Synthesis Report | April 2018

Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam

PoR Transport

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on behalf of

This project has been commissioned by the Havenbedrijf Rotterdam Nv. The responsibility for the content rests solely with the authors and the opinions expressed are those of the individual authors.

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Status: April 2018

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Abbreviations, Units and Symbols

Abbreviations

3D	Three-dimensional
BWM	Ballast Water Management
CFC	Chlorofluorocarbon
COP21	Conference of the Parties 21
CNG	Compressed Natural Gas
CSP	Concentrated Solar Power
DB	Deutsche Bahn
D(D)2050	Scenario names in this study: (deep) decarbonisation 2050
DMFC	Direct methanol fuel cells
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
ESI	Environmental Ship Index
EU	European Union
Fig.	Figure
GC	General Cargo
GDP	Gross domestic product
GHG	Greenhouse gas emissions
GWP	Global warming potential
HFO	Heavy fuel Oil
HVO	Hydrotreated Vegetable Oils
IAPH	International Association of Ports and Harbors
IEA	International Energy Agency
IMO	International Maritime Organization
LNG	Liquid Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MRV	Monitoring, Reporting and Verification Directive
P2F	Power-to-fuel
P2G	Power-to-gas
P2L	Power-to-liquid
PEM	Proton exchange membrane fuel cell
PM	Particle matter
PoR	Port of Rotterdam
PV	Photovoltaic
RES	Renewable energy source
T2W	Tank-to-wheel
TPED	Total primary energy demand
UNFCCC	United Nations Framework Convention on Climate Change
W2T	Well-to-tank
W2W	Well-to-wheel
WI	Wuppertal Institute
WPCI	World Ports Climate Initiative

Units and Symbols

$	US-Dollar
%	per cent
€	Euro
°C	Degree Celsius
a	Annum / year
bn	Billion (10^9)
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-eq.	Carbon Dioxide equivalent global warming potential
g	Gramm
GJ	Gigajoule
Gt	Gigatonne
Gtm	Giga tonne kilometer
GWh	Gigawatthour
h	Hour
H_2	Hydrogen
H_2O	Water
HFOs	Hydrofluoroolefins
kg	Kilogram
km	Kilometer
kt	Kilotonne
kW	Kilowatt
kWh	Kilowatt hour
MJ	Megajoule
Mt	Megaton
MWh	Megawatt hour
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_X	Nitrogen Oxide
SO_x	Sulfur Oxide
TEU	twenty-foot equivalent unit
tkm	Tonne kilometer
TWh	Terawatt hour
WACC	Weighted average cost of capital

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Executive Summary

The Port of Rotterdam aims to take a proactive role in promoting an active climate policy in the EU as well as in transport and logistics, and in adapting to the changing business environment by developing new roles and businesses in line with deep decarbonisation. With annual CO_2 emissions of well over 30 million tonnes in the port area emitted by the industrial cluster and around 24.8 million tonnes emitted by transportation to and from Rotterdam, the port is one of the major European GHG emissions hotspots.

This synthesis report presents the main results of the “Deep Decarbonisation Pathways for Transport and Logistics related to the Port of Rotterdam” project. Further detail can be found in five background reports, which can be accessed separately. The **overall objective of the project** is to quantify the GHG emissions of all transport activities related to the Port of Rotterdam and to develop potential scenarios for a decarbonised future by 2050. Furthermore, recommendations are provided on how best to support climate mitigation action in the field of freight transport and prepare for future climate mitigation related changes in the transport sector.

The Port of Rotterdam is the largest European port and among the top twenty ports globally, loading and unloading over 460 million tonnes of cargo in 2015. It serves large parts of the European economy, particularly in North-West Europe and along the River Rhine. Data from 2015 shows that liquid bulk is the major contributor to freight and transport volume, contributing 225 Mt or almost 50 % to freight volume. Containers and other general cargo account for roughly one third of the freight volume. The longest travel distances (over 9 500 km on average) are incoming general cargo, almost double the distance of liquid bulk. Overall, the transport on maritime ships amounts to 3 378 Gtkm, equivalent of 21.4 million tonnes of CO_2 emitted. Hinterland transport account for an estimated 2.22 Mt CO_2 emissions, including “empty back” transports.

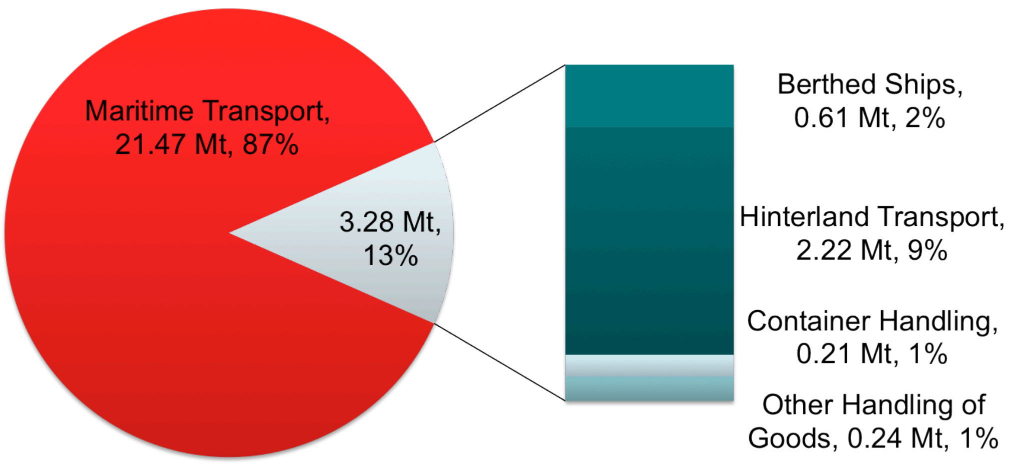

Figure 0-1 Transport-related CO_2 emissions connected to the Port of Rotterdam

The quantification of maritime transport emissions to and from the port is based on data from the Port of Rotterdam and public data, e.g. from the IMO. The resulting level of approximately **21.5 Mt of CO_2 emissions for 2015/2016 is used in this report as a valid estimate of emissions linked to maritime transport to and from Rotterdam.** These account for about 2 % of global emissions from the maritime sector. Berthed ships, hinterland transport and port operations add a further 3.28 Mt CO_2 emissions, with the majority attributable to hinterland transport (see Figure 0-1). The high share of sea freight in transport-related emissions is mainly due to the significantly longer distances travelled by maritime shipping. A tonne of sea freight travels, on average, 7 233 km with CO_2 emission factors of 6.4 g/tkm with correction for partial load and 4.0 g/tkm without. In the hinterland, the average distance travelled is 233 km with emission factors of 25.1/15.9 g/tkm for inland navigation, 19.2/12.6 g/tkm for rail transport and 65.7/51.9 g/tkm for trucks, with and without correction for partial load.

The core businesses at the Port of Rotterdam are the transhipping and transportation of goods and freight, as well as petrochemical and other industrial activities. These activities will change significantly in a future world with much lower GHG emissions and the almost total cessation of the use of fossil resources. While the consequences of decarbonisation for the industrial cluster are the subject of a previous study (Wuppertal Institute 2016), for the transport business these changes raise two main issues:

- "What and how much will be transported in a decarbonised future?"
  In answer, we developed two scenarios for 2050 quantifying the amounts of all major bulk goods that would be transported via Rotterdam in a deeply decarbonised future with GHG emissions reductions of at least 95 %.
- "How will transport be (deeply) decarbonised?"
  In answer, we again developed two scenarios for 2050 looking at factors such as completely different modes of transport, transport with new and improved technology and transport using a different non-fossil energy supply.

In contrast to previous existing scenarios and studies, this project focuses on the year 2050. Detailed pathways that may lead to a decarbonised future are only made for maritime transport. Nevertheless, possible options for hinterland transport were also considered in the development of the future scenarios for 2050.

From the scenarios on "(Deep) decarbonisation effects on transport" it can be concluded that deep decarbonisation will significantly affect transport volumes in both maritime and hinterland transport. Imports will be strongly affected when the bulk used in the power plants and refineries in Rotterdam, as well as in its hinterland, are significantly reduced or phased out. This will result in a massive decline in the transportation of oil and oil products as well as of coal, which will only partly be compensated for by the additional transportation of biofuels or alternative synthetic energy carriers. In contrast, exports via maritime transport, as well as general cargo imports (both largely containerised), are expected to increase. Overall, the growth of container transport has the potential to compensate for the decline in bulk freight volume.

In the hinterland, due to the strong correlation between freight and mode, combined with active measures to switch containers from road to ships and rail, **container volumes on ships are predicted to increase by 112 %** (from 31 Mt to 65 Mt) **and on trains by 110 %.** This would require terminal capacity extensions in both the Port of Rotterdam and along the Rhine of an estimated 50 % to 100 % (the latter with modal shift).

Not only will deep decarbonisation affect transport volume, but the decarbonisation targets will also require transport modes to become more efficient, less polluting and – ultimately – fossil-free. Therefore, in addition to operational and technical efficiency measures, the **"(Deep) decarbonisation of transport"** scenarios considered four alternative energy carriers (synthetic methanol, hydrogen, synthetic methane and renewable electricity), all of which could enable complete greenhouse gas emissions abatement. These were then grouped into two scenarios for 2050: a power-to-liquids (P2L) scenario and a mixed power-to-liquids and power-to-gas (P2L/P2G) scenario. It was further assumed that biofuels and/or liquefied natural gas (LNG) may play an important role as a bridge but will be phased out by 2050 due to lack of sustainable availability and/or limited emissions reduction potential. It is assumed that electricity will become cost-competitive between 2020 and 2030 for short sea shipping and that the same will be true for hydrogen for medium ship ranges over 1 500 km, covering respectively around 9 % and 4 % of shipping volumes by 2050. Synthetic fuels will dominate long distance maritime shipping because of the strong cost decreases over coming decades, as assumed by several studies.

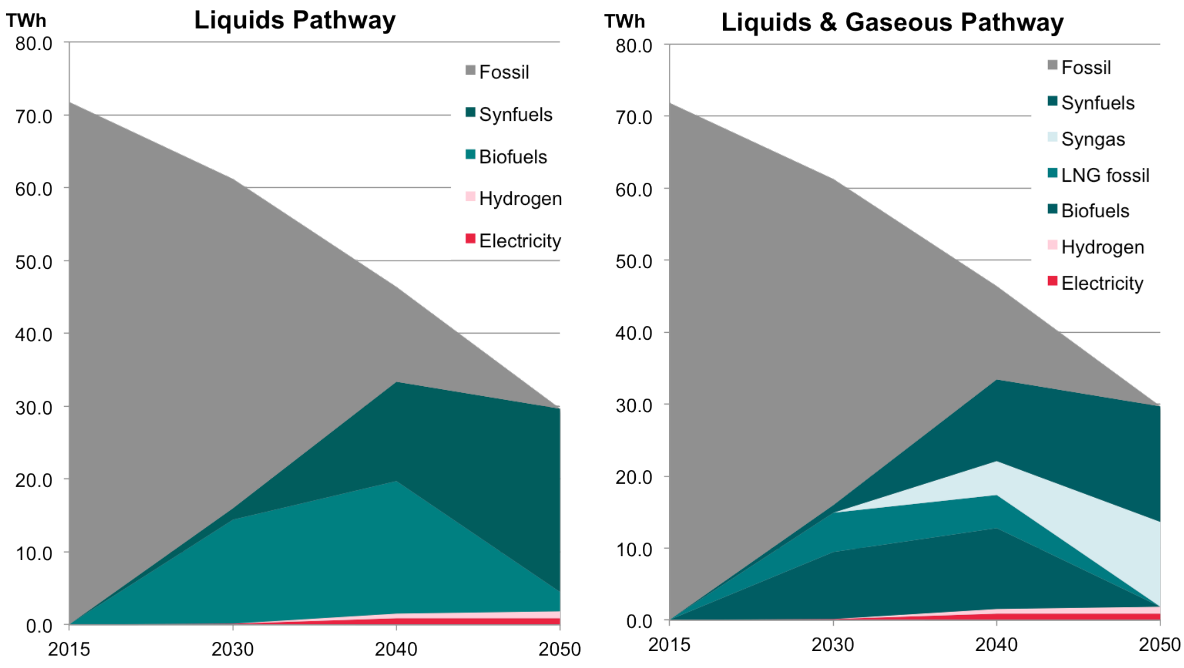

Figure 0-2 **Amount of fuels used for maritime transport to and from Rotterdam 2015 to 2050 (TWh, T2W), two pathways (power-to-liquids: left; power-to-liquids and gas: right)**

Goods and freight transported to and from Rotterdam via **maritime shipping** used 79 TWh of mainly fossil energies in a well-to-wheel perspective in 2015 (72 TWh as direct tank-to-wheel energy demand, see Figure 0-2). This is equivalent to 21.5 million tonnes of CO_2 emissions. By 2050, maritime transport volumes at the Port of

Rotterdam are expected to decline by around 11 %. In parallel, efficiency in maritime shipping will improve by around 50 %, with half of these savings being compensated for by the energy losses from the generation of the synthetic fuels. However, as electricity is assumed to come from 100 % renewable sources in 2050, CO_2 emissions from maritime shipping would be close to zero by 2050.

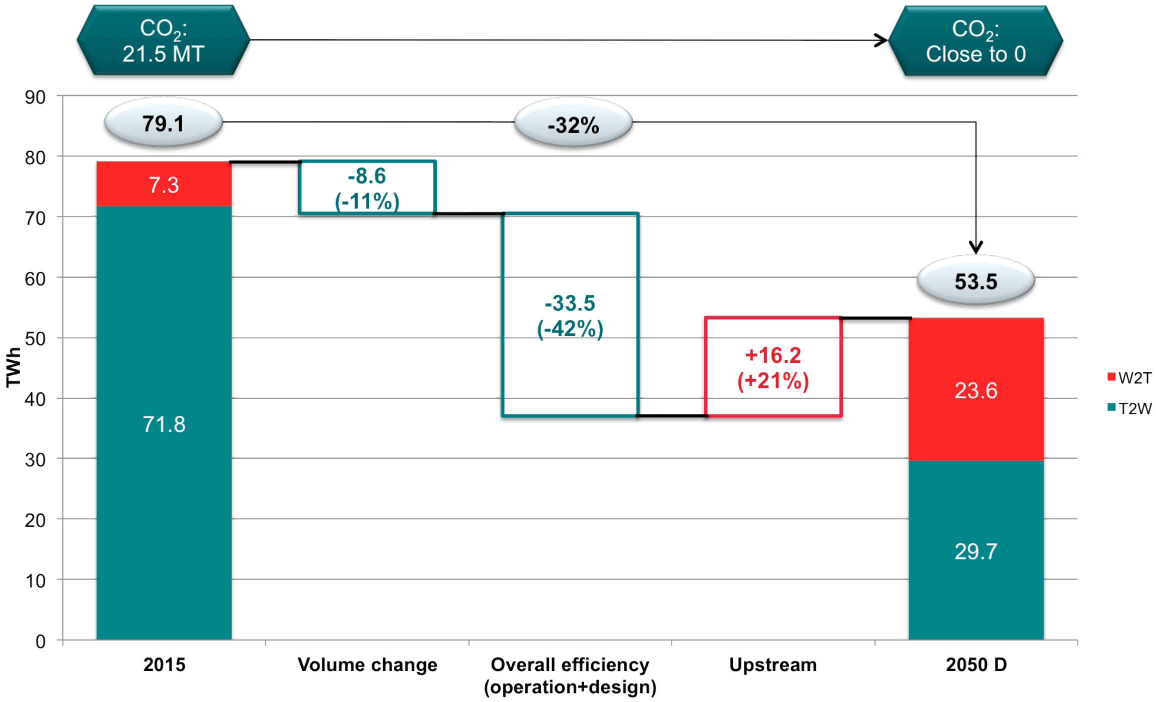

Figure 0-3 Scenario results for energy demand and CO_2 emissions of maritime transport 2050 related to Rotterdam (compared to 2015, liquids pathway)

For hinterland transport in 2015, well-to-wheel energy demand was slightly below 11 TWh, causing around 2.2 million tonnes of CO_2 emissions (Figure 0 3). Currently, tank-to-wheel energy demand is dominated by inland navigation and road transport (each accounting for around 40 %). The most important changes in deep decarbonisation scenarios are a slight decline in overall transport volume and a shift from inland navigation towards road transport. These result from a significant decline in bulk goods and a strong increase in container transportation, which will only partly be compensated by modal shift towards ships and rail. For the non-fossil fuel supply of hinterland transport, four scenarios were developed, each focusing on specific energy carriers. However, it is difficult to predict the future mix of these prototypical scenarios. While railway and pipelines are already almost completely electrified, battery-based inland navigation also seems to be a promising long-term solution. For road transport, however, there is currently no single solution that presents a clear advantage. The results show there is a clear trade-off between renewable energy demand and infrastructural challenges. However, all the scenarios depend on technological/economic developments in future transport energy supply, which will be strongly driven by the future of passenger transport.

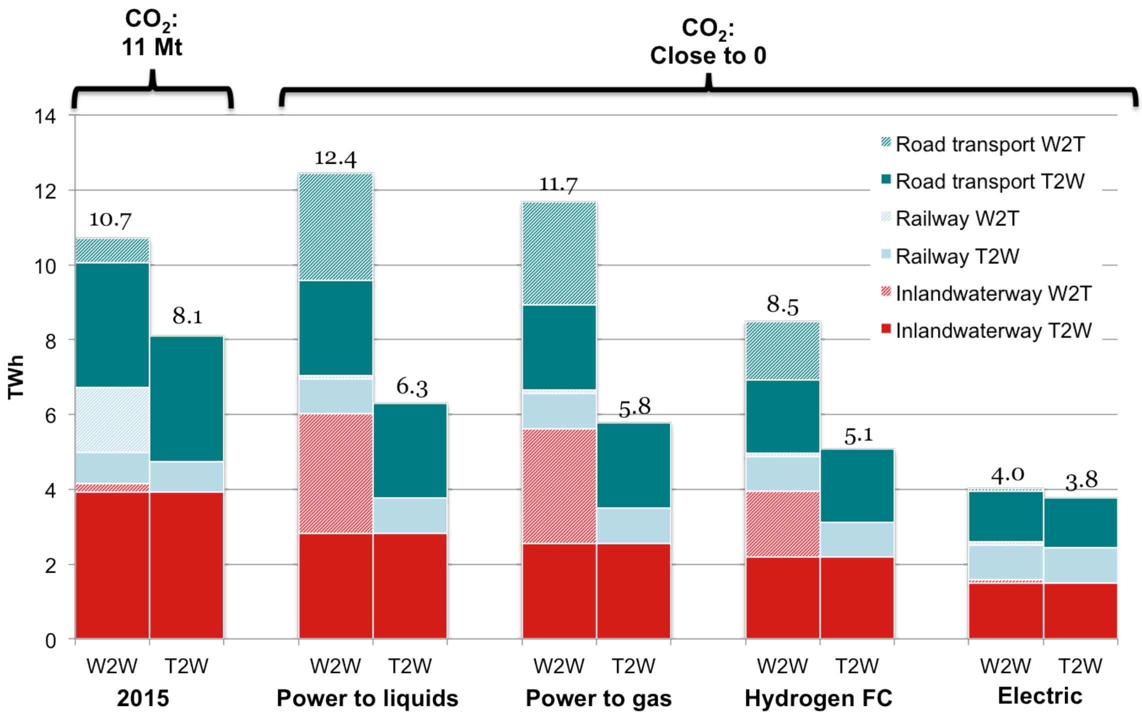

Figure 0-4 **Scenario results inland, energy demand 2050D – four scenarios and CO_2 emissions**

Overall our scenarios for 2050 show:

A) Decarbonisation will significantly change the amount and structure of freight transported, with a clear trend away from bulk and towards containerised transport, which will have significant structural effects on the port operation and particularly on hinterland transport.

B) There are several technological routes for converting transport systems to net zero carbon. However, all of these imply major efficiency gains through operational and technical measures and a switch to non-fossil fuels. For the latter, different routes do exist but there is still strong uncertainty about which option will be the best or will dominate for most transport segments. For all the scenarios, significant amounts of renewable electricity (between 56 and 67 TWh) will be needed, both as energy carriers and (in particular) as input for the generation of hydrogen and hydrogen-based synthetic liquid or gaseous fuels.

Based on the scenario results, a number of **recommendations** can be given to the Port of Rotterdam and other related actors so they can actively prepare for and support the deep decarbonisation of goods and freight transport.

Due to the significant uncertainties about future decarbonised transport systems – in terms of the technologies and their speed of development and market introduction, the infrastructure needed and the related costs – it can be difficult to identify early 'no regret' options for action that go beyond studying current trends and piloting the various options currently discussed.

However, a number of concrete early no regret actions for the Port of Rotterdam have been identified.

- First of all, the IMO, a number of national governments and stakeholders from the shipping industry and the Rotterdam Port Authority are already active and ambitious for GHG mitigation in maritime shipping. The port should, therefore, extend its existing activities and lobby intensively for more ambitious targets and related measures to increase energy efficiency and switch fuel supply to non-fossil energy carriers. The port itself is already active and should intensify its activities to improve operational practices, as well as go through with monitoring and verification to increase energy efficiency and reduce emissions from maritime shipping.
- Closely linked are further actions to fully decarbonise handling facilities at the port; e.g. by electrifying all stationary and mobile motors, increasing uptake rates for land-based electricity supply for ships at berth and supplying heating and cooling energies from waste energy from industrial installations or with green electricity. This could be linked to own renewable energy generation at the port.
- With regards to the future fuel supply of maritime transport, liquefied natural gas (LNG) seems to be a promising bridge solution as it offers immediate (but limited) GHG emissions reductions and strong pollution reductions, and could easily be converted to renewables-based synthetic methane as soon as that technology is available. The port might, therefore, consider strengthening its existing activities to support the uptake of LNG by large shares of ships. Furthermore, for short distances, battery electric and hydrogen fuelled ships may soon be available options. Developing pilot projects with owners of e.g. tug boats, ferries and inland ships to offer electricity or hydrogen could be developed as no regret options.
- Our scenarios also show that structural changes in hinterland transport will be of strategic relevance to the Port of Rotterdam. To tackle the resulting infrastructure challenges (i.e. to enable much higher container volumes to be transported on inland ships instead of by truck), an integrated vision and action plan for the future decarbonised transport in the Rotterdam hinterland seems to be crucial. Such a plan would need to be developed in cooperation with national and regional governments.
- Finally, most of the challenges of deep decarbonisation will not affect the port itself, but rather its "business partners" i.e. the logistics and transport companies and service providers operating at the port. Therefore, we recommend establishing a continuous "Rotterdam decarbonisation of transport dialogue" with all stakeholders to improve early awareness of the evolving decarbonisation challenges for the Port Authority and for the companies active at the port. Such a dialogue could be based on a decarbonisation concept founded on measures already implemented and/or planned by the port and could also become a nucleus for joint pilot projects or studies of relevant trends.

1 Introduction and Background

Global, European and Dutch climate policies will have a significant effect on the way businesses operate at the Port of Rotterdam, given its high exposure to the use, handling and conversion of fossil fuels.

In 2015, 195 nations reached the Paris Agreement at COP 21 aiming to combat climate change. This agreement changed the global political landscape and calls for its members to develop plans “to reach global peaking of greenhouse gas emissions as soon as possible [...] and to undertake rapid reductions thereafter” (UNFCCC 2015, Art.4.1). Full GHG neutrality of the parties’ economies “in the second half of this century” is the aim. The EU has taken action in response to the agreement and is currently in the process of refining its long-term strategy. This will involve and require fundamental changes to European energy supply and demand in order to achieve the EU targets for greenhouse gas (GHG) emissions reductions. Consequently, there will be significant repercussions on both the European economy and individual companies, including the organisation of transportation and, particularly, its energy supply, as well as the volume of fossil energies transported.

The Port of Rotterdam aims to take a proactive role:

- by promoting an active climate policy in the EU as well as in transport and logistics; and
- by adapting to the changing business environment and developing new roles and businesses in line with deep decarbonisation.

