Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

TNO 2021 R12635

Transition to e-fuels: a strategy for the Harbour Industrial Cluster Rotterdam

Background report

Date	December 2021
Author(s)	Karin van Kranenburg, Thijmen van Bree, Anastasia Gavrilova, Jorrit Harmsen, Caroline Schipper, Ruud Verbeek, Sara Wieclawska, Frank Wubbolts
Number of pages	81 (incl. appendices)
Sponsor	SmartPort
Project name	CHAIN
Project number	060.43136

Project partners:

Management summary

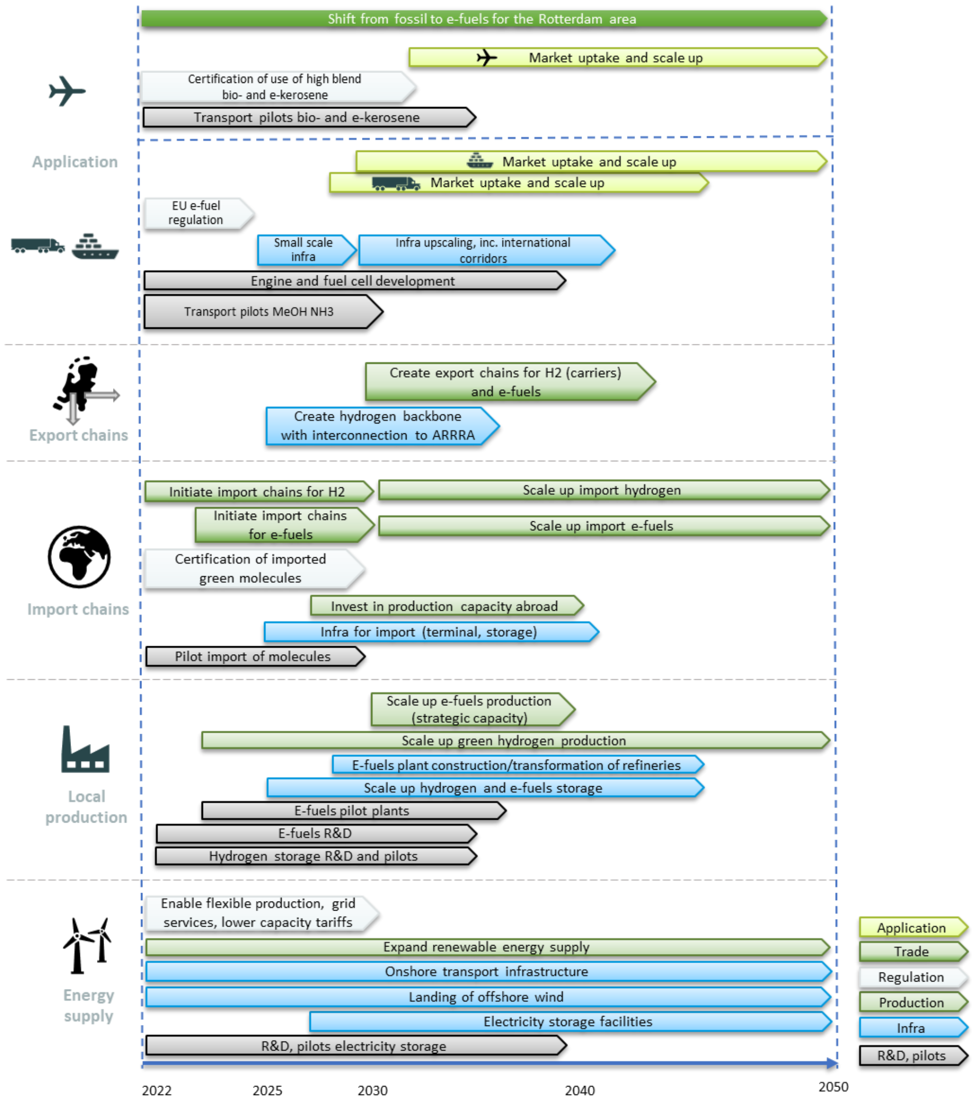
The Harbour Industrial Cluster (HIC) Rotterdam faces a challenge to deliver a contribution to make transport, and especially the heavy duty modalities that are hard-to-abate, more sustainable. Rotterdam is home to the second largest fuel cluster in the world. In addition, Rotterdam is an important global logistics hub, which is of great significance to the Dutch economy. It is therefore of vital importance to design a strategy for the Harbour Industrial Cluster (HIC) Rotterdam concerning the transition to sustainable fuels. E-fuels and green hydrogen, the topic of this study, are expected to start playing a role in sustainable transport from 2030. E-fuels are expected eventually to cover a considerable share of the demand for sustainable fuels (besides biofuels). Together with project partners a *strategy for the transition to e-fuels (including green hydrogen) in HIC Rotterdam* has been designed.

The two main goals for the strategy are:
1. Reduction of CO_2 emissions in heavy duty transport (long haul road transport, shipping and aviation) by application of e-fuels and green hydrogen, to be CO_2 neutral in 2050, in order to achieve the Paris climate targets.
2. Maintain or strengthen the economic and logistic position of HIC Rotterdam and of value chain partners, to contribute to societal welfare by creating new value chains and as such maintaining employment.

The designed strategy is based on the following three pillars:
1. ***Local production and import*** of hydrogen and e-fuels. Currently, a large amount of energy is imported to the port of Rotterdam in the form of crude oil. It is expected that import of energy continues to play a significant role after the energy transition, but in the form of sustainable feedstock, fuels and hydrogen (carriers).
2. ***Positioning and role of the Rotterdam area*** during and after the transition towards e-fuels. Based on the SWOT analysis and input from project partners, various strategic directions are recommended.
3. ***Transition*** from fossil fuels to e-fuels, concerning choices around speed of changes, types of fuel, investment in infrastructure, integration with chemical feedstocks production and consequences of choices made.

Local production and import	Positioning and role of the Rotterdam area	Transition
• Import of e-fuels from countries with low cost renewable electricity; develop limited strategic production capacity. • Local production of H_2, as far as enough RES is available. Complement with import. • Integration and synergy between fuels and chemical feedstock production.	• Broaden and shift current position in fossil fuels to a hub position for hydrogen and e-fuels, both for delivery to the transport sector and to the hinterland • Landing of large quantities of electricity from offshore wind is of vital importance for the cluster • Cooperation throughout the (existing and new) value chains • Create interregional/international cooperation • High level of integration with chemical cluster	• Be a fast mover: learn from first movers, move fast to gain market share and scale up • Position Rotterdam as a hotspot for investments in green H_2 and e-fuels • Refineries: transition of modern refineries into integrated energy and chemical sites • Prepare for ammonia and methanol as transport fuels for maritime • Prepare for spatial integration of new clusters • Reuse of existing infra • Flexibility, to be able to cope with different scenarios

With the different elements of the basic strategy in mind, the transition path towards realization of the strategy can be outlined. The roadmap shows how the strategy translates into actions over time and is made up of several layers: energy supply, local production, import chains (to Rotterdam), export chains (from Rotterdam to the hinterland), and application in heavy duty transport. For each of these layers, a distinction has been made between actions needed in terms of R&D, infrastructure (distribution, storage, refuelling infrastructure), production, regulation, trade and application of e-fuels.



Now that the basic strategy and the roadmap towards realization of the strategy are clear, it is important to analyse which external factors, such as decisions taken in other sectors, policies and innovations, should be taken into consideration. They can strongly influence the speed of the transition, which will have a great impact on the strategy to be followed for the period 2030-2050 and the preparation period until 2030. To check the robustness of the strategy a scenario analysis has been carried out. Three scenarios (Acceleration, Frontrunners and Inertia) have been defined, with variation in: 1) the speed of GHG emissions reduction and 2) whether or not climate targets are met in the EU and at the global level. These factors are presumed to have large impact, but are highly unpredictable.

	High ←	*Achieving climate goals*	*→ Low*
	High ←	*Cooperation*	*→ Low*
	Acceleration	**Frontrunners**	**Inertia**
Description	EU and RoW (rest of the world) achieve climate goals	EU achieves climate goals, as well as some other countries, regions and cities; RoW does not	EU and RoW do not achieve climate goals
Characteristics	High drive towards sustainability; cooperation between countries and businesses	EU cooperates with countries and regions that strive for sustainability; other countries let economic/ fossil interests prevail	Everyone for himself, economic interests prevail over sustainability
Development of RES in Europe	quick	quick	slower, but still economic driver (dependent on CO_2 tax for fossil)
Development of RES abroad	quick	slower	slower, based on economic driver
Adoption of e-fuels in Europe	quick	quick	slower
Adoption of e-fuels RoW	quick	slower	slowest
Availability of biomass	shortage	higher availability for Europe	no shortage on short term

Based on the building blocks that have been discussed and the answers on the questions around the impact of the transition to e-fuels on the Port of Rotterdam, in conclusion the following main lessons are identified as key take-aways for the different elements of the analysis:

Basic strategy
Rotterdam is well positioned to play a significant role in the transition to e-fuels. Hydrogen will be one of the main feedstocks in this transition. Green hydrogen will be produced locally as much as possible, because it is less expensive to produce gaseous hydrogen in HIC Rotterdam than importing it by ship as LOHC or liquid hydrogen. For e-fuels, the creation of limited strategic production capacity is important to set the transition in motion and reduce geopolitical dependence. But in the long run the lion's share of e-fuels, other than hydrogen, will probably be imported. There are two main reasons for why importing a large share of the e-fuels needed. First of all, the Netherlands itself does not have enough energy available from renewable sources. In addition, the production of e-fuels in the Netherlands is considerably more expensive than importing them from abroad. Geopolitical independence is a point of attention in the choice of countries from which to import.

With the transition to e-fuels, the port of Rotterdam will be able to retain its function as energy hub. However, unlike now, this will be less from its role as a fuel producer, but mainly as a transit port for hydrogen and e-fuels to the hinterland.

Roadmap

To actually get the transition to e-fuels off the ground, cooperation throughout the entire chain, and from regional to global level, is essential. An integrated approach, i.e. timing and implementation based on dialogue between the stakeholders of the various components, must be adopted, ensuring coherence between the components of the roadmap.

An example is storage capacity in the value chain: because fuel production needs a practically constant supply of hydrogen, the creation of large-scale storage facilities for electricity and hydrogen is crucial

Scenario's

The elements of the basic strategy are important in all scenarios, but with different accents and at a different pace. The share of e-fuels in the mix of renewable fuels (which will also consist of biofuels) will initially vary considerably per scenario.

Flexibility in the strategy is crucial. This applies equally to the choice of e-fuels, geopolitical (in)dependence and the speed of scaling up.

The speed of implementation of the transition towards e-fuels will impact the duration of the need for coexistence of both fossil and sustainable production capacity and related infrastructure. The longer it takes, the more complicated spatial integration will be.

Concluding, it can be stated that the transition to e-fuels will face HIC Rotterdam with lots of challenges, but when all stakeholders unite forces they can pave the way towards a future in which transport has become sustainable and in which HIC Rotterdam can maintain its role as major energy hub.

Contents

1 Introduction

The energy transition, needed to realise climate goals, will have a major impact on all actors involved in the transport value chain. This includes end users, refineries and other fuel producers, port operators, vehicle suppliers, refuelling infrastructure providers, storage providers and all connected value chains. Large reductions in CO_2 emissions are necessary to maintain a "license to operate." Battery-electric vehicles will play a key role in reducing CO_2-emissions from passenger cars, vans, buses, and urban and regional distribution trucks. For heavy-duty, long haul road transport, shipping and aviation, however, batteries will not suffice. For these sectors, therefore, (nearly) emission-free fuels will have to be produced and stored (see Figure 1. Besides green hydrogen, biofuels will play a significant role. However biomass may not be sufficiently available to meet worldwide demand for sustainable fuels. Therefore, e-fuels, produced from green hydrogen, will most likely supply a considerable share of the demand for sustainable fuels. E-fuels are expected to start playing a role in sustainable transport from 2030. E-fuels[1] and green hydrogen, and their potential role for the Port of Rotterdam in the transition to a sustainable logistics and energy hub, are the topic of this study.

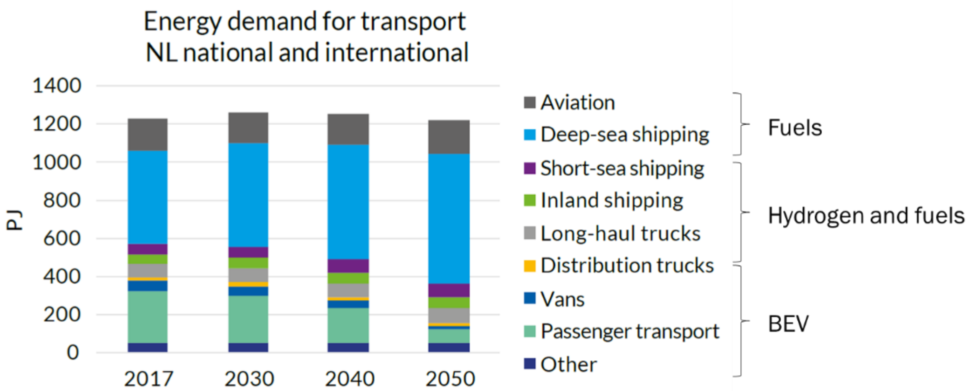


Figure 1: Energy demand in NL for national and international transport modalities, fuelled/bunkered in NL, and an approximate distribution of the most logical option(s) to make these modalities sustainable. The high energy efficiency of battery-electric vehicles (BEV) compared to vehicles with a combustion engine causes a significant reduction in energy demand for a.o. passenger transport, vans and distribution trucks.

Currently, a very large amount of fuel for national and international modes of transport is produced and bunkered in the Rotterdam port area. Rotterdam is home to the second largest fuel cluster in the world. In addition, Rotterdam is an important global logistics hub, which is of great significance to the Dutch economy. It is therefore of vital importance to design a well-thought-out strategy for the Harbour Industrial Cluster (HIC) Rotterdam concerning the transition to sustainable fuels.

In the Power2Fuels project (TNO, 2020) a mapping of suitable e-fuels per transport modality was prepared, and for each modality the techno-economic

[1] E-fuels are defined as fuels, based on green hydrogen and CO_2 or nitrogen. Other synthetic fuels, e.g. synthetic fuels based on biomass or recycled carbon like CO, are not in scope of this study.

performance of different e-fuels was compared. In another study, space requirements were determined of an e-fuel production cluster large enough to supply all fuel demand in the Netherlands from long haul road transport, shipping and aviation (approx. 600 hectares, of which 2/3 for direct air capture) (TNO, 2020). Space in the Harbour Industrial Cluster (HIC) Rotterdam is scarce, which raises the question whether the production of the (e-)fuels should and can take place in Rotterdam (Detz, Hers, Schipper, & Westerga, 2021). Next to that, space for the landing of offshore wind power is limited, and the Dutch (renewable) electricity production capacity also has limits. On top of that, countries with abundant renewable energy sources can provide electricity at lower costs. At the same time, Rotterdam has for decades been an important fuel and (petro-)chemical cluster with good infrastructural connections and a good location for the landing of wind energy (until 2030, a total of 7.4 GW could land at Maasvlakte).

These challenges and their impact on the existing cluster prompted SmartPort and Voltachem to ask TNO and a group of stakeholders from different parts of the value chain to consider the following questions[2]:

- What would be a logical role for HIC Rotterdam in the e-fuels value chain? What is the best way for HIC Rotterdam to distinguish itself from other clusters?
- Which part of the value chain can best be attracted to Rotterdam (production, storage, infrastructure)? Which e-fuels, intermediates or required raw materials will be produced in Rotterdam, and which will be imported? Where will the imported fuels, intermediates or raw materials be produced, and in what form will they be transported?
- What is the impact of these choices on the fuel and chemical cluster, the logistical position of the port, the energy system and the value chain?

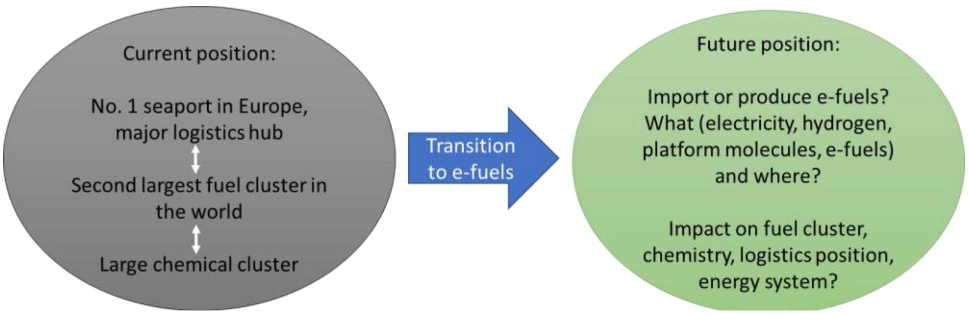


Figure 2: Research questions

The CHAIN project was initiated to answer these questions by means of a structured approach.

Port of Rotterdam has already outlined their hydrogen strategy in a vision of Rotterdam as an international hydrogen hub (Havenbedrijf Rotterdam, 2020). This vision combined with the results of the Power2Fuels project served as a basis for CHAIN. The e-fuels identified as most relevant in the Power2Fuels

[2] This has been a cooperative project with stakeholders from the industry. The following partners participated in the project: BP, Deltalinqs, Gate Terminal, Nouryon, Port of Rotterdam, Shell, Sohar Port/Freezone and Vopak.

project, namely e-methanol, e-diesel, e-ammonia, e-LNG and e-kerosene, form the scope of the CHAIN project, in addition to green hydrogen.

In CHAIN, a strategy for the transition to e-fuels has been developed for the period 2030-2050, together with project partners and supported by analysis from TNO. Reducing CO_2 emissions from transport fuels, while maintaining or strengthening the economic and logistical position of Rotterdam, served as the starting points for the design of the strategy. Based on the strategy developed, a roadmap was developed which offers a perspective for action. The robustness of the strategy was assessed for various future scenarios.

The report starts with an overview of the current economic and logistic position of the port, followed by a cost comparison of different sustainable fuel options and a SWOT analysis of the Rotterdam region (Chapter 2). Chapter 3 describes the impact of the transition from fossil fuels to e-fuels on the value chains. First an economic assessment of e-fuels and hydrogen import versus production in Rotterdam is presented. Next, the impact of the transition on the chemical sector is described. Based on the results from these chapters, a basic strategy for the transition to e-fuels in the period 2030-2050 has been developed in Chapter 4, including a roadmap towards execution of the strategy. Chapter 5 focusses on strategies for different scenarios, whereas the key take-aways can be found in Chapter 6.

2 A transition to e-fuels: starting point

As has been sketched in the introduction, the energy transition and the related climate goals will have a major impact on all stakeholders involved in transport, including those that are active in HIC Rotterdam. At present, a great deal of fuel for national and international transport modalities is produced and bunkered in the Rotterdam port area. Rotterdam is home to the second largest fuel cluster in the world. In addition, Rotterdam is an important global logistics hub, which is of great significance to the Dutch economy.

Before designing a strategy for HIC Rotterdam regarding a transition to hydrogen and e-fuels, it is important to have a clear picture of the current position of the cluster, the broader spectrum of sustainable fuels (including biofuels), strengths and weaknesses of the cluster and opportunities and threats for a transition to e-fuels.

In this chapter, an overview of the current economic and logistic position of the port area is presented in 2.1. Subsequently the impact of a transition to sustainable fuels for long haul transport (including biofuels, green hydrogen and e-fuels) on costs is analysed (2.2). In the last paragraph (2.3) a SWOT analysis is performed as a starting point for the strategy, that will be elaborated in chapter 4.

2.1 Economic and Logistic position

2.1.1 Historic overview[3]

Between 1880 and 1914, the port of Rotterdam developed into Europe's largest port thanks to the import and export of bulk goods from the coal and steel industry in the German Ruhr area. With the Rhine at its disposal, Rotterdam had the cheapest transport modality, inland shipping, for bulk goods. Iron ore, coal, wood and grain were the main goods transhipped in Rotterdam.

After the Second World War, coal production got off to a slow start, particularly in Germany. Germany did not have enough capacity to produce its own coal and importing it from Rotterdam via inland waterways was cheap. Later, coal demand was largely replaced by oil demand. The discovery of large oil deposits in the Middle East by American oil companies opened up a new energy source for Western Europe. The Marshall Plan financed the import of Middle East oil into Europe, as well as the further expansion of refining capacity.

The enormous growth and scaling up of the oil industry in Western Europe after 1945 had major implications for the European transport network of seaports, inland ports, railways and roads. As a result of the growing demand for oil, new transport modalities were introduced, including the construction of pipelines. Oil tankers were also constantly growing in size, which meant that ports had to be radically adapted. In order to maximize the economies of scale in oil transport, oil refineries were established in ports.

Rotterdam profited from this trend and became Europe's largest concentration of refinery capacity in the 1960s and 1970s. The three major port expansions

---

[3] Based on (Boon, 2014)

between 1945 and 1975 - Botlek, Europoort and Maasvlakte I - and the growth of the oil industry ensured that Rotterdam was already the largest port in the world by 1963. The large share of Rotterdam in the bunker fuel market and the relatively low prices for these bunker fuels, have contributed to this strong position. However, this was not a matter of course, which became particularly clear in the relationship between the port and the hinterland.

The growing demand for the transport of oil in the German hinterland presented the port of Rotterdam with major challenges. In 1955, news reached the port that a group of oil companies wanted to build a crude oil pipeline to their new refineries in the Rhine-Ruhr area. However, Rotterdam lost the battle to the north German city of Wilhelmshaven.

After failed talks about a Trans-European pipeline network in 1956, Royal Dutch/Shell decided in 1957 to build a pipeline to the German hinterland (Cologne). This pipeline was supplemented in 1968 with a larger crude oil pipeline and an oil products pipeline connecting the Rotterdam refineries with the major industrial and urban centres along the Rhine. Partly due to the construction of these pipelines, the Rotterdam oil port developed a large hinterland in the German Rhine area.

The above historic overview shows that crucial elements in the development of the strong position of the Port of Rotterdam are the combination of a strong logistic and industrial position, good connections to a large hinterland, timely investment in port facilities (deep harbour basins) and the presence of Shell.

Today, the port faces new challenges to make long haul, heavy duty transport sustainable. In the transition to sustainable fuels, e-fuels are expected to capture a large share. One of the upcoming developments is the transition to sustainable fuels, of which e-fuels are expected to capture a large share. As a starting point for the analysis of the potential impact of a transition to sustainable fuels, we will sketch the current macro-economic and logistic position of the Port of Rotterdam.

2.1.2 Importance of Port of Rotterdam for the economic position of The Netherlands

In this section, we describe the relative economic position of the Port of Rotterdam and its fuel cluster in perspective of the Dutch economy as a whole. The first analysis is based on employment, followed by an analysis of gross value added (GDP contribution). For reasons of data availability the analysis of gross value added was executed at a higher level of aggregation.

Employment

The Rotterdam port provides direct employment for about 100,000 employees, which is about 1% of employment in The Netherlands. Employment numbers in the Port of Rotterdam increased by approximately 1,650 employees in 2019 compared to 2018. Compared to 2015, the increase in direct employment is 25%. The increase in employment is mainly visible in ‘road transport’ and ‘other, business and non-business services’.

To identify changes in the relevant sectors for CHAIN (manufacturing of cokes and refined petroleum and chemicals and chemical products, and fuel-related wholesale trade activities) we have to also look at other data sources that show more detailed numbers for these specific sectors. However, these sources have a regional coverage, so the relative size of the numbers will be used as an indication of the importance of Rotterdam and for some numbers we will make some calculations to get to comparable numbers.

Table 1: Development of direct employment in Port of Rotterdam

Main sector and sub-sector	Employees		
	2015	2018	2019
Mode	*54,389*	*63,649*	*65,067*
Navigation	1,236	1,820	1,910
Inland navigation	6,148	6,507	6,369
Road transport	27,223	36,340	37,374
Rail transport	1,234	1,287	1,347
Pipeline	52	56	57
Transport services	10,180	9,350	9,710
Transshipment/storage	8,316	8,290	8,300
Location	*25,817*	*35,220*	*35,460*
Food industry	2,038	1,380	1,460
Chemical industry	4,523	4,010	4,070
Basic metals and metal products industry	1,414	750	790
Other industry	8,685	8,210	8,250
Wholesale trade	5,071	4,590	4,660
Other, business and non-business services	4,086	16,280	16,230
Total	80,206	98,869	100,527

Source: (Erasmus Universiteit, 2018), (Erasmus Universiteit, 2020)

The Rijnmond Region[4], covering most of the geographical span of the Port of Rotterdam, has a share of 7.1 percent in total employment of the Netherlands. In the period 2013-2018 average annual (total) employment growth in Rijnmond and the Netherlands was more or less equal at a pace of 0.6 percent per annum. Table 2 provides an overview of the relative position and employment growth in economic activities that are relevant for the fuel cluster. The table provides totals for 2-digit sectors (in black) comprising both fuel related and non-fuel related activities, as well as the detailed 4-5 digit subsets (the grey coloured branches) that can be directly attributed to fuel production, -trade, transport and logistics. For both the Netherlands as a whole and Rijnmond the number of persons engaged (nominal figures for year 2018), the relative size compared to Dutch total employment and average annual growth rates are shown.

Table 2 clearly shows that a substantial share of all manufacturing of cokes and refined petroleum products in the Netherlands is located in the Port of Rotterdam: over 75 percent of employment in the refinery industry is located in Rijnmond. Manufacturing of chemicals and chemical products are also relatively over-concentrated in the Port of Rotterdam. Rijnmond has an employment share of 11.4 percent in these activities compared to a share of 7.1 percent in total

[4] COROP-plus region CP2910, comprising the municipalities: Albrandswaard, Barendrecht, Brielle, Capelle aan den IJssel, Hellevoetsluis, Krimpen aan den IJssel, Lansingerland, Maassluis, Nissewaard, Ridderkerk, Rotterdam, Schiedam, Vlaardingen and Westvoorne.

employment in the Netherlands. Data on the more detailed (4-5 digit level) shows that primarily activities based on ‘other organic basic chemicals’ are taking place in Rijnmond.

