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DECARBONISATION OPTIONS FOR THE INDUSTRY CLUSTER BOTLEK/PERNIS ROTTERDAM

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17 August 2022

Manufacturing Industry Decarbonisation Data Exchange Network

Colophon

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The Hague, 2022
PBL publication number: 4946
TNO project nr. 060.51840 / TNO 2022 P10726

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Acknowledgements

We would like to thank our contact persons from the main companies and DCMR (Dienst Centraal Milieubeheer Rijnmond) for their valuable information and feedback.

MIDDEN project coordination and responsibility

The MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) was initiated and is also coordinated and funded by PBL and TNO. The project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. Correspondence regarding the project may be addressed to: D. van Dam (PBL), Dick.vanDam@pbl.nl, or S. Gamboa (TNO), Silvana.Gamboa@tno.nl.

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Contents

Summary

In this report the decarbonisation strategies for an industrial cluster were analysed. The area investigated is Botlek/Pernis in the Port of Rotterdam. In total, over 40 companies were evaluated (both individually and together), including several terminals, two oil refineries, a waste incineration plant, combined heat and power generators, industrial gases producers, petrochemical companies and other chemical companies. The information about the sites was gathered from MIDDEN reports, open literature and several interviews.

The annual CO_2 emitted amounts to 13.9 million tonnes (Mt) for Botlek/Pernis. Final energy use includes 63 PJ of steam and 19 PJ of electricity. For fuel and feedstock, natural gas use is 31 PJ and residual gas use is 57 PJ. Hydrogen produced and used, mainly as feedstock, amounts to 55 PJ. For steam and combined heat and power generation, another 52 PJ of natural gas and 16 PJ of residual gases are used. Material streams and energy flows were collected for the respective companies and included in a database.

Apart from an electricity and natural gas infrastructure, the Botlek/Pernis area has several dedicated infrastructure systems. A steam pipeline supplies steam from AVR Rijnmond and Cabot to adjacent sites. The OCAP initiative by Linde Gas Benelux exports the CO_2 captured and delivered by Shell Pernis and Alco Energy Rotterdam to the greenhouse horticulture. The Rotterdam Multicore pipeline system transports gases and other chemicals from the Pernis area all the way to the Maasvlakte. Other steam infrastructure includes the Rozenburg area around Air Liquide and Air Products and the Shell and Esso refinery systems. Further connections between companies include exchanges of industrial gases and refinery gases. The chlorine cluster around Nobian serves Huntsman, Shin-Etsu Botlek, Hexion Pernis and Tronox with exchanges of chlorine, hydrogen chloride, sodium hydroxide and brine.

This report furthermore addresses the decarbonisation plans and options. For the partial decarbonisation towards 2030, a few cluster projects for Botlek/Pernis are of importance. One being Porthos, facilitating the transportation and storage of 2.5 Mt/yr of CO_2 under the North Sea. Furthermore, the H-vision project aims to collect the refinery gases and convert the gases centralized in an autothermal reformer (ATR) for pre-combustion carbon capture and storage (CCS), realizing a CO_2 emission reduction of 1.7 Mt/yr, which is to be transported and stored. Storage facilities are therefore crucial for the H-vision plans. Besides these cluster projects, the decarbonisation by electrification is another important pillar, demanding a reinforcement and extension of the current electricity network.

Based on several MIDDEN reports, interviews within the industry and consultation with experts, a 2030 scenario was constructed for the most plausible (i.e. expected based on current company intentions) decarbonisation plans. In this calculation, the total amount of CO_2 emissions that can potentially be avoided is around 5-6 Mt/yr, being for over 90% due to Porthos and H-vision contributions. Around one third to 50% of the residual gas would be directed to the ATR of H-vision, producing an additional 17-21 PJ/yr of hydrogen. The overall electricity demand is expected to increase with 16-18 PJ/yr, almost half of which is for CO_2 capture and gas transport, the other half mainly for e-boilers. In these calculations, the current status of the facilities in terms of energy and material demand remains constant for the period 2020-2030. There were no signals of changes to different industrial processes, with the exception of the construction of the Shell Pernis biofuel plant.

For 2050, a qualitative description was made of further decarbonisation possibilities in Botlek/Pernis. The production scale of the mineral oil refineries is expected to decrease over the upcoming years,

possibly shifting the current focus of the Rotterdam Port as one of the largest fuel producers worldwide. Meanwhile, electrolyser capacity used for green hydrogen production is expected to increase significantly, although the offshore electricity supply could be a limiting factor. The Port of Rotterdam expects to function as a hydrogen hub in the future, with large imports and transfers of hydrogen. The future of the combined heat and power systems present in Botlek/Pernis is uncertain. A large growth of demand for baseload or flexible CO_2-free electricity is expected.