With annual CO_2 emissions of well over 30 million tonnes in the port area and around 24 million tonnes from transport to and from Rotterdam, the port is one of the major European GHG emissions hotspots. As a result, the Port of Rotterdam has a particular responsibility to actively contribute to European GHG emissions reduction efforts. Against this background, for several years the Rotterdam Port Authority has been showing a keen interest in becoming a frontrunner in climate mitigation and in learning about ways of significantly reducing the port region’s GHG emissions. In 2016, the Port Authority commissioned the Wuppertal Institute for Climate, Environment and Energy to conduct a study on *Decarbonisation Pathways for the Industrial Cluster of the Port of Rotterdam* (Wuppertal Institute 2016a). The study explores the consequences of global decarbonisation for the Port’s industrial cluster and identifies possible scenarios illustrating how the port could prepare for such a future and take a pro-active stance towards deep decarbonisation. Recently, it was announced that the port aims to reduce emissions in line with the Paris Agreement: CO_2 emissions reduction by 49 % in 2030 and by 80 % - 95 % in 2050 compared to 1990 levels (PoR 2017a, PoR 2017b).

Not only climate change, but also future decarbonisation activities will have a major impact on the Port of Rotterdam. The bulk of the port’s economic activities currently focus on trading, handling, converting and using fossil fuels, i.e. fossil carbon. This makes the port’s businesses particularly vulnerable to global and European decarbonisation efforts. The stepwise phasing out of fossil resources is at the very core of any decarbonisation strategy and moving economic activities towards low carbon will only be possible if businesses adapt to the challenge of zero GHG emissions production and value chains. Since these are often technically possible, it is crucial to create new value chains for a decarbonised future. The Port of Rotterdam is – together with the companies active in and around the port – an important player. Adopting an active and innovative role towards achieving climate neutral businesses and economies will be of great impact.

The overall objective of this study is:

- to quantify the GHG emissions of all freight transport activities to and from Rotterdam and to develop potential deep decarbonisation scenarios for these activities, covering maritime transport as well as port operations and hinterland transport; and
- to advise the Rotterdam Port Authority (a) how to support climate mitigation action in the field of freight transport and (b) how to best prepare for future changes in the transport sector and create a conducive business environment for companies trying to take advantage of emerging business opportunities.

A previous study focused on the decarbonisation of the port's industrial cluster (Wuppertal Institute 2016a). The Rotterdam Port Authority has now decided to extend its focus by quantifying the GHG emissions of all transport activities to and from Rotterdam, as well as by developing potential deep decarbonisation scenarios for its transport business and sector. The results of this analysis are documented in this report. Following a quantification of the transport-related GHG emissions, deep decarbonisation scenarios were developed; these cover maritime transport as well as port operations and hinterland transport. For maritime transport, two pathways towards a decarbonised future by 2050 were also outlined.

This report takes into account the uncertainties related to future developments in the transport sector in order to derive robust and low-risk measures for the Port Authority and the area's businesses. Where possible, existing Port Authority initiatives and sustainable transport activities in the port area were considered.

In parallel to this project period, and shortly before the publication of this synthesis report, two studies on deep decarbonisation of maritime transport, the OECD/ITF (2018) "Decarbonising Maritime Transport" and LR/UMAS (2017) "Zero-Emission Vessels 2030. How do we get there?", were published. In terms of the technological decarbonisation options, there is a large overlap with the strategic options presented in this report.

However, in contrast to the studies listed and IMO (2015), this report specifically addresses the Port of Rotterdam, which (a) serves North-West Europe – currently regarded as a front runner region in energy transition towards fossil decarbonisation; and (b) includes hinterland transports as Rotterdam is a central point of interconnection between maritime and hinterland transport.

Therefore, this report provides a more detailed bottom-up analysis of transport volumes in a deeply decarbonised future and it also focuses on important actors, such as the Port of Rotterdam and its business partners (mainly in the shipping and logistics industries), as well as the Dutch and other governments.

This report is divided into four parts.

After explaining the background and providing a brief introduction to the topic in Chapter 1, the second chapter deals with the status quo. It presents the structure of transport to and from the Port of Rotterdam and quantifies the related CO_2 emissions with a special focus on the limitations of such CO_2 emissions accounting. Chapter 3 discusses the central strategies of deep decarbonisation of transport, as well as the related scenarios for 2050 for both maritime and hinterland transport. It also shows possible pathways to fossil-free maritime transport. Based on the scenario results, Chapter 4 derives recommendations for the decarbonisation of transport in 2050 and finally outlines possible first steps.

This synthesis report summarises the main results of the project and builds on the following background reports, which are available separately:

- Technologies and fuels for decarbonising maritime and hinterland freight transport
- Decarbonisation-driven future changes in European transport
- Implications of anticipated future developments for the Port of Rotterdam
- Quantitative assessment of maritime transport, CO_2 and fuel: status quo
- Future transportation scenario 2050 – freight, modes of transport and fuel

2 Status Quo

The Port of Rotterdam is the largest European port and among the top twenty ports globally, loading and unloading over 460 million tonnes of cargo in 2015. It serves large parts of the European economy, particularly in North-West Europe and along the River Rhine. As well as the hinterland destinations served by the port via barge, rail, truck and pipeline, a lot of goods are also reloaded to and from seagoing ships serving smaller ports all over North-West Europe, including the UK and Scandinavia.

2.1 Transport via Rotterdam

According to 2015 data, bulk is the major contributor to freight and transport volume, with liquid bulk contributing 225 Mt, or almost 50 %, to freight volume and dry bulk accounting for 88 Mt (Figure 2-1). Containers and other general cargo account for 154 Mt or roughly one third of the freight volumes.

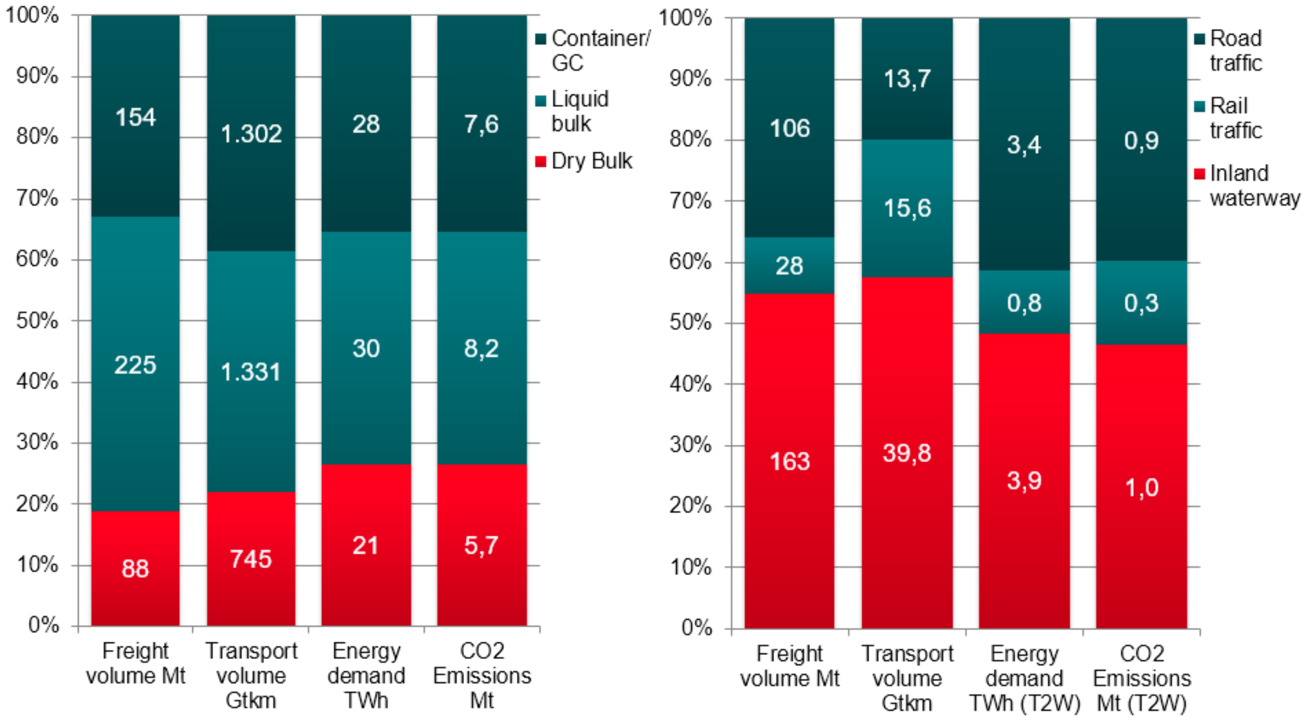

Figure 2-1 Status quo sea freight (left) and hinterland transport (right), 2015 Data from Port of Rotterdam and own calculations

In terms of the balance between input and output, much more liquid bulk is imported than exported, solid bulk is almost only imported and containers are roughly balanced. Routes, transport distances and ship types, however, differ significantly between the types of freight. While dry bulk and containers/GC travel on average 8 500 km, liquid bulk travels one third less – 6 700 km on average (Table 2-1).

Overall, the 467 Mt of freight unloaded and loaded in Rotterdam from/onto maritime ships travel on average effectively around 3 378 Gtkm, or 7 233 km. However, this number increases to 4679 Gtkm with included empty back transport (compare Figure 2-2). The ships needed for delivery of these transport volumes emit in total around 21.4 million tonnes of CO_2.

Table 2-1 Maritime average distance per tonne (tkm/t)

	Incoming	Outgoing
Dry Bulk	9 058	2 377
Liquid Bulk	5 212	8 214
Container/GC	9 538	7 396

A huge share – but not all – of the goods unloaded in Rotterdam are further transported to various hinterland destinations via barges and inland waterways, trucks, trains and pipelines. On the same routes, goods are transported to Rotterdam and loaded onto maritime vessels.

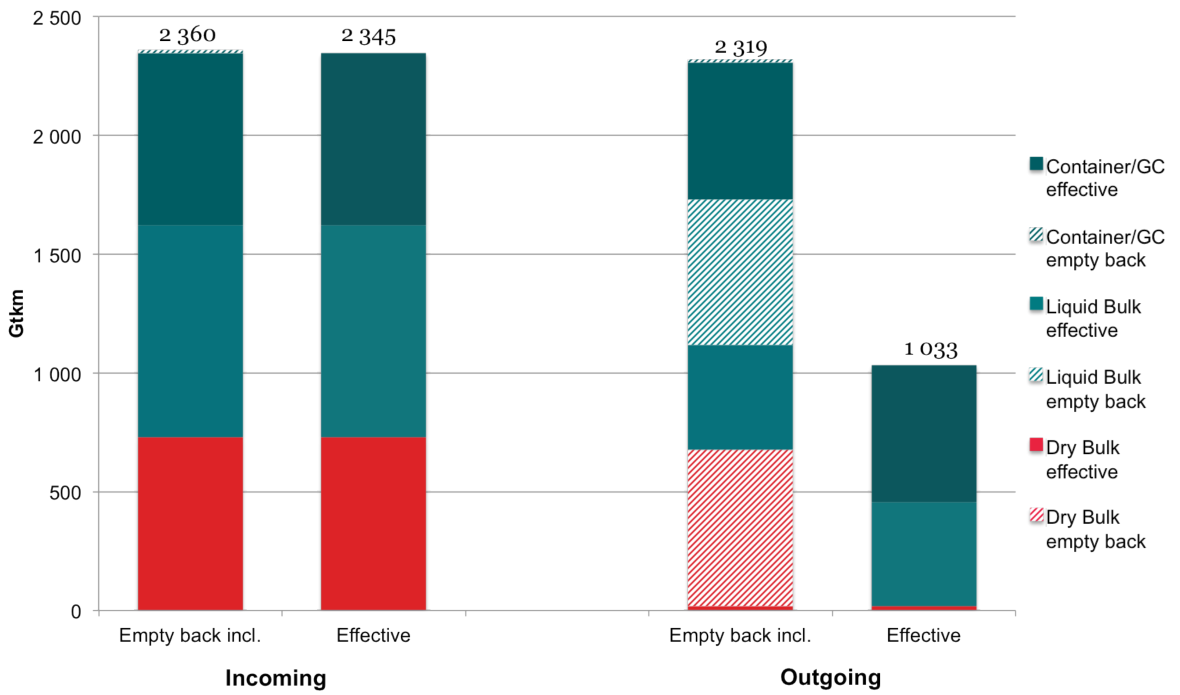

Figure 2-2 Status quo Transport Volumes Maritime 2015 (Gtkm)

With a freight volume of 163 Mt, inland waterways account for 58 % (39.8 Gtkm) of the hinterland transport volume. This is matched by an energy demand of 3.9 TWh and CO_2 emissions of 1 Mt – both based on the tank-to-wheel (T2W) approach (Figure 2-3).

In the case of inland waterway transport, shares of freight transport, transport volume, energy demand and CO_2 emissions are relatively similar. For road and rail transport this ratio is different. Road transport accounts for only 20 % of the transport volume (13.7 Gtkm) with a share of 36 % of the freight volume (106 Mt). This is due to short transportation distances of 129 km on average (158 km including empty return travel). However, road transport contributes 40 % of CO_2 emissions (0.9 Mt) in the hinterland with a share of energy demand of 41 % (3.4 TWh). The reverse is true for rail transport[1] . Accounting for 9 % of the total freight volume (28 Mt), rail transport comprises 23 % of the transport volume in the hinterland (15.6 Gtkm), while the energy demand is only 10 % (0.8 TWh) and the contribution to CO_2 emissions is 0.3 Mt (14 %). In summary, the graph shows that inland waterways and road transport are particularly critical areas of focus for the deep decarbonisation of hinterland transport.

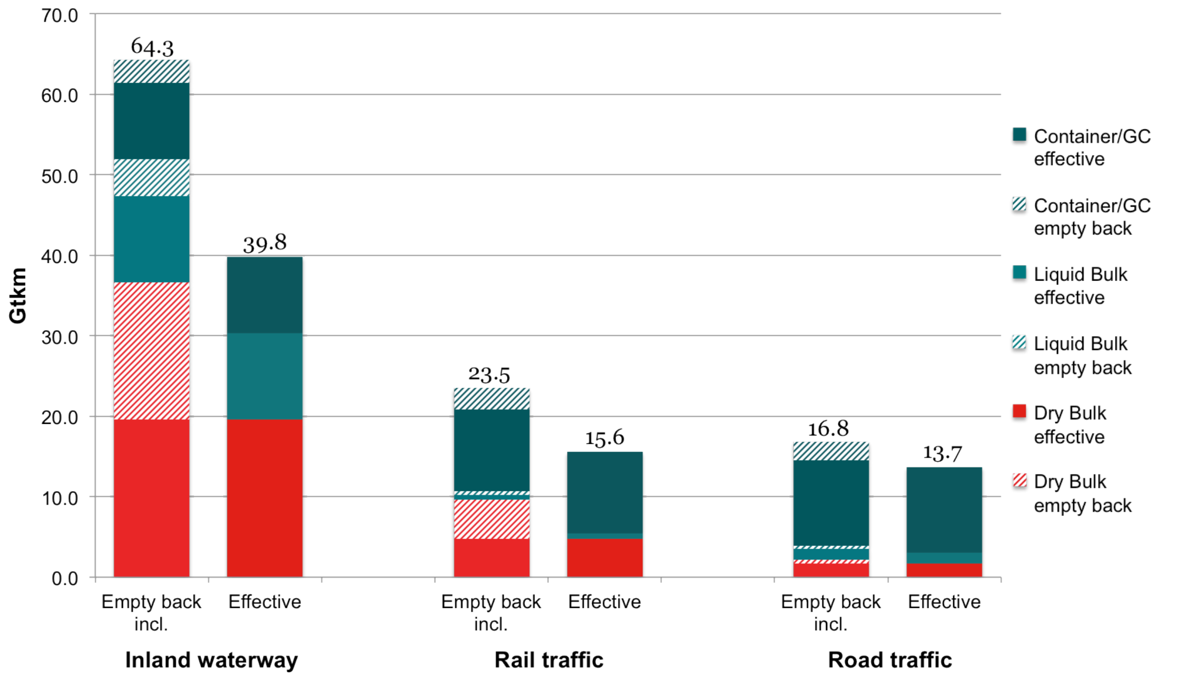

Figure 2-3 Status quo Transport Volumes Hinterland 2015 (Gtkm)

The total 2.22 Mt CO_2 emissions by hinterland transport were estimated according to the so called "freight approach" and include "empty back" transports. It was further assumed that 80 % of all incoming ships are loaded with outgoing goods and vice versa. Pipelines of less than 100 000 tonnes were not included.

2.2 Scope and limitations of the CO_2 emissions quantification

One of the aims of this study is to provide an overall quantification of the transport to and from Rotterdam and its related CO_2 emissions. As the Port of Rotterdam is an important hub for global transport and given the complex and meshed nature of the latter, the quantification is a challenge and the results have certain limitations due to the methodology used and the data available.

- The quantification is based on the data available from the port and on other publicly available data.
- It is difficult to clearly delimitate the actual transport relating to the Port of Rotterdam.

[1] For rail transport and other electricity-based modes (pipelines), the T2W assessment is based upon electricity generation (the emissions of the power plants are included, but not those for mining the fossil fuels) and not, as is common in other studies, solely on the train operations themselves.

Consequently, the scope of this study pragmatically encompasses all transport "touching" the Port of Rotterdam, in so far as these types of transport can be identified and might be influenced by the port. However, two quite different categories are identifiable: a) ships and other vehicles loading and unloading in Rotterdam; and b) goods and freight that have been loaded and unloaded in Rotterdam. There is specific data available for both these categories but, given the resources of this project, it was not possible to fully combine the ship data with the goods and freight data. Each was, therefore, analysed separately with comparisons made in the conclusion to the project.

This leads to the fact that two methods were applied to assess the total CO_2 emissions of maritime transport to and from Rotterdam. These are conceptualised in the following figure.

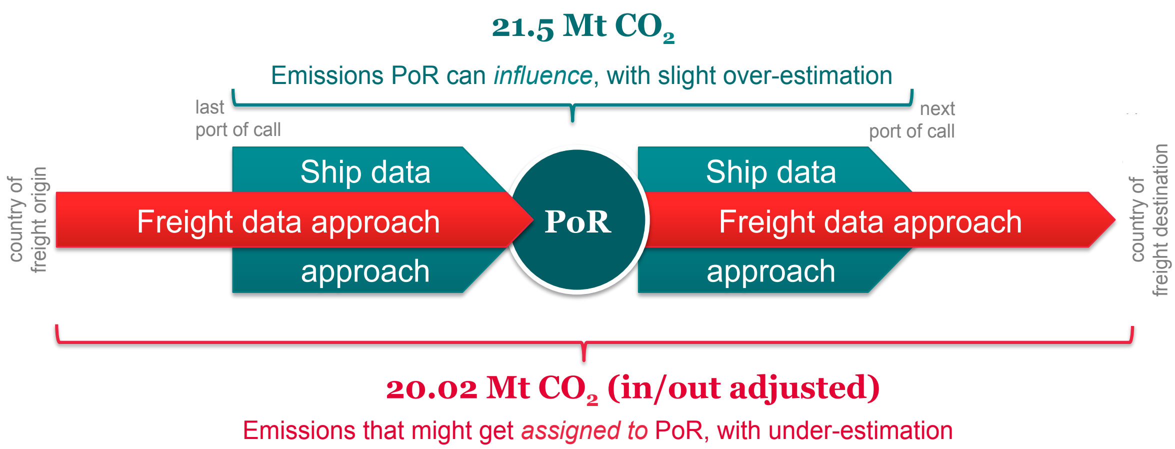

Figure 2-4 Two approaches for the assessment of CO_2 emissions of maritime transport in relation to the Port of Rotterdam

The first approach, the "ship-data approach", used a list of all ships calling at Rotterdam. This register contains size and type of each ship, as well as its previous and next ports of call. There was, however, no data available regarding the amount of freight each ship had loaded or unloaded.

- This data enables the precise identification of the ship type in question and a good estimate of its typical energy demand and CO_2 emissions based on matching the ship's type and size with representative data from IMO (2015). An exact quantification of the travelling distances to and from the last/next port is also possible.
- On the downside, the transport chain often does not start at the port of the ship's departure (last port of call) and does not end at the port of destination (next port of call). This is particularly relevant for ships carrying general cargo and loading/unloading at several ports on a trip rather than direct line shipping, as is typical for bulk freight. In such cases, the ship-data approach only covers part of the transport chain. Consequently, this approach generally does not encompass the complete transport chain in terms of its geographical extent.

The ship-data approach can provide a good estimate of the emissions of all ships calling at Rotterdam on their routes to and from their next/last ports of call. It is, however, evident that these emissions underestimate the distances travelled by these ships, as most of the general cargo ships call at several ports on their trip. On the other hand, this approach overestimates the share of these emissions that might be allocated to freight loaded or unloaded at Rotterdam, as the general cargo ships typically carry lots of freight on board that is neither loaded or unloaded at Rotterdam[2].

The second approach, the "freight-data approach", uses data on freight unloaded and loaded in Rotterdam with information about its country (or region for hinterland transport loads) of origin or destination. The freight data, however, does not contain any information about the ship that carried the load.

- Using this approach yields a complete coverage of the geographical extent of transport touching Rotterdam, as final destinations and origins of all goods loaded and unloaded are recorded.
- However, this approach tends to underestimate the size and number of ships needed for transportation as it lacks information about the load factor of the ships (a ship's energy demand does not vary much whether it is fully loaded or loaded to 50 % or less). It also does not provide information about e.g. bulk freight ships that typically come in full but then return the same distance empty. Therefore, this approach – despite accounting fully for the transport in geographical terms – underestimates the energy usage.

To overcome these limitations, we combined both approaches for our calculations. Emissions were estimated using a correlation of freight type and destination with typical vessels used for these goods and routes. In addition, capacity usage was factored in by adding energy demand and emissions for the empty shipments (e.g. crude oil tankers), typically returning empty from Rotterdam to the port of origin, while assuming typical capacity usage during the loaded sections of the ships' journeys.

Using the ship-data approach, we estimate that the Port of Rotterdam could be related to (a slightly overestimated) 21.5 Mt CO_2 emissions, as the trips covered all call at Rotterdam. In comparison, an uncorrected freight-data approach leads to an estimate of emissions of at least 14.4 Mt CO_2 (inbound 9.8 Mt, outbound 4.4 Mt) potentially assigned to the Port of Rotterdam. These emissions relate to the total maritime voyage of the goods loaded and unloaded at Rotterdam (assuming 100 % load factors for 100 % of ships). If the freight-data approach is modified using capacity factor and empty return transport data, it results in similar global emissions levels as the ship-data approach.

Therefore, **the level of 21.5 Mt of CO_2 emissions is used in this report as a valid estimate of emissions** linked to maritime transport to and from Rotterdam.

From a potential for action point of view, the ship-data approach has some advantages as it focuses on the ships that actually stop in Rotterdam and, therefore, may be influenced by regulations and incentives put in place by the Port Authority. The Port Authority might be in a position to influence the ship owners via information, fees or provision of infrastructure.

[2] An extreme case would be a container ship with 100 000 TEU stopping at Rotterdam and unloading just one container. According to the ship-based approach, all emissions on its trip, e.g. from New York, would be taken into account, although only 1/100 000 of the freight on the ship was bound for Rotterdam - the rest was for other ports.

For inland transport there was no data available on concrete numbers of vehicles loaded and unloaded. Consequently, only the freight-data approach could be used, in combination with typical values on load factors and empty return transport.

Our quantification approach also has some limitations regarding the hinterland side, as e.g. ship-based transports to North-Rhine Westphalia are typically assumed to be on ship only and go to Duisburg or another port in the state. However, particularly for general cargo, the "last mile" is then typically delivered by truck, which is not accounted for in our approach. Overall, however, the margin of error relating to this incomplete coverage is estimated to be small, since it is less relevant for truck transport and limited for other modes. For the sake of completion, the emissions relating to the handling of freight in the port have been estimated (see below).