Table 2: Employment in The Netherlands and Rijnmond region

		Total employment (2018)				**Average growth 2013-2018**	
		Netherlands		Rijnmond		Netherlands	Rijnmond
SBI code	*SBI name*	*Persons engaged*	*share in NL economy (%)*	*Persons engaged*	*share Rijnmond in NL economy (%)*	*in %*	*in %*
A-U	**Total economy**	**8,672,115**	**100**	**613,175**	**7.1**	**0.7**	**0.6**
19	Cokes and refined petroleum	5,243	0.1	3,937	75.1	0.8	0.9
20	Chemicals and chemical products	49,822	0.6	5,655	11.4	0.0	1.4
20141	*Petrochemicals*	*3,665*	*0.0*	*204*	*5.6*	*0.2*	*18.4*
20149	*Other organic basic chemicals*	*5,175*	*0.1*	*1,539*	*29.7*	*1.2*	*1.7*
46	Wholesale trade	538,998	6.2	38,389	7.1	0.6	1.0
46711	*Wholesale of solid fuels*	318	0.0	43	13.5	2.8	-4.6
46712	*Wholesale liquid and gaseous fuels*	4,679	0.1	1,801	38.5	0.4	-0.5
46713	*Wholesale of mineral oils (non fuel)*	1,398	0.0	363	26.0	0.8	7.3
49-53	Transport and storage services	443,727	5.1	52,293	11.8	0.3	-0.3
4920	*Freight rail transport*	527	0.0	329	62.4	-1.7	2.1
4941	*Freight transport by road*	124,936	1.4	8,285	6.6	1.3	0.5
4950	*Transport via pipelines*	379	0.0	81	21.4	0.8	12.0
50201	*Sea and coastal freight water transport*	4,870	0.1	1,831	37.6	-4.0	-2.3
50401	*Inland water transport (freight)*	6,455	0.1	1,176	18.2	-1.5	-2.5
50402	*Inland water transport (tankers)*	1,251	0.0	516	41.2	-0.8	-1.4
52101	*Storage in tanks*	2,307	0.0	1,386	60.1	1.2	0.3
5222	*Service activities incidental to water transportation*	5,264	0.1	2,397	45.5	1.8	-1.4
52241	*Cargo handling for sea transport*	8,118	0.1	5,935	73.1	1.7	1.5
52291	*Other transportation support activities*	52,070	0.6	9,786	18.8	2.2	1.6

Source: LISA (2019), MRDH employment register and employment register Overig Zuid-Holland (adjustments TNO)

In all Wholesale trade activities the Rijnmond region has an employment share that is equal to its relative size of the economy: 7.1 percent. However, fuel-related wholesale trade activities are strongly concentrated in the Port of Rotterdam, especially trade in liquid and gaseous fuels and (non-fuel) mineral oils, but Wholesale trade in solid fuels is also relatively over-concentrated in the Port of Rotterdam (with a share of 13.5 percent in total Dutch employment in this particular economic activity).

Employment in all Transport and storage activities is strongly concentrated in the Port of Rotterdam. Compared to the share of Rijnmond in total employment in the Netherlands, only freight transport by road is somewhat smaller. Rijnmond has highest relative employment shares in rail and sea transport related activities.

Added value
In terms of added value, we see that in the port of Rotterdam the value is quite stable over the years. When we, however, look at the share of the chemical industry, the most relevant sector for our study, we see that it is decreasing over the years. The total contribution of the Port of Rotterdam to the Dutch GDP is about 2%. (CBS, 2017 and (Erasmus Universiteit, 2020)

Table 3: Development of direct seaport related added value in Rotterdam

Main sector and sub-sector	Added value		
	2015	**2018**	**2019**
Node	*6,683*	*6,412*	*6,552*
Navigation	263	437	442
Inland navigation	753	658	614
Road transport	1,768	2,210	2,378
Rail transport	80	78	86
Pipeline	134	134	142
Transport services	1,684	1,421	1,422
Transhipment/storage	2,002	1,474	1,467
Location	*6,071*	*8,243*	*8,557*
Food industry	293	204	442
Chemical industry	2,145	1,542	1,507
Basic metals and metal products industry	130	103	103
Other industry	2,394	1,652	1,659
Wholesale trade	573	1,758	1,915
Other, business and non-business services	535	2,984	2,931
Total	12,754	14,655	15,109

Source: (Erasmus Universiteit, 2018) (Erasmus Universiteit, 2020)

The Rijnmond region's contribution to Dutch GDP is somewhat larger than the contribution of the relative employment size. Table 4 shows that in 2018, Rijnmond had a share of 8.1 percent in total gross value added of the Netherlands, compared to the earlier mentioned share of 7.1 percent in total employment. Although we could only analyse gross value added at an aggregated level of economic activities (2-digit SBI codes), a similar conclusion can be drawn from the employment analysis of the previous section: about 75 percent of gross value added created by the manufacturing of cokes and refined petroleum products in the Netherlands comes from activities in the Rijnmond region, of which the major share can be attributed to the Port of Rotterdam. The gross value added of the refinery industry in the Port of Rotterdam was about 900 million euro in 2018. With about 1.4 billion euro and 6.2 billion euro respectively, Rijnmond also had a relatively large share in gross value added generated in 2018 by the Chemical industry and Transport and storage activities in the Netherlands. The share of Rijnmond in Wholesale trade is approximately in balance with its total GDP contribution (8.3 percent of Dutch Wholesale trade value added is generated by firms in Rijnmond which is in the same order of the share of 8.1 percent in Dutch GDP).

Table 4 does not provide details on the gross value added generated by the subset of fuel-related activities within the main economic activities. For this we can only make a rough estimation by combining the employment shares of Table 2 with the aggregated gross value added numbers of Table 4. If we project the employment shares of fuel-related production within the Chemical industry (the numbers for Petrochemicals and Other organic basic chemicals in Table 2, which count to approximately 31 percent of total Chemical activities in Rijnmond) on the gross value added of the Chemical industry in the Rijnmond region (1,364 million euro as shown in Table 4), fuel-related gross value added generated by Chemical production in the port of Rotterdam was about 420 million euro in 2018. If we add this to the 902 million euro gross value added of the Refinery industry from Table 4), about 1.3 billion euro gross value added can be attributed to fuel production in the port of Rotterdam. This is about 2.4 percent of total gross value added generated by Rijnmond’s economy.

In addition, the employment numbers in fuel-related Wholesale trade (Solid fuels, liquid and gaseous fuels, mineral oils as shown in Table 2) add up to approximately 5.7 percent of all Wholesale trade activities in Rijnmond. If we project this share to the gross value added of 4,961 million euro generated by Wholesale activities in Rijnmond (as shown in Table 4), we arrive at 285 million euro. Total fuel-related production and trade of the port of Rotterdam than counts about 1.6 billion euro (420 million in fuel-related chemical industry + 902 million in refinery industry + 285 million in fuel-related wholesale trade) or 2.9 percent of Rijnmond’s total gross value added.

This estimation excludes fuel transportation and storage activities. The employment numbers as shown in the previous section (Table 2) can only partly be attributed to fuel-related activities as these numbers comprise generic transport and storage activities in the Port of Rotterdam.

Table 4: Gross value added in the Netherlands and Rijnmond region

	Gross value added (2018)				Average growth 2013-2018	
	The Netherlands		Rijnmond		The Netherlands	Rijnmond
	mio. euro	*share in NL economy (%)*	*mio. euro*	*share Rijnmond in NL economy (%)*	*in %*	*in %*
Total economy	**692,632**	**100**	**56,216**	**8.1**	**1.8**	**1.4**
Cokes and refined petroleum products	1,201	0.2	902	75.1	6.0	6.1
Chemicals and chemical products	12,015	1.7	1,364	11.4	1.8	3.3
Wholesale trade services	59,488	8.6	4,961	8.3	3.7	2.3
Transport and storage services	32,986	4.8	6,172	18.7	0.8	0.2

Source: CBS, LISA (2019) and employment registers MRDH and Overig Zuid-Holland (adjustments TNO)

2.1.3 Potential impact of e-fuels for logistic flows and bunker market

In this section an overview is provided on the position of fuels and chemical products for the logistics market of the Port of Rotterdam. Results are presented for three topics:

- Size of fuels and chemical products in maritime throughput
- Size of fuels and chemical products in hinterland transport
- Size of the transport fuel and bunkering market

Maritime throughput

The port of Rotterdam is an important global hub. In 2018, the Port is the largest European port in terms of throughput and the 10th largest port worldwide. Liquid bulk has a significant share in this. In 2019, 211 million ton was transhipped which accounted for 45% of total throughput. Port of Rotterdam has a significant market share in the throughput of liquid bulk, with a throughput of 47.5% of total liquid bulk throughput in the Hamburg - Le Havre range and 16% of all ports in Europe. Throughput of liquid bulk has been stable in the last few years. Due to the lower demand for crude oil due to the economic effects of COVID-19, the throughput of liquid bulk decreased with 10.4% in the first three quarters of 2020 (Nieuwsblad Transport, 2020).

Table 5: Rotterdam maritime throughput statistics 2017 – 2019 (million ton) (Port of Rotterdam, 2020)

	2017	2018	2019
Dry Bulk	80	78	75
Liquid Bulk	214	212	211
Containers	143	149	153
Breakbulk	30	30	31
Total	467	469	469

A large share of liquid bulk transhipment in the port of Rotterdam consists of imports (78% in 2019). This consists for a large part of imports of crude oil that is refined in the port area or transferred to a hinterland location. Exports consist mainly of refined mineral oil and other liquid bulk products.

Table 6: Rotterdam maritime liquid bulk throughput statistics in 2019 (million ton) (Port of Rotterdam, 2020)

	Inbound	Outbound	Total
Crude Oil	103	1	104
Mineral oil products	36	32	68
LNG	7	1	7
Other liquid Bulk	19	12	32
Total liquid bulk	165	46	211

Other main ports in the liquid bulk market in the Hamburg - Le Havre range are Antwerp (72 Mt throughput) and Amsterdam (50 Mt throughput). Antwerp has three main refineries (partly sourced through pipeline via Rotterdam), chemical industry and distribution of mineral oil products. Amsterdam focusses mainly on storage and distribution of mineral oils (gasoline, diesel and kerosene).

Hinterland throughput

A large share of the maritime imports in Rotterdam is redistributed to the hinterland via different supply routes. The following table presents the total hinterland transport flows in the Netherlands of relevant goods for different modalities. The following freight flows were included here:

- Petroleum and petrochemical products (NSTR 3) includes transport of crude oil, transport fuels (such as petrol and kerosene) and energy gases (e.g. LNG). This segment gives a good impression of the overall transport fuelling market and petrochemical industry in Western Europe that is facilitated via Dutch ports;
- Fertilizers (NSTR 7) such as ammonia are a possible market for synthetic production and therefore included in the overview;
- Chemical products (NSTR 8) are often refinery products derived from oil products.

The table does not show the total transport volume due to two reasons:

1. Part of the transport via pipeline is missing in the statistics (only international transport flows are published by CBS). The breakdown in different good categories is unknown.
2. There is a (small) overlap in the transport volumes between the modes (for instance freight that is first being transported via inland waterway to a regional distribution point and further transported via road to the end destination).

Table 7: Hinterland transport of relevant flows in the Netherlands in 2019 (million tons) (CBS, 2020)

	Petroleum and Petro-chemical products	Fertilizers	Chemical products	Total	Share in total transported volume per modality
Road	30.5	34.6	96.6	161.7	21%
Inland Waterway	39.6	4.4	43.8	87.8	28%
Rail	0.9	0.1	6.4	7.4	18%
Pipeline	-	-	-	134[1]	100%

[1] Only international flows.

Dutch transport fuel market

Table 8 presents an overview of consumption of the main transport fuels in different modalities in the Netherlands in 2019. In total, 26 million tonnes of fuel ware consumed[5]. The market for road transport and shipping fuels were roughly equal in size. Both represent around 42% of total consumption, the share of aviation is 15%. Figures do not include the consumption of gas or electricity in transport.

For road and rail transport, it is uncertain which share of the demand is sourced through Rotterdam and which part through Antwerp or Amsterdam. For aviation, kerosine towards Schiphol is both provided via pipelines from both the ports of Rotterdam and Amsterdam. Port of Amsterdam reports that 50% of aviation demand is sourced via their port (Port of Amsterdam, 2021).

Table 8: Consumption of liquid fuel in transport in 2019 in The Netherlands (CBS, 2021)

	Fuel type	mln ton
Road transport	Petrol	6.51
	Diesel	4.33
	LPG	0.13
Rail transport	Diesel	0.02
Aviation	Kerosine	3.86
Shipping	Fuel Oil (high and low sulphur)	8.35
	Gas Oil	2.80

For the shipping market, a large share of national demand is bunkered in the Port of Rotterdam (80%). The global waterborne bunker demand is estimated at around 267 million metric tonnes per year (Fuels Europe, 2019). Europe handles around 20% of this volume. Bunkering in Europe is concentrated in a limited number of large bunker ports, not surprisingly the ports that process large volumes of containers, and or dry and liquid bulk. As such, the so-called ARA-region (Amsterdam – Rotterdam – Antwerp) represents around 20 million tonnes (Fuels Europe, 2019). In 2019, the bunker volumes in the ARA region are: 9 million tonnes for Rotterdam, 6.5 million tonnes for Antwerp and 1.7 million

[5] CBS statistics do not specifically mention fuel consumption by mobile machinery. It is unclear whether this is included in the figures of road transport

tonnes for Amsterdam (40% of the Amsterdam volume is to serve the inland shipping market).

Summarizing
The analysis in this paragraph provides important elements for a strategy towards e-fuels. It shows that the German hinterland could be an important market for green hydrogen and e-fuels[6]. Since the energy transition creates a new era in the fuel and chemical market, being a fast mover is of strategic importance. Also, being able to offer these new fuels at competitive prices is important. Supplying e-fuels at a price level competitive with other countries/ports requires strategic alliances with countries that have access to abundant, low-cost renewable energy. The construction of (hydrogen) pipelines will also contribute to creating strategic advantages. In terms of creating employment and value added, wholesale trade services and transport and storage services seem to contribute most.

2.2 Impact of sustainable fuels on transport costs

2.2.1 Cost levels of sustainable fuels

In the transition to more sustainable transport costs are important. For long haul transport both biofuels and e-fuels are applicable, as well as green hydrogen in some cases. Though the focus of this study is on e-fuels and green hydrogen, a comparison was made between cost levels of these three options. As a reference, the expected price development of fossil diesel was included in the analysis.

Fossil fuels
Fossil fuel price levels are highly dependent on crude oil prices and the CO_2 tax on fuels is expected to have more impact on fossil fuel price levels. The International Energy Agency has developed scenarios, based on assumptions on both carbon prices and oil prices developments (International Energy Agency-task41, 2020). Figure 3 presents the expected cost levels for fossil fuels in these scenarios, including carbon prices (ranging from €17 to €122 per ton CO_2), for 2040. Overall, a fossil fuel price between €80 and €110 per MWh (€22 - €31 per GJ) is expected. In all scenarios fossil fuel prices are expected to rise significantly, compared to current fossil fuel cost levels of €30 - €50 per MWh.

The broad range of the fuel prices (excluding the carbon price) is in line with a forecast of the US Energy Information Administration, (US EIA, 2019). For 2040, they project a maximum price of about $170[7] per barrel and a minimum price of about $45 per barrel.

[6] Probably the same holds for other sustainable fuels, like biofuels.
[7] $170 per barrel converts to €25 per GJ. Current difference between diesel fuel and oil price is about €4.4 per GJ. So $170 per barrel would lead to a diesel fuel price of about €29 per GJ. Equivalent: $45 per barrel would lead to a diesel fuel costs of about €11 per GJ (€40 per MWh).

EUR/MWh, significantly higher levels than todays of 30-50 EUR/MWh.

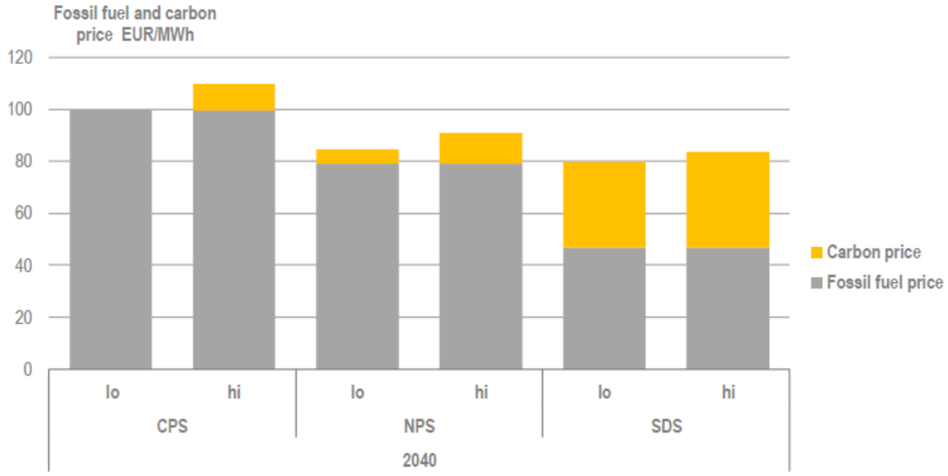


Figure 3: Forecast of fossil fuel costs (diesel and petrol) in €/MWh for different scenarios (CPS = Current Policies Scenario; NPS = New Policies Scenario; SDS = Sustainable Development Scenario). Source (International Energy Agency-task41, 2020)

Biofuels

In the IEA study (International Energy Agency, 2021) also an extensive analysis is done on expected cost levels for different types of biofuels, based on different production processes and feedstocks. The IEA study evaluates three costs scenarios (see Figure 4):

1. current costs
2. costs after technical improvements
3. costs with lower financing costs

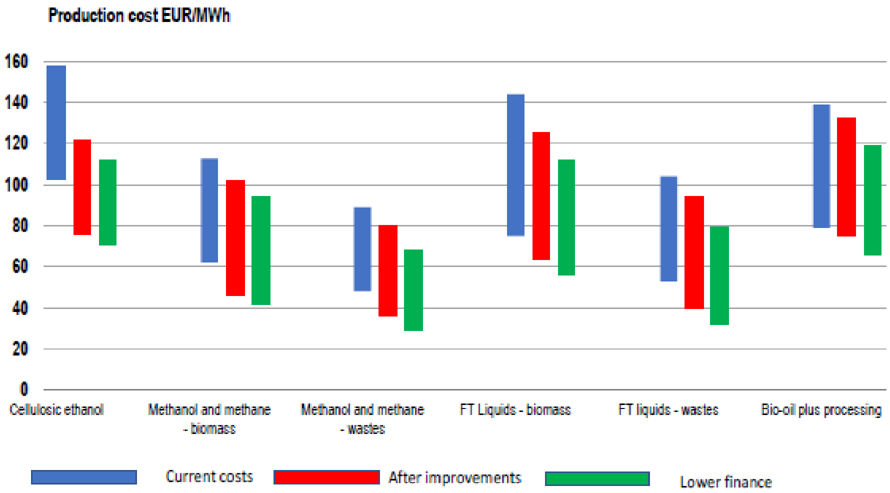


Figure 4: Cost projection for different types of biofuels (International Energy Agency-task41, 2020)[8]

[8] FT liquids are made via gasification of biomass or waste and consequently Fischer-Tropsch synthesis to produce liquid fuels, e.g. diesel and kerosene. Bio-oil is an upgraded pyrolysis oil

In this analysis, the middle scenario ("after improvements") is chosen as a benchmark. The third scenario with lower financing costs[9] may probably only become realistic after 2045, when production volumes are high and business cases are very stable. For feedstock, biomass is taken (excluding residual-biomass).

Besides the biofuels in Figure 4, the IEA report also gives the current costs range of several biofuels which are currently already produced in large quantities such as FAME and HVO (both from PPO, pure plant oil and from UCO, used cooking oil). The costs of these biofuels are not expected to decrease in the future, since there is already large scale production and the alternative sustainable fuels are generally more expensive. The Renewable Energy Directive II, RED II (JEC, 2018), limits the growth of biofuels using energy crops and UCO by putting a cap on the blend percentage. .

In Table 9, an overview of the costs range of relevant biofuels for long-distance transportation are given. The average costs shown on the right column is used for the comparison with the E-fuel costs.

Table 9: Fuel production costs in €/MWh and €/GJ. Based on (International Energy Agency-task41, 2020)

	Year	Feedstock	Costs €/MWh	Costs €/GJ	Average €/GJ
Fossil diesel	**2040**	Fossil	80-110	22-31	26
FAME	**2020-2040**	PPO	67 - 100	19 - 28	23
HVO	**2020-2040**	PPO	75 – 122	21 - 34	27
Bio-ethanol	**2040**	Cellulosic	76 – 122	21 – 34	27
Bio-methanol and bio-LNG	**2040**	Biomass	48 – 100	13 – 28	20
FT liquids	**2040**	Biomass	64 – 125	18 - 35	28
Bio-oil	**2040**	Biomass	75 - 132	21 - 37	28

E-fuels

Costs for production of green hydrogen and e-fuels are highly dependent on energy costs, and in case of carbon e-fuels, on costs for CO_2. Calculation of production costs of the different e-fuels in this study is done with the Supply Chain Model developed by TNO[10]. In this model, the costs for CO_2 are based on DAC (Direct Air Capture). In the fuel costs for low LCoE[11] (€30/MWh) and high LCoE (€70/MWh) are presented.

(PO). For bio-oil, the PO is upgraded either via hydrogenation or via co-processing in a fossil fuel refinery. The maturity of both routes is still low, especially for the hydrogenation.

[9] When technologies mature, the technical risks diminish. This will usually lead to lower financing costs. In this case it was reduced from 10% over 15 years to 8% over 20 years. This results in an annual financing costs reduction from 13.1% to 10.2% (interest + depreciation).

[10] TNO's Supply Chain Model is an economic model that calculates complete supply chain costs for import of green hydrogen and hydrogen based carriers from different countries and compares these to local production in the Netherlands. Costs are based on expected CAPEX levels for 2030.

[11] LCoE: Levelized Cost of Energy is an average price of electricity per MWh, based on CAPEX and OPEX of the energy generating asset.

Table 10: Fuel production costs in €/GJ for green hydrogen and e-fuels for different LCoEs, based on TNO's Supply Chain Model.

	Costs in €/GJ (LCoE €30/MWh)	Costs in €/GJ (LCoE €70/MWh)
Green hydrogen	21	37
E-methanol	36	57
E-diesel (FT)	42	66
E-ammonia	32	53

Comparison of production costs for different fuels

In Figure 5 a comparison of the cost forecasts is presented. It is clear that biofuels may become cost competitive to fossil diesel by 2040. Though the e-fuel costs in Figure 5 are based on a rather low LCoE of €30/MWh, e-methanol, e-diesel and e-ammonia are significantly more expensive. Green hydrogen is one of the least expensive options, also compared to fossil and biofuels. However, for green hydrogen, costs elsewhere in the value chain are much higher (see next paragraph).

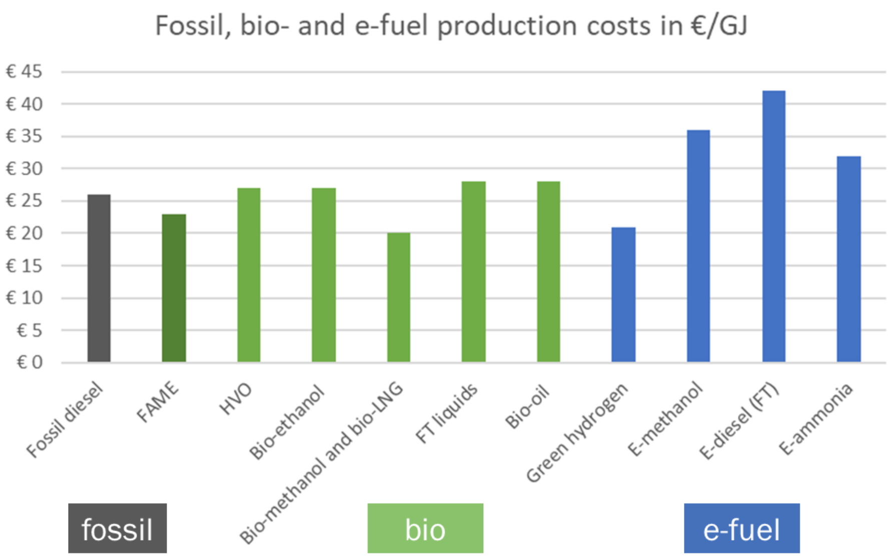


Figure 5: Comparison of production costs for fossil diesel (IEA, 2040, including carbon tax), biofuels (IEA, 2040) and e-fuels (TNO, based on LCoE of €30/MWh and DAC, 2030[12])

2.2.2 *Impact on transport costs*

Application of sustainable fuels will not only have impact on the production costs of fuels, but also on the costs for vehicles (e.g. fuel cells, tanks), compression or liquefaction (in case of hydrogen and LNG), fuel distribution and fuelling stations or bunkering. These value chain costs vary between the different transport modalities, as analysed in (TNO, 2020). In Figure 6 the costs for the complete value chain for long-haul truck transport, inland shipping and short-sea shipping are presented. Since the costs for deep-sea shipping are almost completely determined by fuel costs (except for LNG due to additional liquefaction; hydrogen

[12] Though the Supply Chain Model is based on 2030, LCoE has more impact on costs than any other cost element. Therefore we assume that costs are comparable to the 2040 forecasts from IEA on fossil and bio cost levels.

is not considered an option for maritime), this modality is excluded from the picture.