Specifically for the cluster Botlek/Pernis, industries will benefit from the possibilities for CCS and hydrogen supply. There are also opportunities for a more optimized steam and waste heat system, but meaningful coordination is lacking. For deeper decarbonisation in the long run, a plan for sustainable carbon feedstocks and residuals is required, to reap cluster benefits.

1 Introduction

This report describes the current situation for Botlek/Pernis in Rotterdam in the Netherlands and the options and preconditions for its cluster decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

Scope

This report focuses on all main industries in the Botlek/Pernis area, and some connected sites in Europoort. Several companies present in that area were reviewed and material and energy streams were outlined. A full list of the companies included is presented in Appendix A (NEa, 2019). This study aims to map the current connections in Botlek/Pernis, dependencies between companies, short-term 2030 decarbonisation plans and the long term 2050 decarbonisation perspective. The majority of the production capacities and energy demands have not been confirmed by the respective companies and can therefore be considered estimates. The main options for decarbonisation are pre-combustion CCS, hydrogen use for heating and electrification of steam supply.

Reading guide

Chapter 2 introduces the Botlek/Pernis region and discusses the companies that are present. Chapter 3 describes the cluster characteristics and dependencies, and Chapter 4 describes the expected decarbonisation initiatives and projects in Botlek/Pernis. The last section of Chapter 4 includes a quantitative 2030 outlook and descriptive 2050 outlook. In Chapter 5 the most important observations are discussed.

2 Current situation in the Botlek/Pernis cluster

In order to obtain an accurate overview of the current situation present in Botlek the companies will be shortly described in this chapter. Location, important installations, main products and processes, feedstock streams, production capacity, energy demands and a short outlook of the possible decarbonisation options for the Scope 1 emissions are described. The Scope 1 emissions are considered to be the emission effects of the plant itself, whereas the Scope 2 emissions are the emission effects originating from purchased electricity, heat or steam. Scope 3 emissions are emissions originating from further up- and downstream. Scope 2 and Scope 3 emissions are out of the scope of this study.

2.1 Botlek/Pernis area

In this report the industrial cluster present in Botlek and Pernis Rotterdam will be analysed. The intertwining of companies is an important aspect of this report and therefore companies with important connections to Botlek and Pernis are included as well. Below in Figure 2.1 the area considered in this report is marked.

Figure 2.1
Botlek/Pernis area

Google Maps image of the area, Rotterdam. Botlek is on the left, Pernis on the right side of the dashed line (Google Maps, 2021)

Figure 2.2
Companies present in Botlek/Pernis, Rotterdam

Image adapted from Google Maps, 35 companies included in this report are visible on the map (Google Maps, 2021)[1]

2.1.1 Greenhouse gas emissions Botlek/Pernis

In the Netherlands, the annual greenhouse gas emissions (GHG) of CO_2 were reportedly 184 Mt in 2019, excluding those from land use (PBL, 2020). The greenhouse gas emissions per capita are relatively high in the Netherlands compared to the remaining countries in Europe, contributing 4.5% to the EU's total (CBS, 2019). A large share of these GHG emissions originate from the heavy industry present in Rotterdam and more specifically Botlek and Pernis. The NEa is the Dutch Emission Authority that is managing the EU ETS for the Dutch sector and all of the CO_2 emission data is obtained from their database (NEa, 2019). For Botlek and the companies present at Pernis, the total emitted CO_2 amounts to 13.9 Mt annually. The industry present in Botlek/Pernis is responsible for more than 25% of Dutch industrial emissions and 7.5% of the total Dutch emissions. In the figure below the companies are presented together with their share in the annual emissions of 2019.