Finally, in terms of GHG mitigation policies, it might be relevant to whom the emissions related to a port are assigned, i.e. who will be held responsible for the emissions related to the port. This report aims to provide a complete depiction of CO_2 emissions for transparency and strategic reasons and to identify options for action by the port. Obviously, this does not mean that the port (alone) should be held responsible for these emissions, neither are the emissions split among ports in a commonly-used emissions accounting approach. Clearly, other actors in the transport system, as well as along the whole value chain, also play a role in generating the transport and may also have levers to reduce GHG emissions resulting from this transport. Such actors should, therefore, also feel responsible for these emissions.

2.3 CO_2 emissions relating to the current transport volumes

Looking at the big picture, CO_2 emissions relating to transport to and from Rotterdam have been estimated for 2015/2016 at around 24.8 million tonnes of CO_2. Of these, the share attributed to the maritime sector (mainly, but not solely, caused by international shipping) accounts for the clear majority (about 87 % or 21.5 Mt). This equates to about 2 % of global emissions from the maritime sector (see e.g. IMO 2015). Berthed ships, hinterland transport and port operations add another 3.28 Mt, with the majority emanating from hinterland transport.

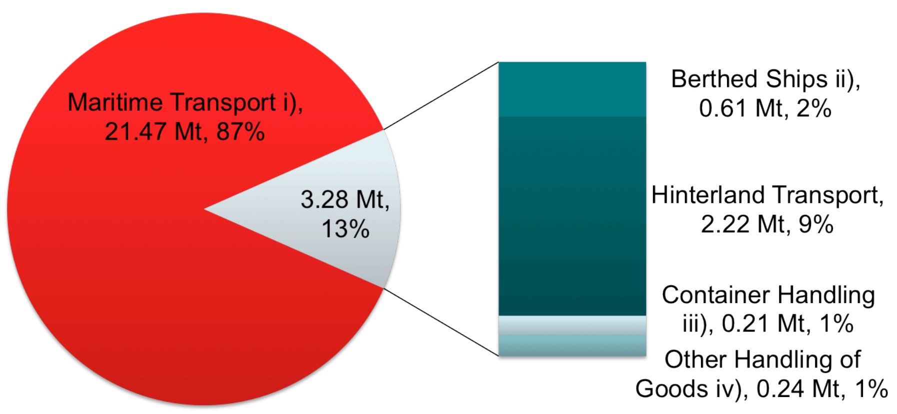

Figure 2-5 Transport related CO_2 emissions in connection with the Port of Rotterdam
i) all vessels calling at Rotterdam, to/from next/last port of call, based upon Port of Rotterdam data and IMO (2015); ii) MARIN (2016, p. 40); iii) CE-Delft (2017); iv) Data provided by the Port of Rotterdam

The high share of sea freight in transport-related emissions is mainly due to the significantly higher distances travelled by maritime shipping, as a tonne of sea freight travels on average 7 233 km, while in the hinterland the average distance is 233 km (both not including empty return travel).

This is not compensated by the higher emission factors of inland transport compared to sea freight, where emission factors are on average 6.4 g/tkm (when partial load of ships and empty return travel is taken into account) or 4.0 g/tkm (Figure 2-5).

Emission factors for inland transport are at least three times as high: 19.2/12.6 g/tkm for rail transport, 25.1/15.9 g/tkm for inland navigation and 65.7/51.9 g/tkm for trucks, with and without correction for partial load. Figure 2-6 gives an overview of the specific emission factors, based on a tank-to-wheel (T2W) approach[3] . Emission factors for seafright have been calculated based on IMO (2015) data and those for inland modes based on UBA (2016). Both are given per tkm for the respective (average) vehicle assuming it is fully loaded and with a correction factor taking into account part load and empty return trips.

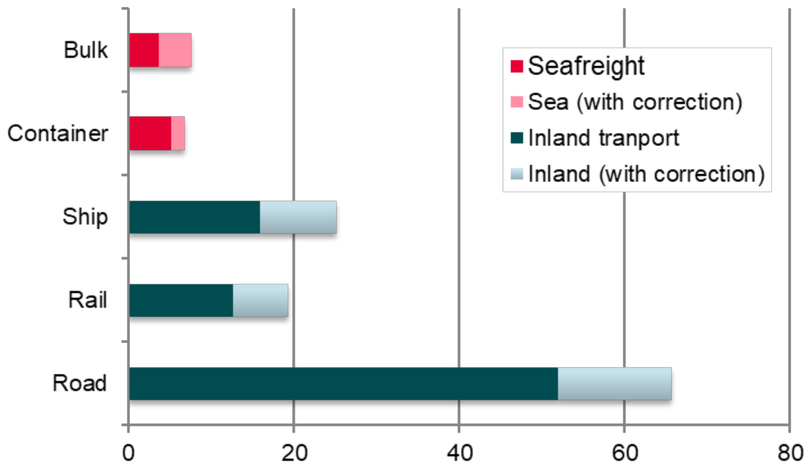

Figure 2-6 CO_2 emission factors 2015 (T2W) in g/tkm by transport mode (correction for partial load / empty return trips).

[3] Tank-to-Wheel (T2W) covers the operation of the respective vehicle. The conversion of the fuel into kinetic energy takes place differently depending on the vehicle technology (e. g. combustion engine, electric motor) and the efficiency of the individual vehicles also differ greatly. Well-to-Tank (W2T) begins with the extraction of raw materials for fuel production and ends with the finished fuel in the vehicle tank. There are a large number of fuel supply chains that can be combined from different raw materials (e. g. crude oil, natural gas or biomass) and production techniques to produce different fuels (e.g. petrol, hydrogen or electricity). If the two systems of the upstream W2T and the operating phase of the T2W are combined, this is referred to as a comprehensive Well-to-Wheel (W2W) analysis (Witschel 2017), (Brinkmann et al. 2005, p. 11).

Box 1 Co-Benefits of Decarbonisation

Apart from the mitigation of direct net CO_2 emissions, decarbonisation of the transport sector yields additional socio-ecological benefits that can, at least partly, be translated into monetary units (UBA 2012). It appears probable that at least some of these effects can be seen as positive side-effects (positive externalities).

As presented in Figure 2-7, carbon-heavy fuels yield higher emissions in terms of soot particles that contribute to the atmospheric fine dust load, as well as to nitrogen oxide (NO_X) emissions. Without further purification, liquid fossil-based fuels and heavy fuel oils (HFOs) especially are also heavy on SO_X, like sulphur dioxide emissions, causing acid rain and other effects (Persson et al. 2013). The purification process itself requires large amounts of hydrogen in the refineries.

Soot particles (themselves a part of another of the suggested planetary boundaries, see Rockström et al. (2009)) are the main source of so-called "black carbon" emissions, which act as contributors to global warming by darkening bright areas, especially ice and snow (see Box 2: "Game-Changer Ice-Free Arctic Passage"), causing higher sunlight absorption and increased ice melt. In addition to these effects, such particles act as aerosols in the atmosphere and have a direct influence on convection and precipitation patterns, changing and potentially increasing incidences of rain and storms (Fan et al. 2018).

NO_X are the main sources of urban smog clouds, as well as a source of ozone depletion and powerful greenhouse gases (Ravishankara et al. 2009; Reese 2018). The particle emissions that contribute to fine dust increase in relation to the length of the hydrocarbon chains and to the height of the vaporisation temperature of the fuels, and there are trade-offs between optimised combustion in terms of low NO_X emissions and low particle emissions. Only (energy-demanding) advanced exhaust gas treatment can significantly reduce these emissions from carbon-heavy liquid fuels. This, in turn, increases the CO_2 emissions intensity due to losses in overall energy efficiency and requires increased usage of catalyst materials like platinum, palladium and other platinum-group metals. Methanol and methane face significantly fewer of these issues, as combustion can be driven in such a way that almost no soot is generated and NO_X emissions are relatively low. SO_X is non-existent in natural gas combustion exhausts and can be avoided in synthetic fuels (Chryssakis et al. 2014).

Incomplete combustion of hydrocarbons (CH) results in CH emissions, of which some compounds are carcinogenic, and some are strong greenhouse gases. All hydrocarbon fuels face this issue, with methane potentially causing more climate-harming CH_4 emissions and more carbon-heavy fuels emitting more hazardous CH compounds. Optimised combustion with air surplus and the application of oxygen catalysts (now routinely used in all road vehicles) can help to avoid these emissions. To further avoid NO_X and particle emissions, particle filters and urea-solution inserting selective catalysts are required (Reif et al. 2011).

All liquid fuels pose high risks for polluting water and soils. Methanol is a special case, as it is highly poisonous in water, yet can be relatively easily diluted and broken down by micro-organisms if spills occur in the open seas.

Using hydrogen as a fuel would avoid all these additional emissions and does not pose ecological risks if directly released into the environment. However, the explosion risk is substantially higher than for other energy carriers.

Noise emissions are also typically higher for cylinder-driven engines than for electric motors, regardless of whether these are powered by electric batteries, direct electricity or hydrogen fuel cells. In terms of requiring less repair and maintenance, electric motors display another advantage as there are less moving parts involved, enabling longer overall lifetimes.

3 (Deep) Decarbonisation Scenarios

The deep decarbonisation of European and global economies will be an important future trend. Unlike trends such as digitisation and globalisation, the phasing out of greenhouse gas emissions from economic activities is a global requirement in order to slow down future global warming and to prevent its most harmful and potentially catastrophic consequences, such as rising sea levels, more severe weather events, accelerated loss of biodiversity etc.

Phasing out greenhouse gas emissions, as planned by the middle of the 21st century for industrialised countries and soon thereafter globally, means that the use and combustion of fossil carbon needs to be terminated by 2050 as one of the core strategies of climate mitigation. Fossil carbon in chemical products, biogenic carbon or carbon captured from the atmosphere might be used for longer periods. This could happen in the case of synthetic fuels using carbon recycled from the atmosphere, which can be regarded as climate neutral or "net zero emission".

Particularly since the Paris Agreement (UNFCCC 2015), governments as well as industries and citizens have become increasingly aware of this target and challenge. There is rapid growth in the number of strategies and national plans, as well as civil society and business activities aiming to achieve these goals.

For the Port of Rotterdam these decarbonisation efforts are relevant in multiple ways. As well as potentially being affected by the consequences of inevitable climate change (which is not the subject of this study), the main businesses at the port, i.e. to transport goods and freight, much of which is fossil fuels, as well as petrochemical and other industrial activities (also not part of this study), will be significantly different in a future world with much lower GHG emissions and an almost complete cessation of the use of fossil resources.

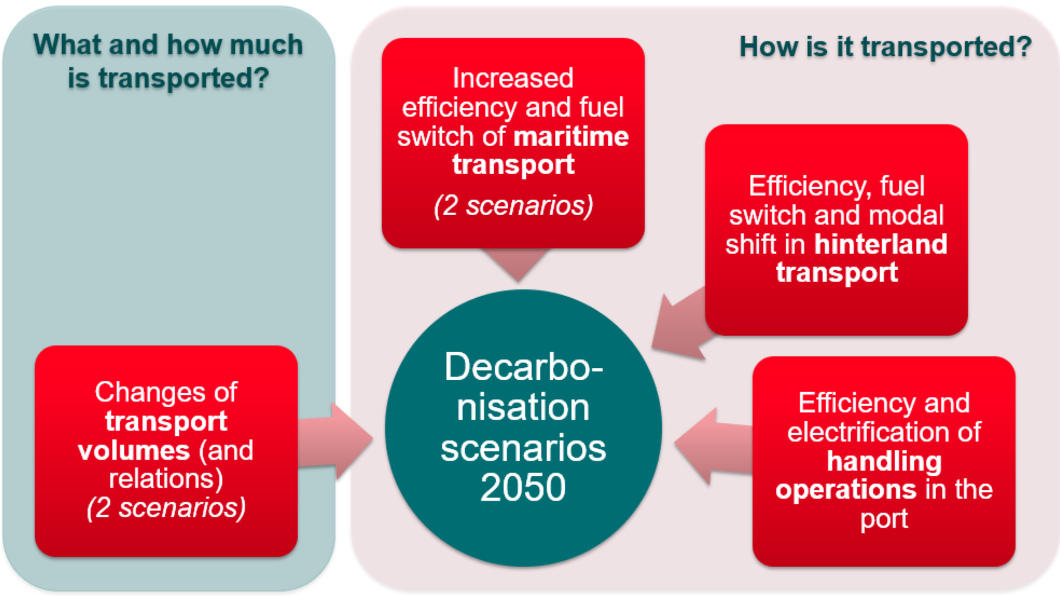

Figure 3-1 Structure of decarbonised transport scenarios by 2050

As Figure 3-1 depicts, the changes that are the subject of this study raise two major issues. On the one hand, they pose the question of what and how much will be transported in a decarbonised future? and, on the other, how decarbonisation will also significantly change the way goods are transported?, e.g. by using completely different modes of transport, with new and improved technology and with a different non-fossil energy supply. Finally, the port not only needs to know what will happen to its businesses in the future but also has the ambition to be an active player in decarbonising transport and, by doing so, to contribute to a more sustainable world and be proactive in anticipating business challenges and detecting new business opportunities in line with a decarbonised future.

In the following, scenarios for the year 2050 are developed and described.

- Chapter 3.1 describes what will be transported in a decarbonised future; while
- Chapter 3.2 deals with the technological and operational changes of future transport.

Chapter 3.2 is divided into three subchapters: maritime transport (section 3.2.1), hinterland transport (section 3.2.2) and the handling operations at the port (section 3.2.3). Each chapter starts with a discussion of the central technical and organisational strategies for the deep decarbonisation of transport, followed by the assumptions and results of deep decarbonisation scenarios for 2050. The strategies discussed refer to current, emerging and future decarbonisation technologies and operational improvements. They include options for efficiency increases, fuel switching and the possible electrification of maritime transport, hinterland transport and handling operations at the port. In Section 3.2.1 also possible pathways towards fossil-free maritime transport are discussed.

All the scenarios discussed in this chapter focus on the long-term future – by the year 2050. This means they try to depict a future that is different to today with regards to GHG emissions and related energy technologies. They all assume that the EU, as well as most other nations globally, will have been successful in reducing GHG emission levels by at least 80 % to 95 % versus current levels and will be on track to reach zero emissions imminently, with the North-West European hinterland of the port being at the upper end of emissions reductions. In the future assumed here, the global economy will have been growing steadily and wealth will be distributed more evenly than today, meaning that the differences between the industrialised nations and the global south will be less than they are today.

The energy and technology side of a climate-friendly world in 2050 have been described in several global scenarios, such as the Greenpeace "Energy Revolution scenario" and the latest IEA "Beyond Two Degrees Scenario". Such scenarios also exist for the EU and several member states, e.g. in the Commission’s 2011 Low Carbon Economy Roadmap and others. In contrast to the above-mentioned scenarios, in this report we focus specifically on the year 2050. Analyses regarding the pathways in between that may lead to such a future are only included for maritime transport (see section 3.2.1). Pathways for hinterland transport were, however, taken into account in the development of the 2050 future scenarios.

3.1 Deep decarbonisation effects on transport

The available scenario studies present – partly diverging – techno-economic visions of a decarbonised future. However, none of those reviewed[4] actually deal with the issue of what these changes in the energy and production systems will mean for maritime transport to and from Rotterdam. On the other hand, by comparing various studies and own estimates on the effects of the energy transition, it can be concluded that deep decarbonisation will not only change the modes and technologies of transport but also strongly affect transport volumes, in maritime as well as hinterland transport.

Changes in Maritime transport volumes

For this study, two scenarios on future transport volumes have been developed based on our review of deep decarbonisation scenarios for Europe and Germany and on analyses by the Port Authority[5].

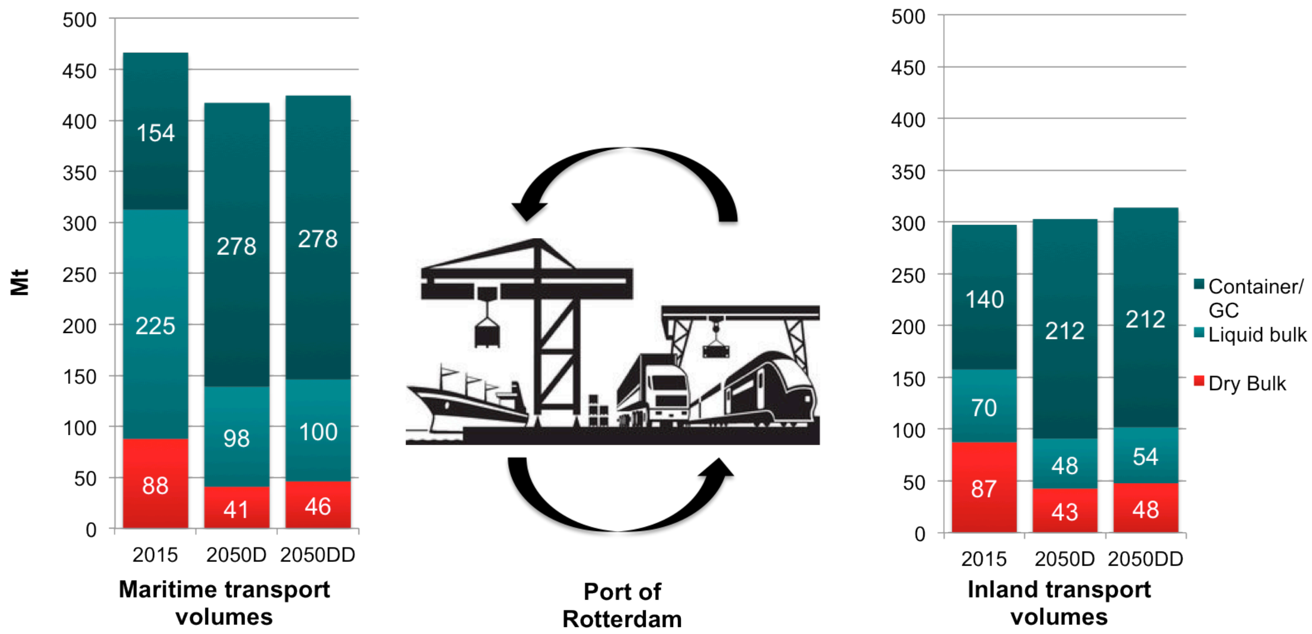

Figure 3-2 Changes in maritime and inland transport volumes between today and two decarbonisation scenarios, by category of freight (Mt)

[4] Just before the completion of this report, a study by OECD/ITF (2018) was published which takes into account global assumptions about reduced global transportation of coal and oil according to IEA (2017) for 2035. The authors consider this to be roughly in line with the RCP 2.6 scenario by IMO (2015) which also assumes declining transportation of fossil energy carriers. For more detail on the study review see our background report.

[5] The reviewed studies were EU-related scenarios focussing energy system decarbonisation as well as sustainable transport futures (EC 2011, Greenpeace et al. 2015, IEA 2017, EC 2016, CERTH/HIT et al. 2014 FVV 2016). These were amended with studies analysing future transport or specific parts of it or specific countries (OECD/ITF 2017, TPR 2015, Benelux Union 2016, CPB/PBL 2015, Öko-Institut et al. 2016, WWF et al. 2014, Öko-Institut 2013, TNO 2015). These were amended with studies on future demand of bulk materials in the hinterland by UBA 2014 plus own studies by Wuppertal Institute.

Both scenarios follow ambitious pathways, with the "D" scenario being slightly more conservative regarding technology options used in comparison to the "DD" scenario. Scenario DD assumes a full phase out of fossil fuels in transport and as feedstock, with synthetic fuels replacing the remaining applications completely by 2050, while scenario D assumes that fossil fuels are still used for feed-stock and for some transport and that biofuels will also be used in transport. Compared to the scenarios developed for the study "Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam" (Wuppertal Institute 2016), both scenarios can be categorised as belonging to the more ambitions climate mitigation scenarios aiming at 95 % GHG emissions reduction by 2050. The D scenario is more or less in line with the "BIO" scenario (with elements of the TP scenario), while the DD scenario fits with the assumptions of the "closed carbon cycle" scenario of that study.

As Figure 3-2 shows, overall maritime transport volumes at the Port of Rotterdam are expected to decrease slightly in the two decarbonisation scenarios. More significant, however, is what happens in the structure of transport. Both scenarios show a high increase in container traffic and general cargo (by 80.5 % by 2050), while transport volumes in liquid and dry bulk reduce significantly: liquid bulk will decrease in maritime shipping from 225 Mt in 2015 to 98-100 Mt in 2050 (by around 56 %); dry bulk will decrease from 88 Mt in 2015 to 41-46 Mt in 2050 (by 53 % to 48 %).

Total bulk volumes will be reduced by around 55 %. In dry bulk, the volume of coal declines by 71 % to 85 % due to a complete phase out of coal in electricity generation by 2050 and significant changes in German steel making (Table 3-1). In the D scenario, coal use in steel mills will decline due to new and more efficient blast furnace technology coupled with carbon capture and storage and greater steel recycling, while the DD scenario assumes that a significant share of steel making will be shifted to new coal-free primary steel making processes. Mineral oil products in liquid bulk are almost phased out (a 77 % to 100 % decrease) (Table 3-2). This decline will be partly compensated for by biofuels. These are assumed in the D scenario to play an important role for transport sector decarbonisation, as well as for feedstock in the chemical industry, and will consequently be imported in significant amounts. In the DD scenario, biofuels are assumed to be limited (see Box 5). Instead, this scenario assumes that synthetic fuels produced from renewable electricity and air-captured CO_2 at places with high and constant potential for renewable electricity generation – or other synthetic fuels – will play a core role as future transport fuels (DD scenario) (Box 7).

Box 2 Game-Changer Ice-Free Arctic Passage

If the arctic passage – either the North-West Passage along the coast and inlets of the Canadian arctic, or along the coast of Sibiria – becomes ice-free, it could save up to 7 200 km which is about a third of the current distance on a shipping route from Asia to Rotterdam. This could strongly reduce fuel usage. Although it can be expected that the arctic passage will be ice free by 2050 there will remain some logistical obstacles such as slower speeds, severe weather and the need to use icebreakers and/or ice-capable vessels which will at least result in higher costs for this route (Bekkers et al. 2015). Also the route touches pristine regions whose local environment is already under a high amount of pressure. Using this route for shipping might further increase the speed of the loss of sea ice in the region and endanger sensitive marine ecosystems. Further, the current southern route touches several countries and ports on the way between South-East Asia and North-West Europe. As future oversee shipping, in a decarbonised future, will shift strongly from bulk towards general cargo which is loaded and unloaded also en route this is another argument to not actively pursue the development of the arctic passage.

One important co-benefit that can be achieved through decarbonising maritime shipping is reducing emissions of black carbon. Current internal combustion engine designs and fuels used in maritime shipping imply relatively high emissions of black carbon. When deposited on snow, ice sheets and glaciers, it reduces the albedo. Resulting higher absorption of solar radiation increases local temperature and supports melting (Boggild, Goelles 2015) (see Box 1). Maritime ships operating e.g. in the North Atlantic may already have an important share in the deposition of black carbon on ice sheets and glaciers in Greenland as well as the whole Arctic. An ice-free Northwest Passage, possible reality for mid-century (Smith, Stephenson 2013), with substantially higher traffic of cargo vessels and cruise ships will lead to further increase in deposition of black carbon in the Arctic (ibid., p. 14f.). Diesel shipping engines emitted 8-13 % in 2010 as per the ICCT-study, of which 70 % were stated to be preventable with state of the art technology already.