The value chain costs are based on the following input:

- Fuel production costs as presented in Figure 5
- Costs for vehicles as presented in Table 11
- Energy efficiencies as presented in Table 12
- Other value chain costs are based on (TNO, 2020)[13].

In Table 11 the costs for new vehicles and vessels are presented. For hydrogen, both a fuel cell (FCH) and an internal combustion engine (ICE) are considered[14]. The ICE powertrain including storage tank is expected to have about 35% lower costs than a FCH powertrain. The costs of the hydrogen tank(s) is the same for both.

Table 11: Costs for new reference vehicles/vessels on alternative fuels in comparison to diesel reference. Reference year 2030-2040. Based on (TNO, 2020).

	Energy convertor	Long haul truck	Inland ship	Short-sea vessel
Diesel (reference)	ICE	€100k	€3.0 mln	€25 mln
Green H_2 700 bar	FCH	€223k	€6.0 mln	€38.4 mln
Green H_2 700 bar	ICE	€160k	€4.9 mln	€35 mln
E-MeOH	ICE	€107k	€3.2 mln	€26 mln
E-diesel	ICE	€100k	€3.0 mln	€25 mln
E-NH3	ICE	€120k	€3.75 mln	€28 mln
E-LNG	ICE	€120k	€4.0 mln	€30.2 mln

The energy conversion efficiencies that are assumed in the analysis are shown in Table 12. The figures represent the average efficiency during the life time. The fuel cell powertrain can lose some 10% efficiency during its lifetime (TNO, 2020).

Table 12: Efficiency for combustion engines and fuel cell powertrains (TNO, 2020).

	Diesel and other combustion engines	H_2 Fuel cell system (+ electric motor)
Long Haul truck	42%	42%
Inland ship	42%	45%
Short-Sea ship	45%	45%

When combining these inputs, they result in the following value chain costs for long haul truck transport (in €/km), and for inland and short-sea shipping (in €/hour):

[13] Costs for the biofuel options are assumed to be the same as for the e-fuel options.
[14] For methanol, ammonia and LNG also the fuel cell energy convertor can be considered. These options are however not included, because the energy conversion efficiency of these fuels with fuels cell is considerably lower than with internal combustion engines. This is due to the extra conversion step in the reformer to extract the hydrogen from the fuel.

Figure 6: Total value chain cost for long-haul truck transport (€/km), inland and short-sea shipping (€/hour) for fossil fuel, biofuels and E-fuels. E-fuels based on electricity costs of €30/MWh and CO_2 costs of €80/ton. Projection for 2040.

Based on this analysis, the following can be concluded on the costs of fuels:
- Fossil fuel prices are expected to rise significantly towards 2040, IEA expects them to double.
- Due to these rising fossil fuel prices, biofuels are expected to be cost competitive by 2040.
- Green hydrogen may have lower production costs than fossil fuels and biofuels in terms of €/GJ, depending on LCoE. Due to costs in the value chain however, green hydrogen is still expected to be more expensive than fossil and biofuels by 2040.
- E-fuels will be more expensive than fossil and biofuels, both in terms of €/GJ as for value chain costs, even with a low LCoE of €30/GJ.

This means that transport will get more expensive in the future. Though biofuels will probably be the most economic option for sustainable transport, green hydrogen and e-fuels are expected to play a significant role in the future, because of a likely shortage of sustainable and socially acceptable biomass in the future to realize sustainability goals in heavy-duty transport only with biofuels[15].

2.3 SWOT analysis of the Rotterdam region

A SWOT analysis of the Rotterdam region regarding the transition to e-fuels, and the production and application of e-fuels has been made, with input from the project partners. This section describes the main strengths and weaknesses of the region, and the main opportunities and threats that the transition to e-fuels entails. Next, the elements of the SWOT are combined in a so-called confrontation matrix, in which a weight has been assigned to each of the cells in the matrix. Key strategic directions were formulated based on the cells with the highest weights. The methodology is shown in Figure 7.

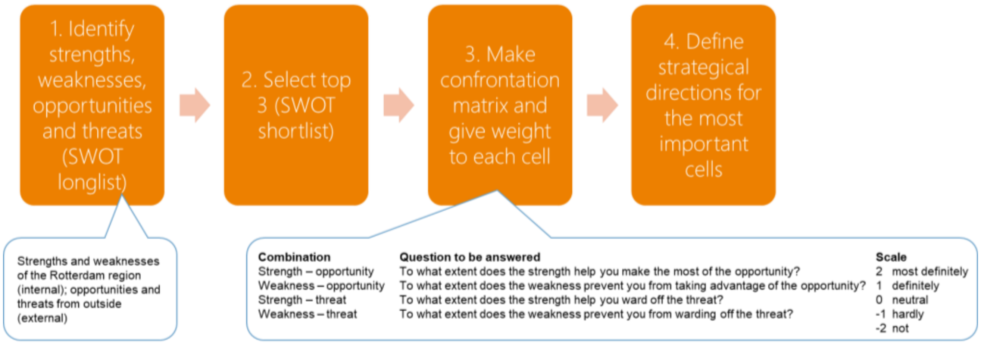


Figure 7: SWOT methodology

A more comprehensive list of SWOT elements can be found in Appendix A: Comprehensive SWOT overview. Figure 8 summarizes the results of the SWOT analysis, followed by a discussion of the key strengths and weaknesses and opportunities and threats.

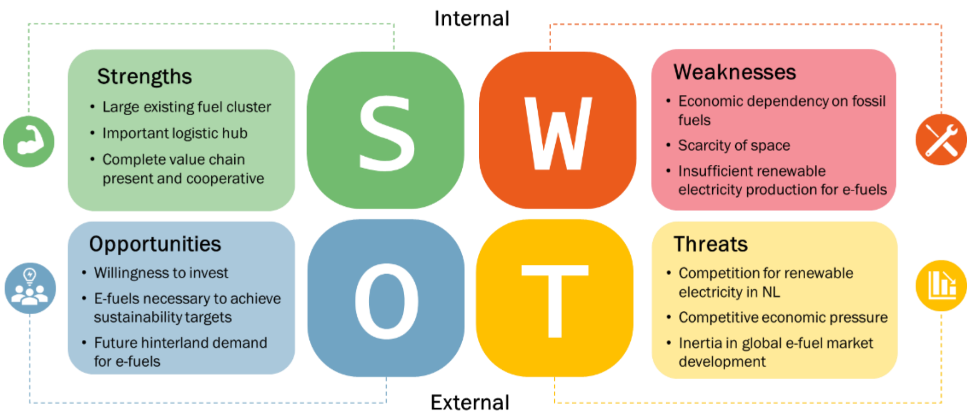


Figure 8: Summary of results of the SWOT analysis

---

[15] Besides biomass demand from the transport sector for sustainable transport fuels, also the chemical industry will need biomass to produce sustainable products.

Strengths

- *Large existing fuel cluster*: Rotterdam already has a very large fuel cluster. This provides a good starting position for an expansion with and shift to e-fuels (and biofuels): there is a lot of experience with fuels, there is already cooperation in the value chain from production on the one end to bunkering and distribution on the other end, infrastructure is already present, there is a lot of experience with complex projects, and customer contacts and logistics chains have already been established.
- *Important logistic hub*: the port of Rotterdam is an important logistic hub, with good connections to the hinterland (e.g. the Rhine/Ruhr area), including pipelines and landing of offshore wind energy.
- *Complete value chain present and cooperative*: the entire value chain, from electricity generation to chemistry and logistics, is represented in the Rotterdam cluster, leading to potential cluster-level benefits. Stakeholders work together, and will therefore be able to get the production and use of e-fuels off the ground. Pilots around the production of green hydrogen and e-fuels are already taking place in various consortia. Because there are similar developments taking place in chemistry as the developments taking place around e-fuels, synergy can be exploited here. Furthermore, scale is an important cluster advantage, particularly for hydrogen and CCS.

Weaknesses

- *Economic dependency on fossil fuels*: Currently, the Rotterdam region has large economic interests in fossil fuels. It is economically attractive to operate the existing cluster, in which much has been invested, for as long as possible. However, according to the IEA, global oil demand will increase slightly until 2030 and decline gradually thereafter, assuming announced policies (International Energy Agency, 2021). In fact, under policies aiming at climate neutrality by 2050, demand will already be reduced significantly by 2030 compared to 2019 (International Energy Agency, 2021). To anticipate this, the Rotterdam industry therefore seems to be opting for a future beyond the strong dependence on oil (Werkgroep Industriecluster Rotterdam-Moerdijk, 2018). However, the low cost of fossil fuels in Rotterdam could thwart a transition to significantly more expensive e-fuels.
- *Scarcity of space*: Space in the Rotterdam region is scarce. However, a lot of space will be needed to land offshore wind energy, for the production of hydrogen and e-fuels and (potentially) for direct air capture (TNO, 2021). This is compounded by the limited allowable environmental space for nitrogen (and other environmental restrictions), which hinders the realization of construction projects.
- *Insufficient renewable e-production for e-fuels*: Of the amounts of fuel that are now produced in Rotterdam, only a small proportion can be produced from locally generated sustainable (offshore wind) energy. According to (Carbon Tracker, 2021), the Netherlands is in the top 5 of countries that are forecasted to have a shortage of electricity from renewable energy sources, after Belgium and Germany (see Figure 9). In addition, there is not enough space to land the required amount of electricity in Rotterdam. To produce all fuels for international transport in Rotterdam, in 2050 about 2000 PJ of sustainable electricity would be required.
  Besides a shortage in renewable electricity, there is little circular carbon from biomass available, while Direct Air Capture technology is still expensive and not mature. On the other hand, there is relatively much waste available from

which carbon could be re-used. There is a lot of much fossil CO_2 available, which could play a role in the transition.

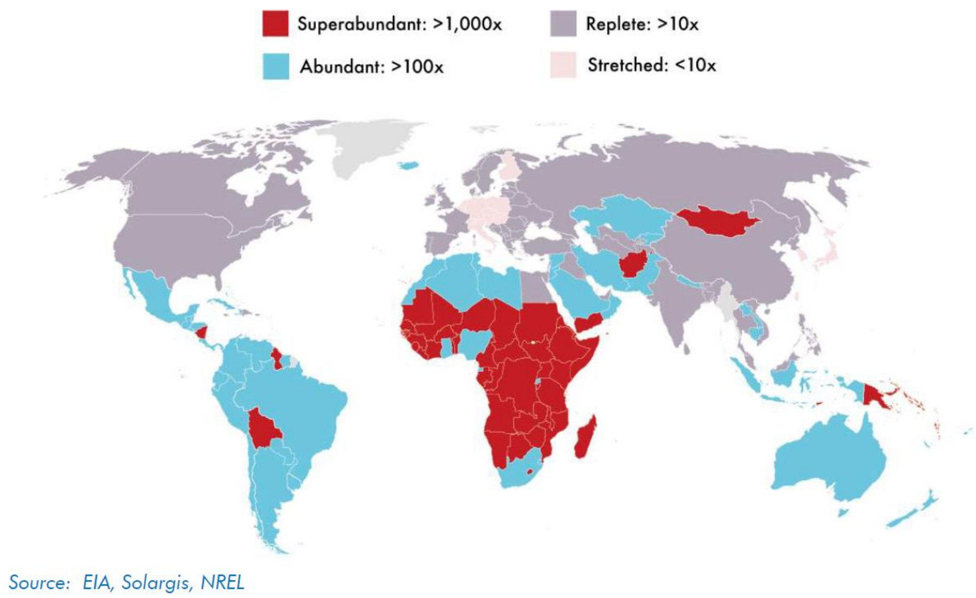


Figure 9: Solar and wind energy potential as a multiple of energy demand (Carbon Tracker, 2021)

<u>Opportunities</u>

- *Willingness to invest (also in R&D)*: At present, there is a great willingness to invest in sustainable technology, including green hydrogen and e-fuels. This willingness to invest is present in both governments (see, e.g., the European Green Deal) and companies. At the same time, there is competition between regions and consortia to attract investments.
- *E-fuels necessary to achieve sustainability targets*: To achieve the sustainability goals, including those set in the Paris Agreement, a transition to sustainable fuels in transport is necessary. Electric vehicles, biofuels and green hydrogen alone are not sufficient for this. E-fuels will therefore be necessary to achieve the sustainability targets.
- *Future hinterland demand for e-fuels*: Not only in the port of Rotterdam, but also in the hinterland, demand will arise for e-fuels to make heavy transport more sustainable. For example, Germany has the third lowest solar and wind technical potential in the world relative to its energy demand (Carbon Tracker, 2021). So Germany will have a great need for imports. The German federal government strongly bets on the import of green hydrogen (Clean Energy Wire, 2020). In 2018, think tanks Agora Energiewende and Agora Verkehrswende concluded that Germany would need the well-directed use of power-based synthetic fuels, including gas, in connection with a phase-out of conventional oil and natural gas to reach its long-term climate targets and that large amounts must be imported. The existing infrastructure and relationship with Germany are great opportunities for the Rotterdam region.

<u>Threats</u>

- *Competition for renewable electricity in The Netherlands*: In addition to the mobility sector, there is a growing demand for sustainable electricity from other sectors. The total amount of electricity from renewable sources generated in the Netherlands will not be enough to meet this demand. In addition, the use of renewable electricity in other applications (e.g. BEVs) will lead to larger CO_2 emission reductions per unit of renewable energy input compared to the use of e-fuels and as such forms a threat (see Figure 10).

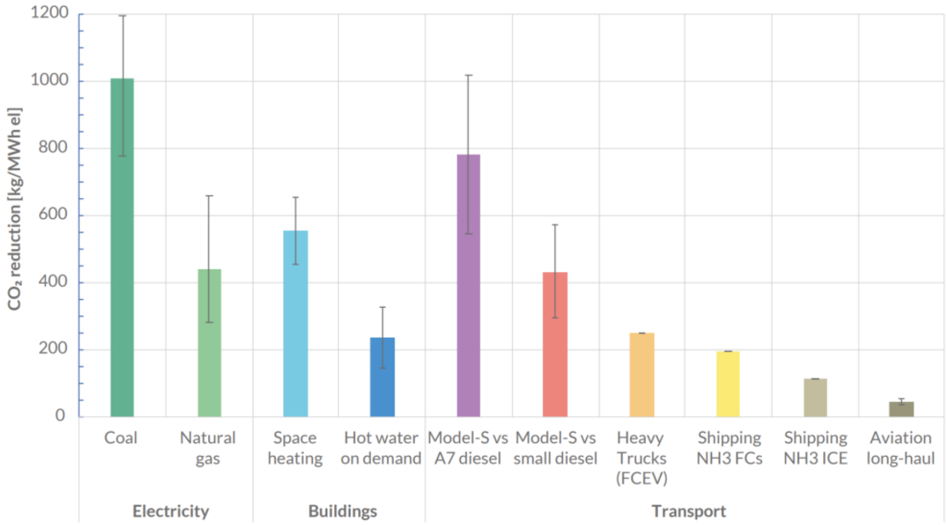
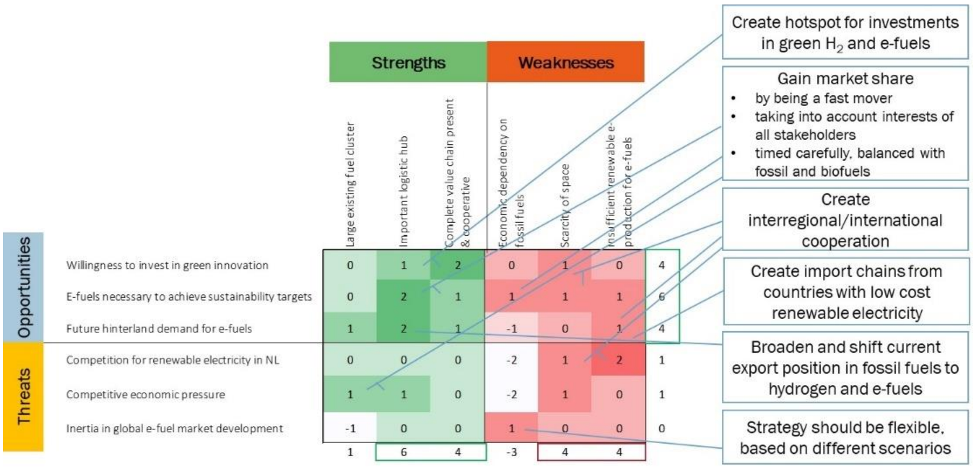


Figure 10: Merit order of electrification (Voltachem, 2020)

- *Competitive economic pressure*: E-fuels will be significantly more expensive than the current cost levels of fossil fuels. Therefore, cost-wise, e-fuels cannot compete with fossil fuels for the time being. Cost levels are an important element in the competitive edge of ports. A transition to e-fuels can therefore significantly increase the competitive pressure from ports, which still offer cheap fossil fuels. On the one hand, the result may be that key players reconsider their investments and portfolio and take their investment decisions (differently) based on the new situation. The question is whether the investment climate in Rotterdam will then be favourable enough. On the other hand, new investments aimed at the energy transition, such as those facilitated by the SDE++, could be postponed. This could put the energy transition several years behind schedule.
- *Inertia in global e-fuel market development*: The transition to sustainable fuels is a global development over which the Rotterdam region has limited influence. At the European level, the market development of e-fuels is highly dependent on stimulating policies and unambiguous regulations. In addition, the fact that it is not yet clear which e-fuels will play an important role in the future energy system inhibits investments. If the Paris targets are not met, there is a good chance that the development of a market for e-fuels will lag behind. Investments in large-scale production will only be made when there is significant demand for sustainable fuels from the logistics sector, as a result of sustainability targets and/or stimulating government policies. EU policy can affect the market for land-based transport; however the markets for maritime shipping and aviation, that have a global character, are harder to influence. Protectionism may have an amplifying negative effect on the development of international trade. Europe may become more vulnerable, with more room for China but also for large tech-based 'corporates' to strengthen their position. This may be at the expense of the position, structure and resilience of the Rotterdam port cluster. Another possible effect of the geopolitical tension is

that there will be less global and European unity in the climate approach, which may make companies cautious in their investments. This then has a delaying effect on the energy transition in the port.
The European Commission states that investments in energy transition and climate should go hand in hand with economic recovery and wants to push the Green Deal forward more strongly. Port of Rotterdam has indicated that it will continue to invest in the energy transition and would like to accelerate this. If sufficiently effective, this could turn the potentially negative impact of the crisis on energy transition into a positive one.

A confrontation matrix is made of the SWOT analysis. In the confrontation matrix, the strengths and weaknesses are confronted with the opportunities and threats, and a weight is given to them (see Figure 11).



	Large existing fuel cluster	Important logistic hub	Complete value chain present & cooperative	Economic dependency on fossil fuels	Scarcity of space	Insufficient renewable e-production for e-fuels	
Willingness to invest in green innovation	0	1	2	0	1	0	4
E-fuels necessary to achieve sustainability targets	0	2	1	1	1	1	6
Future hinterland demand for e-fuels	1	2	1	-1	0	1	4
Competition for renewable electricity in NL	0	0	0	-2	1	2	1
Competitive economic pressure	1	1	0	-2	1	0	1
Inertia in global e-fuel market development	-1	0	0	1	0	0	0
	1	6	4	-3	4	4	

Combination	Question to be answered
Strength – opportunity	To what extent does the strength help you make the most of the opportunity?
Weakness – opportunity	To what extent does the weakness prevent you from taking advantage of the opportunity?
Strength – threat	To what extent does the strength help you ward off the threat?
Weakness – threat	To what extent does the weakness prevent you from warding off the threat?

Scale	
2	most definitely
1	definitely
0	neutral
-1	hardly
-2	not

Figure 11: SWOT confrontation matrix

In particular, the darker coloured fields in the confrontation matrix require attention in the strategy. They provide strategic directions. Based on the SWOT analysis and the confrontation matrix, the following input for the strategy has been formulated:

Rotterdam can respond to the expectations for a significant e-fuels market by using its strength as major logistics hub. When Rotterdam starts offering e-fuels, a significant volume can be built up quickly. At the moment, the willingness to invest in sustainable technology is high[16]. This offers an opportunity to create a position in Rotterdam in the field of e-fuels.

Especially the strengths "important logistic hub" and "complete value chain present" make the Rotterdam region an attractive hotspot for investments in green hydrogen and e-fuels. In addition, thanks to the presence of the fossil fuel

[16] See e.g. the European Green Deal, and the number of sustainable energy projects that are initiated by industry consortia. Nouryon/BP/HbR plans for 250 MW elektrolyser (Nouryon, 2019) and Shell has plans for a 200 MW plant at Maasvlakte 2, starting in 2023 **Invalid source specified.**.

cluster, much infrastructure is already present. At the same time, similar developments are taking place in the chemical sector: green methanol will play an important role as a sustainable platform molecule, green hydrogen is an important means of increasing sustainability, and green ammonia is particularly important in the fertilizer industry. The processing of circular carbon is also important in chemistry. This offers opportunities to strengthen developments in these areas in terms of infrastructure, development of an innovation ecosystem, skilled workforce, co-siting, and other potential synergies. This position can be used by the region to attract investments.

Actors from the entire value chain are already present in HIC Rotterdam. Access to markets is well-established and a lot of existing infrastructure (such as pipelines) and logistic connections can be reused for the supply of e-fuels. By being a fast mover, Rotterdam can build up a position here. However, ports like Antwerp and Hamburg have similar plans. For example, Antwerp is developing green methanol facilities, whereas Hamburg plans to produce green hydrogen.

The current economic interests in fossil fuels could also have an inhibiting effect on building a position as e-fuels producer. Therefore, it is important that fossil fuel producers are stimulated to take a stake (role) in the transition to e-fuels. Other obstacles, the lack of locally generated sustainable electricity and lack of space can (partially) be overcome by setting up import chains with countries where electricity from sustainable sources will be available in abundance, at lower prices than in Europe. In addition, it is important to work together with other regions for the storage of hydrogen in salt caverns.

In addition to bunkering and refuelling markets in Rotterdam, there will also be a sales market for e-fuels in the hinterland. Currently, Rotterdam is already a major supplier of fuels to the hinterland (mainly Germany). It is expected that the demand for fossil fuels and oil will gradually shift towards a demand for sustainable fuels and green hydrogen.

A threat is the potential loss of competitiveness, due to the (for now) significantly higher cost levels of e-fuels compared to both fossil fuels and biofuels. In the transition period, it is important to find customers with willingness-to-pay, either because they are early adopters or because they operate in markets with above average sustainability requirements. The question is whether the time will come when the transition to sustainable fuels will be enforced. As an important logistics hub, Rotterdam has the opportunity to (locally) influence how quickly this transition takes place. This transition, and the degree to which it is enforced, must be carefully timed: if this happens too soon, part of the logistics chain will seek out competing ports; at the same time it is important to accelerate the transition to sustainability. A constant balancing act is therefore required, based on the interests of the various players and on the growth in demand for sustainable fuels from the logistics sector. Meanwhile, companies will only invest in e-fuels when market demand justifies the investments. To increase this demand, incentives are needed to persuade companies to no longer use fossil fuels.

The speed of the transition to e-fuels ultimately depends largely on external factors. If development is too slow, Rotterdam can accelerate locally using its important position as a logistics hub, and its transition power due to the presence of almost the entire value chain. Three scenarios have been developed that deal with external factors influencing the pace of the energy transition. These are described in Chapter 5. Flexibility in the strategy will be key, to make the strategy robust in all three scenarios.

3 Impact of the transition on value chains

The transition to e-fuels will affect existing value chains. When e-fuels are imported in the future, driven by abundant energy from renewable sources at low cost elsewhere in the world, new value chains will develop. In this chapter, an elaboration of a number of value chains for production and distribution of feedstocks and e-fuels (via import or locally) is presented (3.1). To this end, the costs of import of e-fuels are compared to the costs of local production in Rotterdam. When e-fuels displace fossil fuel products in Rotterdam, this also affects the value chain of chemical products since these are manufactured mainly from crude oil. Therefore, this chapter also analyses the entanglement of manufacturing fuels and chemical products (3.2).

3.1 Economic assessments of import chains

Currently, a large amount of energy is imported in the port of Rotterdam in the form of crude oil. It is expected that import of energy will continue to play a significant role after the energy transition, but in the form of sustainable feedstock, fuels and hydrogen carriers.

In this chapter an economic analysis is presented on import of various e-fuels and hydrogen carriers from countries around the world. E-ammonia (NH_3), e-methanol (MeOH), liquid hydrogen (LH_2) and a liquid organic hydrogen carrier (LOHC) are incorporated in the analysis. The costs of importing e-ammonia and e-methanol are compared to the costs of local production in Rotterdam. Liquid hydrogen and LOHC are assumed to be used as gaseous hydrogen in Rotterdam. Therefore the costs of import of LH_2 and LOHC are compared to the cost of local production of gaseous green hydrogen in Rotterdam.

3.1.1 Assumptions and methodology

Scope and sources

Calculating the cost of import chains requires robust assumptions on Levelized Cost of Electricity (LCoE) and Full Load Hours (FLH). Only renewable electricity sources are included in these assumptions, since the overall goal is to identify the most economically feasible ways to import **green** hydrogen and e-fuels to the Netherlands.

Costs are calculated for 2030 using TNO's Supply Chain Model (Voltachem, 2020). This timeline is chosen since this time horizon allows to use realistic CAPEX and OPEX predictions (i.e. is not too far in the future) on the one hand, and is also far enough to imagine that some of these chains can already be set up on small to medium scale (i.e. is far enough in the future) on the other hand.

The following countries were included in the analysis[17] and some alternative (neighbouring) countries' data was used if no data were available for the original country.

---

[17] The choice of countries was agreed upon with the steering group of the CHAIN project.