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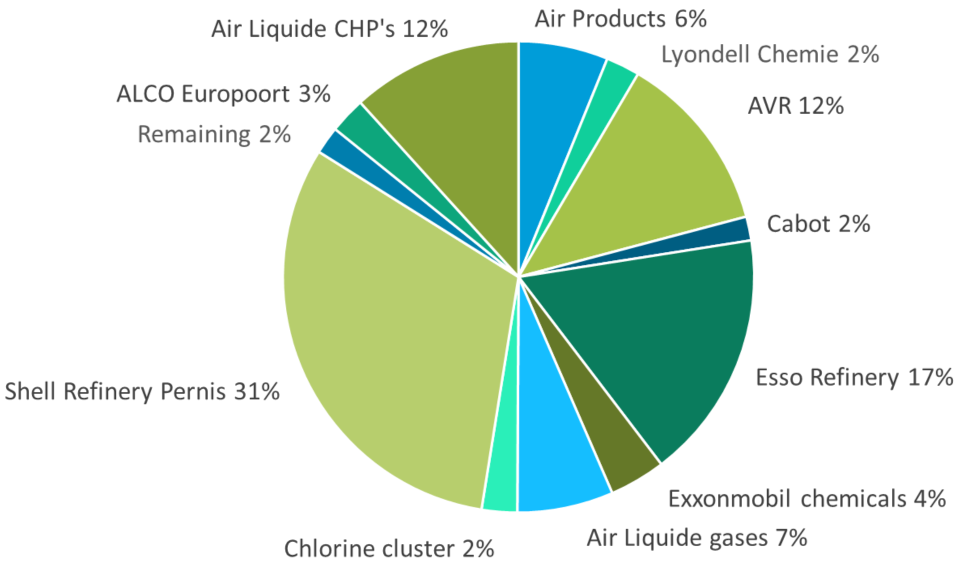
1 AL is an abbreviation for Air Liquide, AP for Air Products

Figure 2.3
Total CO_2 emissions of the companies in this report of 13,882 kt/yr in 2019 and their shares (NEa, 2019)

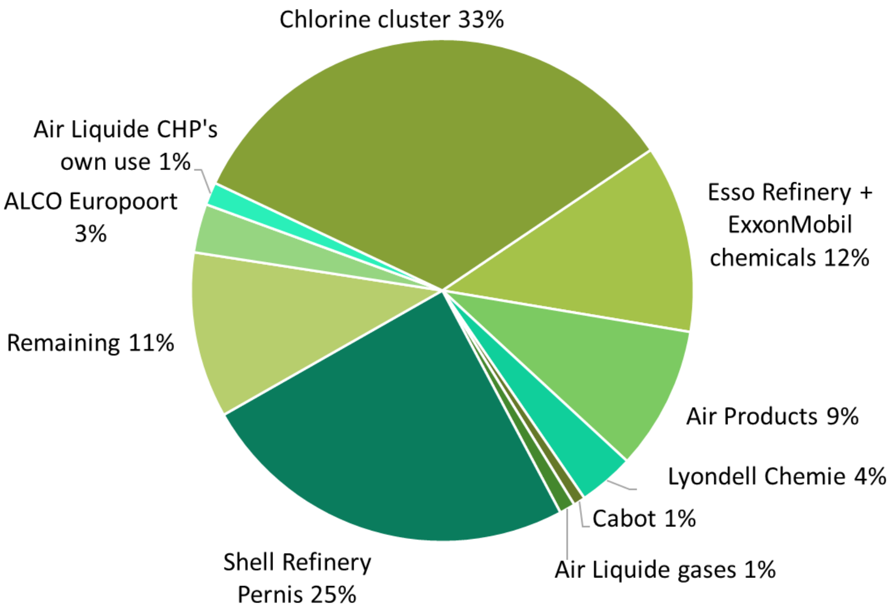


The combined heat and power generation group ('Air Liquide CHPs') here includes only the separate entities Pergen VOF, Enecal and Eurogen. Nobian, Huntsman, Shin-Etsu and Hexion Pernis are represented by the 'Chlorine cluster' part. AVR emissions are both fossil and biogenic. All of the remaining companies and terminals are represented by the 'Remaining' part; a full list is visible in Appendix A.

2.1.2 Electricity use in Botlek/Pernis

The total electricity use in Botlek/Pernis is based on several MIDDEN reports that estimate the electricity demands on a yearly basis (PJ/yr). Similar to the previous graph, in Figure 2.4 certain companies are grouped together for clarity.

Figure 2.4
Total final electricity use of the companies in this report of 18.9 PJ/yr and their shares



The chlorine cluster including Nobian, Shin-Etsu, Huntsman and Hexion Pernis are consuming a large part of the annual electricity. Nobian's final electricity use is 4.5 PJ/yr due to the extensive electrolyser activities for the chlorine production.