Table 3-1 Assumptions for dry bulk freight to and from Rotterdam in two decarbonisation scenarios for 2050 (own assumptions based on Wuppertal Institute 2017, 2016, IEA 2017a, TPR 2015)

	Scenario 2050 D	Scenario 2050 DD
Coal	change 2050 vs. 2015: -71 %	change 2050 vs. 2015: -85 %
	Coal used for power generation will be phased out and amount to zero in the PoR hinterland by 2050 in both scenarios. Coal in steel generation will decline by 10 % due to higher shares of secondary steel making and more recycling. The market share of the PoR in coal transportation is projected to remain stable.	As well as the phase out of coal in power generation, its use in steel generation decreases even further than in the 2050 D scenario due to higher shares of secondary steel making and more efficient production technology which reduces or even replaces the use of coal (top gas recycling uses less coal and direct reduction uses hydrogen instead of coal).
Iron ore	change 2050 vs. 2015: -55 %	change 2050 vs. 2015: -10 %
	While oxygen steel production in Europe is expected to decline only slightly, secondary steel production will be reduced significantly and imports of steel slabs are projected to rise.	Crude steel production is expected to remain at current levels, but the shares of electric arc/secondary steel are projected to increase, resulting in the import of scrap instead of ore. Furthermore, there is a switch towards hydrogen-based steel making, leading to increased material efficiency.
Other dry bulik	change 2050 vs. 2015: -78 %	change 2050 vs. 2015: -78 %
	This value is an extrapolation of the Port of Rotterdam's "Lean & Green scenario", which assumes a strong decline in other dry bulk by 2040.	See 2050 D.
Dry biomass	change 2050 vs. 2015: +/-0 %	change 2050 vs. 2015: +/-0 %
	The level of transported dry biomass is expected to remain constant as no major imports for a bio economy are projected.	See 2050 D.
Agribulk	change 2050 vs. 2015: +/-0 %	change 2050 vs. 2015: -50 %
	The amount of agribulk transported via the Port of Rotterdam is not projected to change by 2050.	The amount of transported agribulk declines due to a more sustainable lifestyle and lower food demand (smaller population, reduced food waste, focus on regional products, less meat consumption resulting in lower demand for animal feed etc.).

Table 3-2 Assumptions for liquid bulk freight to and from Rotterdam in two decarbonisation scenarios for 2050 (own assumptions based on Wuppertal Institute 2017, 2016, IEA 2017a, TPR 2015)

	Scenario 2050 D	Scenario 2050 DD
Crude oil	change 2050 vs. 2015: - 77 %	change 2050 vs. 2015: - 100 %
	The focus on energy efficiency measures and renewable energy deployment in the EU leads to decreasing seaborne crude oil transportation. While fuel demand in heating is completely abolished, reductions in transport are about 2/3 and in feedstock -20 % (in line with production values by IEA 2017a). Business activity at the PoR is also directly affected by the closing of local oil refineries.	Additional disruptive technological innovation, especially in the transport and basic materials industries, allows for a complete substitution of crude oil products and thus renders seaborne crude oil transportation unnecessary. All remaining use of hydrocarbons is supplied by synthetic fuels/feedstocks.
Mineral oil products	change 2050 vs. 2015: - 77 %	change 2050 vs. 2015: - 100 %
	The decline in transport volumes of mineral oil products equals that of crude oil. It is assumed that there will be little import/export when overall production and use of oil products is phased out.	See 2050 D.
LNG	change 2050 vs. 2015: +/-0 %	change 2050 vs. 2015: -100 %
	As in the case of other fossil fuels, very little LNG is expected to be consumed in 2050. However, as its combustion results in lower GHG emissions than that of other fossil fuels, it is used mainly in the transport sector where few alternatives to fossil fuels are available, as well as backup for power generation.	As in the case of other fossil fuels, it is assumed that LNG can be substituted by the direct use of electricity or by synthetic methane and, consequently, there will no longer be demand for the seaborne transportation of LNG.
Liquid biomass	change 2050 vs. 2015: +100 %	change 2050 vs. 2015: +/-0 %
	Since this scenario focuses on biofuels as the main substitute for fossil fuels, the transport volumes of liquid biomass increase strongly compared to 2015 (to 22.8 million tonnes (all import) in 2050 compared to 0 in 2015).	This scenario assumes that synthetic fuels substitute fossil fuels where required. Hence, no seaborne transportation of liquid biomass is assumed for 2050 (as for 2015).
Hydrogen	change 2050 vs. 2015: 0 %	change 2050 vs. 2015: +100 %
	As direct import/export activities of hydrogen in 2050 are currently considered unlikely, no future transport activities are assumed in this regard.	Hydrogen imports from renewable electrolysis, e.g. in the North Sea, might become relevant by 2050. However, it is assumed that most of it will be transported via pipeline.
Power-to-X fuels/ gases	change 2050 vs. 2015: 0 %	change 2050 vs. 2015: +100 %
	As this scenario focuses on biofuels as the main substitute for fossil fuels, no imports of synthetic fuels are assumed.	Instead of biofuels, synthetic fuels substitute fossil fuels as feedstock for the chemical industry and non-electrified transport. Based on these assumptions, a seaborne transport volume of 71.5 million tonnes (all import) is assumed for 2050 (compared to 0 in 2015, calculated as 100 % methanol).
Chemicals and other wet bulk	change 2050 vs. 2015: -10 %	change 2050 vs. 2015: -10 %
	As a result of increased material efficiency and technological innovation, demand for chemicals decreases slightly compared to 2015. The production of high-value chemicals within the EU decreases by 20 % (IEA 2017) but imports are projected to rise by 10 %.	See 2050 D (but switch to organic and synthetic sources).
Vegetable oils	change 2050 vs. 2015: +/-0 %	change 2050 vs. 2015: -50 %
	As the majority of vegetable oil is used as an input into food production, its future transportation level is difficult to estimate and thus expected to remain constant.	A more sustainable lifestyle and less meat consumption result in lower demand for animal feed and, consequently, its feedstock.

General cargo, and particularly container transport volume, will grow by over 80 %. This scenario is based on the "lean and green scenario" developed by the Port Authority. It assumes that due to already high levels of material wealth in North-Western Europe, stronger global competition in the manufacturing sector and decentralisation trends in Europe, freight amounts in the field of general cargo will grow more slowly than in the past and will, to an extent, decouple from economic growth, which will be stronger in the services and digital economy. It was assumed, however, that over and above these trends general cargo will largely be untouched by decarbonisation, while megatrends such as globalisation or digitisation will have an increased impact. For 3D-printing as well as novel modes of transport, however, we expect only limited effects on the transport to and from Rotterdam (Box 4 & Box 3).

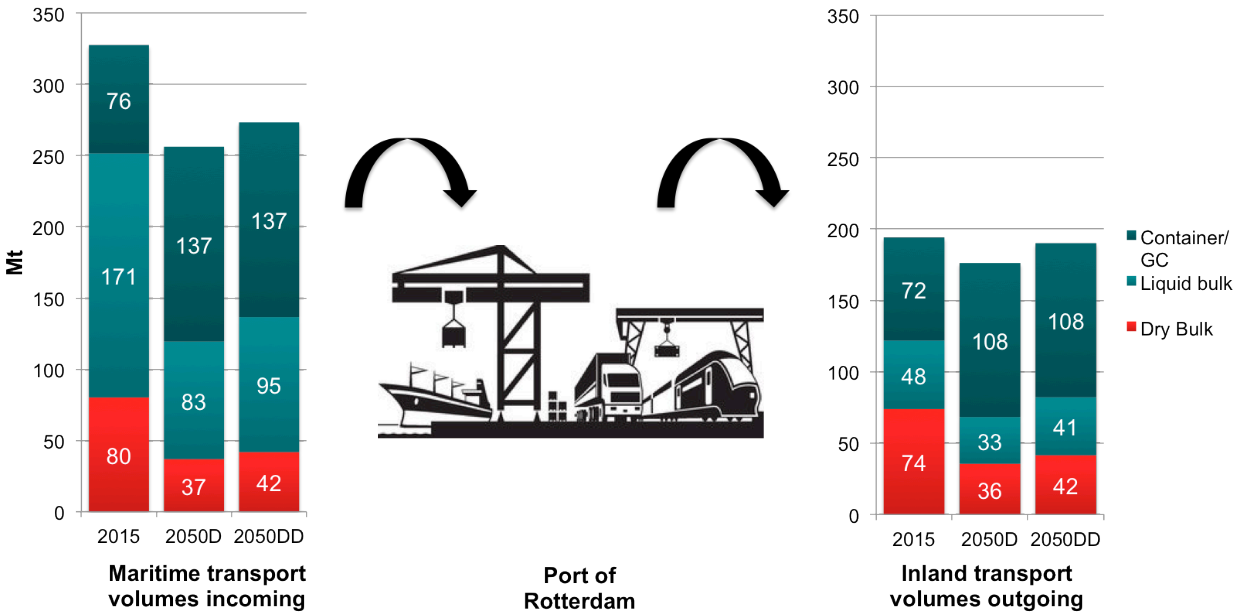

Figure 3-3 Maritime transport - incoming and inland outgoing transport volumes

Maritime transport volumes arriving at the Port of Rotterdam will be affected by decarbonisation pathways significantly more than outgoing inland transport volumes (Figure 3-3). This is mainly because of the huge amounts of bulk that are currently used in the Rotterdam power plants and refineries, which will be phased out or significantly reduced in a decarbonised future. In contrast, goods leaving the Port of Rotterdam via maritime transport are expected to increase, while liquid bulk will decline from 53 tonnes in 2015 to 15 in scenario 2050 D and to only 5 in 2050 DD (Figure 3-4). Transportation via container is the most relevant in both incoming inland and outgoing maritime transportation.

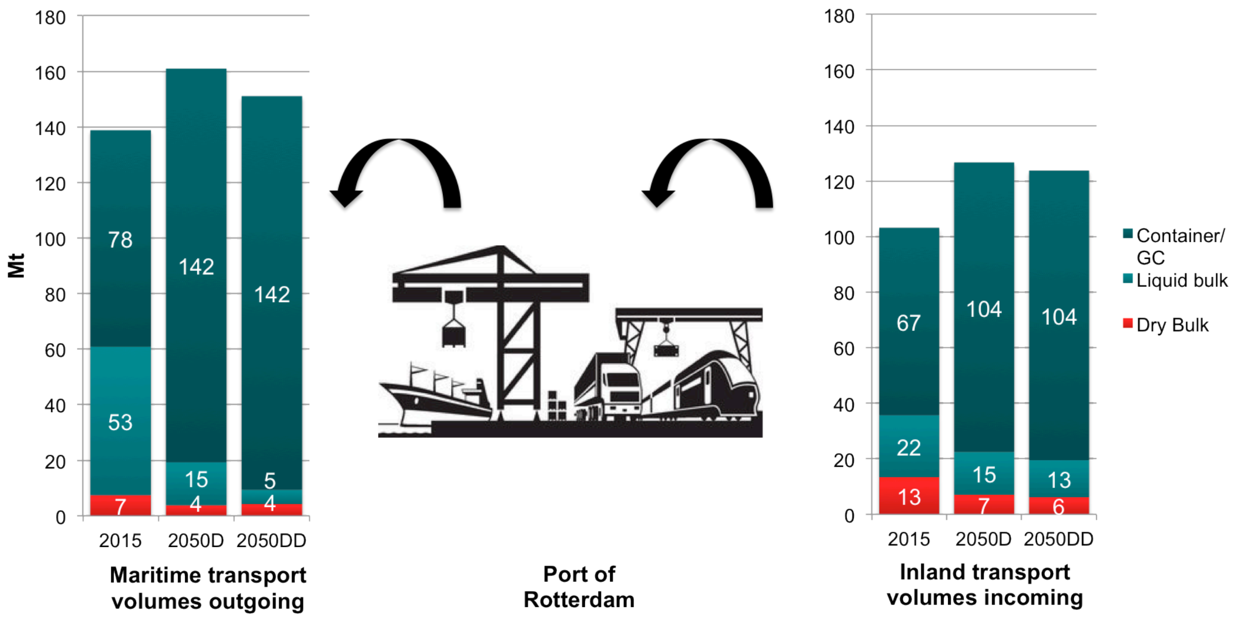

Figure 3-4 Maritime outgoing and inland incoming transport volumes

Box 3 Novel modes of transport

Apart from the significant technological advancements of traditional transport modes, as discussed in this study, a couple of completely new technologies are currently being discussed and demonstrated. Two particularly appealing concepts are: (a) the hyper loop, a concept to construct evacuated tubes through which (electric) vehicles will be able to run at very high speeds with very low friction losses; and (b) unmanned small helicopters, so-called drones, which are already used to deliver parcels etc. in dense city districts or on islands.

In our study we do not consider these two potential solutions for transport and logistics as our focus is on the huge volume of goods and freight transported through the Port of Rotterdam. The hyper loop is mainly advantageous due to its potentially high speed, which would enable faster ground transport and thus make it an energy saving and potentially low carbon alternative to flying, particularly for passenger transport but also for urgent goods. Although such systems have already been described for Germany (Werner et al. 2016), and there might also be such systems in the future in the Netherlands, it seems as if they would be particularly advantageous where speed of delivery is decisive. Consequently, it would probably not be logical to have a container for e.g. three weeks on a ship and then deliver it at 1 000 km an hour e.g. to a location in Germany. If the delivery of the freight had been urgent, it would probably have come by air from Asia. Therefore, if such a system were to be developed, it would either be used as additional infrastructure for the electrified transportation of goods within the Port of Rotterdam area, or for long distances it might start at Schiphol and go to destinations in the east of the Netherlands, Germany etc.

In terms of drones, which are increasingly being used, we assume that their preferable field of application is for the so-called last mile delivery of smaller volumes of goods in remote or densely crowded areas. The drone's fields of application, therefore, lie in the part of the transport chain that is not covered by this study.

Source: Werner et al. (2016)

Box 4 Game-changer 3D-printing?

3D-printing is one of the most important and promising technologies currently emerging. Particularly in prototyping, moulding, machine and equipment building its applications are booming, due to its flexibility, down-scalability of production and the possibility to construct complicated parts that are impossible to design in one piece with other techniques.

Due to its advances, some expect that in the future the bulk of goods used will simply be decentrally printed, using a very limited amount of material inputs supplied via pipelines. In such a future, much of the bulk transported today could become obsolete and transport (but also trade, retail and delivery) would significantly change. In our opinion, however, such a future is still a long way ahead and may not even be a realistic vision.

Firstly, there are likely to be many standard products for a very long time that are produced and consumed in very high volumes, such as cars, consumer devices etc. It is probable that the production of most of these goods, or at least a large proportion of them, will be more efficiently achieved via conventional routes (rolling, pressing, assembling), either because of e.g. the physics of the casing of a car or because of the complexity of an electronic product. Customised parts for those products, as well as spare parts for repair, could potentially be more efficiently produced decentrally via 3D printing. The bulk of volume, weight and numbers will probably, however, remain traditionally produced, transported and distributed. However, such trends might lead to different production locations and producer models that also could result in significant changes in transport; e.g. a local factory might produce very individual cars from a raw or pre-product that is then equipped with individual inner lining, steering wheel, mirrors etc. with the latter partly produced locally by 3D printing. Although such a development could potentially significantly change value chains in the automobile industry and would also result in changes in transport and logistics, overall volumes and types of freight would remain similar to today's levels.

In addition, large-scale 3D printing would result in (a) significant material savings, due to more lightweight parts (IEA 2017b) and less home scrap as parts are produced in their final shape and nothing has to be cut off etc. and (b) in a switch from finished goods to be transported to the supply of powdery or liquid plastics, ceramics and metal feedstock for 3D printing instead, as long as it is not possible to widely use ubiquitous materials. Such a trend towards locally-sourced materials is probable for water and air but could also cover e.g. sand or other locally-available materials which, together with other components, could be used to constitute larger parts of the mass of 3D-printed products. As long as such substitution does not occur, and materials' characteristics such as volume, size, weight of consumer goods and machinery remain relatively stable, transport volumes will also remain fairly stable. However, future feedstock sources could change significantly, and transport needs will depend on how they will be delivered. Some bulk feedstock might be transported by pipelines, but the more diverse materials would probably still be in sacks in containers, or in special tanks in the case of liquids or powders.

Therefore, there is high uncertainty about the likely speed of 3D printing replacing traditional technologies in mass production. Even if this does happen, the probable compensating effects on transport volume lead us to assume that 3D printing will not have a significant impact on the mass transportation of goods by 2050.

Sources: Barnatt (2016), IEA (2017b)

Changes in inland transport volumes and structures

In contrast to the maritime side, the decarbonisation scenarios for hinterland transport result in a slight increase in volume, but what is more significant is their clear structural effects. In hinterland transport, decline in bulk does not fully compensate for growth in general cargo (Figure 3-5). Nowadays, the different freight types are clearly linked to respective modes and destinations, e.g. oil and oil products are mainly transported via pipeline or by barge and train to the chemical clusters in the Netherlands, Flanders and the Rhine/Ruhr region. Coal and ore, on the other hand, are mainly transported by barge to Duisburg and by train to South-West as well as North-East Germany. Additionally, 60 % of general cargo and containers are transported by truck, mostly destined for the Netherlands.

Given this strong correlation between freight and mode, the changes in freight types envisaged for 2050 will have significant effects on the modal split in hinterland transport. These changes in inland transport volumes were modelled in both scenarios, 2050D and 2050DD, and compared to recent data from 2015. As the results for each scenario are similar, only the D scenario results are presented here.

The scenario variant "without modal shift'" (w/o MS) assumes that changes in freight type shares will directly affect transport volumes by mode. As a result, 80 % growth in container/GC in these scenarios will directly lead to high growth in road transport. Equally, the decline in bulk will generally lead to decreased volumes of inland navigation.

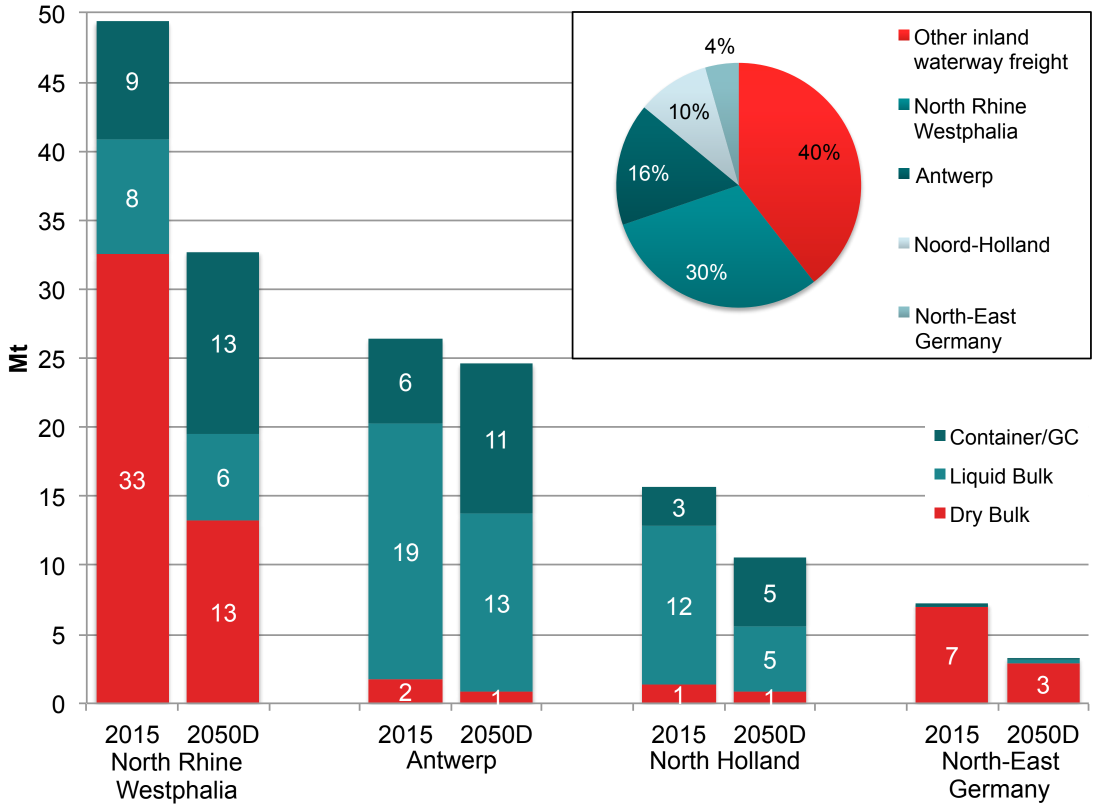

Figure 3-5 Largest freight regions by inland waterway (2015 and 2050D)

While total hinterland transport volumes remain fairly stable (2 % increase), the structure of transport changes significantly (see Figure 3 5). The increase in general cargo volumes clearly overcompensates for bulk freight decline in road transport and, therefore, leads to significant growth for this mode in the w/o MS variant by around 25 %. In inland navigation, general cargo volumes also grow significantly and will account for almost 50 % of the tonnage in 2050. This growth, however, will not be enough to fully compensate for the severe reduction in solid and liquid bulk (and other general cargo). Increasing container transport will overcompensate for declining liquid bulk in rail transportation and result in a 18 % growth in rail transportation.

In a next step it was assumed that part of the increased capacity due to the decline of inland navigation will be used to shift container transport from truck to barge in the 2050D scenario. Such a switch, however, will mainly occur for destinations along the River Rhine where large container ships can travel efficiently. Compared to the variant without modal shift, this will result in a further 12 % increase in container transport via inland ships and 7 % increase in containers transported by rail and a 9 % decrease in truck transportation. Clearly, these changes in freight structure will require parts of the shipping fleet to be converted to carry containers instead of bulk. Furthermore, the significant expansion of container terminals and multimodal terminals will be necessary to load containers from ships and railway onto trucks for final delivery to the customer. Container volumes on ships will increase by 112 % and those on trains by 110 %, which might result in the need for significant extensions to be made to the container terminal capacity (between 50 % and 100 %), particularly if the modal shift from truck to ship is successful.

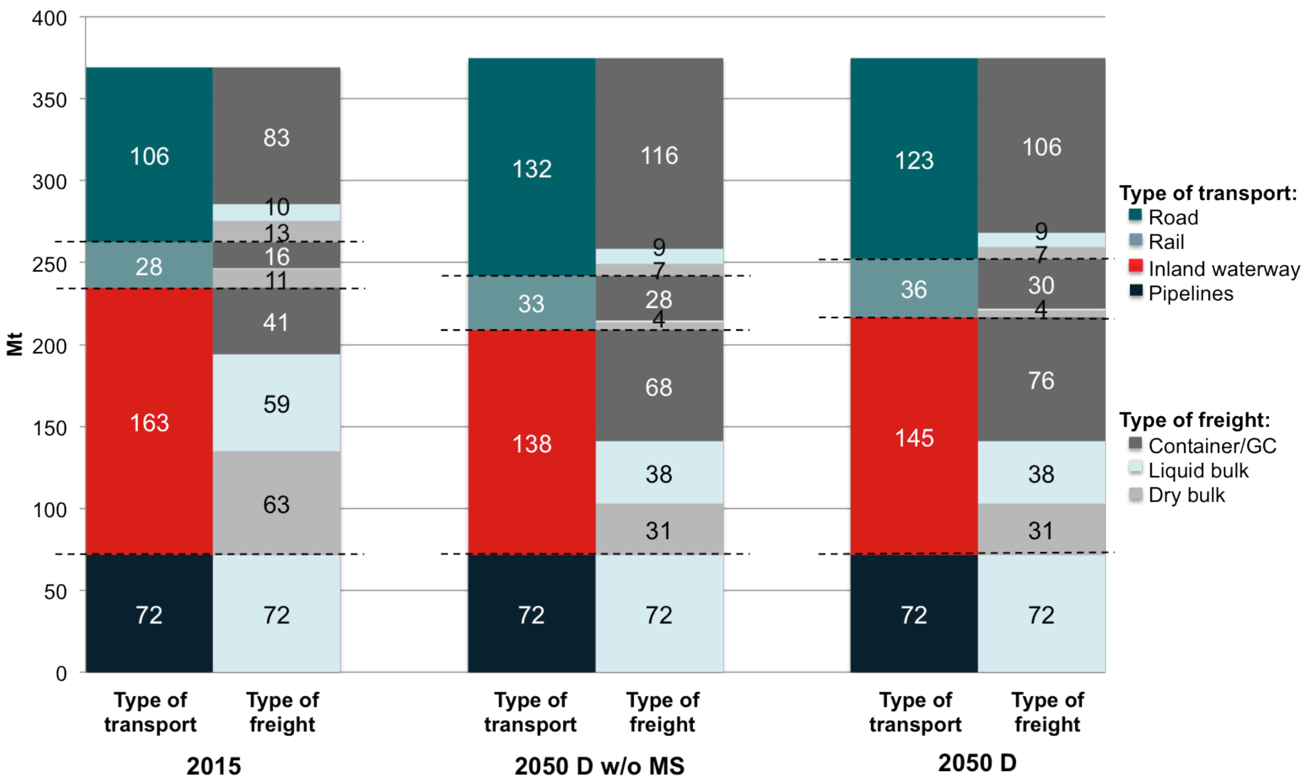

Figure 3-6 Changes in inland transport volumes (Mt), Scenario D 2050

In 2015, 106 Mt of freight to and from the Port of Rotterdam was transported by road. While in scenario 2050D w/o MS the volume is expected to increase by around 25 % to 132 Mt, scenario 2050D will see an increase of only 16 % to 123 Mt. These changes will significantly influence the total road transport volumes. Rail general cargo volumes, on the other hand, are likely to increase from 16 Mt in 2015 to 28 Mt and 30 Mt (2050D w/o MS and 2050D). However, the dry bulk rail transport volumes will decrease by 36 % and thereby lower the increase of total rail transportation. In total, rail transport will grow from 28 Mt to 36 Mt, an increase of 29 %. In contrast inland navigation volumes will decline by around 11 % in spite of the high growth of containers transported.