Table 13: Country selection and alternatives

PoR countries	Alternative if no data were available
Australia	-
Canada	-
Chile	Argentina
Morocco	Spain
Namibia	South Africa
Netherlands	-
Oman	-
South Africa	-
United Kingdom	-

To obtain LCoE and FLH 2030 estimates by country, TNO performed a review of several existing reports containing the analysis of renewable energy potential in selected countries. Where no other data were available, assumptions from the HyChain 2 model (Hychain – energy carriers and hydrogen supply chain, 2019) were used.

Energy source selection
As a first step, the main source of renewable energy was selected for each of the 9 countries. Assuming most of the renewable energy in each country will come from the least expensive source, LCoEs in 2030 for different sources (solar, onshore and offshore wind) were compared. For most countries solar is estimated to be the cheapest source, except for the Netherlands (no data for solar and onshore wind) and UK (onshore wind is cheapest).

Average LCoE and FLH calculation
FLH of solar energy are about 20% (onshore wind in the UK is also low – 23%), so another renewable energy source will be required to ensure that production plants can keep running when no energy from wind or solar is available. This is necessary because the production plants of the four carriers can't be easily turned on and off (this will be elaborated further under the topic "Chain size and configuration"). The second cheapest source was therefore selected for each country – typically onshore or offshore wind. The combined FLH were then calculated[18] assuming that half of the time the 2nd source will be overlapping with the 1st, so $FLH_{combined}=FLH_1 + 0.5*FLH_2$. The same logic was allied to derive a combined LCoE.

Where data for a specific country was not available, another data point was used, depending on what is available:
1. Alternative (neighbouring) country data
2. Regional data (e.g. average solar FLH for Africa)
3. Data from HyChain 2 model
4. Global average

[18] Though this method may lead to some outliers (e.g. UK seems to be too low compared to NL, partly explained by the fact that UK is based on onshore wind and solar, where NL is based on offshore wind), consequent application of the method has prevailed in the analysis.

For Namibia, HyChain data was used to differentiate it with South Africa, as no data was found during the LCoE analysis.
As combining solar and wind energy still does not ensure 100% FLH, it was assumed that part of the energy produced during peak hours is stored and used during off-peak. The cost of stored energy is $LCoE_{combined}$ + 60 EUR / MWh[19].

In countries where other sources of renewable energy with higher FLH are available, this penalty of additional costs of electricity storage can be minimized. For example, thermal energy in Iceland could significantly improve the business case for green hydrogen, since it is available continuously (Port of Rotterdam, 2021).

Using the approach described above, assumptions on renewable electricity were obtained and fed into the Supply Chain Model of TNO (Figure 12). Other necessary country-specific parameters were also obtained and included in the model (see Table 8).

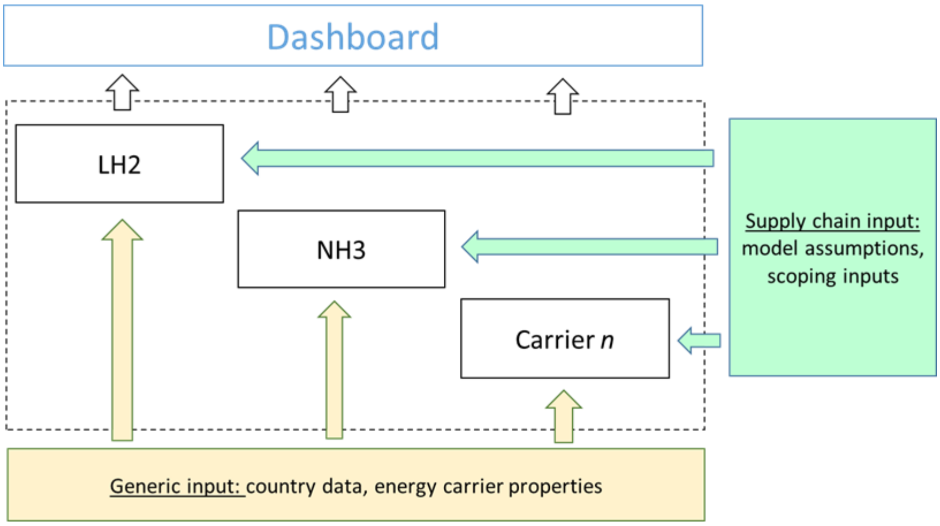


Figure 12: Schematic representation of TNO's Supply Chain Model

[19] See: (Lazard, 2020). Currently large scale storage starts at about 120 EUR / MWh, the assumption is that this cost goes down by a factor of 2 by 2030.

Table 14: Country-specific assumptions fed into Supply Chain Model

Country-specific parameters	Reference	Unit	Netherlands	Canada	Morocco	Australia	Oman	UK	South Africa	Namibia	Chile
Combined LCoE, wind & solar power (where applicable) in 2030	Multiple LCoE reports (see below)	€/MWh el	74 (offshore wind only)	37 (35 – utility solar 40 – onshore wind)	59 (28 – utility solar 78 – offshore wind)	26 (22 – utility solar 30 – onshore wind)	37 (22 – utility solar 53 – onshore wind)	28.2 (23 – onshore wind 40 – utility solar)	33.3 (21 – utility solar 46 – onshore wind)	47.9 26 – utility solar 78 – offshore wind)	43.6 (22 – utility solar 62 – offshore wind)
LCoE estimates source	-	-	TNO, Julich, DENA (2021); Hy3 – Large-Scale Hydrogen Production from Offshore Wind to Decarbonise the Dutch and German Industry	Ram et al (2018)	Fraunhofer (2018). Levelized Cost of Electricity Renewable Energy Technologies	Ram et al (2018)	Ram et al (2018)	Ram et al (2018)	Ram et al (2018)	HyChain (2018)	Ram et al (2018)
Cost for stored electrical back-up power in 2030	LCoE + storage costs 60 €/MWh	€/MWh el	134	97	119	86	97	88	93	108	104
Shipping distance (one way to PoR)	Ports.com	nm	0	3,400	1,700	13,188	6,765	524	8,157	6,605	9,730
Shipping speed		km/h	-	29	29	29	29	29	29	29	29
Local interest rate	HyChain, WACC used	%	7.2	8	13	10	10	7	12	13	11

Chain size and configuration

The sizing of the system for hydrogen and e-fuel production was based on experience from other projects where similar production assets were modelled. The size of the renewable energy asset that will supply green electricity for hydrogen and carrier production was assumed to be 3000 MW. The electrolyser is scaled at 2700 MW (90% of the solar / wind asset capacity) and defines the size of other infrastructure, e.g. conversion plant, number of ships etc. The configuration of the system in the Supply Chain Model includes 12 hours of hydrogen buffering to ensure the flow to the production plant plus batteries for renewable electricity back-up. This electricity back-up is used to keep production plants running (keep the plants warm and pumping), even when the electrolysers are not producing hydrogen and production plants are not producing carriers. Another option would be have larger hydrogen storage and no batteries. In that case, baseload production of carriers could be realised.

A different scale and configuration of the system would affect the cost of the chain. It is important to note that conversion plant CAPEX and scaling factor are highly uncertain parameters since currently the infrastructure of this scale does not exist. In the current version of the Supply Chain Model, these techno-economic parameters were taken from literature, estimates by TNO and project experience. The accuracy of in cost estimates may be up to ~50% per process block. However, since basic assumptions for each of the routes are the same, the overall comparison between routes is more accurate.

3.1.2 Results

All in all, the cost of different chains is mainly defined by the LCoE and FLH, since they define the cost of hydrogen and energy used during production. The merit order of different countries is almost the same for each carrier. Distance and therefore shipping costs affect this country ranking to only a small extent.

Carrier comparisons

Under the assumption included in the analysis, import of ammonia and methanol as fuels for use in the Netherlands are sensible from a cost perspective (see Figure 13 and Figure 14). Almost all countries offer lower chain costs compared to producing these fuels in the Netherlands, given the high LCoE in the Netherlands. For ammonia and methanol their use as fuels was assumed, so no cracking back to hydrogen in NL was included in the cost.

Overall, methanol is more expensive than ammonia because of high Direct Air Capture (DAC) CAPEX and lower chain efficiency. The cost difference between import and local production differs between the countries. However not too much value must be put to the exact order of the countries, because of the inaccuracy in LCoEs and the fact that, within one country, LCoEs per project may even vary significantly.

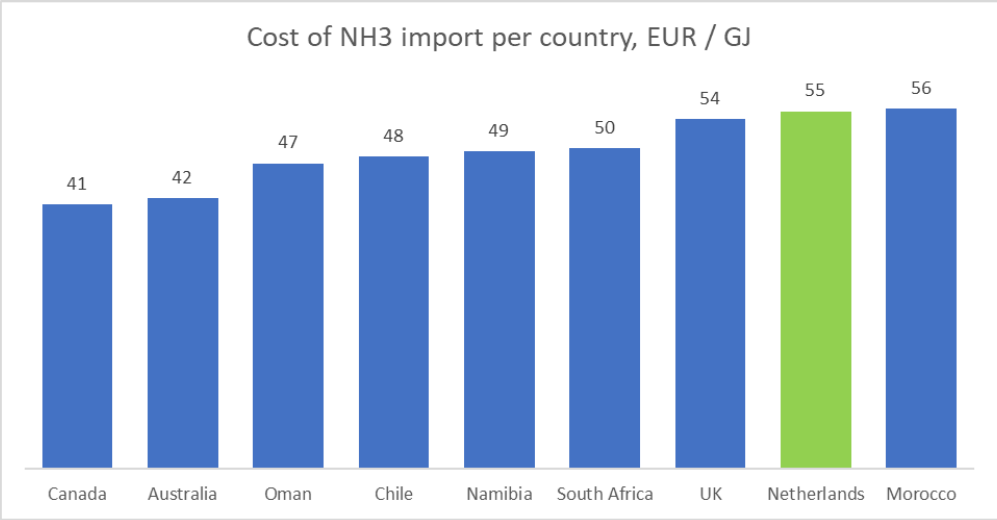


Figure 13: Cost of renewable ammonia delivered to PoR, EUR / GJ

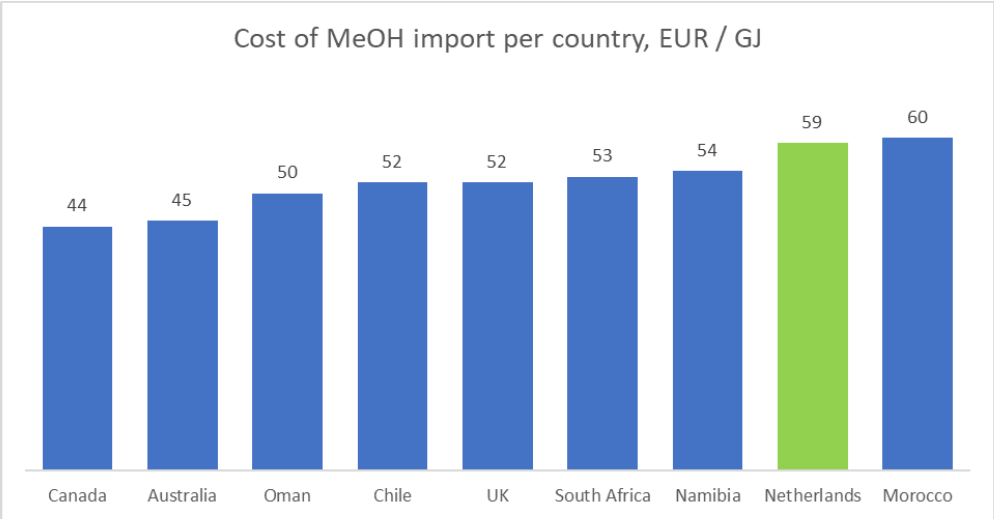


Figure 14: Cost of renewable methanol delivered to PoR, EUR / GJ

For hydrogen the results are opposite: import of LOHC (toluene is used as a model chemical for LOHC) and liquid hydrogen is significantly more expensive than production of gaseous hydrogen in the Netherlands (see Figure 15 and Figure 16). Both liquified hydrogen and LOHC need to be converted back to hydrogen to be used domestically as gaseous hydrogen, so the chain costs of these carriers were compared to the cost of producing hydrogen in the Netherlands (without liquefaction or conversion to and from LOHC).

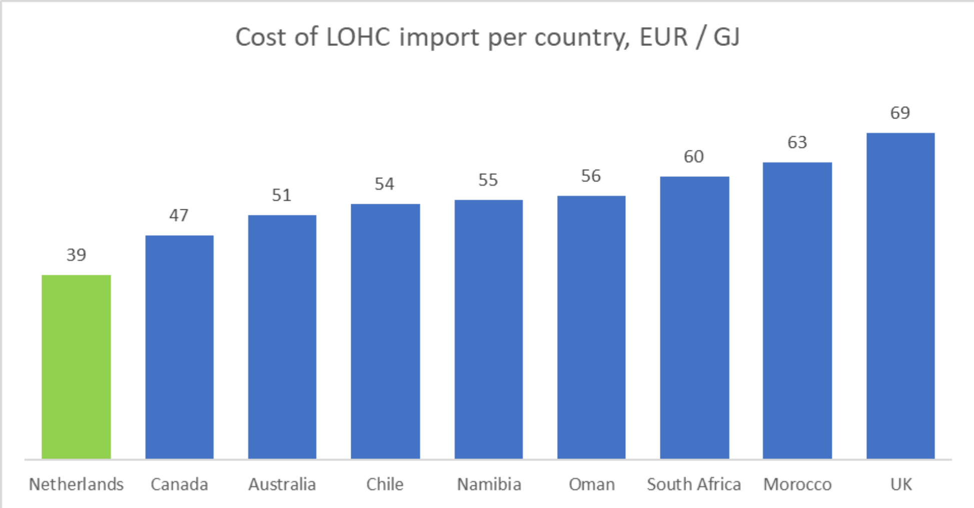


Figure 15: Cost of renewable hydrogen delivered to PoR via LOHC, EUR / GJ

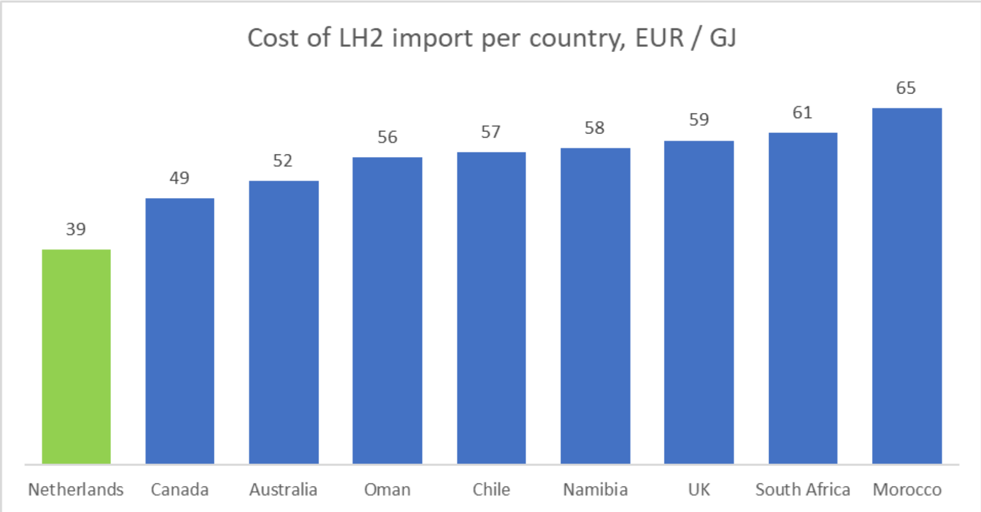


Figure 16: Cost of renewable hydrogen delivered to PoR via liquefaction route, EUR / GJ

However, if NL expects a very high hydrogen demand (e.g. from industry or mobility) that cannot be covered by domestic production or import by pipeline from nearby countries, these carriers could be interesting.

Even if delivered via pipeline, LOHC does not seem to be economically attractive, because shipping comprises only 8-10% of the total chain cost as will be shown below. Compressed hydrogen might be economical if imported via pipeline, but this would depend on the pipeline and compression costs and is not included in this study.

In case hydrogen will be used in liquid form or as LOHC (e.g. for shipping), the comparison between local production and import will be less unfavourable for import.

Chain cost composition per carrier

Ammonia

For ammonia local H_2 production comprises 60-80% of total cost. Local H_2 production comprises 80% of total cost for the Netherlands as the other cost components are not present, e.g. transport by ship. Omitting the Netherlands, local H_2 production comprises ~65-70% of total cost. Conversion is the second biggest (~25%) component.

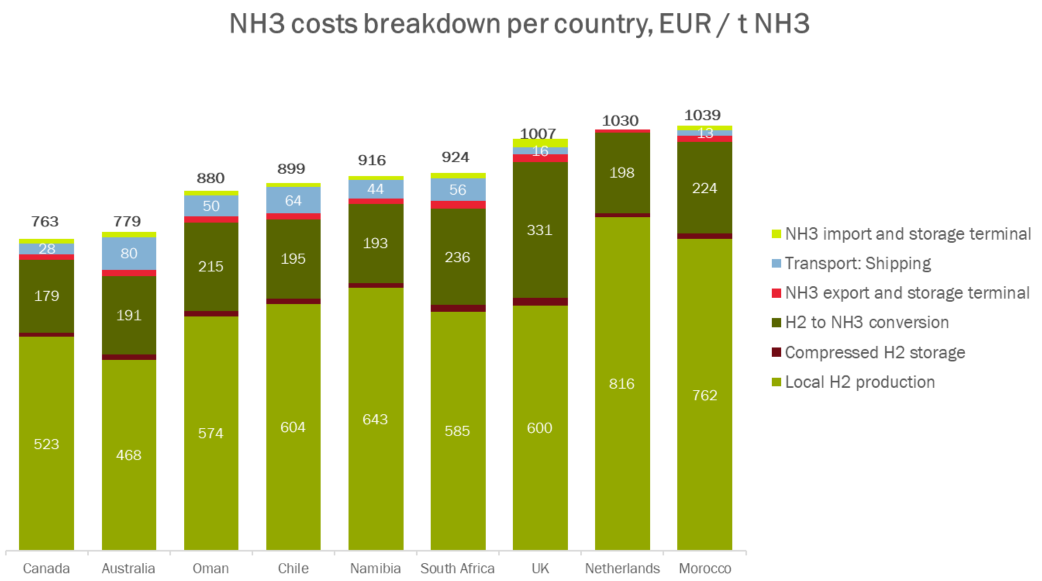


Figure 17: Renewable ammonia (delivered to PoR) cost breakdown, EUR per ton

Methanol

Local H_2 production comprises 60-80% (60-70% omitting the Netherlands) of total cost. Conversion and Direct Air Capture are the second and the third biggest component (10-20% and 10-15% respectively).

Capture from concentrated sources could also be used as a source of CO_2 and would be considerably cheaper than Direct Air Capture, but it would still result in CO_2 emissions. CO_2 captured from fossil-based industrial processes will eventually be emitted into the atmosphere when methanol is burnt. Direct Air Capture, in turn, allows to have a closed carbon cycle through the atmosphere.

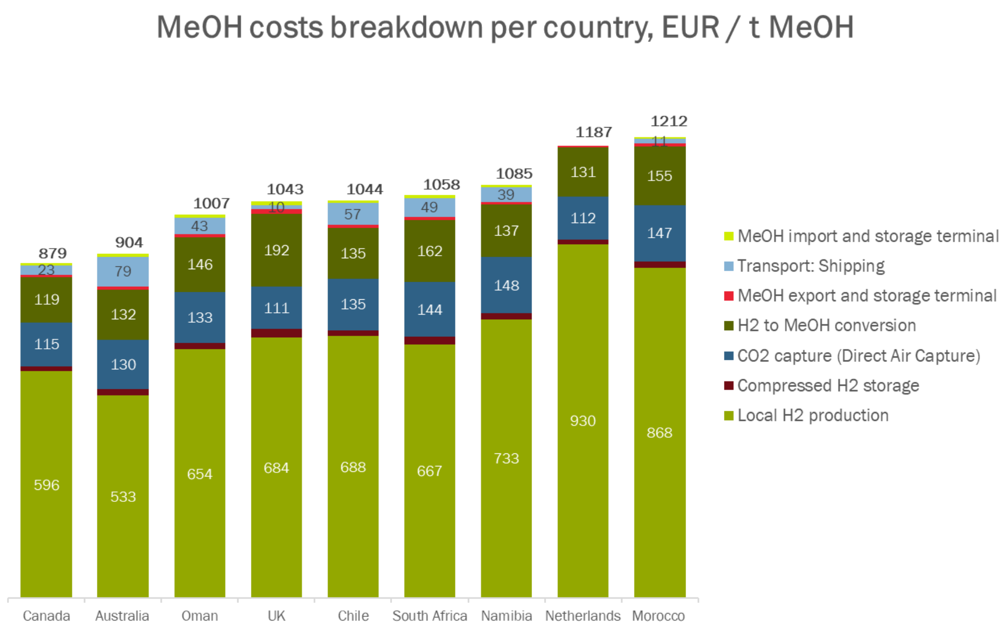


Figure 18: Renewable methanol (delivered to PoR) cost breakdown, EUR per ton

<u>Liquified hydrogen</u>

As mentioned above, all liquid hydrogen production abroad was compared to gaseous hydrogen production in in the Netherlands (i.e. without liquefaction) as reference case.

Shipping and handling of liquified hydrogen is technically more challenging compared to ammonia or methanol shipping, so the share of shipping costs in the overall chain cost is higher for liquified hydrogen (8% on average, compared to 5% for ammonia). Local hydrogen production comprises 40-60% of total cost: this is a lower share compared to ammonia and methanol, because other cost components are relatively bigger for liquified hydrogen chain. Conversion is the second biggest component (25-40%). Especially for the UK conversion is expensive: 40% of the total cost, while it is 25-30% for the other countries. Reconversion back to gaseous hydrogen is a rather simple and hence a cheap step.

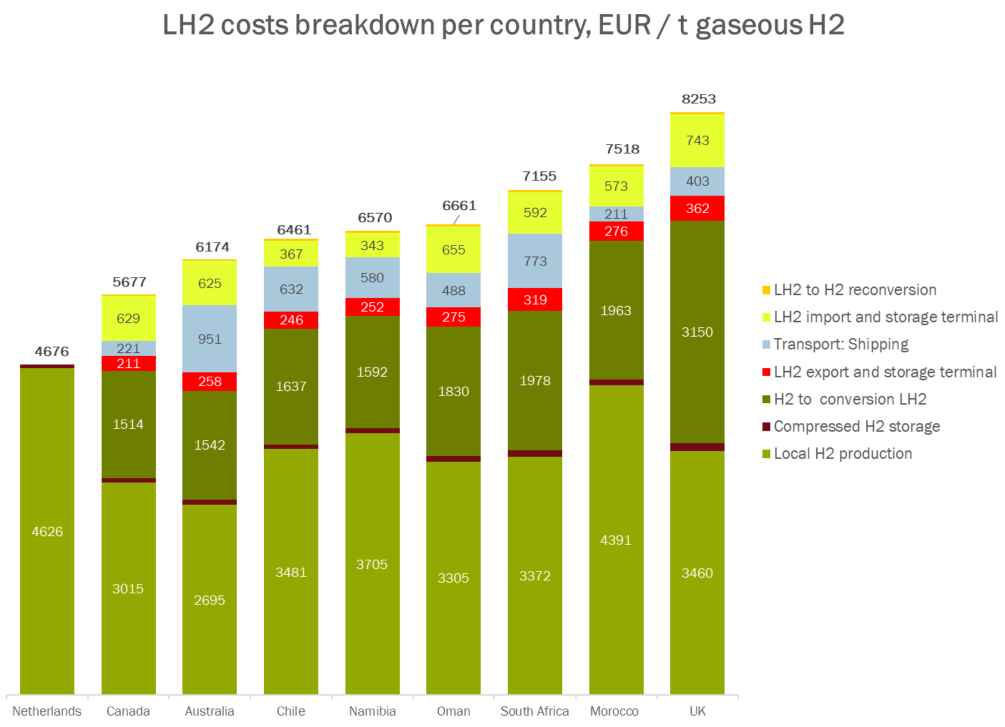


Figure 19: Green hydrogen (delivered to PoR via liquefaction route) cost breakdown, EUR per ton

<u>Liquid Organic Hydrogen Carriers</u>
LOHC is the most expensive carrier of all four. This is mainly due to a lower chain efficiency (60-70%), since all costs are shown per ton of hydrogen delivered to the Netherlands.

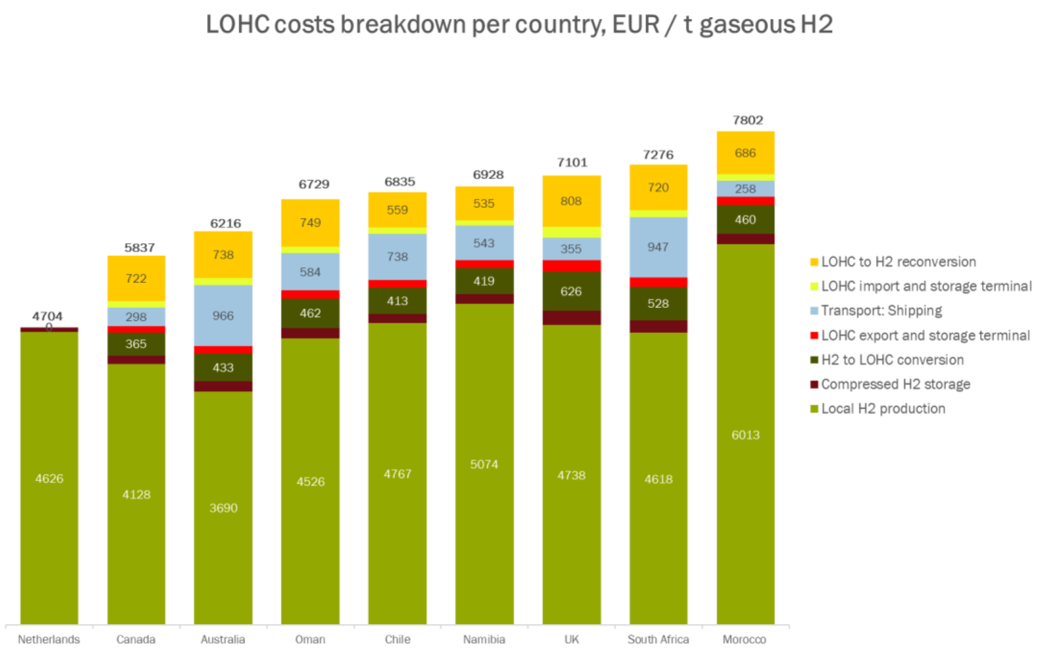


Figure 20: Green hydrogen (delivered to PoR via LOHC) cost breakdown, EUR per ton

Again, all LOHC production abroad is compared to gaseous hydrogen production in NL. When the LOHC is not dehydrogenated in Rotterdam for use as gaseous hydrogen, but is transported further, e.g. to the hinterland or to fuelling stations, the comparison between production in Rotterdam (plus cost for further transport) and import will be less unfavourable for import.