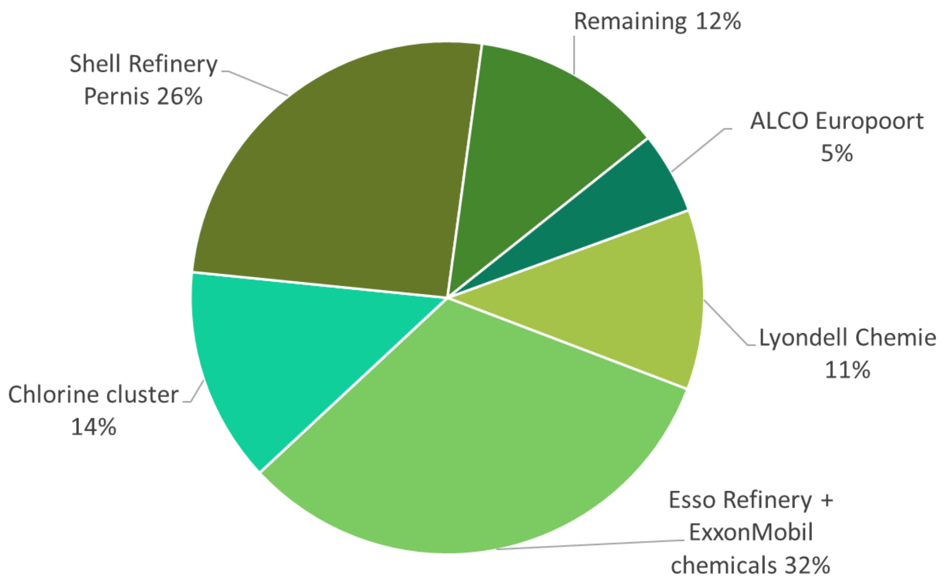
The electricity demand for the processes investigated in Botlek/Pernis amounts to 19 PJ/yr. The annual generation of electricity amounts to 16-17 PJ/yr, originating from around 10 CHP installations present in Botlek/Pernis.

2.1.3 Steam use in Botlek/Pernis

The annual steam use for processes in Botlek/Pernis is based on several MIDDEN reports that estimate the steam use and demands. Part of the steam used is generated on-site, several companies import steam and some export excess steam. Similar to the previous graph, in Figure 2.5 certain companies are grouped together for clarity.

As expected, the majority of the steam is used by the refineries of Esso and Shell. Other major consumers are the ExxonMobil chemical sites including RAP, RPP and ROP. The annual amount of steam imported in Botlek/Pernis is 30-31 PJ/yr, whereas the supply amounts to 35-36 PJ/yr.

Figure 2.5
Total final steam use of the companies in this report of 62.6 PJ/yr and their shares



2.2 Companies present in Botlek/Pernis

2.2.1 Air Liquide

Air Liquide Industrie B.V. is part of Air Liquide, the business was founded in 1902 by Georges Claude and Paul Delorme. Air Liquide is present worldwide and specialized in industrial gases, technologies and services for the industry as well as the health sector (Air Liquide, 2021). In 1931, Air Liquide was founded in the Netherlands and is located at the Merseyweg 10, next to the Huntsman and Lyondell plants. Air Liquide produces hydrogen, carbon monoxide and synthesis gas, mainly for refineries and chemical industry. Furthermore, Air Liquide operates three cogeneration units in the Botlek/Pernis.

The hydrogen, CO and synthesis gas is produced by steam methane reforming (SMR) and autothermal reforming (ATR) installations. Air Liquide has three units in Botlek that produce the industrial gases, indicated as SMR, ATR and SMR2. The greenhouse gas emissions of the SMR and ATR are reported together, while the SMR2 is a separate entity in the NEa emission registry. The steam methane reforming unit converts natural gas (feed and fuel) into high quality hydrogen with co-product CO_2 via an highly endothermic reaction. The in-and outputs of the SMR can vary depending on the availability of feedstocks or the demand of the customer. Natural gas and steam react to produce hydrogen, CO can simultaneously be produced depending on the presence of the water gas shift reaction. Due the flexibility of the SMR, the energy consumption values for the SMR processes in Table 1 have a range. The main product of the ATR is synthesis gas and it co-produces hydrogen. Natural gas is partially oxidized, requiring a relatively pure oxygen feedstock (Cioli, Schure, & Van Dam, 2021).