Effects of transport changes on energy demand and emissions

Deep decarbonisation scenarios will also have direct effects on transport emissions. On the one hand, changes in maritime freight volumes and particularly the definite shift from bulk to general cargo and containers will have clear effects on destinations, distances and emissions. More general cargo and container shipping, excluding empty return transportation, will entail longer distances and slightly higher emission factors – mainly due to higher average speeds and partly due to lower capacity utilisation in container shipping.

On the other hand, the strong structural impact on hinterland transportation, as outlined, will reduce the distances as containers and general cargo (as opposed to bulk) are typically transported to closer locations. At the same time, emissions will increase due to a higher share of transport by road.

Box 5 Sustainability of Biofuels

Biofuels are an available and often relatively affordable alternative for fossil fuel applications. Their use, however, is linked to a number of problems. First is their sustainable availability as the use of both agricultural and forestall biomass directly or indirectly competes with food production. Additionally, their effective GHG mitigation is a matter of intense debate. In theory, the CO_2 balance of biomass is net zero as the only carbon that is emitted was previously captured from the atmosphere. However, such a perception misses significant causes of GHG emissions related to biomass use. These include, for example, the GHG effects of N_2O emissions related to fertiliser use in agricultural production (see e.g. Crutzen et al. 2016), methane releases from biomass gasification processes and CO_2 releases from agricultural soils and from forestry (Erb et al. 2017). Other ecological issues, such as high water demand and loss of biological diversity due to large-scale plantations, may add to the problems.

Based on several available studies (Zeddies et al. 2014, Schweinle et al. 2010, Thrän et al. 2010), we have assumed that the world's sustainable forestry biomass potential could be around 20 to 30 EJ. For a more detailed discussion, please refer to Section 3.5 of the report by Wuppertal Institute (2016a). A comparison with the current (but increasing) energy demand of maritime transport of around 10 EJ, and given competing use in other energy sectors, shows that availability alone might clearly limit biomass as a core solution for decarbonising maritime transport. Furthermore, given the huge number of problems related to biomass use it is highly questionable how much biomass would be sustainably available for shipping purposes. Therefore, other alternatives such as photovoltaic and wind energy seem to offer higher energy yields per unit of space and cause less problems. As such, these alternatives will be necessary for decarbonisation in the long term.

3.2 Deep decarbonisation of transport

Not only will deep decarbonisation affect transport volumes, as has already been discussed, but decarbonisation targets will also require transport modes to become more efficient, less polluting and finally fossil-free.

The strategies for the deep decarbonisation of transport can be grouped into three central types of modification: no technological shift such as operational efficiency and modal shift (as discussed in the previous section); technological change; and changes in the nature of fuels (see also Chapter 3). The following figure provides an overview of possible future strategies for deep decarbonisation, differentiated according to modification options and modes of transport, which underlie this synthesis report.

		Fuel Change		Technology Change		Non-Technology	
		liquid	gaseous	gaseous	electric	operational	(multi) modal shift
chapter		P2L (Methanol)	P2G-CH_4	P2G-H_2	Battery (B) / OH-Line (OHL)		
3.2.1	**Maritime shipping**	✔	✔	(✔)	(✔ B)	✔	
3.2.2	**Inland navigation**	✔	✔	✔	✔ B	✔	✔
	Road	✔	✔	✔	✔ B/OHL	✔	✔
	Rail				✔ OHL	✔	✔
	Pipeline				✔	(✔)	
3.2.3	**Handling in the Port of Rotterdam**				✔	✔	

Figure 3-7 Potential changes of energy carriers by transport mode

3.2.1 Maritime transport

Currently, 80 % of global trade (in physical units) is transported via maritime shipping. Over 85 000 registered seagoing merchant ships use more than 330 Mt of fuel annually and emit around 1 000 million tonnes of CO_2 or about 2 % of global CO_2 emissions from fuel combustion, as well as 4 % - 9 % of SO_X and 10 % - 15 % of NO_X emissions (IEA 2017c, p. 5). Since 1970, maritime shipping has grown by an average of 3 % per year, slightly above global gross domestic product (GDP) growth over the same time span, and most studies expect this trend to continue over the coming decades at only moderately lower rates. Consequently, Martinez, Kauppila and Castaing (2014) expect CO_2 emissions from international freight to increase by a factor of 3.4 to 4 between 2010 and 2050.

Strategies for decarbonising maritime freight transport by increasing energy efficiency can broadly be subdivided into:

- technical and operational measures that allow for the increased efficiency of energy use during the operation of vessels at sea and at ports; and
- fuel switch of existing or novel propulsion technology towards renewably produced net zero carbon energy carriers such as electricity, hydrogen, synthetic fuels, ammonia or others.

Table 3-3 Assessment of potential reductions of CO_2 emissions from shipping by using known technology and practices. Source: OECD/ITF 2018 modified, IMO 2009 and own assumptions[6]

<table>
<tr><th>Measures</th><th>Fuel savings / CO_2 reduction potential (from OECD 2018)</th><th>Combined a)</th><th>Combined a)</th><th>Combined a)</th></tr>
<tr><td>Operational</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Speed</td><td>0 - 60%</td><td rowspan="4">10 - 60%
(10 - 50%)</td><td rowspan="16">25 - 90%
(25 - 75%)</td><td rowspan="19">25 - 100%
(d)</td></tr>
<tr><td>Ship size</td><td>0 - 30%</td></tr>
<tr><td>Ship-port interface</td><td>1%</td></tr>
<tr><td>Onshore power</td><td>0 - 3%</td></tr>
<tr><td>Technological (ship & engine design)</td><td></td><td></td></tr>
<tr><td>Light materials</td><td>0 - 10%</td><td rowspan="7">15 - 60%
(10 - 50% b))</td></tr>
<tr><td>Slender design</td><td>10 - 15%</td></tr>
<tr><td>Propulsion improvement devices</td><td>1 - 25%</td></tr>
<tr><td>Bulbous bow</td><td>2 - 7%</td></tr>
<tr><td>Air lubrication and hull surface</td><td>2 - 9%</td></tr>
<tr><td>Fuel cells</td><td>2 - 20%</td></tr>
<tr><td>Heat recovery</td><td>0 - 4%</td></tr>
<tr><td>Alternative fuels and renewables</td><td></td><td></td></tr>
<tr><td>Advanced biofuels</td><td>25 - 90% a)</td><td rowspan="4">0 - 50%
(6 - 25% c))</td></tr>
<tr><td>LNG</td><td>0 - 20%</td></tr>
<tr><td>Wind</td><td>1 - 32%</td></tr>
<tr><td>Solar</td><td>0 - 12%</td></tr>
<tr><td>Electricity based energy carriers</td><td></td><td></td><td></td></tr>
<tr><td>Hydrogen, Ammonia, Electricity</td><td>0 - 100%</td><td rowspan="2">0 - 100%
(d)</td><td rowspan="2"></td></tr>
<tr><td>Synthetic fuels (P2L, P2G)</td><td>0 - 98% A)</td></tr>
<tr><td colspan="5">a) own estimate (in brackets: IMO 2009); b) includes LNG, renewables and speed; c) LNG and renewable energies only; d) not included by IMO 2009</td></tr>
</table>

Table 3-3 provides a condensed overview of the available technical and operational strategies to increase energy demand and reduce GHG emissions from maritime transport including powertrain electrification or renewable energy carriers. Due to the diversity in age, size, design and status of the current and future fleet of maritime vessels, there is a wide range of potential energy efficiency improvements.

6 We do not include nuclear in this table although it is occasionally used as alternative propulsion system in maritime shipping (e. g. on military ships and ice breakers). This is reasoned by the particular risks and costs associated with nuclear power. In addition, the enormous potential danger to the environment and human health (in terms of radioactive waste and/or nuclear disaster) outweighs the possible contribution to climate protection.

The main single area of potential for avoiding CO_2 per tkm during the design process of new ships is in propulsion improvement devices and fuel cells (up to 25 % and 20 % reduction potential respectively). In terms of the operation of existing and new ships, optimal speed and fleet management for ship size are the most promising fields of action, offering potential reductions in CO_2 emissions of up to 60 % and 30 % respectively. Overall, the avoidance of CO_2 per tkm combining all categories (operation, ship and engine design, and the use of renewable energies and LNG) could range from 25 % to 90 %. These values were arrived at by considering the operational and technical aspects as described below.

Operational strategies to increase energy efficiency include, for example, optimising the utilisation of ship capacity, ship size and slow steaming.

- By increasing the size of the ship, it is possible to reduce unit costs in terms of transported tonne kilometres, as well as energy consumption. The size of a ship and the length of its waterline are important determinants of hydrodynamic resistance and energy use per tkm. To what extent the optimisation of the ship size can contribute to decarbonisation is not wholly clear. Different effects can occur with increased ship size, depending on whether the impacts are viewed from the perspective of an individual ship on a specific route or from the system perspective. If a larger ship can transport the same cargo volume from one port to another, greater energy efficiency can be anticipated. However, the deployment of larger ships is often based on the implementation of geographically larger hub and spoke systems, in which case substantial rebound effects can occur.
- It should be noted that slow steaming can, on the one hand, lead to significant energy efficiency gains on a tonne kilometre (tkm) basis as a function of the amount of speed reduction. On the other hand, the reduced productivity (annual tkm) of slow-moving ships can lead to more vessels operating to meet a certain demand for sea freight traffic within a certain period of time. Therefore, the reduction in emissions from one ship may be counteracted by an increase in the number of vessels in service, which also require additional resources for their production. To make a significant contribution to decarbonisation, slow steaming must be introduced as a permanent regulatory measure (by obligation and/or incentive) instead of being applied temporarily by ship operators depending on market demand and fuel price. Here, ports can influence the reduction of ship speed “based on port queuing management - also called virtual arrival” (Gibbs et al. 2014, p. 342). The term virtual arrival refers to the reduction of the ship's speed when delays are to be expected in the port of destination, with the aim of avoiding inefficient "hurry and wait" modes. Virtual Arrival Management is a method of ensuring “just-in-time” management of maritime transport, which contributes to reducing fuel consumption and thus, ultimately, to reducing GHG emissions. Ports play a crucial role in this approach as they must be able to implement pre-booking systems and fully identify and track the potential causes of port delays (e.g. berth availability, availability of transhipment equipment etc.). Although this approach is an effective means of reducing fuel consumption and CO_2 emissions, Gibbs et al. mention an opportunity risk for ports by reducing their opportunities for selling port services (e.g. preventive maintenance). Such opportunity risks generally occur with all potential operator cost-increasing measures taken by individual ports.

- The optimisation of capacity utilisation is not a new organisational strategy, but it is one of the most important for reducing energy consumption and CO_2 emissions per tonne kilometre. It corresponds closely to the economic viability of sea freight transport and requires cooperation between competitors to exploit the remaining potential. In addition, the spatial structure of world trade would also have to be more balanced with a narrower gap between exporting and importing countries, leading to the avoidance of empty journeys.

Technical strategies to increase energy efficiency can be differentiated according to the degree of dependence on the drive system used. Strategies that are independent of the propulsion system include improvements in weight, in hull via slender design and bulbous bow, rudder and propeller design and other propulsion improvements, as well as air lubrification and automated underwater monitoring and maintenance. Further technical strategies for increasing energy efficiency are closely related to conventional propulsion and auxiliary power systems. They are focused on upgrading either through entirely new designs or retrofitting components of existing designs.

In maritime shipping, in addition to increasing energy efficiency, decarbonisation of energy use can be achieved by switching to alternative energy carriers. The most promising options are power-to-liquid (P2L) options such as Fischer-Tropsch diesel or methanol involving hydrogen from renewable electricity and the reuse of CO_2 from industrial sources or the atmosphere. Both options can be used with existing conventional drives and infrastructures. At a later stage, methanol could be combined with direct methanol fuel cells (DMFC) to electrify the propulsion system. Hydrogen could also play a central role in maritime shipping. It should be noted, however, that hydrogen is associated with high transportation and storage requirements.

Finally, additional renewable energy generation on board via PV, sails, kites or wind turbines mounted on the ship can also reduce the ship's fuel use. The energy-saving potential of these options varies widely depending on ship type, speed, weather and route travelled. OECD/ITF (2018) estimate savings potentials ranging from 1 % to 32 % for wind and from 1 % to 12 % for PV, depending on technology and use characteristics.

Table 3-4 Energy efficiencies for different fossil and non-fossil fuel types

	Liquid	**Gaseous**	**Liquid**	**Gaseous**	**Gaseous**	**Electric**
	Fossil liquids	Fossil CH_4	P2L (Methanol)	P2G-CH_4	P2G-H_2	(Battery)-Electric
W2T: generation, transport & storage	**80-94 %**	**80-95 %**	**35-59 %**	**65 %** synthesis, **40-51 %** with compression/ cooling	**65-70 %** synthesis **52-59 %** with compression/ cooling	**90-100 %**
T2W: fuel to engine motion to freight motion	**43 %** (engine/ truck)	**40-47 %** (engine/ truck)	**40-47 %** (engine/ truck)	**40-47 %** (engine/ truck)	**50-60 %** (engine/ truck)	**80-95 %** (engine/ truck)
W2W: overall energy efficiency	**30-40 %**	**30-45 %**	**21-35 %**	**30 %**	**30 %**	**72-90 %**

Important aspects for a decarbonised world with alternative fuels are the related well-to-tank (W2T), tank-to-wheel (T2W) and well-to-wheel (W2W) efficiencies (Table 3-4).

Energy efficiencies for battery-electric operations are 80 % in all three categories (Schmidt et al. 2016), or even up to 100 %, but electric options and P2G-H2 are limited in maritime modes (see below). W2T refers to generation, transport and storage, where efficiencies are found to be up to 94 % or 95 % for fossil liquids or fossil methane (Schmidt et al. 2016 and Fasihi et al. 2016, 2017; Ren et el. 2008 and Zittel et al. 1996) and in the range of 42 % to 65 % in P2L and gaseous P2G-X fuels (Schmidt et al. 2016a, 2016b and Fasihi et al. 2016, 2017). T2W translates as fuel for engine and freight motion and the efficiencies vary between 40 % and around 50 % for most fuels and up to 60 % for P2G-H2 (Schmidt et al. 2016a, 2016b). W2W (the overall energy efficiency) is 40 % to 45 % for fossil liquids and fossil methane, around 30 % for P2G-CH4 and P2G-H2 (Stirn 2017) and as low as 21 % for P2L.

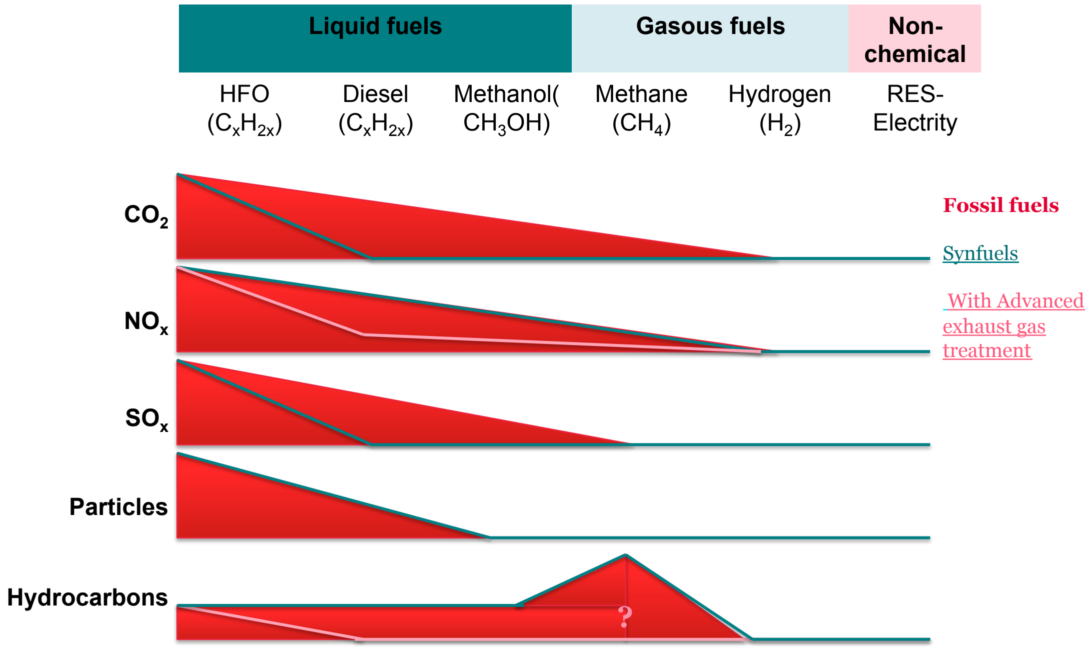

Figure 3-8 Emission characteristics of different fuel types

Looking at Figure 3-8, it can be seen that liquid fuels generate the highest pollution levels. HFOs (CxH2x) is highest in CO_2, NO_x, SO_x and particles, followed by diesel, regardless of its fossil, synfuel origin or advanced exhaust gas treatment. The advantages of methanol of the liquid fuels are its low emission levels and its particle-free burning property. Only two alternatives are considered for gaseous fuels: methane and hydrogen. CO_2 and NO_x emissions from methane are the lowest of all the emitting fuels, and it does generate almost no SO_X or particles. However, while liquid fuels emit relatively low levels of hydrocarbons, ongoing research shows the potential for critically high emission levels. The other gaseous alternative, hydrogen, is free from emissions but remains a challenge in terms of technological safety. RES electricity is the only non-chemical fuel and is free from all conventional emissions at consumption level.

The electrification of maritime ships could be an interesting zero carbon option, given the fact that green electricity is expected to be available at very low prices (lower than those of conventional marine fuels) at most ports around the world. In addition, electric engines and related drive trains are cheaper and almost twice as efficient as conventional ones. Additional weight and space requirements for the batteries are not significant barriers (Lloyd’s Register, UMAS 2017), particularly since these may improve further due to strong technological development for automobile applications. With regards to battery charging, as well as charging via electricity connections, it might also be possible to simply exchange empty batteries at ports for recharged ones. The main problem for electric drives is the capital cost of the batteries. Lithium ion batteries currently cost around 273 $/kWh (Curry 2017) and achieve an energy density of 200 Wh/kg. In this study we anticipate that they will reduce to 500 Wh/kg and prices will come down to around 80 €/kWh (see also OECD/ITF 2018, which anticipates 73 $/kWh by 2030).

However, even if batteries improve significantly in the future, a battery system capable of storing 1 MWh of electricity would cost over € 80 000 – compared to the cost for a MWh of green electricity of between € 20 and € 50. With such high initial investment in capital costs, the battery life time and particularly the range of the ships (i.e. the amount of energy they need to store) become crucially decisive for their cost efficiency. The following figure gives an overview of the most important regions and ship sizes for short sea shipping from Rotterdam, with typical distances and battery capacities required for the ships to make a return trip without recharging.

Table 3-5 Battery capacity needed by ship range and size (energy demand of ships calculated from IMO 2014 with 75 % efficiency increase due to hull improvement and electric drive train assumed)

Region Average distance Ship range	Feeder Western & Central Europe 553 km 1 500 km	Feeder Scandinavia & Baltic 1 663 km 3 750 km	Short sea Mediterranean & Northern Africa 4 347 km 11 250 km
Storage capacity needed: **Container ship 0 - 999 TEU**	206 MWh	516 MWh	1 547 MWh
Container ship 1000 - 2999 TEU	259 MWh	647 MWh	1 941 MWh
Container ship 5000 - 7999 TEU	596 MWh	1 490 MWh	4 471 MWh

Table 3-5 shows that battery capacity, as well as cost, increase significantly in line with distance travelled and ship size, in spite of the greater efficiency of larger ships. Resulting battery costs start from €16 to €21 million for container ships below 3 000 TEU with ranges of 1 500 km, and could be as high as €360 million for larger container ships serving the Mediterranean with a range of 11 250 km. Given the current costs of ships (about €20 million for 500 TEU ships and around €100 million for 6 500 TEU ships) the batteries would almost double the cost of the ship for shorter distances and could cost several times as much for longer distances.

However, when comparing total fuel costs (to include battery costs), electric systems might be able to compete in certain circumstances. Figure 3-9 shows that over 20 years and with low battery costs, as projected, battery electric shipping might compete within ranges of 1 500 km even with HFO at 4.2 ct/kWh (a price which would relate roughly to $70 per barrel oil and €40/t CO_2). For ranges of 3 750 km, electric shipping could still compete with biofuels. At higher ranges, however, battery costs make electric shipping uncompetitive. The only realistic way to introduce battery electric ships to longer distances would be in 'en route' relay stations. Batteries could be changed quickly to allow for maximum ranges of 3 000 to 5 000 km, thereby reducing battery size and costs.

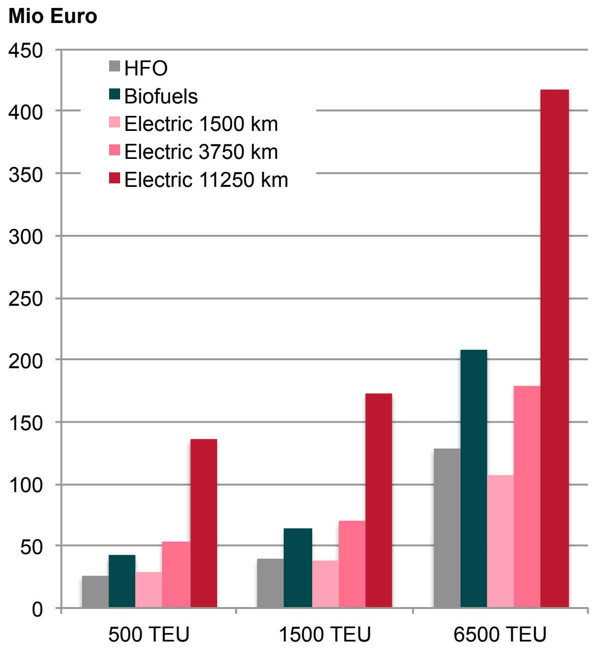

Figure 3-9 Energy costs for 20 years for different ship sizes and ranges (electric includes battery costs) (HFO 4.2 ct/kWh, Biofuels 7.0 ct/kWh, Electricity 4.0 ct/kWh)

The main technologies for improving efficiency in maritime transport have been presented and discussed above. Based on the third IMO GHG study (IMO 2015, p. 139), we have assumed in this report that an efficiency improvement value of 50 % compared to the 2015 fleet average, together with innovations in ship design and improved design, would be achievable under clear policy frameworks for the decarbonisation of transport.

This is an ambitious target, yet it lies well within the IMO assumptions and is based on operational measures and improvements and ship design. Further improvements in maritime transport emissions, however, would require significant switches in fuels used.

A switch in fossil transport fuels from liquid to gaseous helps reduce pollutant emissions and may yield efficiency gains of up to 12 %, with subsequent GHG emission reductions of around 20 %. The IMO concludes that, “larger improvements in efficiency have a higher impact on CO_2 emissions than a larger share of LNG in the fuel mix” (IMO 2015, p. 21). This means that a shift to non-fossil fuels or energy carriers is inevitable in the long run if the total abatement of GHG emissions is to be achieved.