Local H_2 production comprises 60-75% of total cost. Shipping or reconversion back to hydrogen are the second biggest component. Reconversion is 10% of the chain cost, which is relatively high. This is mainly due to the fact that this process requires a lot of energy. Conversion costs are considerably lower compared to liquified hydrogen.

Import of intermediates

An alternative to import of e-fuels could be the import of intermediates. For the Rotterdam region, an important aspect is to maintain economic activity around the production of fuels. It is therefore important to also consider chains in which raw materials and/or intermediate products are imported and the final fuels are produced in Rotterdam: what are the possibilities and how would they fit into the strategy for the transition? In particular, e-diesel and e-kerosene are candidates for this. Detailed results of an economic analysis of production of e-diesel and e-kerosene from imported intermediates can be found in (Saric, Detz, & van Kranenburg, 2021). The results of this study are summarized below.

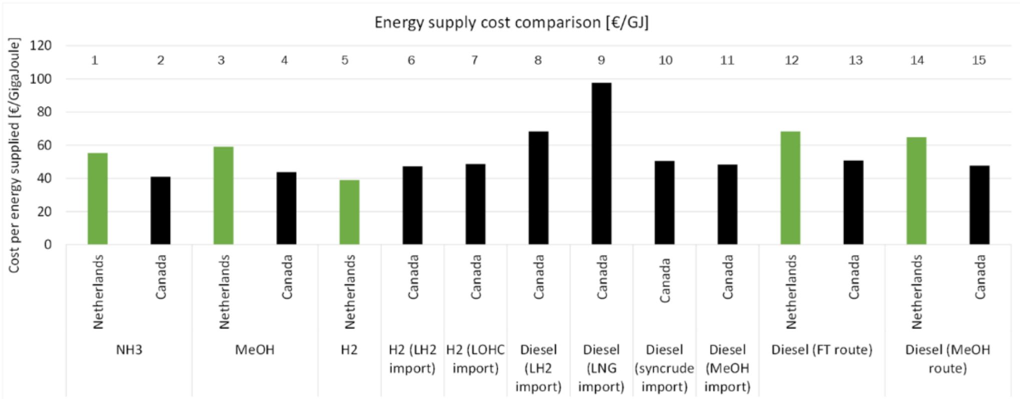
E-diesel and e-kerosene can be produced in a Fischer-Tropsch plant that uses FT-crude as feedstock. The FT-crude is produced from hydrogen and CO_2, or from e-LNG. An alternative to a Fischer-Tropsch plant is the production of e-diesel or e-kerosine from e-methanol.

In Figure 21 the results of the economic analysis of local production of e-diesel[20] from intermediates is compared to import (from Canada) and local production in Rotterdam of different e-fuels and hydrogen are presented.

For the production of e-diesel (and e-kerosine) the methanol route is found most efficient and results in lowest cost. Cost of production via Fischer-Tropsch is close to cost of the methanol route. Especially the e-LNG route is inefficient and costly, and also import of liquid hydrogen to produce e-diesel in Rotterdam is significantly more costly.

Import of e-diesel (and e-kerosine) is slightly more cost effective than producing the fuels locally from imported intermediates, such as methanol or FT-crude. However, import of FT-crude presents technical challenges. Also, the step from intermediate to e-diesel (and e-kerosine) results in a higher value product, while the additional expenses are fairly limited. It seems therefore logical that the producer of FT-crude converts it into the final diesel (and kerosine) product. Import of green methanol to produce diesel and kerosine, on the other hand, seems more rational, since methanol is also a platform molecule for the chemical industry and a global methanol market already exists. Therefore local production of e-diesel and e-kerosene from imported green methanol is considered a serious alternative to import of e-diesel and e-kerosene.

[20] The costs of production of e-kerosene will be approximately the same as of e-diesel. Fractions can be tuned depending on process conditions.



- Lowest production cost per GJ of fuel are via H_2 production in NL (39 €/GJ H_2), column 5.
- Lowest production cost per GJ of fuel imported are via NH_3 supply (41 €/GJ NH_3), column 2.
- Lowest cost to supply e-diesel (column 8-15) is via the methanol route with e-diesel import (48 €/GJ Diesel), column 15.
- Lowest e-diesel supply costs are 9% higher per GJ fuel compared to MeOH import from Canada (column 15 vs column 4).

Figure 21: Comparison of import and local production costs of different e-fuels (column 1-4 and 12-15) and hydrogen (column 5-7) with local production of e-diesel from imported intermediates produced from renewable energy (column 8-11).

When taking into account all considered e-fuels and hydrogen, in terms of costs per GJ of fuel, local production of hydrogen (column 5 in Figure 21) has lowest costs. However, costs of storage, distribution, tank infrastructure and vehicles are significantly higher for hydrogen than for e-fuels (van Kranenburg & Schipper, 2021). Of all the e-fuels that are analysed, ammonia has lowest cost per GJ.

3.2 Interaction between sectors

When e-fuels displace fossil fuel products in Rotterdam, this also affects the value chain of chemical products since these are manufactured mainly from crude oil. This section analyses the entanglement of manufacturing fuels and chemical products.

Today fuel products are mixtures, while chemicals are pure compounds. From the perspective of manufacturing chemicals from crude oil, all by-products are valorized as fuels. Therefore importing e-fuels into the Rotterdam cluster should also affect the value chains of chemicals. Chemicals however are going through their own transition where circular-carbon from recycled materials and carbon resources of biological origin displaces the naphtha fraction from crude oil. Part of the by-products from refining and chemicals manufacturing are today burned for energy to drive the processes, which generates CO_2 emissions.

In the same way that e-fuels can displace fuel fractions from crude oil, circular-carbon such as waste-based, bio-based and CO_2-based carbon can displace the naphtha fraction. Both displacements reduce the number of options for refineries to generate margin from crude oil refining. Some refineries are equipped to perform key chemical conversions, which makes them more capable of handling circular and bio-based feedstock instead. Circular feedstock from waste and bio-based materials is generated inland and hence from there it will need to find its way to the circular conversion operations. When the burning of by-products is largely replaced by electrification or by e-fuels without CO_2 emission, this means that ‘by-products’ should be converted to products rather than burned for energy. While renewable electricity can replace part of this energy, its inherent intermittency needs to be handled.

The inevitable transition away from fossil resources and towards circular carbon feedstock for fuels and chemicals thus needs logistics and value chains to be developed and scaled towards Rotterdam, if the conversion is still to take place there. Because carbon-free energy and circular resources are scarce and therefore valuable, the competitiveness of the cluster as a whole might benefit from a shared responsibility for energy- and carbon-efficiency by all operators in the region. Also the intermittency of renewable electricity may be better handled in a shared effort.

3.2.1 Introduction

According to a CIEP paper by (Nivard & Kreijkes, 2017) in the EU today operate in the order of 85 crude refineries, some of which are coupled to chemicals production. With five refineries the Rotterdam area is home to the largest refining cluster in Europe. Two of those are complex integrated refineries with advanced conversion capabilities. The paper discusses a mid-term outlook for refining in ‘business as usual’ competition. The CIEP paper states that while forward and backward integration does determine to some extent the competitiveness of refineries, there is competition especially from imported fuel products. The paper distinguishes between refineries ‘more resilient to competition’ and ‘exposed to competition’ with respect to import of refined oil products to the region where a refinery operates.

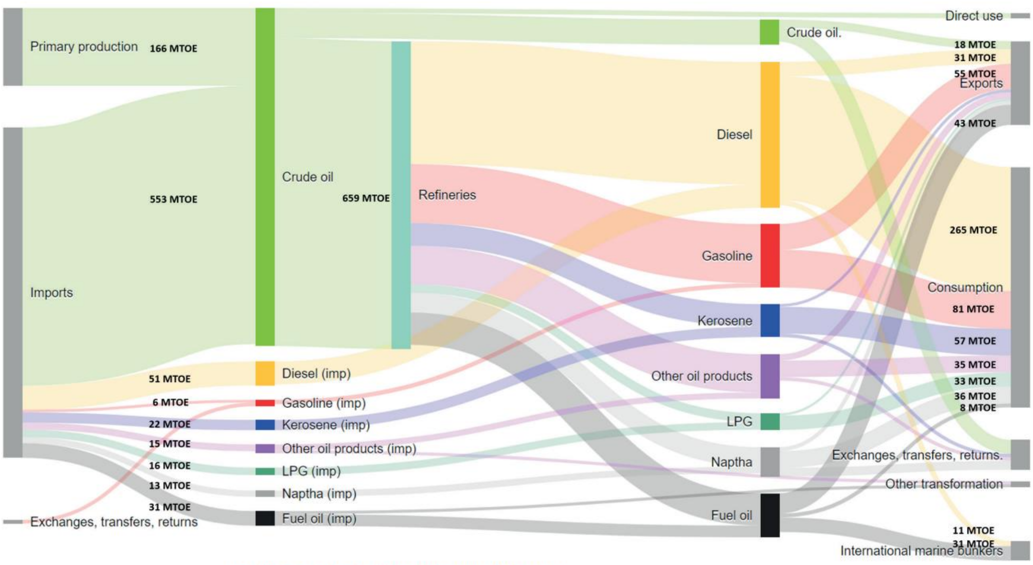


FIGURE C.1: EUROPEAN PETROLEUM OVERVIEW

Figure 22: European petroleum overview (Nivard & Kreijkes, 2017)

Figure 22 shows the European overview of import and export of petroleum and petroleum products. This is a representative picture of an average refinery. Refineries integrate with chemical complexes through the naphtha fraction. Those integrated refineries can be expected to have a larger share of naphtha in their product slate than average.

While the general notion is that today the forward-integration of refineries with petrochemicals enhances their competitiveness, the chemical industry is now also under pressure to move away from fossil-based products and switch to circular-carbon resources.

The CIEP paper does not analyse how fuel products may be displaced by imported ‘e-fuels’ or how circular-carbon resources could displace naphtha. Therefore this section of the present work analyses the displacement of refinery products by e-fuels (mainly for heat and power) and by circular carbon resources (mainly for chemicals).

This section first outlines the nature of fuels and chemical products, and how these are both manufactured from fossil resources. Then the work identifies circular-carbon resources, their processing domains and outlines how their value chains might integrate to eventually replace fossil-carbon as a resource for chemicals.

3.2.2 Fuels, lubricants and chemical products

The most stable molecules in crude oil usually end up in fuels or lubricants. These are generally the molecules with saturated straight chains of carbon. While fuels are mixtures, chemicals are pure compounds that are reactive. Chemicals are almost without exception derived from specific light and un-saturated hydrocarbon molecules. Most chemical products can be traced back to this selected group of chemical intermediates that is today derived from oil and gas.

While fuels may be changed for non-carbon containing energy carriers (hydrogen, ammonia), for chemicals there is no alternative for carbon-based molecules. Therefore the volume of carbon-based chemical products should be expected to remain unchanged and also the required volume of resources.

3.2.3 Products from fossil-carbon resources

Figure 23 shows a schematic representation of hydrocarbon resources, crude oil and natural gas, and the typical products produced by a ‘petrochemical’ refinery complex. The fuels are roughly made up of the saturated hydrocarbons and the chemicals are derived from the short-chain unsaturated components. The fuels are called by general names to identify mixture, while for the chemicals specific molecules are indicated.

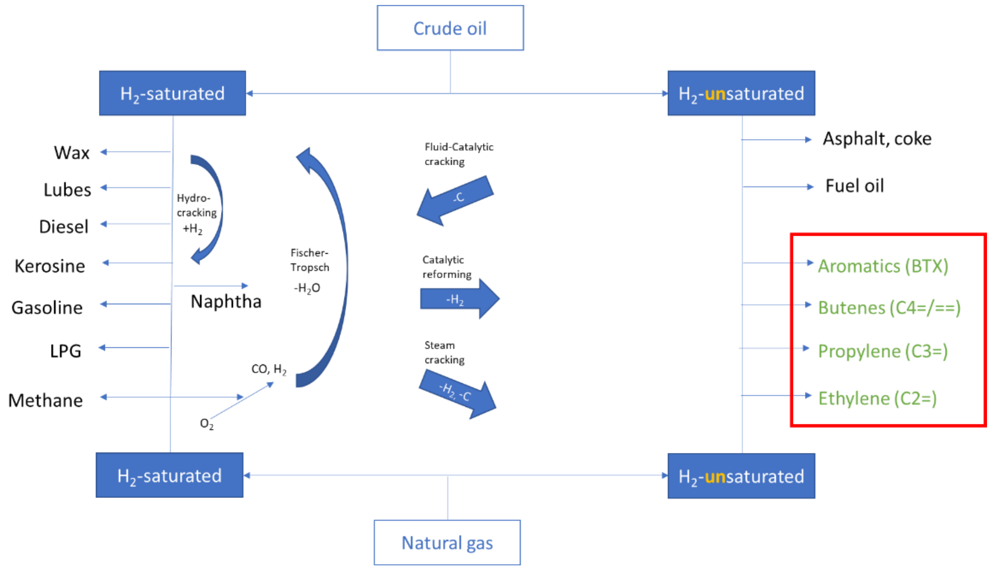


Figure 23: Fossil resources (crude oil, natural gas) and the derived products

Fuels are usually mixtures of longer chain saturated compounds, while chemicals are pure substances of short and unsaturated molecules. Larger unsaturated molecules, as found in the residue, are also used as fuel, mainly for shipping and are a source of coke e.g. for metallurgy or making electrodes.

Platform chemicals

There are four distinct groups of molecules that are 'cracker' platform chemicals: these are the basis for other chemicals that are ingredients or reactants for many chemical products, such as:

- Ethylene
- Propylene
- Butene-group
- 'BTX'-group

A more detailed picture of chemical products manufactured from these platform chemicals is provided by Independent Commodity Intelligence Services ((Independent Commodity Intelligence Services, 2020).

Co-production of fuels and chemicals

Refineries fractionate crude oil into fuels and naphtha, where the latter is the basis for cracker-platform chemicals. The volume of chemicals is on average small compared to the volume of fuels. Integration of refineries and chemical complexes is beneficial because they share resources, integrate by-products such as heat and there is an immediate and steady outlet for the products of the connected oil refinery. Because stand-alone refineries and stand-alone chemical sites cannot benefit from such integration, they are disadvantaged compared to well-integrated petrochemical complexes.

3.2.4 Circular-carbon for chemicals

Carbon is the basis for many synthetic chemical products and for most of the fuels today. While non-carbon fuels (hydrogen, ammonia) may arise as a new and next generation energy carriers, carbon as the 'backbone' of chemicals is not foreseen to change. Therefore when fossil-carbon phases out, as basis for carbon-containing products there are three main groups of circular carbon resources:

- Those derived from bio-materials
- Those derived from recycled synthetic materials
- Those derived from captured CO_2.

3.2.5 *Converting circular-carbon resources to products*

The map below shows characteristic conversions and intermediates for three domains that can be distinguished today: bio-processing, recycling and petrochemicals & energy. The bio-processing and the recycling domain aims to recover valuable components and sell the remainder, which needs heavier 'chemical' processing. Only the petrochemical and energy domain has developed the capability to process the heaviest carbon fractions through gasification. The resulting syngas is a versatile starting point for production of several classes of chemicals.

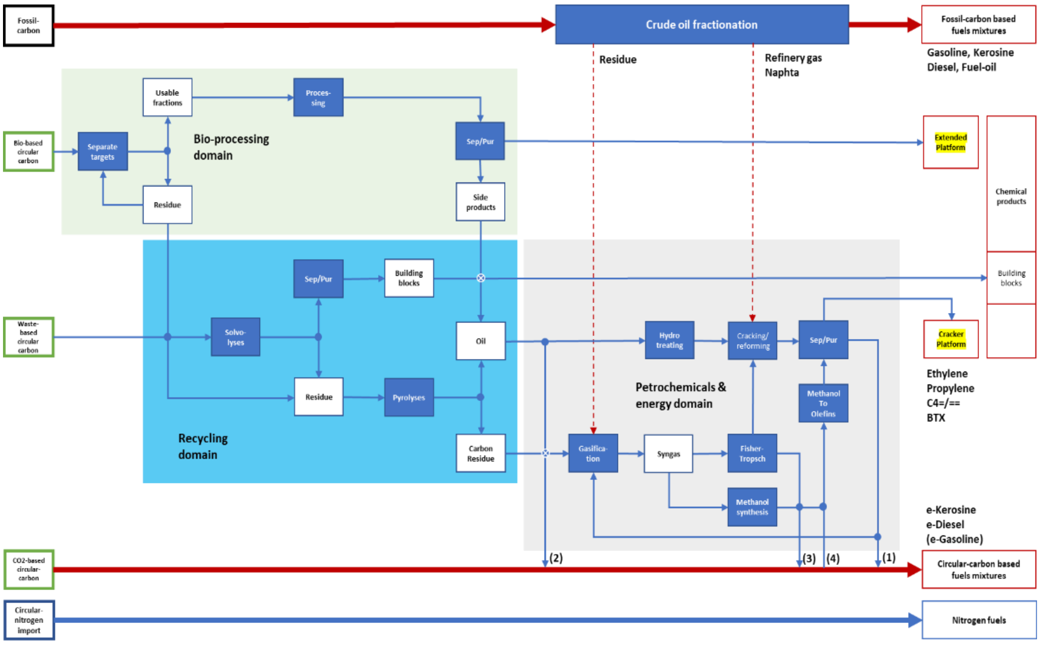


Figure 24: High-level diagram of the intersection between fuels (red lines) and chemicals (blue lines). Circular-carbon resources are indicated with green squares, fossil-carbon in black and nitrogen-based in blue

Figure 24 is not meant to present a full picture of options, as e.g. it shows no route to CCS. Number (1) through (4) indicate suggested cross-overs between chemicals and CO_2-based circular carbon fuels.

While today most carbon-based waste streams and by-products (refinery gas, fuel oil, biomass-residue, plastics) are combusted, in the future it may be more profitable to drive the carbon towards products instead of fuels, increasing the overall 'carbon-efficiency' towards products. This would ultimately be enabled by the local availability of renewable electricity (for heat and work in processing, or direct electrochemical conversion) and hydrogen as well as oxygen from water electrolysis.

Similar to the key cracker products several key bio-derived chemicals can be identified to manufacture a variety of chemical products and materials. Examples of such bio-based 'extended' platform chemicals are ethanol, furfural, hydroxymethylfurfural, 2,5-furandicarboxylic acid, glycerol, isoprene, succinic acid, 3-hydroxypropionic acid/aldehyde, levulinic acid, lactic acid, sorbitol, and xylitol (Takkellapati, Li, & Gonzalez, 2018) The by-products from these operations may very well be valorised in the production of cracker-feed and fuels, adding to the synergy of the cluster.

The value chains of bio-processing, re-cycling and petrochemicals towards their main products already exist on their own today and ways have been developed to valorise their by-products. With further pressure to reduce CO_2 emissions the value chains around the use of in particular these by-products will likely re-arrange.

Circular-carbon will displace crude oil
The core of the chemicals manufacturing will in this view be a circular-carbon cycle. This cycle is today fed by mainly fossil carbon resources. Bio-based resources have already started to displace fossil carbon (e.g. bio-ethanol and bio-diesel fuel). Next category scaling up will be recycled synthetic materials (i.e. recycled chemical products). Once the breakthrough of renewable energy enables the capture of CO_2 and its conversion to oxygenated intermediates and hydrocarbons, this will be the final category of circular-carbon to challenge fossil resources.

Products from captured CO_2 are suitable as fuels and as feedstock for producing chemicals. For fuels such products can be used as a basis, where fuel specifications may allow blending in of other components. If the cost of such products is competitive for use as fuels, they would likely be interesting as a basis for producing chemicals as well.

Cross-overs between chemicals and fuels
Chemicals are pure compounds and their production will produce a side-stream of by-products. Fuels with more general performance specifications can be blends, so the by-products from chemicals production may be added to fuels.

In the high-level example of Figure 24 several options for cross-over from chemicals to fuels are suggested:
- Divert by-products from the separation trains to the fuels-stream (1)
- Divert fractions from the recycling domain to fuels (2)
- Divert syngas-based products to fuels (3)

The most likely candidates for carbonaceous products from captured carbon would be methanol and Fischer-Tropsch (FT) liquids, which are the basis for FT-fuels. Both can be a basis to produce chemicals through e.g. cracking and a Methanol to Olefins process. Number (4) in Figure 24 indicates as an example how e-methanol, that mainly finds demand as a fuel, might be converted to chemicals through the MTO-process.

3.2.6 *Introducing e-fuels in local fossil value chains*
Introducing e-fuels into existing value chains will displace particular products in the areas of fuels, chemicals and electricity & heat. Table 15 below is a high-level

analysis of displaced products, their main resource today and other streams that may be considered for use as or conversion to those displaced products.

Introducing e-synthetic commodities can be expected to have most prominent effect on products derived from crude oil and from natural gas. In particular products from refineries (gasoline, kerosine, naphtha, diesel) and by-products from refining (fuel oil, refinery gas) would be displaced.

Table 15: Displacement of current products in areas of Fuels, Chemicals and Energy by ‘e-alternatives’, synergy value and side-streams that may be affected

IMPORT of fully RENEWABLE resource	Impacted VALUE CHAINS	PRODUCT DISPLACED BY IMPORTED RESOURCE	TODAY's MAIN RESOURCE for displaced product	POSSIBLE SIDE STREAMS as alternative resource
e-Ammonia	Fuels	**Fuel-oil for shipping**	Crude oil	-
	Chemicals	**SMR-ammonia**	Natural gas	Refinery gas Fuel-oil
	"Energy"	**Electricity + heat**	Refinery gas Natural gas	Fuel-oil
e-FT-liquids	Fuels	**Kerosine**	Crude oil	Fuel-oil
		Diesel	Crude oil	Fuel-oil
	Chemicals	**Naphtha**	Crude oil	Fuel-oil
	"Energy"	**-**	-	
e-Methanol	Fuels	**Gasoline**	Crude oil	Fuel-oil
	Chemicals	**SMR-methanol**	Natural gas	Refinery gas Fuel oil
	(Polyolefins)	**Naphtha**	Crude oil	
	"Energy"	**-**	-	
e-L-Hydrogen	Fuels	**Gasoline**	Crude oil	Refinery gas Fuel oil
		Diesel	Crude oil	Refinery gas Fuel oil
	Chemicals	**SMR-hydrogen**	Natural gas	Refinery gas Fuel oil
	"Energy"	**Electricity + heat**	Natural gas	Refinery gas Fuel oil

The Port of Rotterdam industrial cluster has no production of ammonia today that would be displaced by imports.

From Table 15 it may be derived that importing e-fuels next to the current ‘fossil’ resources may disrupt the existing value chains in several ways. E-fuels will therefore:

- Reduce options for refineries to optimize their operations transforming crude oil into a range of products with added value
- Displace natural gas for the production of heat and electricity

Import of e-fuels in general reduces opportunities for refineries to valorise side-streams, such as refinery gas and fuel oil: when shipping becomes less an outlet for fuel-oil, the refinery may incur higher cost to purchase lighter crude oils to reduce the share of the heavy fraction. Turning the fuel-oil into electricity instead comes with substantial CO_2 emission, which requires additional investments to avoid CO_2 emissions to air. Converting the fuel-oil to lighter products generates additional CO_2 from the added conversion operations. The import of FT-fuels in particular reduces the options for refineries to move components in crude oil between the different fuel fractions. The refinery gas fraction foresees in the major share of the internal energy requirements of the refinery itself and also it may be exported. Alternatively, the refinery gas could also be turned into electricity and exported to the grid, generating an income from the local power market. When e-fuels are available they may displace both fuel oil and refinery gas. Therefore, scheduling the refinery between available low-cost (heavy) crudes and high-value products becomes much more difficult while also generating CO_2 as a by-product comes with additional cost.

The non-carbon e-fuels (e-hydrogen and e-ammonia) may be a sensible alternative for producing heat and power. They would then displace mainly natural gas and perhaps also refinery gas, and in the future also compete with energy generated and stored locally. For both these e-fuels the emissions of NxOy that form during combustion need to be controlled.

Waste heat from industry would decline when operations are reduced or the energy efficiency is increased.

3.2.7 Refineries in the transition

As e-fuels and electricity replace fossil fuels, the ratio between the product fractions of a refinery changes over time. At the same time, when the world is moving away from fossil resources, the volume of crude oil processed as a whole will decrease.

Refiners can influence the ratio of the products through the types of crudes that they buy, the process conditions and the choice of catalysts. Although not all refineries have the exact same capabilities to adjust their product slate, the markets will adjust and find a new price-equilibrium.

