlands, about 50% of plastic waste gets recycled, half of which is exported to recycling customers abroad. The other half of plastic waste typically gets burned in waste incineration plants. [42] In the EU, the recycling rate is lower and lies at approx. 30%. Again, half of the plastic collected for recycling is exported. The reason for large export volumes include a lack of capacity, a lack of recycling technology as well as financial reasons. While a large share of export volumes was previously shipped to China, the country recently banned plastic waste imports, so that other solutions for recycling large waste volumes need to be found in Europe. [43] Also, a lack of recycling plants and incinerators can lead to waste mismanagement, which contributes to increased landfill volumes and the so-called "plastic soup" (accumulated plastic waste in water bodies) [44].
The analysis shows that large amounts of local waste are available for recycling in the Netherlands and in Europe, and that the current bottleneck for waste recycling is the availability of recycling facilities. This provides great future potential for carbon-recycled methanol production from municipal solid waste. In addition, the demand of plastic, and thereby the availability of plastic waste streams, is constantly growing. Figure 31 shows how the global plastic production has increased from the year 2000 to 2015. In the future, the produced plastic volumes are expected to further increase, as Figure 32 shows.

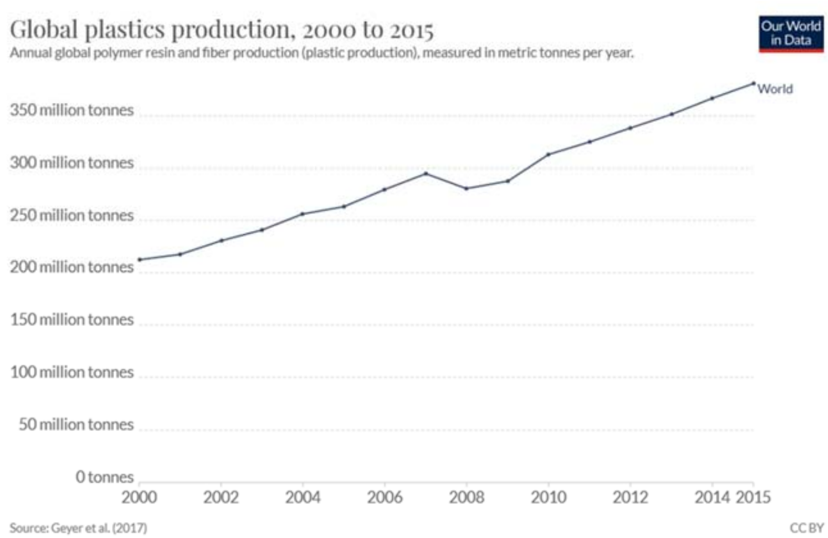



Figure 31: History of global plastic production. The short decrease of annual production in the years 2009 and 2010 is a result of the 2008 financial crisis. Source: Our World Of Data 2018 [45].


Figure 32: Forecast of global plastic waste management value. Source: Markets And Markets 2019 [44].

In conclusion, production and supply of biomethanol and methanol from fossil MSW to the shipping sector appears to be a viable option for sustainable transport in the future (both direct biomethanol production and production via green gas).
For methanol from waste streams, the current limiting factor is the availability of recycling facilities. For biomethanol, the large-scale deployment will depend on a strong and stable policy framework over an elongated period of time, in order to gain confidence of the relevant stakeholders. Recast renewable energy directive (REDII) appears to be a good way forward, but more needs to be done on a national level. However, biomass and waste streams should not be the only solution to reduce greenhouse gas emissions. All viable solutions will be required for the maritime sector and for a more sustainable methanol economy in general. This includes also the development of alternative methanol production methods like power-to-methanol, which we discuss in the next section.

### 4.3.4 *e-Methanol*

E-Methanol is produced from green hydrogen (obtained through electrolysis of renewable electricity), carbon dioxide and electricity. $CO_2$-hydrogenation is used to realize circularity. As a sustainable source, $CO_2$ is acquired by capture from exhaust gases of point sources or by direct air capture (DAC). For methanol as a marine fuel, $CO_2$ for production captured by DAC or from biomass is considered for obtaining a net-zero emission situation. However, DAC will not yet be applied on a large scale before 2030. Instead, $CO_2$ from point sources like natural gas, coal or biomass-based power plants or industrial sites will be used during the transition period. In the case of DAC, costs for $CO_2$ will highly depend on electricity prices. For $CO_2$ from point sources feedstock costs charged by suppliers will apply.
In the future ETS and $CO_2$ taxes may be passed to purchasers by suppliers of $CO_2$, dependent on future regulation and the business models that suppliers use.

$CO_2$-hydrogenation can take place in the liquid and the gas phase. For our cost- and efficiency analysis, we consider a gas phase conversion, as the liquid phase conversion requires more energy. Our information on the production of e-methanol is based on the 2020 TNO report “Power-2-Fuel Cost Analysis” [46] as well as a recent scientific paper [47].

As stated before, e-methanol can also be produced by hydrogenation of CO. The CO can be taken from exhaust gases from industry. This production route is not fully circular, since it uses CO from fossil sources. However, this route has benefits: it makes use of exhaust gases, it is relatively energy efficient and the technology is mature. Therefore, it is an interesting pathway during the transition towards fully circular e-methanol production.

### Cost

The production cost of e-methanol depends strongly on the production of the respective feedstocks: electricity, hydrogen and carbon dioxide.
With water being an abundant resource, the cost of hydrogen production by electrolysis depends primarily on the price of electric energy, which may originate both from green and fossil sources. In 2018 and 2019, the price of grid electricity in the Netherlands fluctuated between 61 and 68€/MWh [48]. Prices of grey and green/renewable electricity do not differ significantly. By making use of low electricity prices during moments of oversupply for hydrogen electrolysis, the costs for electricity can be lowered.

The price of carbon dioxide varies strongly and its development in the future is rather uncertain.
For direct air capture, recent literature suggests that $CO_2$-prices range from 100USD/t to 300USD/t and are expected to drop below 50 or 60USD/t by 2040 [49] [50], while some sources predict costs as high as 1000USD/t [51]. However, $CO_2$ may also be captured from point sources, which results in $CO_2$-prices in the range of 60 to 130 USD/t $CO_2$ [52], and from €10 to €100 per ton on long term [53].

| | $CO_2$ capture cost short-midterm (€$_{2015}$/t$CO_2$) | $CO_2$ capture cost long-term (€$_{2015}$/t$CO_2$) |
|---|---|---|
| Natural gas power plant | 20–60 | 10–60 |
| Coal power plants | 30–170 | 10–100 |
| Petroleum refining/ petrochemical | 60–140 | 30–90 |
| Cement industry | 70–150 | 30–50 |
| Iron and steel production | 50–70 | 30–60 |
| Ammonia production | < 20 | < 20 |
| Bioethanol production, biogas upgrading | < 20 | < 20 |
| Ambient air | – | 20–950 |

Figure 33: Capture cost for $CO_2$ in €/ton [53].

To analyze the price range of e-Methanol, we suggest different scenarios with low, medium and high prices for power and $CO_2$[4], respectively. For electricity, we choose three scenarios of 30€/MWh, 50€/MWh and 70€/MWh, and assume a price of 55€, 110€ and 220€ per ton $CO_2$.

[4] $CO_2$ costs include both feedstock costs for $CO_2$ and ETS or other $CO_2$ taxes when applicable.

CAPEX costs are fixed at 1.52€/GJ methanol[5]. The sensitivity of production costs for electricity prices and $CO_2$ costs is visualized in Figure 34.

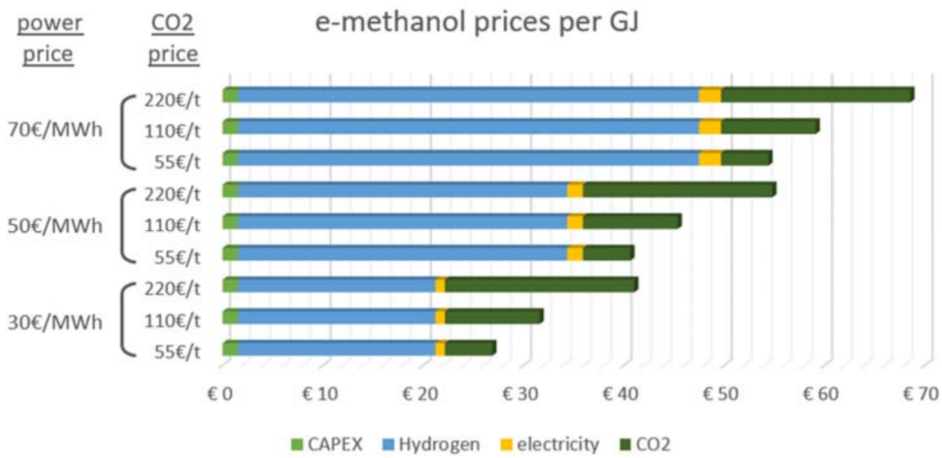



Figure 34: Price of e-methanol for different scenarios of feedstock costs Calculations based on TNO 2020 [54].