Currently, there is debate about a wide range of potential fossil free fuel options. After considering a broad range of energy carriers, four main systems were deemed relevant and considered in more detail. These are:

- Power-to-Liquid (P2L)
- Power-to-Gas methane (P2G-CH4)
- Power-to-Gas hydrogen (P2G-H2)
- Electrification

For all of these, tank-to-wheel (T2W) and well-to-wheel (W2W) energy efficiencies have been outlined in Table 3 4 above. Ammonia, which also features in other studies (OECD/ITF 2018, LR & UMAS 2017) has not been taken into account (see Box 6 below).

Box 6 Ammonia as a Transport Fuel?

Decarbonisation has caused an increasing interest in all available low-carbon options for energy supply. In some instances, basic chemicals like methanol or ammonia have a substantial track record regarding other purposes than currently being used as transport energy. This offers the advantage, that trade, production and distribution of such basic chemicals is well-established which guarantees diversity of demand and may be helpful while implementing the more dispersed distribution infrastructure typically required for transport fuels. Ports often serve as hubs for such imported basic chemicals which enhances distributing those. This is the case for transport energy of maritime vessels but also other modes of transport.

Ammonia (NH_3) which nowadays is for the most part being used to produce fertilizers, offers the advantage that it is not comprised of any carbon. Ammonia can be produced from a variety of energy carriers including hydrogen. In fact, it can serve to transport hydrogen that otherwise requires liquefaction in order to achieve a volumetric energy density suitable for large scale shipping.

Ammonia can be blended with conventional fuels or directly used with modified internal combustion engines. However, its high auto-ignition temperature of 651 °C, low flame speed and narrow flammability range pose limitations for use with internal combustion engines (Gross and Kong 2013).

In principle ammonia may be used with fuel cells. However existing Proton exchange membrane (PEM) fuel cell designs will be spoilt by minor ammonia residues and requires very high purity of hydrogen from ammonia.

However, it should be noted that ammonia itself is a greenhouse gas and that nitrogen oxide (NO_X) emissions such as nitrous oxide (N_2O) yield Global Warming Potential (GWP) values that are 240-280 times higher than those of CO_2, depending on the time horizon considered (Pachauri et al. 2015). It is therefore doubtful that a switch to ammonia would result in a larger mitigation effect in terms of global warming.

Besides its high GWP value, N_2O became "the dominant ozone-depleting substance emitted in the 21st century" (Ravishankara et al. 2009), as nitrogen oxides are powerful scavengers of ozone molecules, comparable with chlorofluorocarbons (CFCs). This currently causes a depletion of the lower ozone layer, particularly in medium latitudes, having direct effect on densely populated regions (Reese 2018). Both NH_3 slip and NO_x exhaust emissions are far higher for ammonia combustion than for hydrocarbon fuels. Depending on the specifics of the storage, engine and exhaust gas system, this might lead to far higher GHG emissions than in the case of hydrocarbon fuels. The demand for extensive exhaust gas treatment would make it important to install large high-performance catalysts on-board hypothetical ammonia-driven ships. The demand for catalytically active platinum-group metals alone is likely to pose substantial restrictions on the large-scale application of this energy carrier.

Another considerable disadvantage of ammonia is its toxicity with humans and ecosystems that is more serious than with numerous other potential options of transport energy. From a general sustainability perspective, it would make sense to switch to environmentally favourable fuels not only in order to decarbonize transport energy use but also to reduce fuel spillage from normal operation and ship wreckage into aquatic environments.

For some reasons, ammonia has played no role in current comprehensive studies on decarbonized fuels for maritime shipping (e.g. Chryssakis et al. 2014, 2015; Moirangthem 2016). This does not necessarily preclude any future use as an energy carrier for transport but makes it less likely.

In a decarbonized world, the main potential of ammonia is probably associated with its own decarbonized production as a feedstock for fertilizers. On top of this might come some still to be determined use as a hydrogen-rich energy carrier for stationary applications where the nitrogen will not be lost but can be used for suitable purposes. Another use case may be storage of renewable power, depending on other options available (ISPT et al. 2017).

The four main non-fossil options have been grouped here into two decarbonisation scenarios. The first is a power-to-liquids (P2L) scenario and the second is a mixed power-to-liquids and power-to-gas (P2L/P2G) scenario. These are, of course, ideal worlds that will not come into being in such a pure way. Both scenarios also include smaller shares of battery electric and hydrogen driven ships for shorter distances (see below). For our analysis, it is helpful to describe the details and consequences of the two scenarios in more depth.

In these two scenarios all CO_2 emissions are assumed to be net zero by 2050, due to the synthetic origin of the fuels and further improvements and mitigation strategies along the value chain. For the liquid synthetic fuels (P2L), CH slip of volatile compounds and especially methane slip for P2G-CH4, remain issues. The estimates under-lying this report assume 5 % CO_2-eq remaining from the values of current CO_2 emission intensities per weight unit of fuel for P2G-CH4 and 2 % CO_2-eq remaining from the values of current CO_2 emission intensities per weight unit fuel for P2L.

Cost developments of non-fossil fuel alternatives

The focus of the scenario design above was on describing a largely decarbonised future transport related to the Port of Rotterdam for the middle of the century, i.e. 2050. To develop measures it is, of course, useful to have an indication of how the processes leading to such a future might unfold. In this section we describe potential pathways towards 2050. As the development of **costs and availability of alternative fossil-free energy** for maritime transport will be the most important factors influencing the uptake of alternative fuel solutions, we first discuss current and expected future costs and the economics of the main non-fossil fuel alternatives.

In maritime shipping, the fossil fuels currently used are low cost and have abundant and simple infrastructure. However, they cause high GHG emissions and air pollution. A cleaner and slightly more efficient fossil alternative currently available is LNG. Its costs as a fuel are even lower than those of liquid fuels. Its handling and storage, however, come at extra cost and, most importantly, ship drive systems must be (re-)designed to be able to use LNG. Biofuels are a liquid non-fossil alternative with lower GHG emissions. However, their production may also cause significant upstream GHG emissions, other pollutants and the destruction of GHG sinks (see Box 5). While the handling of hydro-treated vegetable oils (HVOs) that can be used as drop-in fuels is straightforward, other biofuels need dedicated tanks and adaptation (cp. IEA 2017c).

Today's marine fuels are very cheap. Heavy fuel oil (HFO), for example, is currently available at around 2 to 3 ct/kWh, mainly depending on oil price levels. Biofuels, on the other hand, are significantly more expensive with costs ranging from almost 4 to 7 ct/kWh for HVO or methanol. This means alternative fuel costs exceed fossil sources by at least 70 % or more. In the case of methanol derived from e.g. lignocellulosic biomass, fuel costs may triple (IEA 2017c). Switching from HFO to HVO would mean additional costs of €800 000 to as much as €2 000 000 for a large container ship for a 20 000 km trip e.g. from East Asia.

The current status quo on marine fuels is changing as fuels cause high sulphur and NO_x emissions and are responsible for significant GHG emissions. Regulation is starting to force ships to switch to cleaner fuels. This trend may lower the cost differential and support the uptake of alternative fuels. For HVO, cost competitiveness seems to be in sight, helped by regulation on pollution and a CO_2 tax. However, the sustainable potential of vegetable oil is estimated to be low, even in reports by the IEA.

Methanol or ethanol made from lignocellulosic biomass would be alternatives offering higher biomass potential with lower sustainability concerns. Nevertheless, these require different motor technology, or at least the modification of existing motors. Therefore, it is assumed here that methanol or ethanol could only be introduced gradually, mainly on new ships designed specifically to use these fuels. In parallel, the production and supply infrastructure would have to be developed. New-build ships will be significantly more fuel efficient (see above), mitigating at least in part the additional costs of more expensive, but cleaner, fuels.

Given the limited availability of biofuels and the fact that they still incur significant indirect GHG emissions, in the long run maritime shipping needs to switch to other non-fossil alternative fuels.

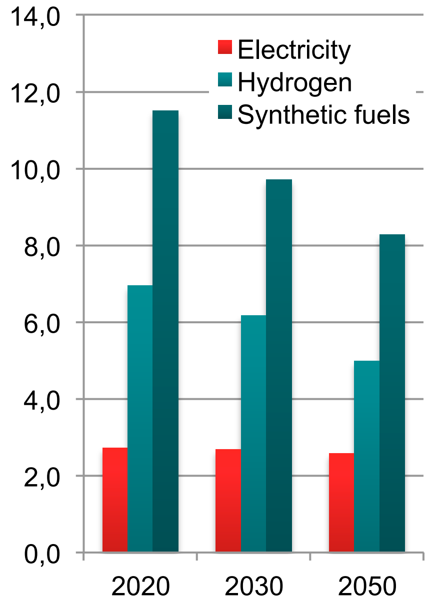

Figure 3-10 Production costs for electricity, hydrogen and synthetic fuels (in € ct/kWh) for different years, 8 000 full load hours, reference scenario (data from Agora 2018)

Figure 3-10 shows the principle of costs of the non-fossil energy carriers: electricity, hydrogen and synfuels. They are produced in a conversion cascade, where every step adds a cost for losses and additional capital expenditures. With increased efficiency of the conversion steps and reduced technology costs, the cost differentials will decline over time but will, nevertheless, remain substantial – even by 2050. As such, the cost differential of moving from cheap electricity to hydrogen or synfuels may more or less equate to the high cost of the batteries needed. The handling of hydrogen is also quite expensive and needs dedicated infrastructure and the costs for hydrogen tanks are substantial. According to Agora (2018), hydrogen tank costs are estimated at 27 €/kWh compared to around 83 €/kWh for future battery costs. We assume here that hydrogen storage on ships would cost around 11 €/kWh[7]. This means that the storage costs associated with hydrogen can be estimated to be below 15 % of the electricity costs for equivalent ranges of ships.

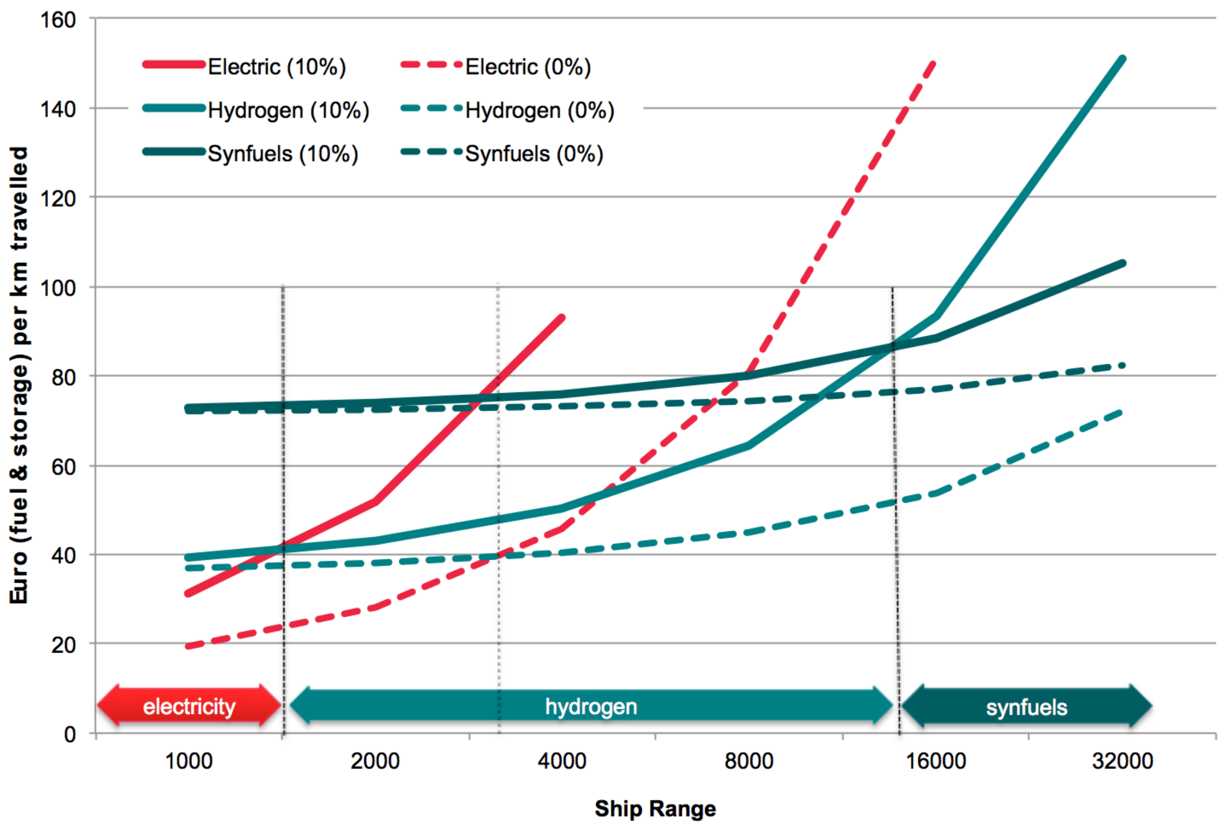

Figure 3-11 Average fuel costs for electricity, hydrogen and synthetic fuels (in € per km travelled) including costs of energy storage on vessel compared to range of ship (assumptions: fuel and battery costs for 2030, new built efficient ships, interest rates of 10 % and 0 %)

Figure 3-11 compares the costs of three energy alternatives for a typical mid-size container ship (6500 TEU), including the costs of energy storage on board. The figure reveals that for typical ranges and typical freight types the respective energy carriers can be competitive. The high storage costs for electricity and hydrogen limit their application to shorter travelling distances where smaller volumes of energy storage are necessary. Electricity will become competitive between 2020 and 2030 on short distances. Initially, ships will only travel feeder distances to Western Europe. Thereafter, Scandinavia and the Baltics might be included, depending on the availability of cheap battery systems and possible capital subsidies for batteries[8]. For short sea shipping, the range of choice might already be too wide for electricity to compete.

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[7] Müller-Syring & Henel (2011) provide an example of stationary 30 bar hydrogen storage tanks that potentially store around 9 000 kWh at a cost of 800 000 €. A 50 % margin for maritime applications added the storage capacity costs would be 11 €/kWh. This value is also in the range of current costs of 13 to 15 $ for automobile 300 to 700 bar high pressure tanks (James 2015, Zakeri & Syri 2015)

[8] Another option to reduce battery costs would be to use retired automobile batteries which will be replaced when their capacity levels are below around 80 % but could still be used in applications where weight and space restrictions are less tight.

Electricity cannot compete in price with hydrogen on ship ranges above 1 500 km if the full capital costs of battery and storage are taken into account. There might, however, be a business case for using hydrogen for medium ranges up to 20 000 km, i.e. short sea shipping to the Mediterranean and Northern Africa that is too far for electrification.

For long distance maritime shipping, synthetic fuels finally are the most competitive option. Their storage is much cheaper. Currently they are still almost 3 to 4 times more expensive than fossil fuels. However, several studies assume their costs will decrease significantly in the coming decades (see overview in Agora 2018). Particularly after 2030, synthetic fuel generation in North Africa, Iceland or other places where cheap renewable electricity is expected to become available at high full load hours will become attractive and increasingly common (see Box 7). It is also assumed that the necessary technology for the electrolysis of hydrogen and its conversion to fuel will become more efficient and cheaper. Agora (2018) estimate that at a global capacity of 100 GWel synthetic fuel production will have achieved maturity with costs close to the technical optimum. While these synthetic fuels might first be bound to higher price markets such as road transport, they will also be available for maritime transport. Here they would reach cost competitiveness to fossil MDO e.g. at prices of as a minimum $80 per barrel oil and €60 per tonne of CO_2 – a scenario which might become reality under strong climate policy after 2030.

Pathways

Based on the discussions above, two pathways towards non-fossil maritime shipping can now be briefly outlined.

These are the (power-to-)liquids (P2L) and the (power-to-)liquids and -gaseous pathway (P2L/P2G) and provide more details within the scenario 2050 D (see Figure 3-12). Both pathways are based on the same assumptions for electricity and hydrogen: that they will increasingly be used in new-build smaller ships dedicated only to feeder or short sea shipping. At these distances, lower energy storage makes them cost competitive energy carriers with very good environmental performance. By 2050, around 9 % of all shipping volumes will be electrified, with around 4 % using hydrogen. Due to increased efficiency of ships and the particular high efficiency of the electric drives, their share of T2W energy demand will, however, remain low (at around 1 TWh each) by 2050

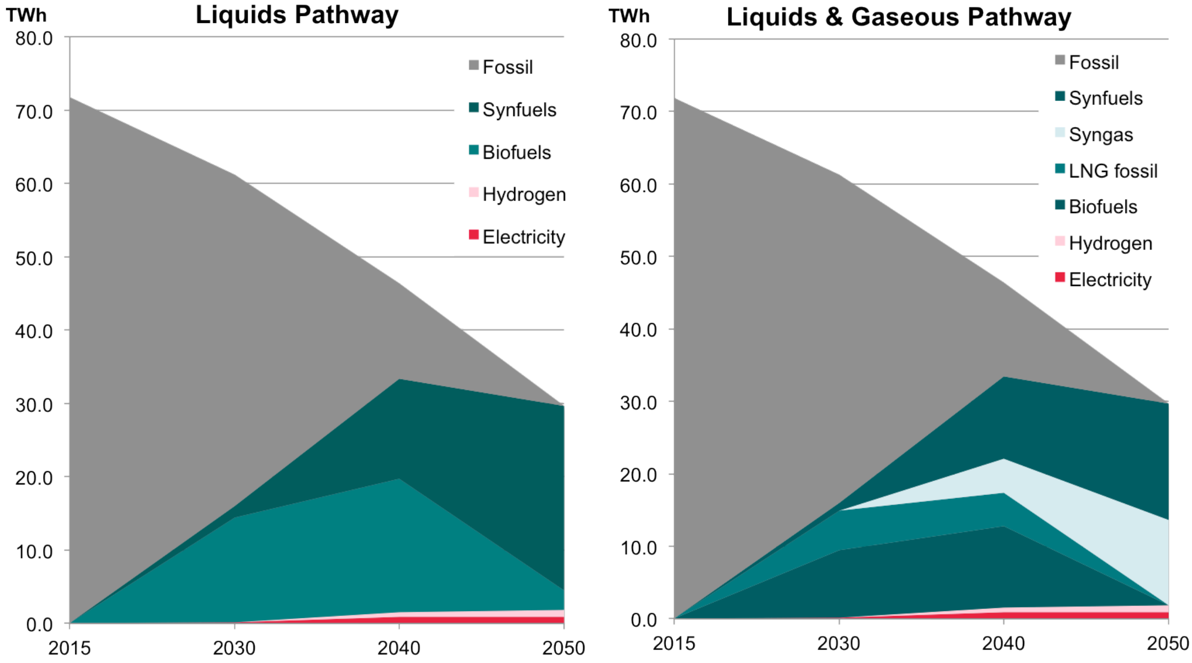


Figure 3-12 Amount of fuels used for maritime transport to and from Rotterdam 2015 to 2050 (TWh, T2W), two pathways

Biofuels are assumed to play an intermediate role in the pathways. It is assumed that a part of the existing fleet of merchant ships will use bio-based drop-in fuels. By 2030, 20 % of the ships existing today could be using 13 TWh of such drop-in biofuels. After 2030, as the number of older ships with conventional motors decline, drop-in biofuels will cover a larger share of the remaining ships.

Table 3-6 Techno-economic aspects of non-fossil fuel alternatives for maritime transport

System	critical technology	time of availability	remark
Electricity	battery	between 2020 and 2030	significant cost decrease plus performance increase expected due to road transport development; new built ships only
Hydrogen	electrolysis	between 2030 and 2050	cost decrease and performance increase expected; stepwise over whole period 2020 to 2050; commercial after 100 GW globally new built ships only
	(storage)	soon	cost decrease in hydrogen storage (could be achieved soon)
Synfuels	electrolysis	between 2030 and 2050	linked to hydrogen production costs (plus cheap RES with high full load hours) retrofit and/or drop in possible

In the liquid fuels pathway, 50 % of new ships built by 2030 are assumed to have motor technology capable of using methanol or ethanol. This will be supplied by ligno-cellulosic biomass and, after 2040, will be gradually substituted by synthetic methanol produced from hydrogen and CO_2. Beyond 2030, all new-build motors will use methanol as standard. This means that HVOs, as well as other biofuels, will supply 20 TWh and 25 TWh in this scenario by 2030 and 2040 respectively. After 2040, the amount will decline to zero as HVO-based ships are phased out and methanol or ethanol-based ships will be supplied by synthetic fuels.

In the liquid and gaseous pathway, bio-based ethanol and methanol play only a minor role in new-build ships. Instead, it is assumed that one third of all new shipping capacity will be designed to use LNG between 2020 and 2050. These will initially use fossil LNG, but by 2050 will have completely switched over to synthetic methane. Biofuel demand will be around 10 TWh between 2030 and 2040 and will then be phased out.

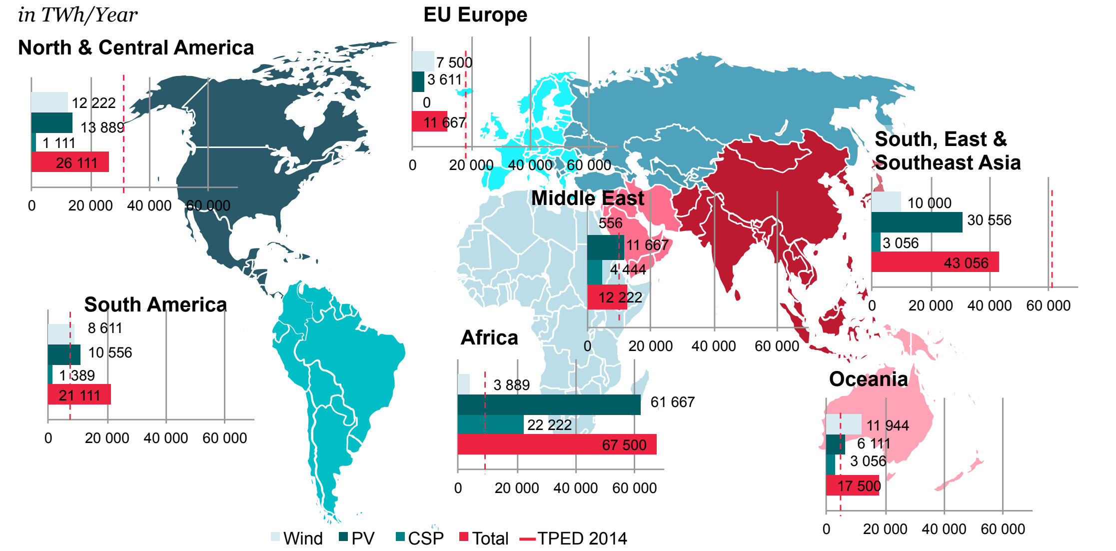
The rest of the fleet will remain on liquid energy carriers in both pathways, but new-build ships will be designed to use lighter qualities, and these will increasingly be synthetic fuels instead of MDO.

Box 7 Availability of Renewable Resources for a P2L Strategy in Marine Transport

Our scenario indicates that completely converting energy use in maritime shipping to and from Rotterdam would need up to 75 TWh of renewable electricity to supply the necessary energy for the electrolysis of hydrogen, the capture of CO_2 from the air and the catalysis processes. Such a strategy has the clear advantage that synthetic liquid fuels could be generated for direct use in the existing motor technology, requiring only very small adaptations to the current fuel supply infrastructure. If synthetic methanol were used, the efficiency of motors would increase – but significant reinvestment would have to be made in the motors and the range of the existing fuel storage tanks would be lower due to the significantly lower energy density. Two-stroke methanol-fuelled diesel motors have recently been developed and are now on the market. Overall, P2L fuels generally fit quite well into a drop-in strategy. Synthetic Fischer-Tropsch-Diesel, or diesel derived from methanol, could be blended into fuels and used in current motors without adaptation. Blending-in of fuels with similar specifications to diesel, such as dimethyl-ether, could require minor adaptations of motors when used in increasing shares.