As e-fuels and electricity displace fuels from fossil-carbon resources and circular carbon does the same for chemicals, this will in the long run (2030-2050) substantially reduce the required crude oil fractionation capacity of the Rotterdam cluster. While the demand for kerosine is expected to remain the same or possibly rise, the throughput of unit operations related to the first processing steps of oil refining, i.e. the physical fractionation of the crude oil, will structurally diminish and see a shift in the ratio of the different products. At the same time some of the unit operations further downstream may be of use to integrate circular-carbon. In such a scenario the main changes to a refinery's setup would be:

- Unit operations that would phase down due to a shift away from crude oil are e.g. the crude distiller, vacuum distiller and visbreaker.
- Unit operations that might be of good future use to integrate with circular-carbon could e.g. be the gasifier, catalytic reformer, hydrocracker and hydrotreater.
- New assets in a cluster could e.g. be water-electrolysers for local hydrogen and oxygen production and plants for conversion of circular-carbon raw

materials to olefins and aromatics such as for example Methanol to Olefins (MtO) and Methanol to Aromatics (MtA).

The scale of operation at conversion refineries is very large compared to chemical sites. Therefore these refinery-assets today are by their scale well-positioned to be re-purposed into large centralized and cost-efficient facilities for the production of intermediates from recycled materials and bio-derived oil fractions.

3.2.8 *Rotterdam in future supply chains of fuels and chemicals*

In the Port of Rotterdam today the value chains of fuels add value through storage, distribution and the refining of crude oil. Imported e-fuels on the other hand need no refining, they are essentially ready for use and therefore they will add value mainly through storage and distribution.

The value chains of chemicals are built on the cracking of the naphtha fraction from crude oil. Mainstream chemicals production will remain largely ‘cracker’ platform based, and new local or regional value chains are developing towards the production of suitable feed from circular-carbon resources for crackers. Besides cracking, specific circular methanol and ethanol based production of olefins and fuels might be developed depending on the development of the ETS prices and regulatory incentives such as the EU Fit for 55 program.

3.2.9 *Competitive chemicals production in Rotterdam*

‘Circular’ cracker feed can be resourced independent of the current crude oil infrastructure. Hence new logistics and value chains will develop also (and maybe especially) further inland to deliver circular cracker-feed to the crackers now served by the Rotterdam fuels cluster.

Crackers located inland may be well positioned to develop value chains based on (regional) circular-carbon resources towards themselves. Also more complex refineries inland may take the opportunity to produce cracker-feed form circular-carbon resources. Therefore, Rotterdam should ensure that there is:
- Access to large quantities of ‘premium’, competitively priced circular carbon resources at the port
- Access to sufficient low-carbon energy to drive pyrolysis and gasification of circular-carbon resources
- Synergy through carbon- and energy- efficiency for the conversions from circular-carbon resources to circular cracker feed and integration with remaining fuels production

Access to ‘premium’ circular-carbon resources
As a direct consequence of the phasing out of fossil carbon, circular carbon resources will eventually be in high demand. The logistics and value chains for end-of-life materials to their next (circular) destination are still less clear. Since resources for circular carbon are critical for the cluster, it is of strategic importance for HIC Rotterdam to facilitate or even secure access for its industries that produce cracker feed. Compared to inland locations the Port of Rotterdam already has a unique position as a bulk hub for intercontinental biomass and waste logistics that it might further exploit. Direction is required for the development of logistics and value chains towards Rotterdam for transport and conversion of the different streams because this would be too important to leave it to chance.

The production of 'e-synthetic' carbon-based chemicals from captured CO_2, such as e-methanol, may take place in areas remote from Rotterdam. The port could benefit as major import hub for this type of circular-carbon resources.

Access to low-carbon energy
The conversions of circular resources to cracker-feed are energy intensive processes operated that must be operated continuously. Therefore intermittent renewable electricity would not be convenient for these assets to run on and low-carbon fuel may be complement or even be preferred over electricity. Alternatively, low emission nuclear power might provide a solution, however this is subject to political decision making.

Synergy through carbon- and energy- efficiency
Assuming that circular-carbon resources will be scarce and that CO_2 emissions are priced, there may be a case for improving the overall carbon efficiency of production. Instead of burning by-products as a last resort, it may be more desirable to chemically transform these by-products into other products. Transformation of these by-products from several co-located industries in a centralized facility may be more efficient than each site for itself.

Electrolysis produces not only hydrogen but also significant quantities of oxygen. Although full combustion as a rule is not desirable because it reduces the carbon efficiency, it may be used for partial oxidation of high-carbon residues to produce syngas. 'Syngas' is a versatile basis for many basic chemical products. Pure oxygen also presents an opportunity for full combustion to CO_2, as it allows the oxy-combustion route to carbon capture, where air-separation for the oxygen is a major share of the cost. This CO_2 can then be geologically stored. Last but not least pure oxygen can be used to improve aerobic fermentation processes that might develop as alternative production routes for fuels, chemicals, feed and food (e.g. alternative proteins).

Electricity grids with high renewables will have much fluctuation and this requires a buffer to steady the supply. Perhaps such stabilization is best not left to each individual site, and it could be set up as a shared utility-service.

3.2.10 Conclusions

- The same way that e-fuels displace fossil fuels, circular-carbon resources will displace naphtha.
- Key 'cracker' platform chemicals will probably remain the basis for many chemical products.
- Refineries with more complex chemical conversion capabilities in addition to crude oil fractionation are likely to be re-purposed to convert bio-derived and waste-derived streams to alternative cracker-feed.
- The logistics and value-chains need to be developed towards the Rotterdam cluster to ensure that resources are available that allow industry to add most value.
- Sharing facilities for energy- and carbon- efficiency as well as stabilization of the electricity supply may contribute to the competitiveness of an industrial cluster.

4 Basic strategy for 2030-2050

Based on the insights from the previous chapters, a basic strategy has been developed for a transition to e-fuels and green hydrogen for HIC Rotterdam. This basic strategy provides insight into trade-offs and associated choices that Rotterdam has to make: should the port focus on its own production, on import, or a combination of both. Another important choice is about a focus on electricity, hydrogen/LOHC and/or e-fuels. Once the basic strategy has been determined, we will outline the transition path / roadmap towards it, including its components: production of e-fuels, required infrastructure (distribution, storage, refuelling infrastructure) and application of e-fuels. Finally, we will indicate possible production locations for hydrogen, CO_2, syngas, platform molecules and e-fuels, both for production in the Netherlands and for import.

4.1 Strategic goals

A strategy starts with formulating goals. These goals should be long-term, “big picture” objectives, rather than a short-term tactic addressing current problems or challenges. The purpose of strategic planning is to set overall goals and to develop a plan to achieve them.

The two main goals formulated as a starting point for this project, and as such for the basic strategy, are:

1. Reduction of CO_2 emissions in heavy-duty transport (long-haul truck transport, shipping and aviation, to be CO_2 neutral in 2050), by application of e-fuels and green hydrogen, in order to achieve the Paris climate targets.
2. Maintain or strengthen the economic and logistic position of the Rotterdam port area and of value chain partners, to contribute to societal welfare by creating new value chains and as such maintaining employment.

With these elements in mind, three pillars for the strategy have been defined (see Figure 25):

1. Local production and import: which energy carriers will be imported, and which will be produced locally in the prot area?
2. Positioning and role of the Rotterdam area
3. Transition

Figure 25: The three pillars of the strategy

4.2 Local production and import

The first pillar concerns local production and import and deals with the question if, and which, fuels should be produced locally or imported.

Import of e-fuels from countries with low cost renewable electricity
Production of e-fuels in HIC Rotterdam will be significantly more expensive than import (see Chapter 2), which favours an import strategy for e-fuels. Fuels, and certainly liquids, are easy to transport and cheaper to produce elsewhere. Costs are however not the only important factor that affect market prices; in case of scarcity, willingness-to-pay will highly influence market prices. If market prices are high enough, a positive business case for e-fuels production in Rotterdam might come within reach. But there is another reason to import e-fuels: Electricity from renewable energy sources (RES) will not be sufficiently available to produce the amount of e-fuels and hydrogen that would be needed for heavy-duty, long haul road transport, shipping and aviation (TNO, 2020). Therefore *import of e-fuels* will be necessary[21].

However, to initiate the transition to e-fuels, HIC Rotterdam, as one of the first, should develop a *strategic e-fuel production capacity*, albeit on a limited scale. As such, HIC Rotterdam, and possibly also the rest of the EU, will not become a major producer, but can be the first in its class to innovate, develop technologies (that could later potentially be exported) and produce e-fuels. Besides that, a local strategic production capacity can reduce geopolitical dependence. For e-diesel and e-kerosene, local production from imported green methanol may be considered as an alternative to import.

Local production of H_2, as far as enough RES is available. Complement with import
The situation for hydrogen is different. Transport and storage of hydrogen are complex. Therefore it is necessary to convert hydrogen to LOHC or liquid if transported by ship. These conversions require a lot of energy and are costly. Therefore, hydrogen can best be produced locally as much as possible[22]. This conclusion might be different when there is a demand for specific LH_2 or LOHC (instead of H_2 in gaseous form). For such applications import is likely to become interesting. One could, for instance, tank liquid hydrogen directly into a ship (Alles over waterstof.nl, 2021).

When hydrogen scales up, important of hydrogen will probably become necessary. This is dependent on, among others, the capacity of off-shore wind that is going to be realized. The hydrogen vision of Port of Rotterdam (Havenbedrijf Rotterdam, 2020) states that in 2050 Rotterdam will be the hydrogen hub for North West Europe, through which 20 Mton (2400 PJ) hydrogen passes annually. To produce this amount, more than 100 GW electrolysis capacity is needed, and even double this amount in electricity production (Havenbedrijf Rotterdam, 2020). For 2030, the

[21] For waste-based and bio-based fuels this might be different as HIC Rotterdam could play a role importing waste/bio-pyrolysis oils or torrefied biomass or pelletized plastic waste for local processing into waste- or bio-based fuels. However, since the scope of this study is limited to e-fuels and green hydrogen, biofuels are not part of the strategy.
[22] This is of course dependent upon the availability of space and could be a limiting factor in this respect.

Port of Rotterdam foresees 2 GW electrolysis (0.5 to 2025), for which 4 GW wind would be needed. With these numbers, import of hydrogen will be necessary since this will not fit in the foreseen energy production from renewable sources.

To import hydrogen by ship, for example in the form of LOHC or LH_2, is one option. Pipeline imports of gaseous hydrogen from nearby countries, such as the UK, Scandinavia or Southern Europe, could also be a possibility[23]. However, import by pipeline is not part of this study.

For potential countries to import fuels from, we refer to Chapter 2. The costs of import are an important factor and rely strongly on the LCoE costs. There is a large uncertainty and variation per RES project.

4.3 Positioning and role of the Rotterdam area

The second pillar concerns the strategic *position and role of Rotterdam* during and after the transition to e-fuels, and deals with topics such as broadening the current role, dealing with large quantities of electricity, cooperation throughout the value chain and internationally and integration with the chemical cluster.

Broaden and shift current position in fossil fuels to a hub position for hydrogen and e-fuels
Transit of goods is of great economic significance, see Chapter 1. The current strong logistic position of the Port of Rotterdam as such is an enabler for being a fast mover in the transition to e-fuels, mainly for shipping and maritime. For road transport, electricity and hydrogen will most likely be the energy carriers to start with, but for long haul road and waterway transport and aviation e-fuels will also play a role.

If Rotterdam will not be a major producer of e-fuels, other competitive advantages need to be strengthened or developed. Examples of such competitive advantages are knowledge of and experience with the transit of (e-)fuels (i.e. import and transit of fuels and hydrogen to Germany and Belgium), existing customer contacts, already operating strong value chains, the reuse of infrastructure (including existing pipelines) and the presence of import terminals (although not specifically for e.g. ammonia). Rotterdam can benefit from these competitive advantages by broadening and shifting its current role as a hub for fossil fuels to a hub position for hydrogen and e-fuels, both for delivery to the transport sector, to industry and to the hinterland. Additional opportunities to broaden and strengthen the role of Rotterdam and retain their license-to-operate are the production of other goods than e-fuels, such as hydrogen and chemicals (e.g. methanol to olefins).

Landing of large quantities of electricity from offshore wind
The production of hydrogen and e-fuels requires large amounts of electricity. This is not only needed for more sustainable transport, but also for emission reduction in industry and other sectors. Besides for hydrogen, offshore wind is needed for e.g. direct electrification of the heat supply (power-2-heat), and also for meeting existing electricity demand, which both reduce more CO_2 emission per unit of energy than

[23] In case hydrogen import by pipeline turns out to be inexpensive enough, it might also become a game changer for production of e-fuels in Rotterdam: it may become economically attractive in that case, and electricity needed for production of e-fuels is significantly reduced when hydrogen is imported.

green hydrogen and e-fuels (see Figure 10). Landing as much offshore wind as possible in Rotterdam should therefore be an essential part of the strategy. Storage (of electricity and/or hydrogen) will be of crucial importance, since the demand side often has a continuous profile in contrast to the intermittent generation of energy through wind.

Cooperation throughout (existing and new) value chains
The production, transport, storage and use of hydrogen and e-fuels requires many different actors, from producers of electricity to users of fuels in logistics. With a shift to new fuel types, new international value chains will emerge, involving both existing and new stakeholders. Collaboration is crucial to the successful operation of these value chains. In Rotterdam, many actors are already working together in the existing value chains. Parts of these existing value chains can form the basis for setting up new (international) value chains. Based on its current position (logistically, economically and knowledge base), Rotterdam can play an initiating role for these new chains and lead the way globally.

Create interregional/international cooperation
In order to accommodate the transition towards lower CO_2 emissions in hard-to-abate transport sectors, the Rotterdam Region can benefit from cooperation with other regions. An example is the possibility of storing hydrogen in salt caverns in the Northern part of the Netherlands. In addition, there is scarcity of space in Rotterdam; potential future activities, such as DAC, require a lot of space and could also be located in other regions than Rotterdam.
Furthermore, in the light of the need to import energy carriers, good international trade relations are important, since geopolitical dependence on countries to import from may arise. This is an important element to take into account in the choice for countries to import from.

Integration with chemical cluster
There is good potential for integration of e-fuels with the chemical cluster. Here e-fuels are not only suitable for the production of heat and power but also as feedstock for products. Green hydrogen as fuel produces high-temperature heat while as feedstock it can be used to upgrade oxidized forms of carbon like CO_2 back to marketable products. Green ammonia can be used as fuel, and is also the basis for fertilizers and functional chemicals that are the basis for a myriad of products. Green methanol or Fischer-Tropsch liquids can be a source of circular carbon that can be converted to more complex carbon-based products that are today based on the naphtha fraction from oil refining. The exploitation of circular carbon is also important in the chemical industry: circular carbon from waste or biomass would likely displace naphtha in the same way that e-fuels displace fossil fuels. This provides opportunities for synergies to strengthen innovation, development and integration in both fuels and chemicals production. This could be in terms of re-use or development of new infrastructure, development of an innovation ecosystem, skilled workforce and co-siting.

4.4 Transition

The third pillar concerns the *transition* from fossil fuels to e-fuels. A transition means changes and changes imply choices. It is therefore that in this pillar choices around speed of change, types of fuel, investment in new infrastructure and reuse of existing assets, integration and consequences of choices made have been given a place.

Be a fast mover

Though it is not always necessary to be a *first* mover, which requires significant upfront investments and brings the risk of betting on the wrong horse, companies in the Rotterdam region do have the ambition to be a *fast* mover. Fast movers may avoid mistakes made by the first mover, they can reduce their own investment requirements as well as their risks, can identify areas of improvement left by the first mover, adopt new and more efficient processes and technologies, and scale up production to reduce costs. By being a fast mover HIC Rotterdam can speed up the transition to hydrogen and e-fuels in a robust manner.

Rotterdam region as a hotspot for investments in green hydrogen and e-fuels

Given the high willingness (of governments, e.g. the Green Deal, and from businesses) to invest in green hydrogen and e-fuels, the momentum should be used to attract investments to Rotterdam. This would be a stimulus for creating a future position in the production, use and transit of hydrogen. Even though in the long term, the lion's share of e-fuels will be imported, it is desirable to also build up (limited) strategic production capacity for e-fuels. This can stimulate the development of innovative production technology for e-fuels and hydrogen, that can be exported in a later stage. This development has already started with the various pilots for sustainable fuel production and the realization of electrolysis capacity.

Refineries: transition of modern refineries into integrated energy and chemical sites

As e-fuels and electricity displace fossil fuel products, circular-carbon resources will displace fossil resources for chemical products and fuels. This will in the long run (2030-2050) substantially reduce the required crude oil fractionation capacity of the Rotterdam cluster. The throughput of unit operations related to the first processing steps, physical fractionation of the crude oil, will therefore structurally diminish. Selected unit operations related to chemical conversion further downstream processing may be of good use to integrate circular-carbon resources from waste and bio-materials.

- Unit operations that would eventually phase down while shifting away from crude oil are e.g. the crude distiller, vacuum distiller and visbreaker.
- Unit operations that might be of good future use could e.g. be the gasifier, catalytic reformer, hydrocracker and hydrotreater.
- New assets in a cluster could e.g. be water-electrolysers for local hydrogen and oxygen production and plants for conversion of circular-carbon raw materials to olefins.

The scale of operation at complex refineries is very large compared to chemical sites. Therefore the chemical conversion-assets of these complex refineries today are by their scale well-positioned to be re-purposed into large centralized and cost-efficient facilities for the production of intermediates from bio-derived and recycled materials. For example, Shell already made plans in this direction (Reuters, 2020). Two of the five refineries in Rotterdam have extensive conversion capabilities that may eventually be re-purposed to produce cracker-feed from circular-carbon resources. Such integrated sites offer potential for synergy and optimization.

Efficiency in both energy use and carbon conversion to products will be key for the performance of these sites as a whole. Since resources for circular carbon, which must replace carbon from crude oil, are critical for the cluster, it is of strategic importance for the Port of Rotterdam to facilitate or even secure access for its industries by building on its role and position of global logistics hub.

Prepare for ammonia and methanol as a transport fuel for maritime
At the moment, ammonia and methanol seem to hold the best cards as renewable transport fuel for the maritime sector. Several consortia around the world are investing in production of ammonia for export, e.g. Air Products in NEOM, Kingdom of Saudi Arabia (1.2 million tons of green ammonia per year), AMCE Group in Oman (0.9 million tons of green ammonia per year), Trans hydrogen Alliance (up to 2.5 million tonnes green ammonia per year via the Port of Rotterdam) and many other initiatives. Also several big shipping companies like Maersk (Maersk, 2021) see ammonia as promising. A big advantage of ammonia is that it is not a carbon fuel. So there is no need to invest in expensive, energy- and space-intensive DAC installations; the needed nitrogen can be separated from free air. However, extra attention will have to be paid to safety, since ammonia is gaseous and toxic, and to the associated NO_x emissions, forming secondary aerosols, when ammonia is used in an internal combustion engine. Safety issues raise concerns to various actors throughout the value chain, including port authorities. Also regulation for the use of ammonia in maritime shipping has to develop.

Methanol, on the other hand, has the advantage that it is easier to handle, since it is a liquid. It also requires less modification on the ship itself. Furthermore, the possibility to use methanol as a platform molecule in chemistry, in addition to its direct application as a fuel (for e.g. shipping and long haul transport) and the possibility to make kerosene and diesel out of it, offers the potential to scale up faster. Many (pilot) projects for the production of sustainable methanol and also for the application of methanol as fuel for shipping are running worldwide. Interesting to know is that bunkering of methanol has already taken place in Rotterdam (Maritiem Nederland, 2021) (Petrochem, 2021).

Besides ammonia and methanol (and e-diesel produced from methanol), hydrogen (particularly for inland shipping) and other e-fuels, such as e-LNG could also play a role for shipping. Since maritime shipping is the largest consumer of fuels in Rotterdam, it is important to quickly get the transition in this modality off the ground. For this purpose it is important to set up (subsidized) pilots with ammonia and methanol for use in the maritime sector.

Spatial integration
Availability of space is an important topic in a transition towards a new energy cluster (TNO, 2021). New energy carriers potentially require more (storage) space than current carriers, since their energy density is much lower. Additionally, adjustment of current assets to make them suitable for new fuel types or building new infrastructure takes time, so companies face a period of time in which both old and new assets will co-exist and as such will require more space. Furthermore, space is required for the integration of off shore wind and for the production of H_2.

This means that choices will need to be made in terms of production versus import of energy carriers and/or fuels, given the availability of space or potential to free up space. Also the use of alternative locations (i.e. outside the port area) should be considered, such as using salt caverns in the north of the Netherlands for storage of hydrogen and potential (off shore) locations for DAC.

Reuse of existing infrastructure
The Rotterdam region has many existing assets that can be (re)used in the transition to e-fuels. Examples named by the project partners are (fuel) pipelines (both within the region, and to clusters outside the region, e.g. to Germany), existing refineries, bunker infrastructure, jetties, etc. Storage tanks will become available when fossil fuels are phased out. Furthermore, there is an LNG terminal in the Port of Rotterdam, which can be expanded with other cryogenic fuels through the development of additional infrastructure. Liquid hydrogen is particularly important in this respect. Additionally, connection to the planned national hydrogen backbone (Gasunie, 2021) is important, which could be very realistic if existing gas pipelines will be used for this backbone.

Flexibility
Because uncertainty is inherent in a transition, staying flexible is key, especially regarding the following subjects:

- which e-fuels: there is still a great deal of uncertainty as to which technologies will be used, particularly for shipping. But also for road transport: how big is the gap that cannot be filled with battery-electric vehicles and hydrogen vehicles; this depends e.g. on the presence of international corridors with hydrogen fuel stations. If a gap remains, it is not yet clear which e-fuels will fill it.
- geopolitical dependence: make sure not to be dependent on production in a single country, i.e. spread your risk. Value chains need to develop, so at this stage it is still unsure which countries are most attractive to import from. Therefore, a broader focus than just costs is important in the selection of supplying countries.
- speed of scaling up: it is still unknown how fast the transition will take place. Will countries meet the Paris targets on time, late or not at all? How soon will fossil fuels be phased out? At what pace will market demand for e-fuels develop? How big will the role for biofuels be? It is important to be able to flexibly respond if things change faster or slower than expected.

- **Summary of three strategy pillars**

The strategy resulting from the analysis and the contents of the three pillars described in this chapter is represented in Figure 26:

Local production and import	Positioning and role of the Rotterdam area	Transition
• Import of e-fuels from countries with low cost renewable electricity; develop limited strategic production capacity. • Local production of H2, as far as enough RES is available. Complement with import.	• Broaden and shift current position in fossil fuels to a hub position for hydrogen and e-fuels, both for delivery to the transport sector and to the hinterland • Landing of large quantities of electricity from offshore wind is of vital importance for the cluster • Cooperation throughout the (existing and new) value chains • Create interregional/international cooperation • High level of integration with chemical cluster	• Be a fast mover: learn from first movers, move fast to gain market share and scale up • Position Rotterdam as a hotspot for investments in green H_2 and e-fuels • Refineries: transition of modern refineries into integrated energy and chemical sites • Prepare for ammonia and methanol as a transport fuel for maritime • Prepare for spatial integration of new clusters • Reuse of existing infra • Flexibility, to be able to cope with different scenarios

Figure 26: Summary of strategy pillars

4.5 Roadmap towards execution of the strategy

Now the basic strategy has been determined, we will outline the transition path towards realization of the strategy. The roadmap shows how the strategy translates into actions over time and is made up of several layers: energy supply, local production, import chains (to Rotterdam), export chains (from Rotterdam to the hinterland), and application in heavy duty transport. For each of these layers, we make a distinction between actions needed in terms of R&D, infrastructure (distribution, storage, refuelling infrastructure), production, regulation, trade and application of e-fuels. Figure 27 shows the roadmap and its different layers. Each individual layer will be discussed in the next sections.