The analysis demonstrates that the total price of e-methanol is dominated by the costs of hydrogen production, which strongly depends on the electricity price. Even if the $CO_2$ price is 220€/ton, costs for hydrogen have the largest share in overall production costs.

Note that the cost of e-methanol shown in Figure 34 does not include the transport of feedstocks, as water, and electricity are assumed to be readily available for any production facility. Furthermore, methanol production is expected to take place very close to the electrolysis facilities, considering that the transport of liquid methanol is much more affordable and less complex than that of compressed or liquefied hydrogen. If the $CO_2$ capture site is located at a distance from the electrolysis and production units, the transport of $CO_2$ also needs to be included. However, the share of feedstock transport costs in the total methanol price is assumed to be small.

### Energy efficiency and sustainability

For the production of one ton of e-methanol, 0.234t of hydrogen is required, equivalent to 28.3 GJ of energy (LHV: 121GJ/t). According to [55] the energy efficiency of hydrogen production by PEM electrolysis can be assumed to be 64%[6], meaning that 44.2GJ of electricity is needed as energy input for water electrolysis.

In addition to hydrogen, the production of one ton of methanol requires roughly 1.5 ton of carbon dioxide. If the $CO_2$ is obtained from DAC, the energy cost can be estimated to at around 5.5 to 12 GJ per ton $CO_2$ [51] [50]. $CO_2$-capture from point sources is much more energy-effective than DAC.

[5] The presented CAPEX only include the production facility of the e-methanol and not of the hydrogen production (included in the electricity price).
[6] In 2030. To realise this efficiency technological development is necessary.

In the reaction from hydrogen and carbon dioxide to methanol, the production yield is roughly 81%, and 624kWh = 2,25 GJ of electricity are required for the conversion process [47]. The energetic details of the production of e-methanol are shown schematically in Figure 35 below.

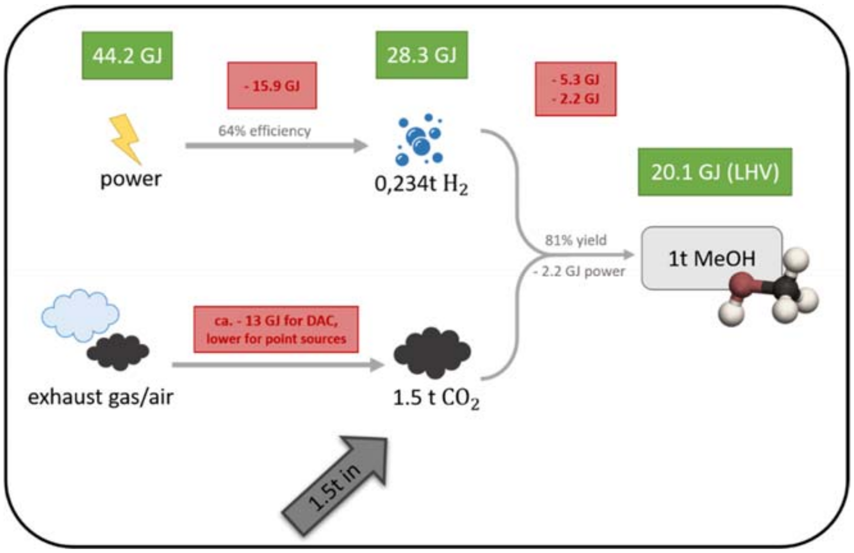



Figure 35: Schematic of the energy losses and $CO_2$-input of e-methanol production.

Focusing on the sustainability of the process, the production of e-methanol can be entirely carbon-negative and consumes slightly above 72kg $CO_2$/GJ methanol, at least if electricity from carbon-neutral power sources is used [47] and green hydrogen is applied. In this case, the $CO_2$-negative methanol production exactly compensates for the $CO_2$-emissions during fuel combustion. With a mixture of renewable and grey electricity, the production process may turn out to be less carbon-negative, carbon neutral or even carbon positive, depending on the details of the source. Carbon negativity or neutrality of the DAC process is expected to only be viable in case the capture itself it is powered by carbon-neutral power sources.

### Production potential of e-methanol

The production potential of e-methanol largely depends on the availability of electricity from renewable sources and $CO_2$. In 2019 the Netherlands produced 21,8 million MWh (78,5 PJ) of electricity from renewable energy sources from wind, biomass and solar energy, according to CBS [56]. When the efficiencies from Figure 35 are applied, 36 PJ of e-methanol could be produced from this 78,5 PJ of electricity. This is however exclusive energy needed for $CO_2$ capture.

There is however demand for other applications from other sectors as well. Total energy use in the Netherlands is shown in Figure 36. Currently, most energy is provided from fossil sources. According to Paris targets, almost all energy will have to come from renewable sources by 2050. Since all sectors will have to decarbonize, and electrification is a major too for this, there will be a lot of competition for electricity from renewable sources.

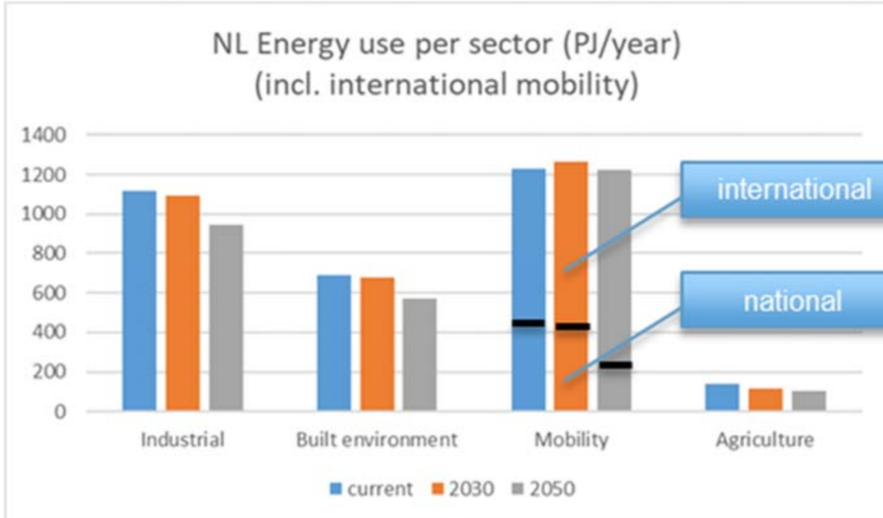



Figure 36: Energy use in the Netherlands per sector, including bunkered fuels for international transport. Energy demand forecast by TNO, based on EBN [57] (figures 2019), Klimaatakkoord [58] (figures 2030), Net voor de Toekomst scenario “Regie Nationaal” from CE Delft [59] (figures 2050). For figures on national and internation mobility NEV 2017 [60], CBS, and EU Reference scenario 2016 [61] were used.

The Netherlands has a large potential for production of electricity from offshore wind, compared to other countries. The total potential for the Dutch continental shelf is estimated at 900 PJ per year [62]. By combining technical developments (increasing the energy density of windmills in MW/km through better design of rotor blades and higher towers) and use of a larger share of the Dutch continental shelf the potential of offshore wind may grow to more than 2000 PJ per year [63].

$CO_2$ can be captured from power plants and industrial sites.
In 2018, $CO_2$-emissions of powerplants were 48 Mt, and that of industry 44 Mt. For comparison: in 2019 400 PJ of fuel was bunkered in the Port of Rotterdam (see 4.5). This is equivalent to 20 Mt of methanol. To produce this amount of methanol, 30 Mt of $CO_2$ would be required. To produce $CO_2$-neutral methanol, DAC would be required. DAC is however low TRL (TRL 4-5) [64], consumes a lot of energy and needs a lot of space [65]. An alternative to the use of $CO_2$ would be the use of CO from industrial exhaust gases. Though both the use of $CO_2$ from point sources and the use of CO from exhaust gases is not $CO_2$-neutral, both can play a role in the migration path towards the production of $CO_2$-neutral e-methanol.

Production of electricity from renewable sources is already applied and scaled up to larger amounts, though production in the Netherlands will probably not be sufficient to replace all fossil fuels by e-fuels. When e-methanol will be applied at large scale for shipping purposes, import will probably be necessary. The methanol itself can be imported from countries that produce large amounts of electricity from renewable sources, but also import of electricity or green hydrogen is an option.

The production of e-methanol is still in pilot phase. An interesting frontrunner is the Olah plant in Iceland [66]. The plant was opened in 2012 and located at a geothermal power station. The plant uses $CO_2$ captured from the power plant as feedstock and the power plant provides the needed electricity for production of hydrogen. The plant is operated commercially and sells methanol to the Netherlands and other European countries [67].

### Comparison with alternative e-fuels

Besides e-methanol, also other e-fuels can be used for shipping. A comparison between hydrogen and four e-fuels (e-methanol, e-diesel, e-ammonia and e-LNG) on practical applicability and economic was made in [46] and [63].