There is no doubt that producing RES electricity-based liquid fuels would need significant amounts of renewable energy plus huge investment, mainly into electrolysis and CO_2 capture technology at locations with cheap availability of RES. Here, locations that provide a high number of full load hours of renewable electricity (e.g. hybrid PV-Wind power plants) are relevant for decreasing the costs, particularly for the electrolysis of hydrogen. Fashi et. al (2015) have shown that such locations are limited but do exist in many regions around the globe. Production facilities to supply the fuels for all maritime shipping transport touching Rotterdam (as estimated in our scenarios for 2050) would need investment of roughly around €10 to €15 billion in the coming decades.

Based on Deng et al. (2015) the figure illustrates for each world region the lowest estimation of wind and solar potential in 2070 (low range values). The PV category considers PV applications at free surfaces and buildings. The wind category aggregates offshore and onshore wind potential. The authors note that the total potential does not aggregate the different technology potentials, as single technology potentials do not consider overlapping areas. Therefore, the total potential numbers are lower than the aggregated single numbers. In addition to the wind and solar potential, the total primary energy demand (TPED) in 2014 of each world region is illustrated (based on the IEA World Energy Outlook 2016).



Feasible technical wind and solar power potential in 2070. Source: Wuppertal Institute (2017).

From an economic point of view, power-based fuels could become competitive over the coming decades if fossil feedstock prices increase and CO_2 prices are introduced. According to data given in DECHEMA (2017), under optimal conditions (high utilisation factors of the producing units and with very low costs for RES electricity), methanol might be produced at a cost of between 15 to 20 €/GJ. A recent study by Agora (2018) is less optimistic and assumes price levels of 25 to 36 €/GJ for synthetic fuels supplied to the German market. Compared to crude oil prices, which are today at 9 €/GJ (70 $/barrel) and could reach levels of 100 $/barrel (13 €/GJ) or more, the synthetic fuels might become close to being competitive in terms of price, particularly assuming significant future CO_2 costs. A study by Fasihi et al. (2017) expects P2L diesel from Northern Africa to become cost competitive with fossil diesel by 2040 at a crude oil price of 169 $/barrel. However, a CO_2 price of 75 €/t, as well as reduced interest rates (5 % WACC), would bring the cost competitiveness level down to 86 $/barrel.

In addition to the economic challenges of supplying P2L to maritime transport, the issue of availability of such amounts of renewable energy is also relevant. The maritime transport to and from Rotterdam covered in this study alone would need over 50 TWh of renewable electricity per year, equal to about one third of current German total RES electricity generation or almost 50 % of current Dutch total electricity generation. However, transport touching Rotterdam accounts for only 2 % to 3 % of global maritime transport (depending on how it is quantified). Thus, a global strategy to convert maritime transport to such RES based fuels could require around 4 000 TWh of renewable electricity as energy input.

This amount is higher than the EU's current total electricity generation and is, therefore, clearly significant. Adding to the problem is the fact that synthetic fuels would, in such a future, also become attractive for other parts of the transport system such as aviation, parts of road transport and as a chemical feedstock. At a conservative estimate, this could easily grow the demand by double, or even more. Current final energy demand of oil products for all transport modes may even amount to around 28 000 TWh according to IEA (2017). However, growth in renewable electricity generation has been impressive over recent years and is projected to become a major driver of future decarbonisation scenarios. For example, the IEA's Beyond 2°C scenario predicts over 32 000 TWh RES generation globally for 2050 and 41 000 TWh for 2060 (7 and 8 times current RES generation levels), which translates into an additional 4 000 TWh globally every 5 years.

In summary, we conclude that opting for P2L would be a highly ambitious strategy which could be feasible in terms of cost and global potential under significantly favourable circumstances. However, using electricity or RES-based hydrogen without further conversion would significantly reduce the energy losses of the system as well as local pollution – aspects which cannot be completely abated using carbon-based synthetic fuels. It would, however, shift investment and conversion challenges from P2L production facilities to ships, storage, battery and propulsion technology and – in the case of hydrogen – energy supply infrastructures. Overall, the preferred strategy will, therefore, probably be a mix of several of the low carbon options discussed with specific solutions for certain applications.

3.2.2 Hinterland transport

This section summarises the decarbonisation technologies applicable to the following modes of transport: inland shipping, road, rail and pipelines. As shown in Chapter 2.1, the decisive factors for the decarbonisation of the hinterland transport are inland navigation and road transport. These two aspects will, therefore, be discussed in detail below.

With **inland navigation**, options for the decarbonisation of energy use are similar to those available for maritime shipping. An exception is that inland navigation is not subject to the corrosive force of sea water and rough conditions at sea. Inland vessels operate over a long lifetime (frequently more than 60 years) and, therefore, the replacement of ships and technical innovation to date has been slow. The implementation of new technologies may require substantial public support or regulation. It is, however, deemed realistic to achieve between 10 % and 30 % energy efficiency improvements by 2050. For this analysis, an increase in efficiency of 30 % was assumed.

Regarding the fuel supply for inland navigation, from a technical point of view P2L and P2G are both options. The former requires very little change while the latter requires a shift to operating and handling gaseous fuels. However, battery electric drives also seem to be feasible and have already been tested. In these cases, the batteries are placed in containers and may either be recharged at stops or simply exchanged for charged battery containers. Due to the smaller size of the electric drive train, the pay-load of electric barges will be slightly greater than that of conventional ships. Finally, similar concepts for exchangeable hydrogen tanks linked to fuel-cell and electric drives would be possible.

These transportation technologies depend on infrastructure and, in the case of P2L or P2G, on growing demand in other transport modes.

In the 2050 (D-scenario), inland vessels will carry a total of 149 Mt, resulting in 39.8 Gtkm. This results in a W2W Energy demand of 6.0 TWh for a P2L scenario and 5.6 TWh for a P2G scenario with methane, or 3.9 TWh with hydrogen. In the case of battery electric ships, around 1.6 TWh would be needed.

For **road freight transport**, electrification and power-to-fuel (P2F) are key strategies for decarbonisation. For road transport via truck, electrification in combination with hydrogen appears to be a viable path. In the field of electrification, three different battery-hybrid systems are possible: overhead line, conductor rail and inductive charging (Viktoria Swedish ICT 2015). The different modes of electrification all achieve almost the same energy efficiency (Fraunhofer ISI et al. 2017) but have substantially different investment costs. An electrification system with overhead contact lines has the lowest infrastructure and total investment costs compared to the other two electrification systems. However, electrification with overhead lines faces several implementation challenges: e. g. ambiguity about the financing of the infrastructure and incentives for logistics service providers to invest in the development of hybrid vehicle fleets. It would also be difficult to operate such a system in the Netherlands or Germany alone as they are important transit countries – it would require an EU-wide approach. For this reason, there are strong arguments in favour of energy carriers for road freight transport that can initially be blended with conventional fuels and can use the existing supply infrastructure. Decarbonised fuels can be used as a blending component with conventional fuels in existing internal combustion engines. The associated infrastructure can serve as a relatively immediate step into a future, where completely new propulsion systems will be needed. Furthermore, these fuels promote decarbonisation as they can be used in both internal combustion engines and fuel cell electric drives. Above all, methanol has numerous advantages over conventional and other fuels for decarbonisation (e. g. Fischer-Tropsch diesel, ammonia). Additionally, the methanol path might be used to electrify drive trains at a later stage, once fuel cells for methanol (DMFCs) have become cost-effective. Also, hydrogen, as well as batteries, are options for the electrification of drive trains for road transport, particularly for vehicles covering the last mile of delivery in urban areas.

For road transport via truck, the different fossil-free energy options again have their pros and cons. Table 3-7 presents some key advantages and disadvantages of the main transport fuel options currently being discussed.

Table 3-7 Fuel alternatives for road transport, in parts based on Fraunhofer ISI et al. (2017)

<table>
<tr><th>Liquid
P2L (Methanol)</th><th>Gaseous
P2G-CH_4</th><th>Gaseous
P2G-H_2
(Fuel-Cell)</th><th>Electric
Battery-Electric
(overhead line)</th></tr>
<tr><td colspan="2">- Distinctly low efficiencies
Necessary: greater expansion of renewable energies in North-West Europe or import of these fuels from regions with high and economically advantageous renewable power generation potentials.
Competitive only if very cheap renewable energy can be used and CO_2 generation is very cost-effective.</td><td>+ Overall efficiency is higher than that of methanol and methane.</td><td>- High costs and low ranges of batteries or high costs and barriers of overhead line infrastructure</td></tr>
<tr><td colspan="2">+ High ranges</td><td colspan="2" rowspan="2">- Pre-financing of the infrastructure necessary
Build-up is capital-intensive and not fully utilised in the first few years. As market penetration increases, the specific infrastructure costs per vehicle kilometre fall significantly.</td></tr>
<tr><td colspan="2">+ Market introduction is easier because the existing fuel infrastructure only needs to be slightly modified. Due to the very low adjustment effort, the acceptance among truck users and manufacturers is likely to be higher.</td></tr>
<tr><td>+ Only minor infrastructure adjustments necessary</td><td>- (Existing) NG filling station network need to be expanded</td><td colspan="2">- Comprehensive infrastructure required</td></tr>
</table>

P2L in particular needs only minor adaptations in motor technology and infrastructure and current systems could generally remain unchanged. The likely drawback is the probable higher fuel costs. P2G requires a shift to gaseous energy carriers, which would need adaptations in tanks on vehicles as well as in filling stations. Advantages are potentially lower pollutants and possible combination with an intermediate strategy focusing on the conversion to fossil natural gas first and to synthetic P2G later. Both fuel change strategies, however, have rather low efficiencies and need significant amounts of renewable electricity to generate hydrogen for conversion into synthetic fuels.

Alternatively, a technology shift would be possible towards hydrogen or different routes of electrification, e.g. via battery electric trucks – as currently announced by tesla – or via hybrid electric trucks combined with overhead lines on the most relevant motorway routes. Hydrogen and electrification have several advantages, i.e. significantly higher energy efficiency as well as lower pollutant emissions. Their disadvantage is the technological change needed, e.g. to battery electric vehicles. It is still a matter of much debate if and when trucks will be available that achieve sufficient ranges and batteries at sufficiently low cost and low weight and volume which enable a reasonable ratio between battery weight and payload. In addition, significant investment into new infrastructure, such as the construction of an extended overhead line system or a network of hydrogen fuelling stations, would be needed and this would have to be prefinanced in advance of increasing the shares of such trucks.

Given the challenges of the P2L and P2G routes on the one hand and the electricity or hydrogen routes on the other, it is currently still uncertain which route will be more economical (i.e. have the lowest additional costs). Available decarbonisation studies are, therefore, still quite divided on which technological route to favour.

For 2050 D 122 Mt of freight will be transported by truck, which results in 18,4109 tkm. This leads to a W2W energy demand of 5.4 TWh for P2L and 5.0/3.5 TWh for P2G with CH4 or hydrogen respectively. A purely electricity-dominated transport mode would require about 1.4 TWh of electricity. (For more details, see background report 5).

For the decarbonisation of rail transport and pipelines, only electrification based on renewable energies is considered as a straightforward strategy as both are already electrified to a large extent. For rail transport, the direct use of electricity is accompanied by a necessary transformation relating to upstream emissions for electricity suppliers. For niches in rail transport (low-frequency track sections and shunting locomotives) either the diesel drive can continue using diesel from climate-neutral P2F production, or it may be possible to switch to existing battery-electric or hydrogen fuel cell-electric propulsion.

Most railways are already electrified, and their efficiency is relatively high. For the scenarios in this study, the complete electrification of train transport was assumed. This will be possible via conventional electrification or for special short distance trains via battery electric engines which are already available on the market.

Complete decarbonisation of rail transport is quite straightforward as it implies the exclusive use of renewable-based electricity. This is supported by the fact that Nederlandse Spoorwegen (passenger transport) has used 100 % renewable electricity since 2017 and DB Group, which includes DB Cargo AG and DB Cargo Nederland N. V., had a 42 % share of renewable electricity in 2016 and targets of 45 % for 2020 and 100 % for 2050.

For the pipelines, electric pumps are assumed for a transport volume of 11.8 billion tkm 65 GWh were needed. As for the railways, the conversion of the electricity supply towards renewable energies is assumed.

3.2.3 Handling in the Port

The scenarios for the “(Deep)decarbonisation effects of transport” refer to the question, "How are goods transported?". One important aspect is the efficiency and electrification of handling operations in the Port of Rotterdam. Handling operations at the port include ships lying at berth, trucks waiting to be unloaded or loaded, operation of container and bulk terminals, heating and cooling of stores, warehouses and offices as well as significant in-port rail, truck, conveyor belt and pipeline logistics.

In addition to technological and operational strategies for increasing energy efficiency, the switch to non-fossil energy carriers, such as full electrification based on renewable energies, battery-powered drive systems and P2G-H2, is an important decarbonisation strategy. Due to the short distances to be covered within the port area, it is easier to implement a fuel switch. With this small-scale fuel change, the port can gain experience for hinterland logistics and, at the same time, achieve the co-benefit of improving local air quality.

In order to advance the electrification of handling operations in the port, the gradual expansion of renewable energies must be driven forward. The Port of Rotterdam has set itself the goal of generating at least 150 MW of new wind energy in public port areas by 2020. Together with its partners, the port is pursuing the vision of achieving a total installed capacity of 300 MW by 2020 (POR n.y.d).

3.3 Overall scenario results

Deep decarbonisation of the European and global economies with emission reductions by the middle of the century by 80 % to 95 % will have various impacts on the volumes, structures and GHG emissions of transport touching the Port of Rotterdam.

As described above, goods and freight transported to and from Rotterdam via maritime shipping, as well as by inland transportation modes, and handling at the port used around 90 TWh of mainly fossil energies in 2015 in a well-to-wheel perspective. The related CO_2 emissions amounted to 24 million tonnes.

In a largely decarbonised world in the year 2050, however, the situation will be significantly different. Decarbonisation will result in a massive decline in the transportation of oil and oil products as well as of coal, which will only partly be compensated for by the additional transportation of biofuels or alternative synthetic energy carriers. The scenarios anticipate that, in a decarbonised world, maritime transport volumes touching the Port of Rotterdam will decline by around 11 % between 2015 and 2050 (Figure 3-13).

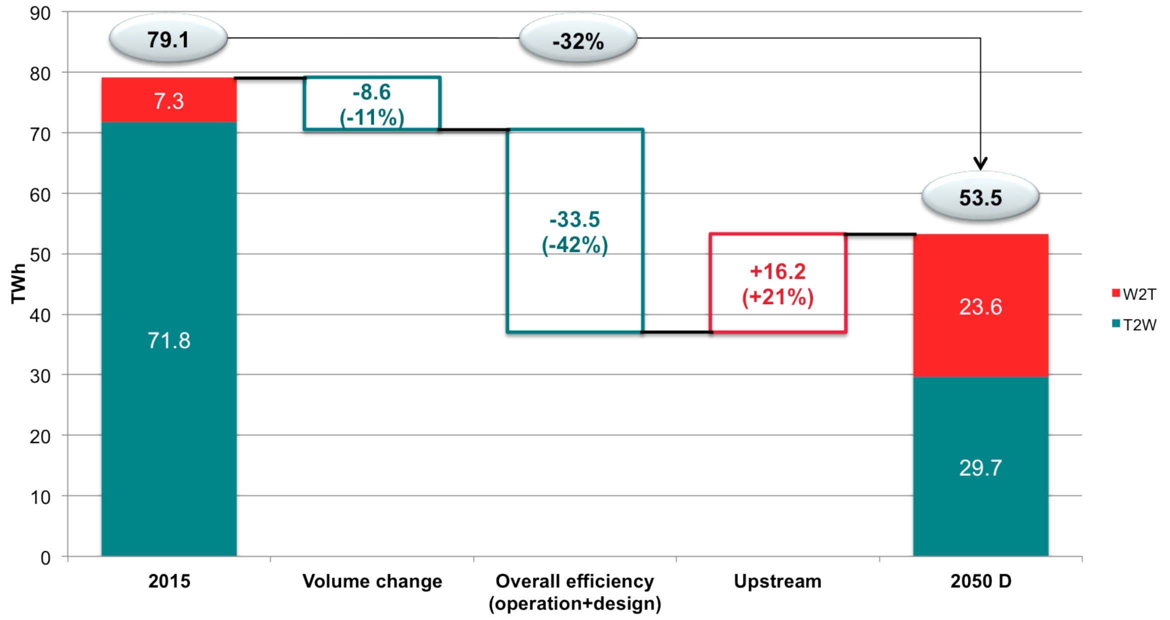


Figure 3-13 Scenario results maritime 2050D liquids scenario

In parallel, efficiency in freight transport will increase due to active policy measures as well as increasing fuel and carbon costs. With efficiency improvements of around 50 %, **maritime shipping** will improve the most, followed by inland navigation and trucks. Efficiency gains will be partly compensated for by the switch to container shipping, which is characterised by higher speed and, therefore, higher energy demand per tkm. Overall these effects result in additional energy demand reductions of 42 %.

Linked to the technical changes in the maritime ships is a switch towards net zero carbon synthetic fuels. These, however, need to be produced from hydrogen generated via electrolysis with renewable electricity. Only feeder transports and short sea shipping, which account for the electrification or conversion to hydrogen of almost 10 % of transport volumes will be technically feasible. As the whole process of synthetic fuel production incurs significant energy losses in the two main conversion steps, an additional energy demand of around 21 % is incurred.

These changes will result in maritime shipping converting from fossil fuels to electricity-based synthetic fuels (and some direct electricity and hydrogen). Due to the conversion losses of the synthetic fuels, energy demand in 2050 in the liquids scenario will only be 19 % lower than in 2015, despite lower transport volumes and much more efficient ships. However, as the electricity is assumed to come from 100 % renewable energies in 2050, CO_2 emissions from maritime shipping would be close to zero by 2050.

A rather similar picture results for the liquids & gaseous scenario (Figure 3-14). Due to slightly higher conversion efficiency of the power to methane route (P2G), as compared to P2L, the energy demand in 2050 is around 4 % lower than in the P2L scenario.

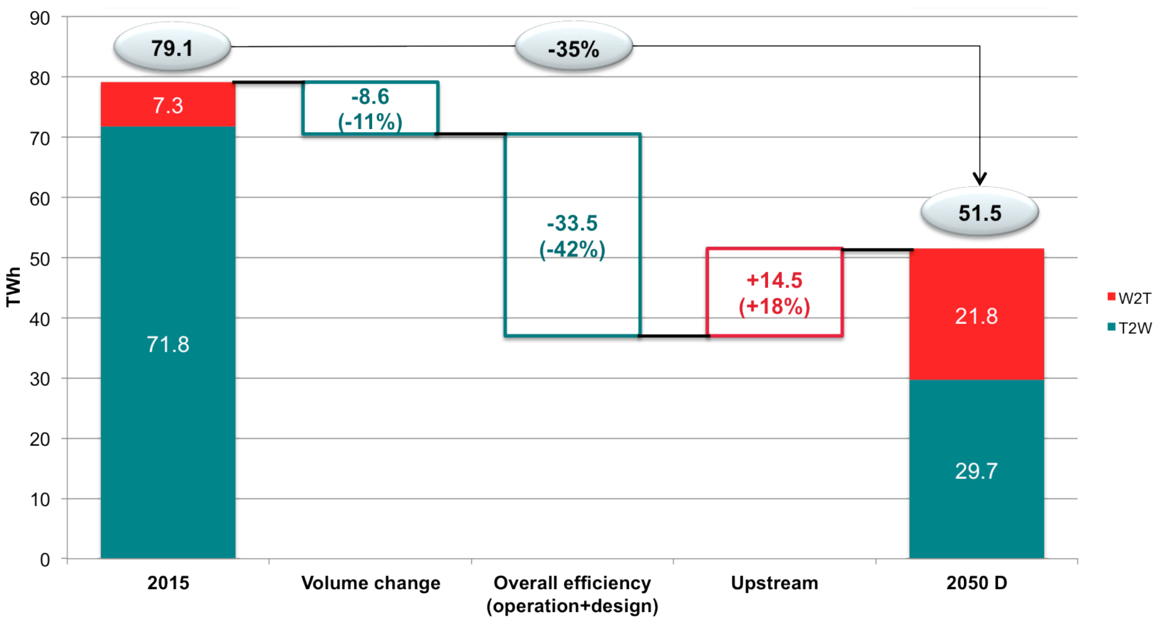


Figure 3-14 Scenario results maritime 2050D liquids & gaseous scenario

Inland transportation of goods to and from the Port of Rotterdam has significantly smaller volumes, mainly due to the greatly reduced travelling distances of the goods. Energy demand for the hinterland transport in 2015 was slightly below 11 TWh with inland navigation and road transport accounting for almost 40 % each. Rail transport was responsible for 24 % of the total energy demand in the hinterland. CO_2 emissions in 2015 had roughly similar shares.

For hinterland transport, as well as for maritime transport, significant structural changes occur. The most important changes are a slight decline in overall transport volumes and a strong shift from inland navigation towards road transport, resulting from the significant decline in bulk goods and the marked increase in container transport.

Figure 3-15 compares four scenarios with different energy supply strategies for the hinterland transport via ship and truck. Trains are assumed to be 100 % electric in all scenarios.

- The P2L scenario for road and inland navigation has the advantage of only minor changes in technology and infrastructure, but results in the highest energy demand (6.3 TWh tank-to-wheel plus another 6.1 TWh for synthetic fuel generation). Another advantage could be the potential for a stepwise conversion from fossil towards drop-in synthetic fuels between now and 2050.
- Slightly more efficient is the P2G scenario. Drive train efficiency gains are slightly higher than in the P2L scenario and the indirect energy use to produce the syngas is lower than for the liquid synthetic fuels. Overall, well-to-wheel energy demand will be 11.7 TWh renewable electricity by 2050. However, this scenario requires a new dedicated energy supply and filling infrastructure for gaseous fuels. Such infrastructure could, however, be used for fossil LNG initially and later easily converted to supply synthetic methane.
- The efficiency advantages are even more pronounced in the scenario assuming hydrogen with fuel cells and electric motors. Its well-to-wheel energy demand

stands at 8.5 TWh. However, as well as the need to develop fuel cell trucks, an expanded network of hydrogen filling stations and decentralised hydrogen production would be needed, which could be challenging (mainly for road transport).

- Finally, the electrification scenario with battery hybrid systems, e.g. hybrid trucks using overhead lines on special motorways and batteries for trips on non-electrified parts of their route, is the most efficient in terms of motor technology and creates almost negligible losses in the supply of renewable electricity. Total well-to-wheel energy demand will be as low as 4.0 TWh, which is less than half the energy used in the next best alternative. Again, this scenario would require dedicated charging infrastructure and possibly require the construction and operation of an expanded network of overhead lines for trucks on European motorways. The availability of suitable battery systems for trucks at attractive prices will be decisive for this scenario.