Table 2.1
Air Liquide material and energy overview

	In/out	Units	SMR	ATR	SMR2	Total	Source
Electricity	Input	(PJ/yr)	0.005-0.025	0.001	0.055-0.300	0.06-0.32	(Cioli, Schure, & Van Dam, 2021)
Natural gas feed	Input	(PJ/yr)	0.94-1.05	0.73	11.26-12.56	12.9-14.3	(Cioli, Schure, & Van Dam, 2021)
Natural gas fuel	Input	(PJ/yr)	0.21-0.26	0.75	2.47-3.12	3.43-4.13	(Cioli, Schure, & Van Dam, 2021)
Hydrogen	Output	(kt/yr)	9.5	10.7	114	134.2	(Cioli, Schure, & Van Dam, 2021)
CO	Output	(kt/yr)	27-48	n/a	162	210	(Cioli, Schure, & Van Dam, 2021)
Synthesis gas	Output	(kt/yr)	n/a	71	138	209	(Cioli, Schure, & Van Dam, 2021)
Scope 1 CO_2 emissions	Output	(kt/yr)	107[a]	n/a[a]	808	915	(NEa, 2019)

a) The emissions of the ATR and SMR are reported together under the same NEa entity.

The emissions reported originate from the use of natural gas as fuel and feedstock. Air Liquide owns several CHP facilities (Pergen, Enecal, Eurogen) of which Enecal and Eurogen are connected to the local Huntsman steam system and these CHP's supply steam and electricity to the SMRs and ATR (Cioli, Schure, & Van Dam, 2021). These CHP emissions are reported under separate NEa entities and further explained in the next section. Air Liquide receives steam from Eurogen and Enecal, the SMR2 receives refinery gas from the Esso refinery. Steam, electricity and industrial gases are delivered to the adjacent Huntsman network. Huntsman receives steam, hydrogen and carbon monoxide, and steam is also delivered to Ducor, Wilmar, Invista and Lucite and to Lyondell. Furthermore, synthesis gas is expected to be delivered to ExxonMobil ROP in Europoort for the conversion of olefins into aldehydes and oxo-alcohols. Hydrogen is delivered to Neste biofuels on the Maasvlakte and possibly to the BP refinery.

The company is involved in several decarbonisation initiatives and partner in the H-vision project as well as the Porthos project (Porthos, 2020; H-vision, 2019). For the ATR and SMRs the short term decarbonisation option would be the capture and storage of the relatively pure CO_2 flows, for instance feeding into Porthos. Air Liquide has planned to first connect the SMR2 to Porthos in 2024. Other considered decarbonization options are e-boilers instead of natural gas fired boilers and CHP's, granting that the electricity is from emission-free sources such as wind turbines or solar panels. This includes a 50 MW e-boiler at the Pergen location. Air Liquide is furthermore involved in developing large scale electrolysers for green hydrogen: the ELYgator project (200 MW, Terneuzen) and CurtHyl project (10-100 MW, Maasvlakte).

2.2.2 Air Liquide CHP facilities

Air Liquide owns three natural gas-fired CHP facilities, producing steam and electricity for other processes and companies. Two combined heat and power facilities, Enecal Energy VOF and Eurogen C.V., are located at the Merseyweg 10 in Botlek-Rotterdam at the Huntsman production site, formerly the ICI site. The third CHP, Pergen VOF, is located at the Shell refinery at Pernis.

The CHP's convert natural gas into steam and electricity and release CO_2 during the process. The electricity produced at Pergen VOF is distributed and sold to Enecogen VOF while the steam is delivered to the Shell refinery at Pernis (450 tonne/hr at 90 bar) (Cioli, Schure, & Van Dam, 2021). At Enecal Energy VOF, the produced electricity is sold to Enecogen VOF and steam delivered to Air Liquide. Eurogen also receives small amounts of residual gases from Lyondell and sends electricity to Lyondell, Huntsman and Enecogen VOF. Steam is delivered to Lyondell, Huntsman and Air Liquide (Cioli, Schure, & Van Dam, 2021).

Table 2.2
CHP facilities material and energy overview

	In/out	Units	Pergen VOF	Enecal Energy VOF	Eurogen C.V.	Source
Natural gas feed[a]	Input	(PJ/yr)	22.0	3.23	3.68	(NEa, 2019)
Steam (at full load)	Output	(PJ/yr)	8.7	1.1	2.1	(Cioli, Schure, & Van Dam, 2021)
Electricity (at full load)	Output	(PJ/yr)	8.5	1.1	2.2	(Cioli, Schure, & Van Dam, 2021)
Scope-1 CO_2 emissions	Output	(kt/yr)	1238.0	182.1	207.4	(NEa, 2019)

a) Natural gas use is calculated based on the 2019 emissions reported by NEa.