With respect to *practical application*, e-diesel is most practical: vehicles often have diesel engines and don't need modifications. Also bunkering and distribution infrastructure can be reused. Due to a relatively high energy density, the number of bunkering events for diesel is limited. For methanol some modifications to the engine are needed, as well as a larger tank. Also, more bunkering events are needed. Methanol is however relatively easy to distribute and store, due to the fact that it is a liquid. E-ammonia, e-LNG and especially hydrogen are more difficult to transport and store, because cooling, compression or liquefaction are needed. E-ammonia and hydrogen also require a new engine or fuel cell. All e-fuels make more bunkering events necessary compared to diesel, except in case of deep-sea shipping, in which case the tank can be made large enough to meet range requirements. Hydrogen is not considered an option for deep sea shipping due to its low energy density and complex storage properties.
For short sea shipping bunkering will be needed every day with compressed hydrogen (700 bar), compared to a range of four weeks with diesel.

For the KPI *Economics*, costs throughout the value chain are analysed[7]. The costs for e-fuels highly depend on electricity costs (for hydrogen and all e-fuels) and $CO_2$ (for all carbon fuels). Figure 37 shows the production costs for e-fuels at an electricity cost level of €30/MWh and €40/ton for $CO_2$ (left picture) and €50/MWh and €200/ton for $CO_2$ (right picture). The figure shows that in case of a high $CO_2$ price e-methanol has a higher price than e-diesel.

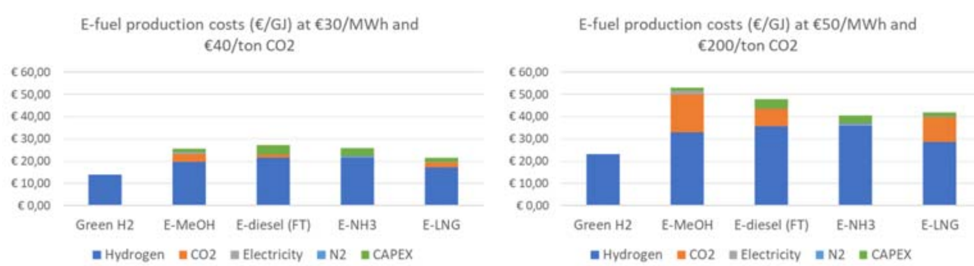



Figure 37: Production costs for e-fuels at different cost levels for electricity and $CO_2$ [54].

The relatively low production costs for hydrogen and e-LNG are increased by additional costs for compression or liquefaction. The cost differences between the different e-fuels are small and since there is a lot of uncertainty on future costs, no clear winner can be nominated.

[7] Based on expected technology cost levels for 2030. Since there is a lot of uncertainty in the analysis on many factors, including technology development, optimal production routes and efficiencies, the cost figures only give an indication of the cost levels and their structure.

Overall, we can conclude that e-methanol is competitive to other e-fuels.
E-methanol is more practical than hydrogen and ammonia, but e-diesel doesn't require any modifications to the vessel and bunkering infrastructure. E-methanol is probably slightly more economical than e-diesel, but this advantage is lost when $CO_2$ costs are high, which will be the case if DAC is required to realise $CO_2$ circularity. Methanol can however be used as a feedstock for e-diesel and e-kerosene and many chemical products, which makes it a relatively safe choice to invest in production facilities.

#### *4.3.5 Conclusions for the upstream supply chain*

Methanol production can be divided in four categories:

- grey methanol, produced from fossil sources like natural gas or coal;
- biomethanol, produced from biogas;
- Carbon-recycled methanol, making use of a similar gasification technology as dry biomass, with waste streams that are otherwise non-recyclable used as a feedstock for methanol production; and
- e-methanol, produced from green hydrogen and a carbon source.

To realise GHG targets, a switch to green carbon-neutral fuels like biomethanol and e-methanol is highly desired and expected in the future.
However, the ongoing transition to methanol-based maritime transport does require grey methanol as short- and medium-term solutions. During the transition from grey to sustainable methanol production in the near future, also blends of fossil and renewable methanol may be used.

European and global methanol production potential are sufficient to produce viable volumes for a transition to methanol as a maritime fuel. As the availability of green or blue methanol from biomass, waste or electrical power is still low, the methanol demand in the short term will be based on fossil fuels, mainly on natural gas. It should be noted that grey methanol is more costly than diesel and does not contribute to GHG reduction. On the contrary, there may be some increase (up to 5% or 10%). It is therefore risky to make a transition in the downstream part, without the outlook of having sufficient blue or green methanol production in the future. Grey methanol will still constitute a significant part of the global supply in the future. The main European and Russian production facilities and their respective capacities are summarized in.

European production locations for green and blue methanol are much more sparse than those using fossil fuels and currently have significantly lower production capacities than their grey counterparts. However, the attention and demand for blue and green production routes is vastly growing, and with that also the supply is expected to increase continuously. Existing European production facilities for green methanol, as well as planned facilities for green and blue methanol are listed in Table 25.

Table 25: Current and planned European production locations of green and blue methanol. In grey the plants are mentioned that are under construction, planned or idled.

| Company/Name | Location | Type of renewable methanol | Production capacity [68] [69] [70] | | Status |
|---|---|---|---|---|---|
| BioMCN | Delfzijl, NL | Biomethanol | 60 kt/y* | 1.20PJ/y | Online |
| Chemrec | Farsta, Sweden | Biomethanol | 2.2 kt/y | 0.04PJ/y | Online |
| Carbon Recycling International | Grindavik, Iceland | E-methanol | 4 kt/y | 0.08PJ/y | Online |
| New Fuel A/S | Aarhus, Denmark | Biomethanol | 1 kt/y | 0.02PJ/y | Online |
| $MefCO_2$ consortium | Lünen, Germany | E-methanol | 0.36kt/y | <0.01PJ/y | Online |
| Enerkem | Rotterdam, NL | Blue methanol from MSW | 60 kt/y | 1.20PJ/y | Under construction |
| Power-to-Methanol Antwerp BV | Antwerp, BE | Green or blue e-methanol | 8kt/y | 0.16PJ/y | Planned 2022 |
| Carbon Recycling International | Grindavik, Iceland | E-methanol | 50-100 kt/y | 1-2PJ/y | Planned 2021 |
| Liquid Wind AB - FlagshipONE | Stenungsund, Sweden | E-methanol | 50 kt/y | 1-2PJ/y | Planned 2022 |
| Haldor Topsoe | Piteå, Sweden | Biomethanol & BioDME | 1.5kt/y of DME | 0.04PJ/y | idled |

(*Production capacity of the location is much higher Depends only on demand and availability of green gas.)

The table demonstrates that current green and blue methanol production facilities are operating on a much smaller scale than production plants of grey methanol, but that significant efforts are underway in several countries to make methanol production greener. This development is likely to pick up momentum with the growing awareness for fuel sustainability, and due to the European Commission's Renewable Energy Directive II. Also, the table shows that the investments made are both in the field of biomethanol and in the field of e-methanol.

Due to the lower price and higher technology readiness level of biomethanol and methanol from MSW compared to e-methanol, however, we first expect a scale up of biomethanol in the coming years. The cost ranges of grey, bio- and e-methanol, and their depencies on feedstock prices are summarised in Table 26.

Table 26: Cost range for grey, bio- and e-methanol, and their dependencies on feedstock costs.

| Methanol type | Cost range | Cost dependent on |
|---|---|---|
| Grey methanol | € 9-22/GJ | Policy, Natural gas price |
| Biomethanol and Carbon-recycled methanol | € 11-33/GJ | Policy, Biomass & green gas price |
| E-methanol | € 27-68/GJ | Electricity and $CO_2$ costs |

From a comparison of e-methanol to other fuels, it becomes clear that a winner cannot be nominated. Hydrogen and ammonia have the benefit of zero $CO_2$ emissions. Both hydrogen and e-ammonia are however more difficult to handle and score lower on practical application.

Ammonia possibly has more safety issues, that require stringent measures. e-diesel doesn't require any modifications to the vessel and bunkering infrastructure.

## 4.4 Downstream supply chain to and within the Netherlands

This section addresses the transportation of methanol from the current production locations of grey (fossil) and green methanol to the bunker locations. The production locations are inside and outside Europe.

The downstream supply chain addresses the distribution of methanol from the production location to the bunkering location and into a ship's tank. The medium- and long-term goal is to use 100% *renewable* methanol as a feedstock. However, some *grey* methanol may be necessary for the transition to methanol as a maritime fuel in the short term. From Table 24, we identify the European production locations of grey methanol that are most likely to be relevant for the Dutch Market:

| **Company** | **Location** | **Production capacity (grey) methanol** [71] | |
|---|---|---|---|
| BioMCN | Delfzijl, NL | 1000 kt/y | 19.9 PJ/y |
| Tjeldbergodden | Kjørsvikbugen, Norway | 900 kt/y | 17.9 PJ/y |
| Mider-Helm-Methanol | Leuna, Germany | 660 kt/y | 13.1 PJ/y |
| BASF | Ludwigshafen, Germany | 480 kt/y | 9.6 PJ/y |
| Shell & DEA Oil | Wesseling, Germany | 400 kt/y | 8.0 PJ/y |
| BP Refining & Petrochemicals | Gelsenkirchen, Germany | 300 kt/y | 6.0 PJ/y |

In addition to the European methanol production facilities, significant amounts of methanol get imported from Trinidad, Venezuela, Equatorial Guinea, the United States and Russia. As section 4.2 concluded, the Netherlands is an important hub for the current import and European distribution of methanol imported from outside Europe.