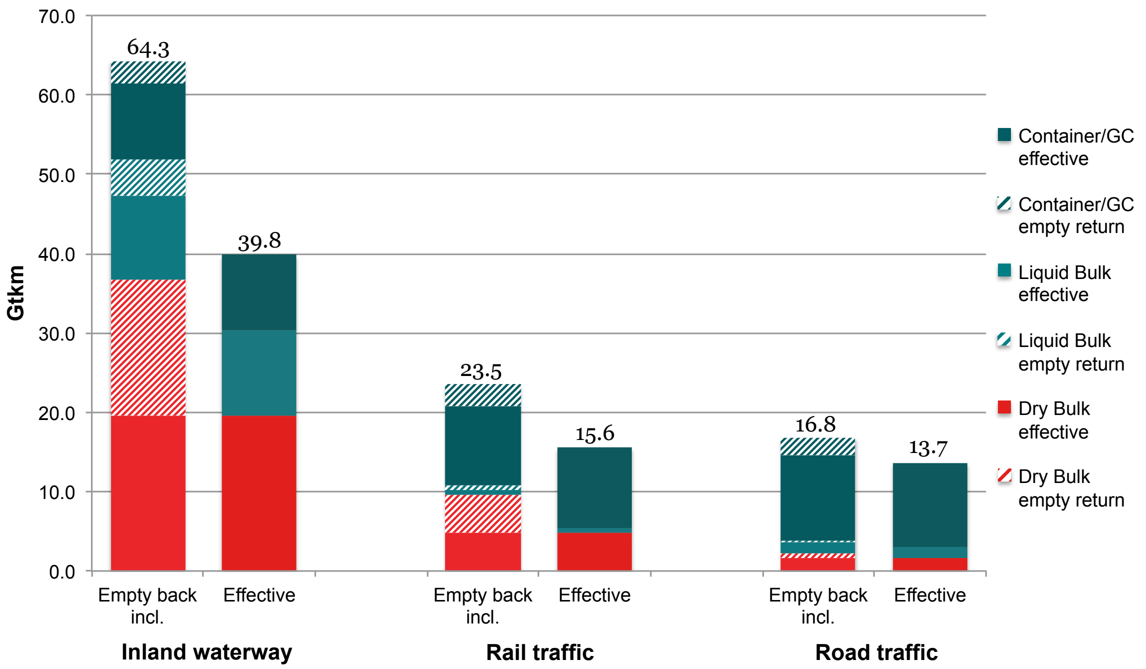


Figure 3-15 Scenario results inland, energy demand 2050D – four scenarios

These scenario results show: (a) that decarbonisation will significantly change the amount and structure of freight transported; (b) that there are several technological routes to convert transport systems towards net zero carbon; and (c) that a clear trade-off between renewable energy demand and infrastructural challenges exists. Furthermore, all the scenarios depend on future technological and economic developments that will be strongly driven by the future of passenger transport.

To date, however, all routes have their specific advantages and disadvantages, which makes it difficult to decide which of the routes or which mix will prove to be optimal for the decarbonisation of transport. While railways and pipelines are almost completely electrified already, battery-based inland navigation also seems to be a promising long-term solution (assuming that battery technology develops as expected). All routes, however, indicate that transport costs might rise and the general underlying assumption is that vehicle efficiency must be improved.

4 Recommendations

In this study, two bottom-up -95 % CO_2 emissions scenarios were developed to analyse how future freight volumes via Rotterdam may be affected by the EU's ambitious climate mitigation targets for 2050. The scenarios and pathways on decarbonised goods and freight transport show that the global shift towards climate friendly renewables-based energy systems will have significant effects on the amount and structure of goods transported via Rotterdam (the same is true for other seaports in Europe and globally). Also transport modes, as well as related infrastructure, will undergo significant changes in technology and operation.

This study focuses mainly on the year 2050 as a proxy for the time when the transition towards fully non-fossil renewable energy systems in Europe and the world should be almost complete. Long-term decisions need to be made now and these must take zero carbon futures into account, since infrastructure and the related assets planned today will be still in operation by 2050. As our study shows, decisions must be made quickly about what new technologies to invest in for the construction of vessels and infrastructure.

Changes in investment patterns imply significant risks for investors given the considerable uncertainties surrounding issues such as future regulations, market demand for greener transport, price development and availability of fossil and non-fossil energy. However, there are a number of no regret measures which prepare for the long-term perspective or are feasible first steps in the right direction.

The following recommendations aim to combine the identification of early potential for action with long-term strategies to pro-actively adapt business and investment strategies to the forecast impacts of climate mitigation on port-related transport. Recommendations are grouped into four fields of action:

- Deal with future potential changes in transport volume and structure due to decarbonisation
- Support and enable efficiency and fuel switch for maritime transport
- Support and enable efficiency, fuel shift and modal shift for hinterland transport
- Pursue efficiency and electrification of handling operations

For each field, we outline possible courses of action for the three main groups of actors: the Port of Rotterdam (and other ports), business partners (mainly in the shipping and logistics industries), and the Dutch and other governments.

4.1 Deal with future potential changes in transport volume and structure due to decarbonisation

Overall, the volume of liquid and dry bulk transport will decline massively due to the phasing out of fossil energy carriers. However, for Rotterdam, containerised transport can be expected to more or less compensate for this decline on a weight basis. The structural change in the transport system and infrastructure will demand the handling of significantly more containers, including their transfer to inland navigation and rail and their respective greening.

Table 4-1 indicates the major trends that will govern changes in transport in the move towards a decarbonised future and the related fields of action.

Table 4-1 Fields of action to cope with future potential changes in transport volume and structure due to decarbonisation

Actor & field of action / Trend	Port of Rotterdam	Shipping lines / logistics companies	Governments (NL, Germany, Belgium, EU)
Growth in overseas container transport	Add terminal and ship handling capacities	Invest in non-fossil container vessels	Support dematerialisation policies
Decline in dry bulk volumes	Opportunity to stepwise re-use dry bulk facilities	Inland navigation: prepare for restructuring/conversion towards container shipping	Support shipping with conversion policies
Decline in liquid bulk and switch from fossil oil products to biofuels or synthetic fuels	Check which adaptations in port infrastructure will be needed and when to engage with pipeline operators for infrastructure switch	–	Support more sustainable transport policy to reduce fuel demand in all modes, support development of (sustainable biomass and) synfuel technology and markets
Strong increase in container transport on inland ships and railways	Strengthen capacities to load containers onto barges and trains Engage with hinterland regions along the Rhine and in Benelux to increase the development of multimodal terminal capacities Engage in logistics models that improve the competitiveness of multimodal container transport	Inland navigation: prepare for restructuring/conversion towards container shipping Develop multimodal business cases and align with truck delivery for "last mile" Railway operators: increase network capacities, develop more flexible train systems	Provide infrastructure support (planning, financial) for the development of multimodal terminals and infrastructure de-bottlenecking Develop international comprehensive plans for multimodal container transport Implement regulatory measures to support shipping and rail
Increasing truck transport volumes	Try to prevent growth in truck use, e.g. via contracts with terminals and provision of alternatives Possibly develop hinterland container terminals connected via rail or barge	–	Implement regulatory measures to curb road transport Increase taxes / road fees for trucks

Most **no regret measures** should focus on exploring trends and piloting future infrastructure solutions in order to anticipate future trends early enough to react or shape them. These measures should, ideally, be pursued in close collaboration with shipping lines, logistics companies and the government to manage the complex system and all its actors along the value chain.

General trends in **seaborne freight** will typically be external and leave little room for influence. It is important for the Port of Rotterdam to work on strategic ideas to adapt the handling infrastructure to the changes in advance of their occurrence. One example could be the early development of import infrastructure for hydrogen and synthetic energy carriers once import volumes reach scale (which may not yet be for a decade or two).

Regarding the **hinterland transport**, stronger cooperation with actors in the hinterland at local, national and EU levels through the development of a project or network, e.g. a future "decarbonised Rhine catchment transport vision" or plan, could be an important first step. This could become a framework not only to develop joint strategic visions but also to create joint pilot projects focusing on the different challenges mentioned above. Further fields of action could be developed and possibly implemented within such a framework.

4.2 Support and enable efficiency and fuel switch for maritime transport

Potentials for efficiency increases of 25 % to 75 %, or even more (see chapter 3.1), have not yet been exploited on a large scale, due mainly to high competition and very low energy costs in the sector. The reduction potential of improved efficiency will not, in any case, be sufficient in the long run to achieve close to zero GHG emissions in shipping. Consequently, carbon efficiency i.e. a fuel switch towards zero fossil energy supply for ships, will be needed as an additional strategy over and above optimising fuel efficiency.

Table 4-2 outlines two efficiency-related fields of action. Ship owners are the main group who need to act here – with governments providing regulatory and fiscal frameworks to make efficiency more attractive to the shipping lines and reduce barriers.

The Port of Rotterdam may become active in a number of diverse supporting roles:

- by lobbying government and market actors for e.g. greener shipping, CO_2 charging and the expansion of emission control areas;
- by providing (limited) incentives for greener ships e.g. via reduced fees or priority handling; and
- by taking an active role in operational measures where appropriate, such as "virtual arrival" or the provision of maintenance services, and by participating in the establishment of monitoring and verification systems.

The Port of Rotterdam is already active in several of these fields. Those activities could, therefore, be specifically adopted under the framework of the port's decarbonisation strategy and stepwise developed towards an increasingly comprehensive set of measures undertaken by the port.

Table 4-2 Fields of action related to increased efficiency of maritime shipping and ships

Actor & field of action Trend	Port of Rotterdam	Shipping lines	Governments
Operational measures to improve efficiency and reduce emissions in shipping (e.g. slow steaming, regular maintenance, improved logistics / load factors)	Support (mandatory) verification systems such as ESI / CSI Provide incentives for cleaner ships Offer (mandatory or reduced price) services (hull monitoring / cleaning, engine-related) "Virtual arrival" and (mandatory) onshore electricity connections	Improve operational standards and give high priority to low pollution practices Use CO_2 shadow values in internal decision making	Introduce CO_2 price to maritime shipping globally or at least for the leading markets (e.g. US, EU, China, Japan) Make verification systems mandatory and connect with ship tracking systems Introduce dynamic fleet standards on average load factors (internationally harmonised)
Measures to improve ship efficiency (mainly when ships are newly built), e.g. hull, propeller design, drive train improvement, PV, sails, kites or wind turbines mounted on ships	Lobby IMO etc. for improved new-built standards Provide incentives for cleaner ships	Invest only in new highly-efficient ships Use CO_2 shadow values in internal decision making Create sector-wide standards for new-builts	Introduce CO_2 charging and create expectation in the sector of continuously increasing CO_2 costs Use procurement, competition or top runner approaches to incentivise development of first of a kind highly-efficient ships Require ship energy and emission standards for ships calling at ports (e.g. depending on age of ship)

Several options exist for **switching the energy supply of the ships** towards non-fossil energy carriers and towards near zero GHG emissions in maritime shipping, but these are not yet commercially available (see Table 4-2). These options should be combined with the efficiency measures above to fully exploit the potentials and to improve the economy of efficiency measures.

Fuel switch opportunities need to be included in investment by ship owners; this will often require greater **investment in ships** and, to some extent, the use of more expensive fuels (Table 4-3). However, these alternative fuels emit significantly less pollution and are often more efficient. Therefore, governments need to create strong, widespread and reliable monetary and/or regulatory frameworks to enable ship owners to redirect their investments towards zero emission or zero emission ready ships. The Port of Rotterdam, in terms of efficiency measures, can support this politically and logistically and through (limited) incentives. In addition, the higher investment costs, combined with the initial risks associated with almost all the non-fossil solutions, may lead to new forms of ship or battery ownership with e.g. leasing schemes, possibly government-supported. The Port of Rotterdam might become an actor providing such schemes to shipping lines active at the port.

In contrast to the efficiency measures, fuel switch strategies also require the development of the associated **energy supply infrastructure at ports**, which may increase uncertainty related to decisions to invest in new zero fossil ships. The provision requires action to be taken by seaports as well as by governments, and possibly also by energy supply companies. It is at least partially a long-term issue, because many energy sources for ships are not yet available. Urgent action is needed to build confidence amongst ship owners about the availability of the necessary infrastructure and so influence their decision making.

Table 4-3 Fields of action related to fuel switch for (maritime) ships

Actor & field of action Trend	Port of Rotterdam	Shipping lines	Governments
Fuel switch for ships	Provide incentives for cleaner ships Create port alliances to provide standardised fuelling infrastructure	Use CO_2 shadow values in internal decision making	Introduce CO_2 charging
• (Sustainable) drop-in biofuels	Provide supply of (sustainable) biofuels (➔ pilot project) Develop standards for sustainable biofuels	Market low energy non-fossil marine transport (cruise vessels but also freight vessels)	Introduce dynamic fleet standards on average emission factors (internationally harmonised)
• New-build ships to have LNG as intermediate solution (later switch to syngas)	Provide LNG fuelling infrastructure Create partnerships with shipping lines to market LNG	Invest in new gas or methanol- fuelled ships Invest in battery electric and hydrogen ships	Fund pilot applications of electric and H_2 fuelled ships
• New-build ships to be designed for methanol **(bio-based, later synthetic)**	Provide methanol supply Pilot bio-based and synthetic methanol e.g. for niches (together with shipping lines)	"	Subsidise battery leasing systems Introduce tough emission standards for shipping within the EU
• New-build ships for short distance niches (feeder, RoRo, Ferries, Tug boats etc.) with **electricity supply**	Pilot battery electric shipping with e.g. tug boats Develop concepts for battery leasing systems with governments and shipping lines	"	Use procurement, competition or top runner approaches to incentivise the development of first of a kind ships with non-fossil fuels
• New-build ships with H_2 **(for short&medium distances)**	Pilot H_2 supply infrastructure connected to the H_2 system and initial ships Support RES H_2 production at the port	"	Subsidise ship new-builds using greener fuels Introduce dynamic minimum emission standards e.g. for tug boats and subsidise new clean boats

Given the early stage of development, no (or little) regret measures for the Port of Rotterdam consist mainly of pilot projects. These are particularly advised for fields where stand-alone solutions can be developed.

- Low GHG solutions already close to entering market are (first and second generation) biofuels and LNG. Therefore, it makes sense for the Port to start developing the corresponding infrastructure and logistics (and/or expand existing pilots) in order to be able to increase their scale as soon as is necessary.

- Hydrogen and electricity are both still quite expensive and less developed, but they could be explored in pilot projects and could also benefit from in-port renewable electricity generation or the existing hydrogen grid. As these energies are relevant for shorter distance transport, they could be mainly developed for specific purposes such as tug boats or RoRo-ships on fixed lines, which would not require the participation of (many) other ports in infrastructure supply. However, infrastructure and ship technology development must be synchronised.
- Methanol seems to be particularly promising as a non-fossil ship fuel, but also as a bulk energy carrier to be transhipped (and possibly also as a feedstock for chemical production in Rotterdam). Its development, however, will still take some time. Starting a methanol supply infrastructure (which would initially deliver fossil or bio-based methanol) might be a good first step. However, the development of the "power-to-fuels" discussion should be closely monitored by the port and discussed with its stakeholders in order to make early decisions as soon as possible.
- For all energy carriers, the Port of Rotterdam should also bear in mind potential synergies between non-fossil energy supply for maritime ships and for inland transport (ships, trucks) as well as in-port transport.

Development of new non-fossil energy carriers and their related infrastructure will depend greatly on public policy and support. Therefore, Dutch and EU policymakers should actively support pilot projects via research and demonstration, as well as investment support, for the infrastructure to be developed at scale.

4.3 Support and enable efficiency and fuel shift for hinterland transport

Transport to and from Rotterdam is very important for inland navigation, but less so for rail and road. Therefore, the port must align itself with strategies pursued by other actors in the hinterland transport sector (see Table 4-4).

It can be assumed that the efficiency potentials for land-based modes of transport are probably significantly lower than for shipping. Therefore, the decarbonisation of hinterland transport requires to an even greater extent the conversion of energy carriers to non-fossil and renewable supply, despite current challenges.

- Railways and pipelines are already typically driven by electric motors. Remaining niches and the supply of the electricity for railway operations will be stepwise switched to renewable sources, as announced by Dutch and German Rail.
- Biofuels and LNG are options for inland navigation. While biofuels also offer potential as drop-in fuels, natural gas would require adapted motors and tanks and fuelling infrastructure. Along the River Rhine, bunkering storage options could be installed. The same holds true for hydrogen, which could be used to drive inland ships. Synthetic fuels could be used, once market-ready, either as drop-in diesel or for ships converted to methanol. Battery electric would need loading infrastructure at several ports and/or locks etc. Given the importance of Rotterdam for inland shipping, the port could push the conversion forward.
- Decarbonising road freight transport may take place in the form of the electrification of long haul freight transport, although this is particularly challenging given

the size and weight of the batteries needed. Alternatives, such as hybrid trucks with battery and overhead lines on main routes, LNG, hydrogen and synthetic fuels are the subject of much debate. They all require significant infrastructure development and there is still high uncertainty about whether these options will eventually be adopted.

Table 4-4 Fields of action related to efficiency and fuel shift for hinterland transport

Actor & field of action Trend	Port of Rotterdam	Shipping lines / logistics companies, transport companies	Governments (NL, Germany, Belgium, EU)
Rail and pipelines: electrification of niches / parts not yet electrified	Require/support electrification of in-port railway engines	Pipeline operators and railway companies: conversion programmes towards non-fossil electricity	Support/require conversion to electric
Inland navigation: range of options apply: LNG (and biofuels) as immediate option with limited potential, H_2 and electrification as well as synfuels (methanol) as (mid to long-term) non-fossil solutions; biofuels as drop-in option ➔ **Strong link to structural changes and modal shift (see above)**	Pilot LNG, H_2 and electric inland vessels in partnership with ship owners Develop (pilot) filling infrastructure (battery leasing systems for ships) Engage with ports in the hinterland to jointly develop LNG, H_2 battery supply infrastructure Partner with ship owners to lobby for public support on fuel switch / ship modernisation	Invest in new vessels with new motor technology Partner with governments and others for investment in multi-modal terminals Prepare for major sectoral restructuring	Support RD&D as well as market introduction of new propulsion technologies Support battery leasing systems for ships Support shipping owners with modernisation of fleets (particularly small ship owners) Create EU-wide framework for sector restructuring / modernisation Establish tight EU-wide emissions regulations for inland navigation
Road transport: efficiency via optimisation, autonomous driving, platooning, fuel switch options: LNG, H_2, biofuels, hybrid overhead line trucks (HOLT), battery trucks	Require transport to and from Rotterdam to develop low carbon as well as space saving solutions Develop pilots for dedicated line transport using LNG, H_2, battery trucks, including pilot applications for filling infrastructure Study developments for truck overhead lines in order to align early with port road access strategies Partner with logistics providers to monitor and verify strategies for green transport	Prepare for investment in fossil-free as well as autonomous trucks Develop logistics and business models for green transport	Support RD&D as well as market introduction of new propulsion technologies Support battery development /mega factories Support battery leasing systems Support truck owners with modernisation of fleets Create EU-wide framework for sector restructuring / modernisation Establish tight EU-wide regulations and incentives for decarbonising road transport Develop a master plan for green freight transport in NW Europe (including modal shift)

As with maritime shipping, the potential role of the Port of Rotterdam is limited. However, here again (government-supported) leasing schemes for clean ships and battery driven trucks or ships (for ships or trucks) might be a field where the port, as an important transport hub, could acquire the role of service provider.

Most new non-fossil energy carriers will also need dedicated energy supply infrastructure covering areas beyond the Rotterdam hinterland (see Table 4-4). Their development requires collaboration with hinterland actors, in the same way as the policies for modal shift (see Chapter 4.1 above). Due to the large uncertainties, no regret actions are limited to studies, networking and pilot projects.

For inland navigation, electrification seems to be very promising, particularly with the expected improvement of battery capacities and costs. The introduction of electric inland ships would require major rebuilding of the existing fleets, supported by strong government incentives (and funding). The Port of Rotterdam could potentially lobby for such a strategy. If implemented, many of the ports and locks along the Rhine and in the main North-West European canal network would have to be supplied with loading stations for batteries and/or battery exchange opportunities.

However, in a first step, ships on standard routes or ships making short round trips and frequently returning to Rotterdam could also operate with infrastructure in Rotterdam only. By developing and providing such infrastructure in cooperation with government strategies, Rotterdam could become a driving force in the electrification of inland navigation. Such a strategy could also be combined with the provision of battery or ship leasing and maintenance at the port (or by the port) and should be checked for synergies with strategies for short distance maritime ships.

In terms of road transport and hybrid trucking with overhead lines, the Port of Rotterdam could ensure it becomes connected to such a grid and synchronises its development with internal strategies to cope with increasing levels of truck transport.

4.4 Pursue efficiency and electrification of handling operations

Handling operations at the port include ships lying at berth, trucks waiting to be unloaded or loaded, operation of container and bulk terminals, heating and cooling of stores, warehouses and offices as well as significant in-port rail, truck, conveyor belt and pipeline logistics. A large share of these operations is already electrified, and further electrification should cover all stationary and mobile drives, as well as external electricity supply for ships at berth and waiting diesel trucks. For heating and cooling purposes, electric heat pumps and also waste heat from industrial installations or other renewable heat sources are readily available solutions for decarbonisation. Linking of these strategies to local renewable electricity generation from wind turbines and photovoltaic could also be considered.

Increasing the share of non-fossil electricity and other renewable energies is typically not a technical problem and is often cost-efficient, but it needs to be implemented according to an integrated strategy. Such a strategy could stipulate clear targets for port operations and negotiate targets for third-party operations. These targets could then be included in the leasing or operations contracts. The heat supply strategy should be integrated with ongoing developments in the industrial companies located at the Port of Rotterdam.

For ships at berth and waiting trucks, mandatory obligations to use land-based electricity supply would probably be needed.

All developments should consider possible synergies with pilot projects e.g. for the electrification of trucks or ships or the use of hydrogen.

4.5 Cross-cutting actions

Overall, the decarbonisation of (maritime) transport is not expected to happen without active support by governments and other relevant stakeholders. A consistent and comprehensive long-term policy is required to build the fundamental framework for decarbonising the sector.

On the part of **governments**, together with the IMO and the UNFCCC, a framework for GHG mitigation in maritime transport is needed. This could consist of GHG emissions targets for maritime shipping contributing to the Paris Agreement under the UNFCCC. Furthermore, this could be combined with effective instruments such as the introduction of a long-term reliable and globally-applied increasing CO_2 charge or tax. These general instruments could be supported by the expansion of controlled emissions zones, strict regulations on pollutant emissions and mandatory efficiency standards for ships that could be implemented stepwise by the main port nations. Germany, Netherlands, Belgium, France, Sweden and Denmark have already initiated a "High Ambition Coalition for Shipping" in collaboration with the Marshall Islands, Tuvalu, Tonga, Kiribati and Antigua. This group aims to press for ambitious targets to be agreed by the IMO in April 2018. Decarbonisation of maritime transport will further significantly benefit from the development of renewable energy generation and RES-based synthetic fuel supply. Governments should, therefore, support these developments by providing targeted RD&D support as well as market pull mechanisms.

On a national or European level, countries should also develop suitable funding instruments to firstly (a) enable reinvestment in vehicle and vessel fleets adapted to new non-fossil technologies, mainly for sectors with many small actors lacking capital (e.g. inland navigation). Secondly, it could (b) support the necessary infrastructure for non-fossil energy supply in freight transport, as well as for increasing container volumes and modal shift in hinterland transport. In addition, the German and Benelux governments, as well as regional governments, should develop a comprehensive strategy covering the complete hinterland of Rotterdam and integrating the infrastructure and regulatory challenges of modal shift with those of decarbonising all transport modes[9] .

Based on the recommendations of this study, many activities already taking place and pilot projects undertaken by the **Port of Rotterdam**, an integrated strategy should be developed covering all decarbonising elements. In addition to clear mitigation targets and the development of ideas for potential business cases, such a strategy should exploit all potentials for action at the Port of Rotterdam. This includes own

9 A potential lever for such a strategy might be the international Convention on the Protection of the Rhine, which broadly covers the Rotterdam hinterland. However, its focus would need to be extended from mainly water and environmental protection to cover a much broader remit.

investment, the development of infrastructure pilots, the use of port fees and handling priorities. Contracts with terminals, tug boat companies etc. can incentivise and/or mandate decarbonisation strategies and raise awareness among partners, stakeholders, policy/lobbying as cross-cutting measures for all fields identified.

Furthermore, decarbonisation challenges typically affect the value chains of the diverse market partners of the port. As successful strategies often require several actors to cooperate, intensive dialogue with partners on the decarbonisation strategy would be vital to ensure the port is prepared and proactive.

Another cross-cutting action could be the improvement and further development of existing monitoring and verification tools (e.g. for tracking ships and their emissions, as well as goods along the value chain). Such tools may, in due course, become important in developing "green logistics products", i.e. proving that a certain product was transported without causing GHG emissions. They also have the potential to change current business models in transport and logistics. Therefore, it might be of strategic value for the Port of Rotterdam to play an active role in the development of such tools in order to support their development and secure access to the tools and data, as well as for potential future value generation.

Finally, **shipping and logistics companies** should prepare to reinvest in fleets and give green logistics higher priority in investment and operational decision making e.g. by introducing shadow carbon pricing into their decisions. Such activities could enable them to prevent stranded assets and to become first movers for decarbonisation and derive competitive advantages when climate-related regulations become effective.

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