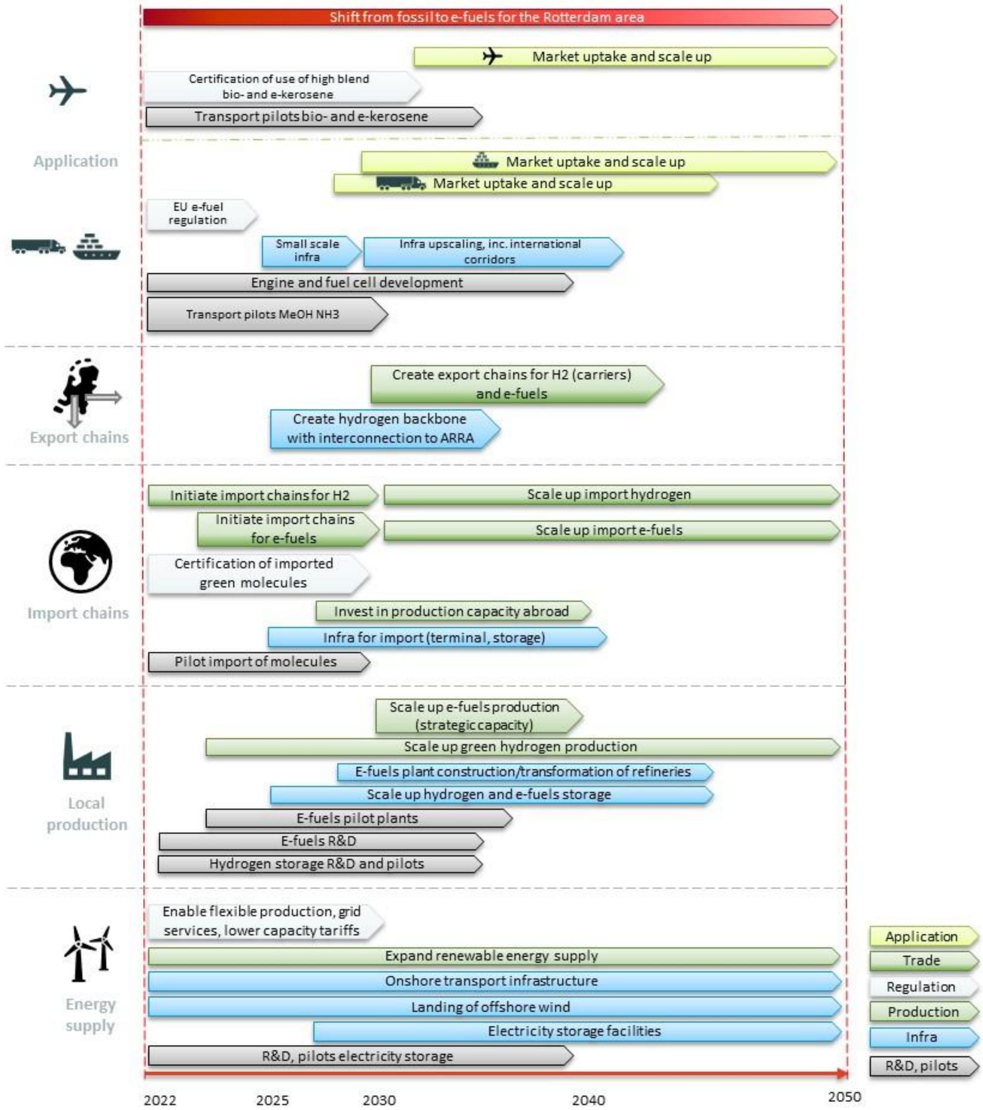


Figure 27: Roadmap for the transition to e-fuels in the Rotterdam region

4.5.1 *Renewable energy supply*

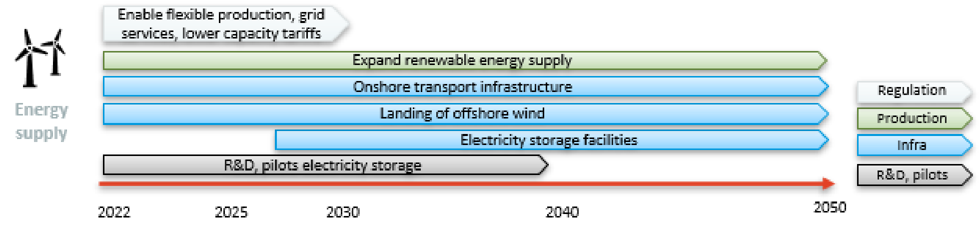


Figure 28: Roadmap: Energy supply

Renewable energy supply is the basis for the production of green hydrogen and e-fuels. Since massive amounts of electricity are needed, creating a large capacity of particularly offshore wind energy is essential[24]. This will initially mainly be used for hydrogen production, but in the longer term also for DAC, which requires a lot of energy. It is preferred to locate hydrogen production near the landing point of offshore wind to minimize the need for costly and space consuming onshore transport infrastructure for electricity.

The production of e-fuels is a high-CAPEX process that cannot be easily interrupted and needs a continuous flow of hydrogen. This means, that either the electricity supply has to be continuous (and thus cannot benefit from moments that the electricity price is low, and that, when using only RES, electricity has to be stored), or large amounts of hydrogen have to be stored. Therefore, electricity storage and/or hydrogen storage will become of vital importance in the supply process. The development of large scale electricity (and also hydrogen) storage requires further R&D and pilots.

4.5.2 *Local production*

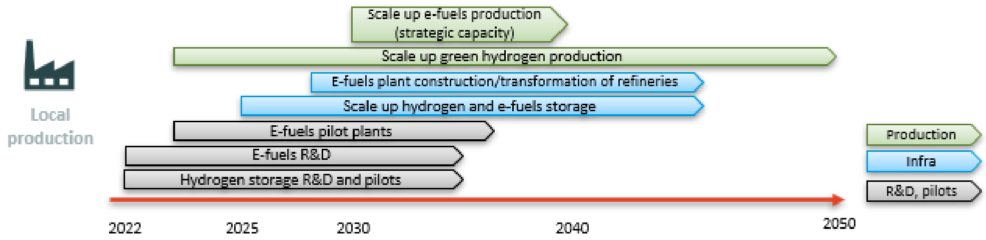


Figure 29: Roadmap: Local production

As explained in the first pillar of the strategy, it is important to ensure that the Rotterdam port develops e-fuel production facilities, albeit on a limited scale. It would be good to start with the production of hydrogen, followed by e-fuels. By doing so, Rotterdam will be the first in its class to innovate, develop technologies (that could later potentially be exported) and produce e-fuels. The EU Green deal could be supportive in this respect.

[24] Future quantities of hydrogen needed (and therefore how much RES is needed for production) are still uncertain, depending on the speed of the sustainability transition and the role of hydrogen in it. In the Hydrogen Vision report of the Port of Rotterdam the following quantities are mentioned:
2030: 2 GW hydrogen, so 4 GW off shore wind to be connected
2040: 18 to 24 GW off shore wind
2050: 100 GW hydrogen, of which a substantial part is transit

It is important to keep in mind that different feedstocks and products have a different time path (e.g. NH_3 will be later than bio-methanol or e-methanol based on fossil CO_2 from point sources, but earlier than MeOH with DAC). Currently, in terms of regulation, there are already opportunities for recycled carbon feedstock (see RED II) where Rotterdam has a location advantage[25] and could produce renewable fuels affordably at large scale. Later on the production facilities can be used for the production of e-fuels with carbon from DAC.

For the (large scale) production of hydrogen, pilots will be started (e.g. Nouryon/BP/HbR plans for 250 MW electrolyser (Nouryon, 2019) and Shell has plans for a 200 MW plant at Maasvlakte 2, starting in 2023 (Shell, 2020). Even though these amounts are already significant, it is still only a fraction of what is needed. For example, to serve the ~960 PJ of bunker fuels sold in the Netherlands for international transportation modes with MeOH in 2050, one would need a capacity of 68 GW PEM electrolysis (baseload production). It is logical to locate hydrogen production close to the landing place of offshore wind, which makes Maasvlakte 2 the preferred location for hydrogen production.

E-fuels production locations will be determined by the location of existing infrastructure in the Rotterdam region that can be reused. Also access to hydrogen supply via pipeline is necessary. This makes production at or near current petrochemical sites a rational choice. For e-fuels production, existing technologies (such as Fischer Tropsch for carbon fuels and Haber Bosch synthesis for ammonia) can be utilized, but R&D is needed to arrive at optimal production processes. In addition, research is needed into CO_2 utilization for carbon fuels. In the short term, captured CO_2 from the cluster could be used, although compared to the use of fossil fuels and storage of the captured CO_2 this does not yield a gain in terms of CO_2 emissions on a system level[26]. Use of biogenic CO_2 is also an option. In the long run however, it is expected that DAC will play a major role when large-scale use of carbon e-fuels will be undertaken. When road transport and shipping would use mainly hydrogen, e-ammonia and e-methanol, available biomass can be used to provide green kerosene. This is important since there are, at the short- to midterm, no green alternatives for kerosine foreseen for long haul aviation. Biomass will be imported, since biomass is hardly available in the Netherlands. Since DAC installations require a lot of space, they will probably not be located in the Rotterdam region (TNO, 2020).

In terms of storage, investments will have to be made primarily in the storage of hydrogen and possibly ammonia. For ammonia, LNG storage tanks could be reused when available. Large-scale storage of hydrogen still requires investment in R&D and pilots. Cooperation with the Northern Netherlands, where empty salt caverns

[25] Recycled carbon streams with high utilization potential, like CO, can be a transition step to manufacture synthetic fuels and then integrate them later with biogenic CO2, DAC sources when technologies for those become mature. In the near future, Rotterdam will be able to store CO_2 in the Porthos project (Port of Rotterdam, 2021).

[26] Compare the following two situations: 1. Capture fossil CO_2 from a point source and produce e-fuels from green hydrogen and the captured CO_2. The produced e-fuels are used in transportation, where the is CO_2 emitted. And 2. Capture fossil CO_2 from a point source and store the CO_2 in an empty gas field. Produce fuels from fossil oil. The produced fossil fuels are used in transportation, where the a same amount of CO_2 emitted as under 1. It can be concluded that the total amount of CO_2 emitted on a system level in situation 1 and 2 is comparable.

seem to offer a good option for hydrogen storage, is important here (PV Magazine, 2021). After a while, in the scaling-up phase, but also dependent on price levels, e-fuels should also be imported, given the limited production capacity in the port area. This would probably be from outside the EU, since the EU will not be the mass producer for the rest of the world. It is therefore important to start building relationships with other clusters and countries around the world.

4.5.3 *Import chains (import of e-fuels from abroad to Rotterdam)*

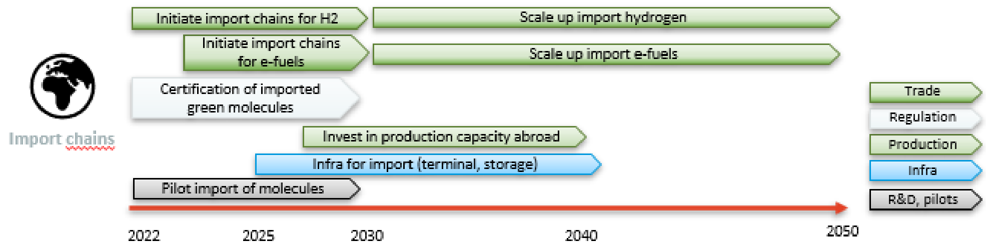


Figure 30: Roadmap: Import chains

For e-fuels import is the most viable option, besides a strategic local production capacity as described above. To have import chains up and running by 2030, they must be initiated by now. Dependent on the pace of the transition, the use of e-fuels is expected to take off from 2030.

Also for hydrogen, import chains should be initiated now (as is already happening with several countries, e.g. Iceland (Port of Rotterdam, 2021)). Imports of e-fuels and hydrogen will be needed for transit to the hinterland, and import of e-fuels (and possibly hydrogen) is also needed for local use.

For imports of both e-fuels and hydrogen, it is important to start pilots in a timely manner (as is already happening between Australia and Japan (S&P Global, 2020)). Certification of green molecule imports must also be arranged, so that regulations and incentives also apply to imported green molecules.

Companies like Shell and BP can also invest in foreign production capacity for e-fuels themselves, as is now the case for fossil fuels. In doing so, they can collaborate with local companies. They can then import the e-fuels produced.

Finally, it is important to make the infrastructure, such as terminals and storage capacity, suitable for the molecules that will be imported. This is already in place for e-diesel and e-LNG, for example, but investments are needed for ammonia, LOHC and hydrogen. Storage tanks for fossil fuels that become obsolete can be reused.

4.5.4 *Export chains (export from Rotterdam to the hinterland)*

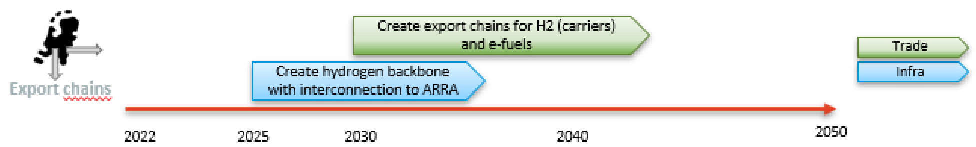


Figure 31: Roadmap: Export chains

For export to Germany, and possibly Belgium, a connection to the planned hydrogen backbone (Gasunie, 2021) is essential. For transit of e-fuels use can be made of ships, and for larger quantities existing pipelines can be used. Both ships and pipelines can also be used for the transport of LOHC to the hinterland.

For transit of hydrogen and e-fuels, import is a precondition. Since The Netherlands does not have enough RES to meet its own needs for hydrogen, import is necessary and could, as such, form a basis for transit. Both storage and transhipment, namely, need the same infrastructure (terminal, storage).

4.5.5 Application

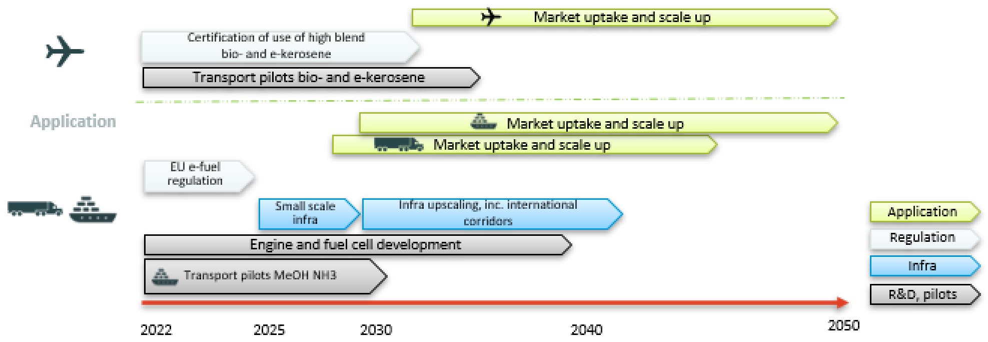


Figure 32: Roadmap: Application

<u>Trucks & ships</u>
For road transport, the use of hydrogen is expected to be the main option where battery electric vehicles do not suffice. Where hydrogen does not suffice either, due to long distances and/or a lack of refuelling infrastructure, e-fuels such as e-methanol and e-diesel can play a role.

For shipping, hydrogen can play a role particularly in inland navigation and for ferries, for example. In maritime shipping, methanol and ammonia are expected to play a major role. It is therefore important to set up pilots for the use of ammonia and methanol in the maritime sector (methanol is already used on a very limited scale) and cooperate with transport companies to match demand and production of e-fuels in the early adopter phase. In addition, other e-fuels such as e-diesel and e-LNG can be used. Although there is still much uncertainty about which e-fuels will eventually win, it is necessary to take steps now to achieve the sustainability targets for 2050.

Regulation and policy are important instruments to make it possible to use e-fuels, for example by means of financial incentives and/or obligations. In addition, it is necessary to regulate safety protocols, safety requirements and permitting for the application of ammonia (in the maritime sector).

Tank and bunkering infrastructure must be created for hydrogen and (new) fuels such as ammonia and methanol, initially on a small scale and expected to be scaled up from 2030 onwards. Because both ammonia and methanol are already commodities in the chemical and fertilizer markets, existing knowledge can be used to develop bunkering infrastructure. Particularly for the application of hydrogen (especially for trucks and inland shipping), it is important that international corridors with refuelling or bunkering stations are created, so that refuelling can take place regularly on international routes. In the maritime sector, at the beginning of the transition, dual fuel engines will be used, which can make use of both diesel and methanol or ammonia, for example. For e-diesel and e-LNG, use can be made of existing bunker infrastructure.

However, for the use of new fuels, development of internal combustion engines and fuel cells is needed. For ammonia applications in particular, there is still work to be done here, although the first engines are already being developed. For ammonia and hydrogen, attention will also have to be paid to the storage tanks in the vehicles. Scaling up of e-methanol and e-ammonia in shipping is expected from 2030 onwards. Upscaling of bio-methanol in shipping will occur earlier. The uptake and scale-up of hydrogen, particularly in truck transport, is also expected before 2030.

<u>Aviation</u>
For long haul aviation, in general, only kerosene is seen as having a role as a fuel by 2050. At the moment, research is mainly being done on bio-kerosene. Meanwhile, attention for e-kerosene is growing. KLM has now operated its first flight partly using e-kerosene.

Certification is necessary for the use of new types of kerosene, such as the various types of bio-kerosene and e-kerosene. In addition, pilots with e-kerosene will be necessary on a larger scale. The market uptake of e-kerosene is not expected before 2030. Until then, mainly bio-kerosene will play a role.

5 Strategies for different scenarios

The starting point for the basic strategy is that the Paris targets will (have to) be met. At the same time, the reality of this moment is that the reduction of CO_2 emissions worldwide currently lags far behind the Paris target to limit global temperature increase to well below 2 degrees Celsius (see Figure 33). At European scale, the existing policy framework would not meet the target of 55% reduction by 2030 and the net zero target in 2050 either; only a 60% reduction would be met by 2050 (DNV, 2021). In the Fit-for-55 package additional policies are developed.

External factors such as decisions taken in other sectors, policies and innovations strongly influence the speed of the transition. This speed will have a great impact on the strategy to be followed for the period 2030-2050 and the preparation period until 2030. Given the fact that there are many more uncertainties in a transition to e-fuels, a scenario analysis was carried out.

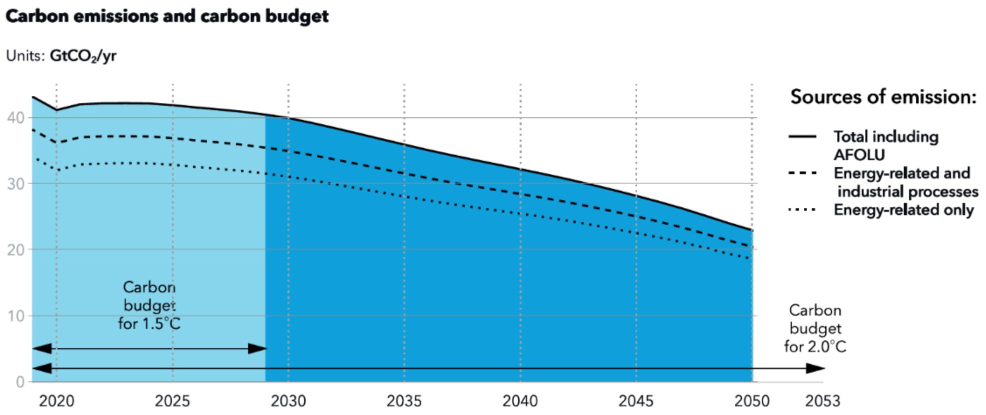


Figure 33: Global carbon emissions forecast. At the current decarbonization pace, the carbon budget for limiting climate effect to 1.5 degrees will be spent by 2030. AFOLU = Agriculture, Forestry and Other Land Use (DNV, 2021)

5.1 Scenario's

In light of these developments, the choice was made to define scenarios in which: 1) the speed of GHG emissions reduction, and 2) whether or not climate targets are met in the EU and at the global level are leading. The following scenarios underlie the analysis:

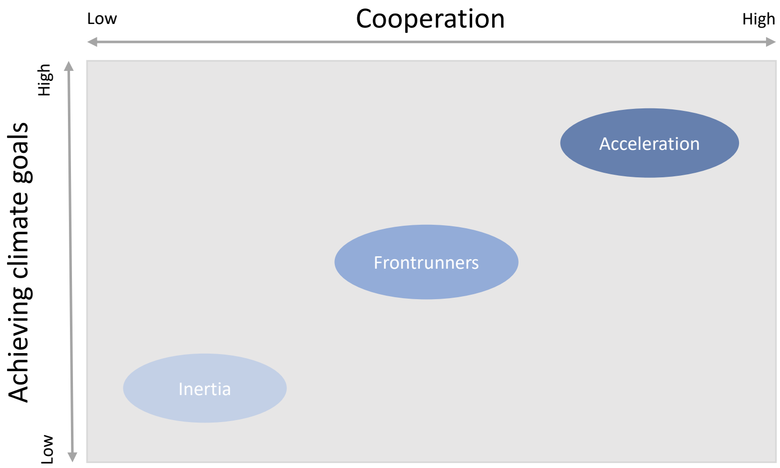


Figure 34: Scenario's

In the scenarios Acceleration and Frontrunners the EU will meet its climate targets (see Table 16). In scenario Acceleration, climate goals will even be realized at a global scale. In scenario Frontrunners, besides the EU, only some frontrunner countries, regions and cities will meet the targets. Based on current ambitions and status, examples could be the United Kingdom, Morocco[27], California[28] and Hong Kong[29]. In scenario Inertia climate goals will be met neither by the EU nor at global scale.

Table 16: Scenario description

	Acceleration	Frontrunners	Inertia
Description	EU and RoW (rest of the world) achieve climate goals	EU achieves climate goals, as well as some other countries, regions and cities; RoW does not	EU and RoW do not achieve climate goals
Characteristics	High drive towards sustainability; cooperation between countries and businesses	EU cooperates with countries and regions that strive for sustainability; other countries let economic/ fossil interests prevail	Everyone for himself, economic interests prevail over sustainability
Development of RES in Europe	quick	quick	slower, but still economic driver (dependent on CO_2 tax for fossil)
Development of RES abroad	quick	slower	slower, based on economic driver
Adoption of e-fuels in Europe	quick	quick	slower
Adoption of e-fuels RoW	quick	slower	slowest
Availability of biomass	shortage	higher availability for Europe	no shortage on short term

Typical characteristics of scenario Acceleration are a high drive towards sustainability, whereby development of RES and adoption of e-fuels both in Europe

[27] UK and Morocco are frontrunners according to Climate Action Tracker (Climate Action Tracker, 2021)
[28] California has set GHG emission reduction target for 2030 at 40% (Energy Innovation, 2021)
[29] Hong Kong scores high on climate leadership and action according to CDP (CDP, 2019)

and abroad goes quickly. This is mainly due to close cooperation between countries. In the Frontrunner scenario it is mainly the EU that strives for sustainability and cooperates with other countries with the same aim. It is therefore that development of RES and adoption of e-fuels goes quickly within the EU and slower outside the EU. The Inertia scenario is characterized by economic rather than sustainable interests. Cooperation between countries is limited and development of RES and adoption of e-fuels is very slow. In terms of biomass, there is no shortage on the short term, as opposed to scenario Acceleration and Frontrunner. In the latter scenario there is higher availability of biomass for Europe, because the transition in the rest of the world takes place at a slower pace, resulting in a slower uptake of biofuels there.

The scenarios are defined qualitatively. The analysis is not about the exact speed of decarbonization, but about the impact that an acceleration or deceleration has on the strategy to be followed.

5.2 Strategy pillar 'Local production and import' for each of the scenario's

In the Acceleration scenario, quick adoption of sustainable fuels takes place, which leads to a shortage of biomass/biofuels. Due to the quick development, local production is not sufficient, so a need for import of sustainable fuels arises. This causes the foreign production of e-fuels and hydrogen to develop and accelerates the development of international supply chains for e-fuels. For hydrogen, the option for import by pipeline and by LOHC/LH_2 should be explored.

In the Frontrunner scenario import chains for e-fuels will develop later since there is more biomass available for NW Europe, due to the lower need in the rest of the world. So initially there is a smaller role for e-fuels, since (less expensive) biofuels can cover the need for sustainable fuels for a longer period. It would be good to study options, pros and cons for a more significant role for biofuels, while, in the meantime, development of e-fuels should go on. Most likely, e-fuels will be produced in Europe for a longer period of time compared to the Acceleration scenario. Import of hydrogen from frontrunner countries (pipeline and LOHC/LH2) needs to be developed. Import chains with the rest of the world develop slower.

The same holds for the Inertia scenario, where the introduction of e-fuels will be postponed and study should be made of options, pros and cons for a more significant role for biofuels. The adoption of hydrogen will and should go on, although maybe at a slower pace, and based more on blue hydrogen. The market demand for green hydrogen will be highly influenced by CO_2 price applicable to fossil based hydrogen and energy costs. Nevertheless, an economic driver for RES for local hydrogen production still exists. Local hydrogen production could meet demand completely. Nevertheless, in the Inertia scenario a mix of green and blue hydrogen can offer flexibility, since ATRs (Autothermal Reforming units for hydrogen production from natural gas) are flexible to a certain level. This can lower costs of hydrogen significantly, since storage of electricity and/or hydrogen can be (partly) avoided. A precondition is that production of green hydrogen should take place when energy costs are low and production of blue hydrogen at moments that electricity costs are high.

5.3 Strategy pillar ‘Positioning and role of Rotterdam area’ for each of the scenario’s

❖ *Broaden and shift current position in fossil fuels to a hub position for hydrogen and e-fuels, both for delivery to the transport sector and to the hinterland*

Fast development of hydrogen and e-fuel demand in the Netherlands and hinterland will take place in the Acceleration scenario. The creation of a hub position for hydrogen and e-fuels will need to be developed at an accelerated pace. Compared to the Acceleration scenario, there will be a bigger role for biofuels in the Frontrunner scenario and the hub will initially focus on throughput from frontrunner countries to the hinterland. In the Inertia scenario, the transition to a hub for sustainable hydrogen and e-fuels will develop later.

❖ *Landing of large quantities of electricity from offshore wind is of vital importance for the cluster*

Due to the speed of development, the Acceleration scenario should give high priority to landing of offshore wind and even prepare for earlier landing of a large capacity of offshore wind. In the Frontrunner scenario, import chains develop slower, so offshore wind is very important to fulfil local hydrogen demand. Also here, landing of offshore wind should get high priority. The same holds for the Inertia scenario, where offshore wind is important for local hydrogen production, although the speed of development of offshore wind capacity is slower.

❖ *Create interregional/international cooperation throughout the (existing and new) value chains*

In the Acceleration scenario, the need for large scale hydrogen storage and import will develop earlier compared to the base case. This means that value chains should also be set up at a faster pace as well as interregional and international cooperation needed for the import of hydrogen and building of value chains.

Rather than to cooperate with any other region or country to build import value chains, in the Frontrunner scenario it seems logical that the focus will initially be on frontrunner countries (though not exclusively). Frontrunner countries will probably invest more (and earlier) in energy and fuel production from renewable energy sources than countries that lag behind in the transition.

Instead of focusing on hydrogen import, focus will be on value chains for biomass/biofuels import in the Inertia scenario. The need for large scale hydrogen storage and import of e-fuels will only develop later.

❖ *High level of integration with chemical cluster*

When looking at the chemical cluster, development of e-chemistry will develop at a faster pace in the Acceleration scenario compared to the base case. Both the fuel and chemistry cluster will benefit from this. In the Frontrunner scenario, there is more focus on biochemistry, both in the fuel and in the chemistry cluster. Lastly, in the Inertia scenario, the initial focus will be more on blue hydrogen and on biochemistry, both in the fuel and in the chemistry cluster.

5.4 Strategy pillar ‘Transition’ for each of the scenario’s

- *Be a fast mover: learn from first movers, move fast to gain market share and scale up*

Following a fast mover strategy fits into all three scenario’s, whereas in the Inertia scenario it might in some cases be good to be a first mover in order to accelerate innovation.