Looking at the renewable options biomethanol and e-methanol, the most relevant production location for the Dutch market is the BioMCN plant in Delfzijl with a current production of 60kt of biomethanol per year. In principle, the entire methanol production capacity in Delfzijl couldd be used to produce green methanol, provided that sufficient amounts of green gas are fed into the NG network, and that green gas is certificates are acquired by BioMCN. In the near future, also the new Enerkem waste-to-methanol plant in Rotterdam is a promising option to produce low-carbon methanol and bio-methanol, as well as a planned e-methanol plant in Antwerpen, Belgium. The Rotterdam methanol plant is currently in development and has an expected capacity of 120kt per year, while the e-methanol plant in Antwerpen with a yearly capacity of 8kt is scheduled to be completed in 2022.

After the production step, methanol should be distributed to the bunkering locations that form the end of the supply chain. This includes the ports Amsterdam and Rotterdam, but also other (Dutch) maritime ports or terminals. For smaller ports, we expect methanol distribution to take place from large storage locations in the main ports, or directly from the production location in Delfzijl or the import terminals in Rotterdam. For large local methanol demands, distribution may take place directly via a bunker vessel (see chapter 3), which itself can sail on methanol.

If the local demand is low, for instance in small ports, it will likely be covered by tanker trucks with the possibility of direct truck-to-ship bunkering (for inland vessels or small maritime vessels). Alternatively, a floating storage ponton can fulfil a local fulfil the bunkering function.

In this section, we analyse the downstream supply chain and address the following questions:

1. How sustainable is the distribution of methanol?
2. What are the costs associated with methanol distribution after production?

### 4.4.1 *General transport infrastructure, costs and emissions*

To estimate the feasibility of methanol distribution via different modalities, we summarize typical costs, energy loss, well-to-wheel or well-to-propeller greenhouse gas emissions and capacities of common transport options in the table below.

Table 27: Estimated cost, energy loss and greenhouse gas emissions of different transport modes.

| **Modality** | **Cargo capacity in tons** | **Cost* in €cent/tkm** [72] [73] [74] | **Energy loss in MJ/tkm** [75] [76] [77] | **GHG emission** in g/tkm** [78] |
|---|---|---|---|---|
| **Inland ARA small** | 300 – 650 | 2.2 – 3.5 | 0.26 – 0.52 | 41 |
| **Inland ARA large** | 1,500 – 3000 | 1.6 – 2.1 | 0.20 – 0.40 | 30 |
| **Inland Rhine** | 5,000 – 10,000 | 1.5 – 2.1 | 0.08 – 0.20 | 21 |
| **Short sea small** | 500 – 5000 | 1.5 – 2.0 | 0.20 – 0.40 | 27 |
| **Short sea med.** | 5000 – 10000 | 1.5 – 2.0 | 0.08 – 0.20 | 21 |
| **Short sea large** | 10000 - 50000 | 0.6 – 1.0 | 0.07 – 0.08 | 15 |
| **Truck small** | 10 | 15 – 30 | 0.46 – 0.80 | 259 |
| **Truck large** | 20 | 6 – 15 | 0.23 – 0.40 | 110 |
| **Rail (electric)** | 25 – 1000 | 1.5 – 3.5 | 0.15 – 0.35 | 10 |
| **Pipeline** | - | ~1.4 | 0.22 | 5 |

* Costs are assuming one-way shipments or loaded returns. In the case of empty vessel returns, the shipping price is increased by a factor of roughly 1,5. [72]

**GHG emissions are well-to-wheel emissions from the year 2017. These are expected to decrease in the near future due to the uptake of more sustainable fuels.

Due to the large capacities of barges and limited man-hours required, use of **inland- or short sea methanol carriers** appear to be advantageous transport options for methanol distribution, at least for large methanol volumes and for medium or long distances. In addition, the distribution vessels themselves may run on methanol in the short term, offering additional flexibility in the supply chain logistics. While at this point in time, rail and pipeline transport exhibit the lowest well-to-propeller GHG emissions, also the reported emissions of ships are expected to decrease in the future by the uptake of methanol as a marine fuel.

For production locations without access to inland or seaports, transport by **rail** may be a cost-effective and sustainable option, as the long-distance rail infrastructure in Europe is well-developed and few man-hours are required for the transport of large volumes. Usage of rail transport is effective for transport of smaller quantities as a chemical tank wagon can load approx. 80 $m^3$ of methanol [79].

However, transport by rail requires additional material handling, as bunkering typically cannot not take place directly rail-to-ship. We therefore add a fixed material handling cost of 2.3€/ton for all rail transport options.

In case of a lack of direct access to waterways or the rail infrastructure, Methanol distribution can take place by **truck**. This also holds if methanol bunkering takes place directly truck-to-ship. However, according to the table above, distribution by truck is the most cost-expensive and least sustainable option and is therefore only feasible for low volumes or short distances (inland shipping).

While also **pipelines** appear to be an energy- and cost-effective, they do not appear to be feasible for methanol distribution due to a lack of an existing long-range infrastructure. The current pipeline network in Northwestern Europe is used for transport of natural gas, crude oil and oil products (such as kerosene in the CEPS network and Nafta and gasoline in the RRR network) and transport of chemical products (such as transport of ethylene between the ports of Rotterdam and Antwerp) [80]. Developing a new pipeline for new applications such as methanol is only suitable for very large volumes due to the high investment and terminal costs [79].

In cases of long distances and a lack of access to ports or the rail infrastructure, **intermodal transportation** poses an attractive and cost-effective option. Truck transport, for instance, is then combined with distribution options on water or rail. In intermodal transportation, vertical movements between modalities cause handling costs of roughly 2-3€/ton, and should therefore be kept to a minimum. In Europe, a distance of 300km is usually assumed to be the threshold above which intermodal transport is more cost-effective than direct road transport. [81]

### 4.4.2 *Examples of European downstream scenarios*

This section presents the energy efficiency and greenhouse gas emissions of selected European downstream scenarios in detail, before turning to import from overseas in the next section. Figure 38 presents a map of selected production and bunkering locations that are relevant for the Dutch market and analyzed in this section. In the first two scenarios, we focus on methanol production in Delfzijl. Subsequently, we also analyze examples of two German-Dutch and one Norwegian-Dutch downstream scenario. Note that, while the Port of Rotterdam is a major bunkering location, it is also an important methanol import hub. Methanol supply via the Rotterdam hub will be discussed at a later point in this report.


Figure 38: Map of Dutch, Belgian and German waterways. Yellow labels denote several methanol production locations. Major Dutch methanol bunkering locations are highlighted in green. Red labels are orientation aids and not relevant in the supply chain analysis. Source: TNO based on Inland Waterways International [86].

*Dutch Scenarios*

Currently, the only Dutch methanol production facility is the BioMCN plant in Delfzijl with a production capacity of 19.9PJ per year. As bunkering and storage locations we considered here the Port of Rotterdam and the Port of Amsterdam. Other bunkering ports (such as Flussing or Den Helder) and terminals in the Netherlands may subsequently be supplied from storage facilities in the large ports, or directly from Delfzijl via truck or bunker vessel.

Methanol transport to the ports of Rotterdam or Amsterdam can either take place via inland waterways for vessels up to 700 ton, or (less likely) by short sea shipping along the Dutch North Sea coast. In the following table, we summarize the main costs and emissions for methanol distribution to Rotterdam and Amsterdam from Delfzijl.

Table 28: Estimated cost, energy loss and GHG emissions for transport of methanol between production in Delfzijl and bunkering in Port of Rotterdam.

| **Scenario 1: NL – NL** | Production: | Delfzijl, NL (BioMCN) | | |
|---|---|---|---|---|
| | Bunkering: | Port of Rotterdam | | |
| | Distribution: | Water, rail or road | | |
| *Transport Modality* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| | *in km* | *in €/t* | *in %* | *in kg/t* |
| Inland ship 650t | 330 | 7.3 - 11.6 | 0.4 – 0.9 | 13.5 |
| Short sea ship small | 340 | 5.1 - 6.8 | 0.3 – 0.7 | 9.2 |
| Rail | 330 | 7.3 - 13.9 | 0.2 – 0.6 | 3.3 |
| Truck large | 300 | 30 - 45 | 0.3 – 0.6 | 33 |

Table 29: Estimated cost, energy loss and GHG emissions for transport of methanol between production in Delfzijl and bunkering in Port of Amsterdam.

| **Scenario 2: NL – NL** | Production: | Delfzijl, NL (BioMCN) | | |
|---|---|---|---|---|
| | Bunkering: | Port of Amsterdam | | |
| | Distribution: | Water, rail or road | | |
| *Transport Modality* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| | *in km* | *in €/t* | *in %* | *in kg/t* |
| Inland ship 650t | 215 | 4.7 - 7.5 | 0.3 – 0.6 | 8.8 |
| Short sea ship small | 300 | 4.5 - 6.0 | 0.3 – 0.6 | 8.1 |
| Rail | 250 | 6.1 - 11.1 | 0.2 – 0.4 | 2.5 |
| Truck large | 210 | 21 - 31.5 | 0.2 – 0.4 | 23.1 |

As already mentioned, methanol distribution by rail exhibits very low transportation cost, energy loss and greenhouse gas emissions. However, the additional material handling in the port causes an extra handling effort and cost estimated at 2.3€ per ton of methanol, which is added to the tables above. As a result, transport by rail does not remain the most cost-effective option.

In addition, Port of Amsterdam only has limited access to the rail infrastructure for chemical transport. Therefore, the transport by rail does not seem to be a likely option for the supply chain.

Methanol distribution appears to be most cost-effective by inland and short sea shipping. The use of ships for methanol transport and direct ship-to-ship bunkering exhibits slightly less favorable energy efficiency and greenhouse gas emissions than transport by rail. However, it reduces additional handling costs (assuming that the storage terminal has direct nautical access) at the destination port compared to rail transport. For practical reasons, we therefore estimate waterway distribution to be more feasible than rail transport. Truck transport remains both the most cost-intensive but also the least sustainable option for methanol distribution in the Netherlands. It is a feasible option for small methanol volumes, preferably followed by direct truck-to-ship bunkering.

*Dutch-German Scenarios*

Additionally, to the Dutch scenarios, it is likely in the near future that production takes place in Germany, and the (grey) methanol is subsequently transported to the Netherlands. The production facilities in Gelsenkirchen, Wesseling and Ludwigshafen have direct access to large inland waterways and are also located directly to the rail network. The three resulting scenarios for import from Germany are therefore similar, with varying distance. Via inland waterways, methanol can be transported to the Netherlands by ARA or Rhine ships of up to 3000t. The results of our analysis are shown in the table below.

Table 30: Estimated cost, energy loss and GHG emissions for transport of methanol between production in German Rhine locations and bunkering in Port of Rotterdam or Amsterdam.

| **Scenario 3: DE – NL** | Production: | Germany, close to river Rhine | | |
|---|---|---|---|---|
| | Bunkering: | Port of Rotterdam or Amsterdam | | |
| | Distribution: | inland shipping or rail | | |
| *Transport* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| *Modality* | *in km* | *in €/t* | *in %* | *in kg/t* |
| | *Gelsenkirchen (BP Refining & Petrochemicals)* | | | |
| Inland ship (650t) | 275 | 6.1 - 9.6 | 0.4 – 0.7 | 11.3 |
| Inland ARA large | 275 | 4.4 - 5.8 | 0.3 – 0.6 | 8.3 |
| Rail | 250 | 6.1 – 11.1 | 0.2 – 0.4 | 2.5 |
| | *Wesseling (Shell & DEA Oil)* | | | |
| Inland ship (650t) | 360 | 7.9 - 12.6 | 0.5 – 0.9 | 14.8 |
| Inland ARA large | 360 | 5.8 - 7.6 | 0.4 – 0.7 | 10.8 |
| Rail | 300 | 6.8 – 12.8 | 0.2 – 0.5 | 3.0 |
| | *Ludwigshafen (BASF)* | | | |
| Inland ship (650t) | 600 | 13.2 - 21.0 | 0.8 – 1.6 | 24.6 |
| Inland ARA large | 600 | 9.6 - 12.6 | 0.6 – 1.2 | 18.0 |
| Rail | 530 | 10.3 – 20.9 | 0.4 – 0.9 | 5.3 |

For the fourth scenario, we assume methanol production to take place at a large plant in Leuna, Germany. As this location has no direct access to inland waterway, options for the downstream chain include transport by truck or rail, as well as intermodal transport by a truck-barge combination via the nearest container terminal in Braunschweig (DE). For the intermodal transport option, we again include additional material handling costs of 2.3€/ton. For this production location, rail proves to be the most feasible and sustainable transport option, followed by truck-barge intermodal transport. It is unsure whether there is a direct rail service between the location in Leuna and the port of Rotterdam. Sourcing from Leuna does seem to be the most likely option due to the long distance and the complicated supply chain.

Table 31 Estimated cost, energy loss and GHG emissions for transport of methanol between production in Leuna and bunkering in Port of Rotterdam or Amsterdam.

| **Scenario 4: DE – NL** | Production: | Leuna (Mider-Helm-Methanol) | | |
|---|---|---|---|---|
| | Bunkering: | Port of Rotterdam or Amsterdam | | |
| | Distribution: | truck; rail; intermodal | | |
| *Transport* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| *Modality* | *in km* | *in €/t* | *in MJ/t* | *in kg/t* |
| Truck large | 660 | 66.0 - 99.0 | 0.8 – 1.3 | 72.6 |
| Rail | 850 | 15.1 - 32.1 | 0.6 – 1.5 | 8.5 |
| I: truck | 130 | 13.0 - 26.0 | 0.2 – 0.3 | 14.3 |
| II: barge(≤2150t) | 725 | 14.5 | 1.5 | 19.6 |
| Handling cost | - | 2.3 | - | - |
| Intermodal sum | 855 | 26.2 - 36.3 | 0.9 – 1.7 | 33.9 |

*Dutch-Norwegian Scenario*

Our fourth example of a downstream scenario assumes production in the large Norwegian plant Tjeldbergodden. The only feasible transport option in this case is North Sea shipping, the resulting costs and emissions are summarized below:

Table 32: Estimated cost, energy loss and GHG emissions for transport of methanol between production in Kjørsvikbugen and bunkering in Port of Rotterdam or Amsterdam.

| **Scenario 5: NOR – NL** | Production: | Kjørsvikbugen (Tjeldbergodden) | | |
|---|---|---|---|---|
| | Bunkering: | Port of Rotterdam or Amsterdam | | |
| | Distribution: | North Sea shipping | | |
| *Transport Modality* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| | *in km* | *in €/t* | *in MJ/t* | *in kg/t* |
| Short sea ship small | 1400 | 21.0 - 28.0 | 1.4 – 2.8 | 37.8 |
| Short sea ship med. | 1400 | 21.0 - 28.0 | 0.6 – 1.4 | 29.4 |
| Short sea ship large | 1400 | 14.0 - 21.0 | 0.5 – 0.6 | 21.0 |

The table shows that, despite the large distance of 1400km, short sea shipping of large methanol volumes from Norway to the main Dutch ports can easily compete with rail and intermodal transport from Germany in cost, energy efficiency and greenhouse gas emissions.

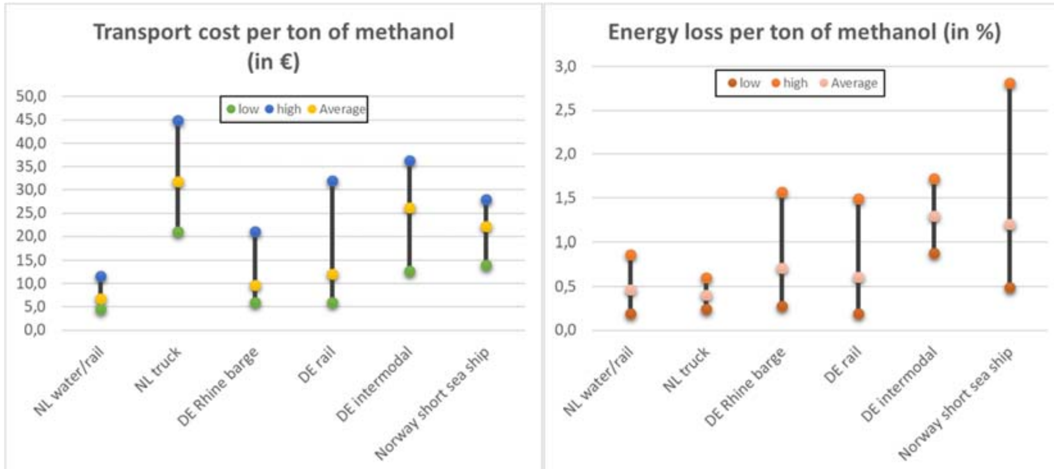



Figure 39: Transportation Costs and energy losses for 1400 km transport distance of the investigated European transport options.

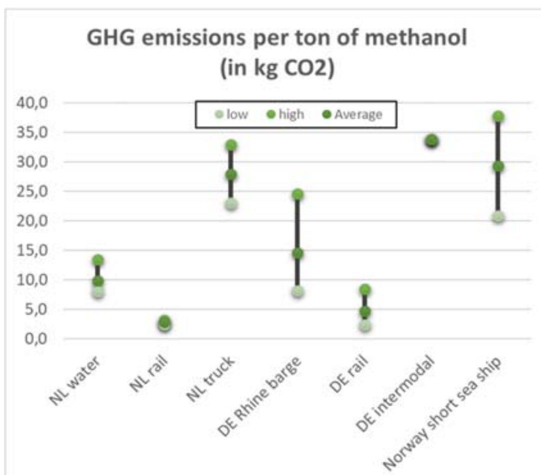



Figure 40: Greenhouse gas emissions of the investigated European downstream scenarios for 1400 km transport distance with different modalities (fossil or sustainable fuel used for transport energy).