- *Position Rotterdam as a hotspot for investments in green H_2 and e-fuels*

Positioning Rotterdam as a hotspot for investments in green H_2 and e-fuels fits in all three scenario’s although there are some differences between them. In the Acceleration scenario, building up a position in innovative technology will payoff soon, as worldwide demand will grow fast. In the Frontrunner scenario, advantage of the frontrunner position should be taken in order to export knowledge and innovative technologies. In the Inertia scenario, investment levels will probably be lower, as well as market size and there will be more focus on biofuels.

- *Refineries: transition of modern refineries into integrated energy and chemical sites*

The transition of modern refineries into integrated energy and chemical sites will be accelerated in the Acceleration scenario. This is necessary since the demand for hydrogen and e-fuel and sustainable chemicals in the Netherlands and hinterland will develop fast.

In the Frontrunner scenario, fossil refineries may stay in operation longer to meet foreign market demand for fossil fuels. Whether and until when EU refineries are allowed to produce and export fossil fuels is in the first place a political decision. Meanwhile transition of modern refineries into integrated energy and chemical sites should go on. The same holds for the Inertia scenario, although the transition will take place at a slower pace.

- *Prepare for ammonia and methanol as a transport fuel for maritime*

The adoption of ammonia and methanol as a transport fuel for maritime will be fastest in the Acceleration scenario. Especially methanol provides a good opportunity since it has a higher TRL level. The development of technology for ammonia fuel cells and safety protocols, on the other hand, should be accelerated.

In the Frontrunner scenario, it will be more difficult to accelerate the transition to e-fuels, since maritime logistic chains are often at a global scale and the RoW lags behind in meeting the climate goals. However, this provides a chance for Europe to set the scene in, for example, ammonia fuel cell development.

In the Inertia scenario, there will be a larger role for biofuels, since the transition to sustainable fuels in maritime will take place at a slower pace.

- *Prepare for spatial integration of new clusters*

Availability of space is an important topic in a transition towards a new energy cluster. New energy carriers potentially require more (storage) space than current carriers, since their energy efficiency is much lower. Additionally, adjustment of current assets to make them suitable for new fuel types or building new infrastructure takes time, so companies face a period of time in which both old and new assets will co-exist and as such will require more space.

Given the high speed of the transition in the Acceleration scenario, the adjustment of current assets to make them suitable for new fuel types or the construction of new infrastructure will start off quickly. New clusters will develop in an integrated manner with current clusters, given the fact that the high speed of the transition allows for a coherent process.

In both Frontrunner and Inertia scenario's, fossil fuel demand remains for a longer period of time as far as the global value chain is concerned, which makes spatial integration more complicated since both new and existing assets will continue to coexist.

❖ *Reuse of existing infra*

The reuse of existing infra is important in each scenario. It is mainly the timing that differs. The Acceleration scenario requires additional capacity and new types of bunker infra (e.g. for NH_3) earlier, due to faster development of hydrogen and e-fuel and sustainable chemicals demand in NL and hinterland. The Inertia scenario will face the need for additional capacity for sustainable fuels later than the other scenario's.

Nevertheless, the reuse of existing infra and the need for new infra differs between various types of infra. For hydrogen pipelines, for example, the need is the same for all scenarios, but the timing differs; H_2 will over time be a mix of grey/blue/green hydrogen and a national H_2 backbone will be needed earlier in the Acceleration scenario compared to a baseline scenario and even later in the Inertia scenario.

For storage tanks, additional capacity and new types of infra (eg for NH_3) will be needed earlier, whereas the continuing mix in demand for both sustainable fuels (for EU) and fossil fuels (RoW) in the Frontrunner scenario may make it necessary to have parallel storage infra.

❖ *Flexibility, to be able to cope with different scenarios*

Flexibility is needed in all three scenario's given the fact that it concerns a transition. There are three main topics related to flexibility in which the scenario's each have their own specific developments: which e-fuels, geopolitical dependence and speed of scaling up.

The question about which e-fuels will be adopted first will crystalize sooner in the Acceleration scenario. Since methanol has higher TRL, it may be adopted quickly in maritime shipping, opposed to NH_3. When the EU will be frontrunner, it will be better able to direct which fuels will win and force the use of sustainable fuels in Europe. Despite that, the maritime sector will face a slower transition and as such there will be a bigger role for dual fuel engines in maritime. In the Inertia scenario, uncertainty which e-fuels will win will remain for a longer period of time.

Avoiding geopolitical dependence is also important. In the Acceleration scenario, however, it is to be expected that countries worldwide are more cooperative (at least in the field of achieving climate goals). The same holds for the Frontrunner scenario, but mainly between frontrunner countries. More geopolitical tension to be expected in Inertia, where countries let their own (protectionism) and economic interests prevail over sustainability. So in this scenario, avoiding geopolitical dependence is most important.

In terms of speed of scaling up, Acceleration shows the highest speed, followed by Frontrunners which in turn is followed by Inertia. In all three scenario's flexibility in speed of scaling up is still necessary.

5.5 Conclusions from the scenario-analysis

The following conclusions can be drawn based on the scenario-analysis:

1. The elements of the strategy for the base case scenario are important in all scenarios, but with different accents and at a different pace.
   a. In the Acceleration scenario, the demand for e-fuels will develop at a higher pace, which makes an accelerated implementation of the elements in the strategy urgent. This reaches from the setup of value chains for import to the implementation of a hydrogen backbone. Both market uptake of relatively higher TRL technologies, like green hydrogen and e-methanol production, and the development of new technologies like ammonia fuel cells should be accelerated.
   b. In the Frontrunner scenario, biofuels will initially have a higher share in the sustainable fuel mix compared to the Acceleration scenario. It seems logical, but not necessarily required, to focus the development of value chains for import on cooperation with frontrunner countries. This scenario offers a great opportunity for Europe to also become a frontrunner in technology development related to e-fuels, and export these technologies to the rest of the world. Modern refineries may continue to produce fossil fuels longer, to meet the demand for fossil fuels outside Europe, if they are allowed to by governments. Making global logistic value chains, like for maritime shipping and aviation, more sustainable, will be more complicated in this scenario. The coexistence of both fossil and sustainable production capacity and related infrastructure will complicate spatial integration.
   c. In the Inertia scenario, the transition to sustainable fuels will be a slow process. For a longer period, the availability of biomass for sustainable fuels will meet demand, resulting in a slower development and uptake of e-fuel related developments regarding technology development, implementation of production capacity and related infrastructure and the development of value chains for import. It is expected that the adoption of sustainable hydrogen will go on, but with a bigger role for blue hydrogen. The mix of blue and green hydrogen will offer more possibilities for flexibility. Local production of hydrogen will meet demand for a longer period, so import of hydrogen at large scale will be postponed.
2. Flexibility is key in all scenarios. In the Acceleration scenario, flexibility is especially needed to scale up at a high pace, whereas in the Inertia scenario, uncertainty regarding which e-fuels will win will remain longer. Avoiding geopolitical dependence will be even more important in this scenario, since countries will tend to let their own economic interests prevail over global sustainability goals.

6 Key take-aways

Now all building blocks have been discussed and the questions around the impact of the transition to e-fuels on the Port of Rotterdam have been answered, in conclusion the following main lessons are to be learned for the different elements of the analysis:

Basic strategy
Rotterdam is well positioned to play a significant role in the transition to e-fuels. Hydrogen will be one of the main feedstocks in this transition. From a strategic and economic point of view, hydrogen will be produced locally as much as possible. For e-fuels, the creation of limited strategic production capacity is important, but in the long run the lion's share of e-fuels, other than hydrogen, will be imported. There are two main reasons for importing a large share of the e-fuels needed. First of all, the Netherlands itself does not have enough energy available from renewable sources. In addition, the production of e-fuels in the Netherlands is considerably more expensive than importing them from abroad. Geopolitical independence is a point of attention in the choice of countries from which to import.

With the transition to e-fuels, the port of Rotterdam will be able to retain its hub function for energy streams. However, unlike now, this will be less from its role as a fuel producer, but mainly as a transit port for hydrogen and e-fuels to the hinterland.

For implementing the strategy, the availability of sustainable electricity is seen as the greatest challenge[30]. Other challenges are spatial integration, market acceptance of more expensive e-fuels, creating the necessary flexibility in the energy system and setting up international value chains.

Roadmap
To actually get the transition to e-fuels off the ground, cooperation throughout the entire chain, and from regional to global level, is essential. An integrated approach, i.e. timing and implementation based on dialogue between the stakeholders of the various components, must be adopted, ensuring coherence between the components of the roadmap.

An example is storage capacity in the value chain: because fuel production needs a practically constant supply of hydrogen, the creation of large-scale storage facilities for electricity and hydrogen is crucial.

Scenario's
The elements of the strategy for the base case scenario are important in all scenarios, but with different accents and at a different pace. The share of e-fuels in the mix of renewable fuels will initially vary considerably per scenario.

Flexibility in the strategy is crucial. This applies equally to the choice of e-fuels, geopolitical (in)dependence and the speed of scaling up.

[30] Based on a poll among market representatives during a workshop organized in the context of the CHAIN project.

The speed of implementation of the transition towards e-fuels will impact the duration of need for coexistence of both fossil and sustainable production capacity and related infrastructure. The longer it takes, the more complicated spatial integration will be.

Concluding, it can be stated that the transition to e-fuels will face the Rotterdam port region with lots of challenges, but when all stakeholders unite forces they can pave the way towards a future in which transport has become sustainable and Rotterdam has good options to retain its position as global energy hub.

Challenges
The transition to e-fuels will face several challenges. A number of these challenges are discussed in this report, but the study also gives rise to new questions that need attention in follow up research. For the Rotterdam area, especially the following questions are relevant:

1. What will be the impact on Rotterdam as a bunker port?
   Currently, Rotterdam has a very strong position in bunker fuels, partly because of the very competitive price that Rotterdam can offer due to its position as fossil fuel cluster. When Rotterdam will import the lion's share of fuels, this will change drastically. What will be a good strategy here?

2. How will feedstock streams for the petrochemical cluster change?
   As described in the report, circular carbon will be an important but scarce feedstock, not only for carbon e-fuels, but also for chemicals. What will be the impact on the Rotterdam cluster, when fossil production will be phased out? Is it a desirable option to reuse fossil carbon during the transition? How much carbon from biogenic and waste sources will be available? Will these developments result in a shift of chemical products produced in Rotterdam?

3. Transition in the hinterland
   Currently a large share of fuels produced in Rotterdam is transhipped to the hinterland. In the defined strategy Rotterdam will stay a logistics hub for delivery of (imported) fuels to the hinterland. How this position will develop in the future is, however, dependent on developments in the hinterland: what are their plans with respect to the transition to e-fuels and other sustainable fuels, especially in the ARRRA cluster? And what are the implications for Rotterdam?

4. What are potential game changers for the strategy?
   The designed strategy in this study is based on future developments that are nowadays expected. Besides that, robustness of the strategy was challenged in the scenario analysis with respect to the speed of the transition. However, game changers might arise in the future, that give reason to adjust the strategy. For example, when a revolutionary breakthrough in battery technology is achieved, the need for e-fuels will be different. And when hydrogen import by pipeline becomes available at a price that is low enough to produce e-fuels in Rotterdam at acceptable costs, import of e-fuels may become less necessary. It will be important to create a broad picture on potential game changers for all PESTLE (political, economic, social, technological, legal, environmental) factors.

7 References

Alles over waterstof.nl. (2021). *Refueling with hydrogen oil at a solar island on the Waal*. Retrieved from https://allesoverwaterstof.nl/waterstofolie-tanken-bij-een-zonne-eiland-aan-de-waal/

Boon, M. (2014). *Oil Pipelines, Politics and International Business - The Rotterdam Oil Port, Royal Dutch Shell and the German Hinterland, 1945-1975.* Rotterdam: Erasmus Universiteit.

Carbon Tracker. (2021). *The Sky's the Limit.*

CBS. (2020). *Goederenvervoer; vervoerwijzen, vervoerstromen van en naar Nederland.*

CBS. (2021). *Uitstoot en brandstofverbruik.*

CDP. (2019). *43 cities score an A grade in new cities climate change ranking*. Retrieved from https://www.cdp.net/en/articles/media/43-cities-score-an-a-grade-in-new-cities-climate-change-ranking

Clean Energy Wire. (2020). *Germany's dependence on imported fossil fuels*. Retrieved from https://www.cleanenergywire.org/factsheets/germanys-dependence-imported-fossil-fuels

Climate Action Tracker. (2021). *Global Update: Climate target updates slow as science demands action* | *Climate Action Tracker*. Retrieved from https://climateactiontracker.org/publications/global-update-september-2021/

Detz, R., Hers, S., Schipper, C., & Westerga, R. (2021). *Ruimtelijke effecten van de energietransitie: casus Haven Rotterdam.* SmartPort - TNO.

DNV. (2021). *Energy Transition Outlook.*

Energy Innovation. (2021). *California Climate Policy - Energy Innovation: Policy and Technology*. Retrieved from https://energyinnovation.org/policy-programs/california-climate-policy/

Erasmus Universiteit. (2018). *Havenmonitor - De economische betekenis van Nederlandse zeehavens 2002-2017.* Erasmus Centre for Urban Port and Transport Economics. Rotterdam: Erasmus Universiteit.

Erasmus Universiteit. (2020). *Havenmonitor 2020.* Erasmus Centre for Urban, Port and Transport Economics. Rotterdam: Erasmus Universiteit.

Fuels Europe. (2019). *Statistical report 2019.*

Gasunie. (2021). Retrieved from Waterstofbackbone: https://www.gasunie.nl/projecten/waterstofbackbone

Havenbedrijf Rotterdam. (2020). *Haven van Rotterdam wordt internationale waterstofhub - Visie Havenbedrijf Rotterdam N.V.* Havenbedrijf Rotterdam.

https://www.cleanenergywire.org/factsheets/germanys-dependence-imported-fossil-fuels. (n.d.).

Hychain – energy carriers and hydrogen supply chain. (2019). Retrieved from https://ispt.eu/projects/hychain/

Independent Commodity Intelligence Services. (2020). *How petrochemicals are used today.*

International Energy Agency. (2021). *Net Zero by 2050 - A Roadmap for the Global Energy Sector.*

International Energy Agency. (2021). *World Energy Outlook.*

International Energy Agency-task41. (2020). *Advanced Bio-fuels - Potential for Cost Reduction: IEA Bioenergy Task 41 Report.*

JEC. (2018). *DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use* *of energy from renewable sources. https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii.* JEC.

Kuipers, B. (2018). *Het Rotterdam Effect - de impact van mainport Rotterdam op de Nederlandse economie.* Rotterdam.

Lazard. (2020). *Levelized Cost Of Energy, Levelized Cost Of Storage, and Levelized Cost Of Hydrogen 2020*. Retrieved from https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/.

Maersk. (2021). *Maersk backs plan to build Europe's largest green ammonia facility*. Retrieved from https://www.maersk.com/news/articles/2021/02/23/maersk-backs-plan-to-build-europe-largest-green-ammonia-facility

Maritiem Nederland. (2021). *Primeur Rotterdam barge to ship bunkering methanol*. Retrieved from https://www.maritiemnederland.com/nieuws/wereldprimeur-rotterdam-barge-to-ship-bunkering-methanol

Nieuwsblad Transport. (2020). *Overslag haven Rotterdam laat voorzichtig herstel zien.* Retrieved from https://www.nieuwsbladtransport.nl/havens/2020/10/21/overslag-haven-rotterdam-laat-voorzichtig-herstel-zien/

Nivard, M., & Kreijkes, M. (2017). *The European refining sector: a diversity of markets?* Clingendael International Energy Programme.

Nouryon. (2019). *BP, Nouryon en Havenbedrijf Rotterdam werken samen aan studie naar groene waterstof*. Retrieved from https://www.nouryon.com/nl-nl/nieuwsberichten/bp-nouryon-en-havenbedrijf-rotterdam-werken-samen-aan-studie-naar-groene-waterstof/

Nouryon. (2019). *BP, Nouryon en Havenbedrijf Rotterdam werken samen aan studie naar groene waterstof*. Retrieved from https://www.nouryon.com/nl-nl/nieuwsberichten/bp-nouryon-en-havenbedrijf-rotterdam-werken-samen-aan-studie-naar-groene-waterstof/

Petrochem. (2021). *Maersk geeft boost aan groene methanol*. Retrieved from https://petrochem.nl/maersk-geeft-boost-aan-groene-methanol/

Port of Amsterdam. (2021). *Direct vervoer van kerosine*. Retrieved from https://www.portofamsterdam.com/nl/business/ladingstromen/natte-bulk/kerosine

Port of Rotterdam. (2020). *Goederenoverslag in de haven van Rotterdam 2020.*

Port of Rotterdam. (2021). *Financiering voor CO2-opslag onder Noordzee is rond*. Retrieved from https://www.portofrotterdam.com/nl/nieuws-en-persberichten/financiering-voor-co2-opslag-onder-noordzee-is-rond

Port of Rotterdam. (2021). *Onderzoek: verschepen groene waterstof IJsland - Rotterdam is realistisch vóór 2030*. Retrieved from https://www.portofrotterdam.com/nl/nieuws-en-persberichten/onderzoek-verschepen-groene-waterstof-ijsland-rotterdam-is-realistisch-voor

Port of Rotterdam. (2021). *Study shows shipping green hydrogen from Iceland to Rotterdam to be realistic before 2030*. Retrieved from https://www.portofrotterdam.com/en/news-and-press-releases/study-shows-shipping-green-hydrogen-from-iceland-to-rotterdam-to-be

PV Magazine. (2021). *Dutch gas giant begins storing hydrogen in underground salt cavern*. Retrieved from https://www.pv-magazine.com/2021/09/21/dutch-gas-giant-begins-storing-hydrogen-in-underground-salt-cavern/

Reuters. (2020). *Shell sees its future with fewer, more integrated refineries yielding renewable fuels, hydrogen*. Retrieved from https://www.reutersevents.com/downstream/operations-maintenance/shell-sees-its-future-fewer-more-integrated-refineries-yielding-renewable

Reuters. (2020). *Shell sees its future with fewer, more integrated refineries yielding renewable fuels, hydrogen*. Retrieved from https://www.reutersevents.com/downstream/operations-maintenance/shell-sees-its-future-fewer-more-integrated-refineries-yielding-renewable

S&P Global. (2020). *Australia-Japan hydrogen project eyes full operations by next decade: conference*. Retrieved from https://www.spglobal.com/platts/en/market-insights/latest-news/coal/112020-australia-japan-hydrogen-project-eyes-full-operations-by-next-decade-conference

Saric, M., Detz, R., & van Kranenburg, K. (2021). *Evaluation of different routes for e-diesel anD E-kerosine supply in the port of rotterdam.* TNO.

Shell. (2020). *Wind als energiebron voor groene waterstoffabriek in Rotterdam*. Retrieved from https://www.shell.nl/media/nieuwsberichten/2020/wind-als-energiebron-voor-groene-waterstoffabriek-in-rotterdam.html

Takkellapati, S., Li, T., & Gonzalez, M. A. (2018). An Overview of Biorefinery Derived Platform Chemicals from a Cellulose and Hemicellulose Biorefinery.

TNO. (2020). *E-fuels: towards a more sustainable future for truck transport, shipping and aviation.*

TNO. (2020). *E-fuels: Towards a more sustainable future for truck transport, shipping and aviation.*

TNO. (2020). *Power-2-Fuel Cost Analysis.* SmartPort.

TNO. (2020). *Power-2-Fuel Space Requirements.* SmartPort.

TNO. (2021). *Ruimtelijke effecten van de energietransitie: casus haven Rotterdam.* SmartPort - TNO.

US EIA. (2019). *International Energy Outlook 2019 with projections to 2050.* U.S. Energy Information Administration.

van Kranenburg, K., & Schipper, C. (2021). *CHAIN report E-fuels.* TNO.

Voltachem. (2020). *Voltachem in Action; overview 2020.* Retrieved from Voltachem - Accelerating industrial electrification: https://www.voltachem.com/images/uploads/Boekje_Voltachem_in_action-10_low_res.pdf

Werkgroep Industriecluster Rotterdam-Moerdijk. (2018). *In drie stappen naar een duurzaam industriecluster - Rotterdam-Moerdijk in 2050.*

Wuppertal Institut. (2016). *Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam.*

Appendix A: Comprehensive SWOT overview

In this appendix, the full list of included strengths, weaknesses, opportunities and threats for the SWOT analysis of the Rotterdam region regarding the transition to e-fuels and the production and application of e-fuels is shown.

Name	Description
Strengths	
Large-scale fuel cluster	There is already a quite large fuel cluster (one of the largest in the world) which means a good starting position. Large scale. Lots of production.
High throughput / high demand	Good transit/high demand (for transport, but also for chemical cluster.)
Logistical pivot	Good logistics (to hinterland). Good throughput to Western Europe. Because of this pivotal role, the port can enforce business. Also multi-modality (rail, pipelines, water and road).
Knowledge network	Innovative capacity of HbR (compared to other ports on a global scale): high knowledge network. (Antwerp and Hamburg also have knowledge and budget for innovation).
Complete value chain present	Complete value chain present
Good cooperation	There is good cooperation between the companies present / organizational network. This is looked at with envy by the rest of the world. Companies know how to find each other.
Developed offshore industry	Offshore industry is developed (and nearby). (Broad scope: both traditional and offshore wind)
Investment money available	Quite a lot of development money is being put into the cluster (from the national growth fund)
Political pressure	Due to the large scale of the Rotterdam port area, the area has a certain centre of gravity in politics
Storage on a global scale	There is also enough storage/transhipment capacity in the Port of Rotterdam for new developments.

Weaknesses	
Legacy fossil fuel cluster	The fuel cluster is already well developed: isn't it a block to the economy? There is a driver to provide fuel oil as cheaply as possible. Dependence on low fuel prices: if it is a strength now, it can be a weakness in your transition. Economic dependency: much of the port's income (lease money and port fees) is related to the old fuel cluster. A large part of the turnover therefore comes from bunkering / transhipment of conventional fuels. To what extent can the cluster keep up with the new movement around e-fuels?
Scarce & expensive space	Space shortage: many new assets 'pushing' for the same space (possibly storage new fuels, new infra, H_2 production, DAC). Space is scarce and expensive.
Environmental space (milieuruimte) limited	Environmental space (milieuruimte) in Rotterdam is limited: building new business can become problematic (N_2 issues, environmental legislation, protected animals)
Competition for space with city of Rotterdam	Pressure from the city of Rotterdam: residential and commercial activities want more space. For example, in the Waalhaven there are still container companies / storage that need to be moved out of the city limits. Low-value activities are pushed further into the port.
Lack of underground storage	No possibility for large-scale underground (hydrogen) storage. No salt caverns nearby (although empty gas fields would be used for CO_2). Both technical and social/political resistance.
Global decisions	Many decisions are made outside the Netherlands: head offices are located abroad: decisions are not made locally. Investments

	are looked at globally. Not only local stakeholders need to be convinced, but also global players. 'Binding' to Rotterdam of large parties is not very big.
Political position NL	The Netherlands is not a political world player
Dutch energy transition too small scale	The amounts of fuel that are now being produced in Rotterdam cannot be made on the basis of sustainable (offshore wind) energy: we have too little (locally generated) sustainable electricity compared to other countries. This is probably not going to change. The question is whether The Netherlands can remain competitive. In The Netherlands, the energy transition is relatively small compared to other countries.

Opportunities	
A lot of investment (including at the knowledge level)	E.g. EU Green Deal: many investments. Percolating through among companies: willingness to invest
Sustainability high on political agenda	A lot of willingness (within the EU and beyond) to develop new solutions. Percolating through among companies: companies see commercial interest.
E-fuels are necessary / large latent demand for e-fuels by customers to meet targets	Biofuels and hydrogen are not enough to meet the Paris Agreement: e-fuels are needed. So they are coming anyway
Hub position Port of Rotterdam in combination with West-EU sales market	Western Europe, and thus Port of Rotterdam, is an interesting market for companies to sell sustainable fuels and hydrogen. For the hinterland, Port of Rotterdam is an interesting hub.
Position as 'fast mover'	Opportunity to gain position as fast mover
Need for technologies	In the global market, there is a great need for knowledge about (the production of) e-fuels
Supply of cheap electricity in the world increases	…whereby price of e-fuels may go down
Synergy with developments in chemistry	Developments in chemistry can partly run parallel: for the sustainability of chemistry, partly the same developments play a role: green methanol plays an important role as a sustainable platform molecule, green hydrogen is an important means for sustainability, and green ammonia is particularly important in the fertilizer industry. The processing of circular carbon is also important in chemistry. This provides opportunities to strengthen development in these areas: in terms of infrastructure, development of an innovation ecosystem, skilled workforce, co-siting, etc.

Threats	
Competition for sustainable electricity in The Netherlands	There is too little sustainable electricity available in The Netherlands
Market for e-fuels does not develop	There will be too few incentives to use / make e-fuels affordable
Competitive ability / commercial pressure	A port that only offers e-fuels cannot compete with ports that continue to offer conventional fuels. Many ports are built on 'making everything as cheap as possible'.
No unambiguous legislation	Legislation is not yet crystallized. And not enough incentive to make the transition
E-fuels are not the cheapest sustainability option	E.g. batteries and biomass are cheaper
Technology is lagging behind	E.g. DAC development lags behind, but is necessary to achieve enough CO_2 reduction

Too much diversity: chain development & investment lag behind	As long as it is not clear which e-fuel will be used for which application, chain development and investments will lag behind
Customers do not go along (or slowly)	Potential customers of e-fuels do not make the investment in other combustion engines and/or the replacement of these engines is too slow (replacement rate / lifetime)
E-fuel development goes (too) slow	...to be of importance for Paris Goals. There is a lot of willingness to invest now: if e-fuels develop too slowly, then 1) investments miss out, 2) there will be too little public support ('too slow' / little CO_2 savings)