In Figure 30 and Figure 40, we summarize the estimates for transport costs, energy loss and $CO_2$-emissions for the five European downstream scenarios investigated above.

### 4.4.3 *European methanol import via Rotterdam*

As mentioned in section 4.2, Rotterdam is the largest European hub for methanol imports from outside Europe. About 35% of European imports pass via the Netherlands and are subsequently distributed to other European countries. The most significant import volumes come from Russia (1.6 Mton in 2019), Trinidad (1.4 Mton), United States (0.6 Mton), Norway (0.6 Mton), Venezuela (0.5 Mton), Equatorial Guinea (0.5 Mton) and Egypt (0.4Mton).

For the European consumer obtaining their methanol from the Rotterdam hub, overseas (or Russian) methanol prices and transport costs to Rotterdam are in principle irrelevant. What does count are the resulting price and availability at the import hub. Nonetheless, we briefly analyze the most common transport routes with regard to their costs, efficiency and greenhouse gas emissions. It becomes clear that the import of methanol from overseas may be cost-effective if overseas methanol prices are low.

Methanol transport from Trinidad and Venezuela to the Port of Rotterdam takes place via the Atlantic Ocean, with transport distances of about 4000 nautical miles, equivalent to approx. 7400 km. Similar distances are passed for methanol transport from the east coast of Egypt and the west coast of Saudi Arabia via the Suez Canal. Assuming that the transport of large methanol volumes takes place in chemical tankers of 50,000 – 200,000 dwt, the corresponding cost, energy efficiency and greenhouse gas emissions must be much lower than those of smaller short sea ships quoted in Table 27. However, the details on costs, efficiency and $CO_2$ performance of chemical tankers used for methanol distribution are still unknown at this point in time. We therefore take the specifications of 10,000-20,000dwt short sea ships as an upper bound for crude estimates. Transport distances, as well as the resulting data for imports from Trinidad, Venezuela, the Middle East and Equatorial Guinea are summarized in the table below. The table demonstrates that energy losses, greenhouse gas emissions and the transport cost per ton of methanol from overseas import is likely to be higher compared to European supply chains. How much higher depends on the transported volumes and type of ship, and is still unknown. The higher transport costs, however, can be compensated by lower overseas methanol prices, so that methanol import from overseas is cost competitive with European methanol.

Table 33: Estimated cost, energy loss and GHG emissions for transport of methanol for overseas imports to Port of Rotterdam.

| **Import from overseas** | | Destination | Port of Rotterdam | |
|---|---|---|---|---|
| | | Modality: | Deep sea shipping | |
| *Origin* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| | *in nm* | *in €/t* | *in %* | *in kg/t* |
| **Middle East** (Saudi Arabia East Coast, Iran, Oman) | 6000–6500 | ≤ 111 | ≤ 3.9 | ≤ 167 |
| **Trinidad, Venezuela** also Egypt East Coast / Saudi Arabia West Coast | approx. 4000 | ≤ 74 | ≤ 2.6 | ≤ 111 |
| **Equatorial Guinea** | approx. 4500 | ≤ 83 | ≤ 2.9 | ≤ 125 |

In contrast to imports from Latin America, Africa and the Middle East, methanol import from Russia typically takes place by intermodal rail-ship transport due to a lack of inland waterway access and infrastructure in Russia. Large volumes are transported to St. Petersburg by rail and subsequently shipped to the Netherlands via the Baltic Sea and the North Sea. While direct rail transport from Russia to Europe may seem an attractive option at first, it is prevented in practice by a mismatch of Russian and European rail standards – Russian trains often do not fit on European rails and *vice versa*.

Table 34 shows the main Russian methanol production facilities as of 2012 [11]. For geographic reasons, the plants in Tomsk and Angarsk are assumed to primarily serve the Asian market. The remaining production locations exhibit distances between 200 and 2200 km to the Port in St. Petersburg and are feasible for the intermodal rail-sea transport option mentioned above. An exception is the methanol plant in Nevinnomyssk, which is located approx. 450km from the Port of Novorossiysk at the Black Sea and may therefore be suitable for intermodal truck transport and short sea shipping via the Black and Mediterranean Sea.

Table 34: Fossil (grey) methanol production in Russia.

| **Company** | **Location** | **Capacity in kt/year** |
|---|---|---|
| Siberian Methanol Chemical | Gubakha, Russia | 1000 |
| Togliatti Azot | Togliatti, Russia | 1000 |
| Tomskneftekhim | Tomsk, Russia | 825 |
| Shchekino Azot | Shchekino, Russia | 450 |
| Novomoskovsk Azot | Novomoskovsk, Russia | 400 |
| Angarsk Petrochemical | Angarsk, Russia | 200 |
| Nevinnomyssk Azot | Nevinnomyssk, Russia | 140 |
| JSC Acron | Novgorod, Russia | 70 |
| OAO Novatek | Yamal-Nenets, Russia | 52 |

Source: ICIS, Europe Chemical Profile Methanol (2012) [11].

Below, we analyze the costs, efficiency and greenhouse gas emissions for import from Russia in more detail. For shipping, we again assume a short sea ship of 10,000 – 20,000 dwt, noting that the costs and emissions of large tankers are likely to be significantly lower.

Table 35: Estimated cost, energy loss and GHG emissions for transport of methanol for overseas imports from Russia for the Port of Rotterdam.

| **Import from Russia** | Production: | Russia (several locations) | | |
|---|---|---|---|---|
| | Destination: | Port of Rotterdam | | |
| | Modality: | Intermodal rail/ship via St. Petersburg | | |
| *Transport* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| *Route & Modality* | | *in €/t* | *in MJ/t* | *in kg/t* |
| Rail to St Petersburg from… | | | | |
| …Novgorod | 200 km | 3.0 – 7.0 | 0.2 – 0.4 | 2.0 |
| …Shchekino | 650 km | 9.8 – 22.8 | 0.5 – 1.1 | 6.5 |
| ...Novomoskovsk | 950 km | 14.3 - 33.3 | 0.7 – 1.7 | 9.5 |
| …Togliatti | 1700 km | 25.5 - 59.5 | 1.3 – 3.0 | 17.0 |
| …Gubakha | 2200 km | 33.0 - 77.0 | 1.7 – 3.9 | 22.0 |
| Handling cost | - | 2.3 | - | - |
| Ship St. Petersburg to Rotterdam | 1300nm | 24 - 36 | 0.84 – 0.96 | 36 |

Our analysis shows that methanol transport from Russia typically exhibits higher distribution costs than from European locations.

The main reason is the lack of inland waterway infrastructure in Russia and different railway standards, meaning that intermodal transport appears to be the only feasible option. Again, the increased costs of methanol transport from Russia may be compensated by low local methanol prices.

#### 4.4.4 *Distribution from Rotterdam to Dutch bunker locations*

In the previous section, we have discussed the import of methanol to the Netherlands. The remaining part of the downstream supply chain is the further distribution from the main hub Rotterdam to other Dutch bunkering locations. This will most likely take place by (bunker-)ships or trucks, as these would allow for direct truck-to-ship or ship-to-ship bunkering. Typical transport distances within the Port of Rotterdam are estimated at approx. 15 km, and the distance to the Port of Amsterdam is roughly 130 km. Smaller ports like Dordrecht and Moerdijk lie at 30-50 km from Rotterdam, and Harlingen and Den Helder at approx. 200-220 km distance. Below, we calculate the transport cost, energy loss and greenhouse gas emissions for these scenarios and get rather intuitive results. Transport costs per ton of methanol vary between 24€cent and 7.70€ depending on the distance and chosen transport modality. For the ports in Groningen, Delfzijl and Eemshaven, with transport distances above 300 km, it seems beneficial to obtain the methanol directly from the production facility in Delfzijl (see also Scenario 1: NL-NL).

Table 36: Estimated cost, energy loss and GHG emissions for transport of methanol for overseas imports to Port of Rotterdam.

| **Distribution from Rotterdam** | Bunkering location: Dutch Ports | | | |
|---|---|---|---|---|
| | Modality: | Truck or inland/short sea shipping | | |
| *Transport* | *Distance* | *Cost* | *Energy loss* | *GHG emission* |
| *Modality* | *in km* | *in €/t* | *in %* | *in kg/t* |
| | *Within Rotterdam* | | | |
| Inland ship (650t) | ~15 | 0.33 – 0.53 | 0.02 – 0.04 | 0.62 |
| Inland ARA large | ~15 | 0.24 – 0.32 | 0.02 – 0.03 | 0.45 |
| Truck | ~15 | 1.5 – 2.3 | 0.02 – 0.03 | 1.7 |
| | *To Dordrecht, Moerdijk* | | | |
| Inland ship (650t) | 30-50 | 0.66 – 1.75 | 0.04 – 0.13 | 1.2 – 2.1 |
| Inland ARA large | 30-50 | 0.48 – 1.05 | 0.03 – 0.1 | 0.9 – 1.5 |
| Truck | 30-50 | 3.0 – 7.5 | 0.03 – 0.1 | 3.3 – 5.5 |
| | *To Amsterdam or Zeeland ports Terneuzen & Breskens* | | | |
| Inland ship (650t) | ~130 | 2.86 – 4.55 | 0.17 – 0.34 | 5.3 |
| Inland ARA large | ~130 | 2.08 – 2.73 | 0.13 – 0.26 | 3.9 |
| | *To Den Helder, Harlingen* | | | |
| Inland ship (650t) | 200-220 | 4.4 – 7.7 | 0.26 – 0.57 | 8.2 – 9.0 |
| Inland ARA large | 200-220 | 3.2 – 4.6 | 0.20 – 0.44 | 6.0 – 6.6 |

#### 4.4.5 *Price for methanol bunkering*

Next to the costs of methanol production and transport, there is also a cost associated with the bunkering operation. The bunkering costs have been analyzed in the recent TNO Report “Power-2-Fuel Cost Analysis" (TNO 2020, R10166) [46] for the case of e-methanol, but do not depend on the specific methanol production scenario. Here, we perform the same analysis, assuming a lower heating value of methanol of 19.9 MJ/kg [82] instead of 22.7 MJ/kg, so that our numbers differ slightly from those in Ref. [46].

For ship-to-ship bunkering of inland vessels, the typical bunker quantity is assumed to be 40 tons and the costs of the bunker ship is estimated at 2200€/day. With a bunker ship delivering on average 4 times a day, the ship-to-ship bunkering costs for inland vessels lie at 14€/ton or 0.68€/GJ.

In the case of shore-to-ship bunkering, there are different options, such as use of an existing terminal location or storage in a smaller storage unit up to investment in a large-scale bunker terminal. A previous study by EMSA assumes a cost of 5 million EUR for a 20,000 $m^3$ bunkering terminal with bunkering equipment [83]. Assuming a lifetime of 15 years and additional operational costs of 50,000€/year, the cost per berth are roughly 1050€/day.
Assuming that 6 ships can daily bunker 100 tons of methanol by shore-to-ship bunkering, the resulting bunkering costs are estimated at 2€/ton, or 0.08€/GJ.

A similar analysis is performed for truck-to-ship bunkering of inland vessels, as well as ship-to-ship bunkering for short and deep-sea vessels. Our assumptions and the resulting bunkering costs are summarized in in Table 37 below.

Table 37: Bunkering costs of methanol for different bunkering options [46].

| **Specs of bunkering facility (ship/station)** | **Unit** | **Inland ship-to-ship** | | **Inland truck-to-ship** | **Inland shore-to-ship** | | **Short&deep sea Ship-to-ship** |
|---|---|---|---|---|---|---|---|
| Typical bunker quantity | ton | 100 | 40 | 35 | 100 | 40 | 800 |
| | GJ | 1990 | 796 | 697 | 1990 | 796 | 15920 |
| Facility costs | €/day | 2200 | 2200 | 2300 | 1050 | 1050 | 10000 |
| Bunker deliveries | 1/day | 4 | 4 | 4 | 6 | 6 | 3 |
| **Bunkering costs of methanol** | **€/ton** | **6** | **14** | **16** | **2** | **4** | **4** |
| | **€/GJ** | **0.28** | **0.69** | **0.83** | **0.08** | **0.21** | **0.21** |

The table shows that truck-to-ship bunkering is the most expensive bunkering option per unit of methanol, and that both shore-to-ship and ship-to-ship bunkering are very cost-effective options, at least for large bunkering volumes.

#### 4.4.6 *Conclusions on the downstream chain: costs, efficiency and sustainability of methanol supply*

Our analyses in the previous sections demonstrate that the distribution of large volumes of methanol is most practical via inland, short sea or deep-sea shipping. With methanol being one of the most widely shipped chemicals worldwide, the infrastructure for waterways transport and ship-to-ship bunkering is already well-established and widely used, facilitating also its distribution as a marine fuel. While also rail poses an effective and sustainable transport modality, additional handling costs and effort arise in the large ports to distribute the fuel further into trucks or bunker ships. Truck transport of methanol exhibits higher costs and emissions than transport via water, and only seems economically feasible in scenarios with short transport distances and low volumes. In this case, bunkering is likely to directly occur truck-to-ship.

For European methanol supply, transport costs vary between 4.5€/ton and 45€/ton, depending on the transport modality and transport distance. For methanol imported from Russia or from overseas locations, the estimated transport costs can rise up to the order of 100€/ton, but may be compensated by lower local methanol prices. The share of transport cost in the total methanol market price varies greatly. Assuming a methanol price of approx. 200 – 500€/ton, it can be as low as <1% or as high as 56%, depending on the exact supply chain scenario.

Focusing on the sustainability of methanol distribution, the energy used for transportation in Europe on the order of 1% of the transported methanol energy. In contrast, the transport of small methanol volumes or supply chains over long distances (e.g. from Russia) can exhibit energy losses of up to 5%. Also, the greenhouse gas emissions of methanol transport are low compared to the $CO_2$ emissions from the subsequent combustion of methanol as a maritime fuel. With 1.4 – 1.5 ton of $CO_2$ released per ton of methanol as a fuel, transport from Europe or Russia adds between 0.3% and 4% to the total greenhouse gas emissions, while import from overseas could potentially increase the greenhouse gas emissions by up to 12%. As expected, $CO_2$-emissions are significantly higher for longer transport distances, so that the most sustainable option is often the supply chain with the least amount of transport. However, depending on the future national and global supply of green methanol, it may be desirable for sustainability reasons to import large amounts of green methanol. Even if transport and distribution continue to take place in deep sea tankers using conventional fossil fuels, the import of green methanol from distant locations can offer a vast $CO_2$-saving potential. In particular, biomethanol (or even biomass) import from countries with large biomass supply like Norway, Sweden or Canada may be a feasible option in the future, depending again on future availability and policy support.

## 4.5 Demand of Methanol as a shipping fuel in the Netherlands and Europe

In the year 2019, the total bunkering demand of the Port of Rotterdam was roughly 10 million cubic meters of fuel with an energy density of approx. 40MJ/l. If this energy of 400PJ were provided in the form of methanol, the demand of the Port of Rotterdam would amount to 25 million cubic meters, equivalent to 20MT of methanol per year. This is more than four times as much as the estimated methanol production in Europe in 2015, and 2.3 times the maximum European and Russian production capacity.

A naïve comparison with the global market shows that the port of Rotterdam would require 20% of the estimated global methanol production in 2020, and the port of Amsterdam requires an estimated additional 30% of that amount. However, not all vessels calling at Dutch ports are suited to sail on methanol for practical reasons. Chapter 2 of this research shows that, due to its lower energy density, sailing on methanol could prove impractical (but not impossible) for larger vessels.

Based on the outcome of the analysis performed in section 2.7, we assume a market potential of 5 to 22% of the Dutch bunker volume to be replaced by methanol. As a result, the port of Rotterdam would require 1.0 – 4.4MT of methanol per year, equivalent to 1.0 – 4.4% of the global supply in 2020 and 0.7 – 2.9% of the global production capacity. The methanol demand of the Port of Amsterdam amounts to 0.3 – 1.3% of the supply and 0.2 – 0.9% of the global capacity.

Future projections for the maritime sector show that the cargo fleet will increase significantly until 2030, and that the maritime freight is expected to almost double compared to the 2015 level. This freight increase is partly captured by an increase in vessel size, especially in the container segment. The table below shows the energy demand of maritime shipping in the Netherlands and Europe in the year 2017, and the respective projection for 2030.

Table 38: Maritime energy demand in the Netherlands and Europe in the years 2017 and 2030. Sources: [33]; CBS [84]; EEA [85].

| **Maritime shipping energy demand** | **The Netherlands** | **Europe** |
|---|---|---|
| 2017 | 495 PJ | 2000 PJ |
| 2030 | 594 PJ | 2260 PJ |

Also, the global methanol demand and production capacities are expected to grow. By 2030, we expect a supply of ca 160 million metric tons while the production capacity is expected to increase to approx. 280Mt. Assuming the upper limit of the forecasted market share that roughly 22% of the original bunkering volume is replaced by methanol, the total Dutch and European demand of methanol as a shipping fuel in the years 2017 and 2030 can be summarized as shown in the table below.

Table 39: Maritime methanol demand (22% of total shipping demand) in the Netherlands and Europe in the year 2017 and projection to 2030.

| **Methanol demand as a maritime fuel** | **The Netherlands** | | | **Europe** | | |
|---|---|---|---|---|---|---|
| | In weight | In energy | % of global capacity | In weight | In energy | % of global capacity |
| **2017** | 5.5MT | 110 PJ | 3.6% | 22.0MT | 440 PJ | 14.4% |
| **2030** | 6.5MT | 132 PJ | 2.3% | 24.9MT | 497 PJ | 8.8% |

In 2030, it is expected that the Dutch demand of methanol for maritime transport applications constitutes 2.3% of the global capacity. The total European demand has a share of 8.8% of the global production capacity.

Based on our analysis of the methanol infrastructure, the increasing demand of Dutch and European ports during the transition to methanol as a maritime fuel can initially be met with the existing production facilities. As current methanol plants on average only run at 65% capacity, we expect production to be quickly scaled up with the demand by 40 – 50%. This means that Europe and Russia may produce an extra 3 MT/year, while the global production could be increased by ca 50MT. In the first years of a large-scale transition, the methanol demand is likely to grow slower than the scale-up of production facilities, and is therefore the limiting factor in the transition period.

# 5 Conclusions and recommendations

***Sailing on methanol seems applicable for most midrange shipping markets***
Based on data analysis of vessel arrival data in the ports of Rotterdam and Amsterdam, sailing on methanol seems applicable for most midrange shipping markets. The often over-dimensioned tank capacity allows them to bunker methanol without serious adjustments to the bunker frequency, sailing pattern, or tank capacity/ship design. This is particularly the case for shortsea shipping markets and shipping markets with point-to-point sailing patterns. Moreover, inland shipping looks also promising for methanol, whereas ultra large container ships are being built with expanded tank capacity. The methanol applicability heatmap is shown below.

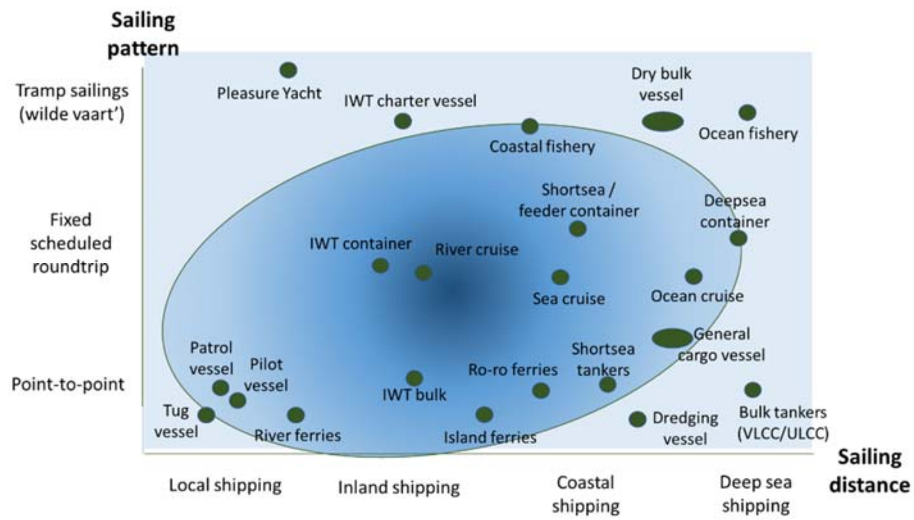



Figure 41: Heatmap of methanol-applicability of shipping segments.

***Methanol bunker demand in 2030 may grow to 5 million m$^3$ in the ARA-region***
The global bunker demand is estimated at around 300 million metric tonnes per year (in 2012). Container vessels constitute of 6% of the world fleet but consume 22% of total yearly bunker volume. Together with dry bulk carriers, oil and chemical tankers they consume almost 60% over global bunker demand. Bunkering in Europe is concentrated in a limited number of ports. The ARA-region (Rotterdam, Antwerp and Amsterdam) handles 20 million tonnes, thus covering 40% of the European market. HFO represents 80%, biofuels and LNG are still marginal in volume, but rapidly increase their share in the modal split. Scenario analysis taking into account the methanol applicability heatmap results in an estimated methanol bunker volume in the range of 0.6 to 2.6 million m$^3$ for Rotterdam and 1.1 to 5.0 million m$^3$ for the whole ARA-region.

***Ship-to-ship bunkering remains the dominant bunker transfer method and bunker infrastructure adjustments are limited***
Today, there are three main bunker transfer methods being applied. Ship-to-ship bunkering is the most common way for maritime vessels, shore-to-ship bunkering is common for barges and local fleet, whereas inland waterway vessels often use a

floating pontoon connected to the shore. And truck-to-ship is a common transfer method for bunkering small volumes. Bunkering at sea is technically possible, but hardly being applied in merchandised shipping.

A transition towards using methanol as marine fuel would have implications, but these can be overcome rather easily and should not be compared with the implications for introducing LNG-bunkering. Truck-to-ship bunkering is suitable for vessels with low bunker demand and is expected to be used in the first pilot phase. Differences in the applicability of safety regimes in terminals between countries may be a point of attention for further research. In case of further growth of methanol,  ship-to-ship bunkering will soon become the dominant transfer method. It requires some additional equipment, training and certification but the bunkering infrastructure needs only marginal adjustments and the ship bunker market will facilitate this if demand is there. Inland chemical tanker barges currently shipping methanol along the Rhine or between Antwerp and Rotterdam may be used to bunkering in the initial stage. Large multifuel bunker vessels are not foreseen to be a mainstream solution, vessels prefer to serve one ship instead of applying a 'milkrun'. Shore-to-ship facilities may become the standard transfer mode for dedicated cruise or roro terminals.

***Bunker prices are volatile, particularly last year***
Volatility of bunker prices is quite high, but last year the bunker market was impacted by the introduction of the 0,5% sulphur requirements by IMO for global shipping and the global shipping demand drop as a result of COVID-19. Cleaner fuels come with a higher price. Methanol is more expensive as conventional maritime fuels, and energy density is more than twice as low. As a consequence, shipping operating costs are expected to increase by at least 50% in case of grey methanol and even more in case of biomethanol or green methanol.

Methanol must be considered as a hazardous substance, because of its volatility, flammability, toxicity and vapour density. It therefore is substantially more risky than HFO or MGO. This results in additional safety requirements with corresponding cost increases: certification, training, ship design parameters, tank requirements and bunker distribution costs. However, there is long experience in shipping and transhipping methanol for industrial purposes. However, the cost increase as a result of these requirements is a fraction of the additional cost for the fuel as such.

***Methanol production is mainly grey and well established, The Netherlands serves as distribution hub in Europe***
Methanol is a well-established market in Europe. Currently around 1.5 Mt is produced in EU27 and around 7.5 Mt is being consumed. Significant amounts of methanol get imported from Trinidad, Venezuela, Equatorial Guinea, the United States and Russia. The Netherlands is an important hub for the current import and European distribution of methanol imported from outside Europe. The Netherlands can consequently also serve as hub for the distribution of green methanol from production locations outside Europe.

Methanol production can be divided in four categories:
- grey methanol, produced from fossil sources like natural gas or coal (called blue methanol when $CO_2$ from exhaust gases is captured),
- biomethanol, produced from biogas,

- Carbon-recycled methanol, making use of a similar gasification technology as dry biomass, with waste streams that are otherwise non-recyclable used as a feedstock for methanol production, and
- e-methanol, produced from green hydrogen and a carbon source.

European and global grey methanol production potential are sufficient to produce viable volumes for a transition to methanol as a maritime fuel. As the availability of green or blue methanol from biomass, waste or electrical power is still low, the methanol demand in the short term will be based on fossil fuels, mainly on natural gas. As the worldwide methanol demand is currently growing, also the production capacities of grey methanol are expected to further increase. As a result, grey methanol will still constitute a significant part of the global supply in the future. Future price developments of grey methanol will be in line with that of the gas market. The price development for the long term will depend on several factors like economic growth, the oil and gas supply and to a significant extend to development of environmental policy measures such as $CO_2$ allowance fees.

***Biomethanol and e-methanol production are not yet mature, being reflected in the prices***

European production for green and blue methanol is currently at significantly lower production capacities than their grey counterparts. The attention and demand for blue and green production routes is vastly growing, and with that also the supply is expected to increase continuously. Future biomethanol prices show a wide range and will be influenced by several factors, including biofeedstock supply, technological development of production, the demand from different sectors, as well as national and international policies. However, the same considerations and price uncertainties also apply to other biofuels such as biodiesel or LBG.

E-methanol is currently at a lower technology readiness level as the other feedstocks. Availability and prices depend a lot on the increase in capacity of green electricity (driving the hydrogen price) and the price of of sustainable $CO_2$-source (DAC).

The cost ranges of grey, bio- and e-methanol, and their depencies on feedstock prices are summarised in Table 26. From 2025 or 2030 onwards a significant amount of grey methanol is likely to be replaced by e-methanol.

Table 40: Cost range for grey, bio- and e-methanol, and their dependencies on feedstock costs.

| Methanol type | Cost range | Cost dependent on |
|---|---|---|
| Grey methanol | € 9-22/GJ | Policy, Natural gas price |
| Biomethanol | € 11-33/GJ | Policy, Biomass & green gas price |
| E-methanol | € 27-68/GJ | Electricity and $CO_2$ costs |

Our analyses for the downstream supply chain demonstrates that infrastructure for methanol is readily available in the Netherlands and that distribution via short sea vessels, inland barges, truck and to a lesser extend rail is feasible. Sourcing could be done via European production facilities or through import via Port of Rotterdam. Even when taking into account a large shift to methanol from maritime applications, we expect that demand can be met since current methanol plants on average do not perform at peak capacity.

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# 7 Signature

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