The CHP are currently fuelled by carbon-based fuels. A small proportion of hydrogen could be added to reduce emissions. CCS can be applied to the flue gases of the CHP, due to the location of the CHP's the connection to the CCS infrastructure is possible. This would require a post combustion CO_2 capture plant. E-boilers provide another viable alternative for steam generation, which would end electricity cogeneration. It is uncertain how long the current CHPs will still be in operation, and whether reduction measures are considered for the remaining lifetime. The oldest, Eurogen, dates from 1994, and Pergen is the most recent one, operating since 2007. For the long-term decarbonisation, a new generation of flexible hydrogen-fired CHP could back-up wind and solar power. This would require the need for storing electricity in the form of green hydrogen (produced by electrolysis). Storing electricity long term in batteries is more expensive compared to storing green hydrogen, e.g. in salt caverns. However, their current deployment is also limited due to economic constraints (ReCharge, 2021).

2.2.3 Air Products

Air Products Nederland B.V is part of the US based corporation Air Products and Chemicals Inc. and the Dutch department was founded in 1967 in Utrecht (Cioli, Schure, & Van Dam, 2021). Air Products has two production sites in the Botlek, one on the Botlekweg 127 connected to the Esso ExxonMobil refinery and one located on Merseyweg 8/Boyneweg 10 (Botlek Europoort, 2021). Air Products, together with Air Liquide, are the two main companies in Rotterdam that produce high quality hydrogen for the refinery sector and as feedstock for chemical productions (Cioli, Schure, & Van Dam, 2021).

The SMR (HYCO4) at the Botlekweg 127 produces 106 kt of hydrogen annually. The input of the SMR consists out of natural gas and refinery gases supplied by the Esso Refinery, equivalent to 12.8-14.6 PJ/yr. The amount of refinery gases supplied is estimated to be 9.9 PJ/yr (Advani & Van Dril, 2020). This Air Products site is well connected in the Botlek region, delivering hydrogen to the Esso ExxonMobil Refinery and the ExxonMobil RAP plant.

The SMR (HYCO2) present at the Merseyweg/Boyneweg was out of use in 2019/2020, pending final decisions on this plant redirection and therefore has no production capacities reported (Cioli, Schure, & Van Dam, 2021). This steam methane reforming unit converts natural gas (feed and fuel) into syngas (hydrogen and CO) or high quality hydrogen with co-product CO_2. Syngas can be supplied to the adjacent Lyondell Chemie plant for the BDO production (Yong & Keys, 2021). Most of the CO_2 produced can be captured, however it is not stored long-term and therefore still included in the NEa registry. The Esso ExxonMobil Refinery supplies the Air Products Merseyweg site also with some refinery gases, the SMR can convert these material streams into hydrogen. However, it is assumed that the current SMR (HYCO2) will be taken out of operation, and replaced by a new HYCO5, which is under development.

Table 2.3
Air Products material and energy overview

	In/out	Units	Botlekweg - SMR	Merseyweg - ASU	Merseyweg SMR/CHP/boilers	Source
Electricity	Input	(PJ/yr)	0.05-0.28	0.72-2.16	None reported	(Cioli, Schure, & Van Dam, 2021)
Gas (fuel + feed)	Input	(PJ/yr)	12.8-14.6	n/a	None reported	(Cioli, Schure, & Van Dam, 2021)
Air	Input	(kt/yr)	n/a	6360	n/a	(Cioli, Schure, & Van Dam, 2021)
Natural gas	Input	(PJ/yr)	n/a	n/a	0.9	(EEA, 2017), est.
Residue liq.	Input	(PJ/yr)	n/a	n/a	0.3	(EEA, 2017), est.
Refinery gas	Input	(PJ/yr)	n/a	n/a	0.3	(EEA, 2017), est.
Hydrogen	Output	(kt/yr)	106	n/a	None reported	(Cioli, Schure, & Van Dam, 2021)
Oxygen	Output	(kt/yr)	n/a	1200	n/a	(Cioli, Schure, & Van Dam, 2021)
Nitrogen	Output	(kt/yr)	n/a	4200	n/a	(Cioli, Schure, & Van Dam, 2021)
Argon	Output	(kt/yr)	n/a	48	n/a	(Cioli, Schure, & Van Dam, 2021)
Steam	Output	(PJ/yr)	n/a	n/a	1.25	calculated
Scope 1 CO_2 emissions	Output	(kt/yr)	767	0	87	(NEa, 2019)

As indicated in the table above, the Merseyweg/Boyneweg facility also has several cryogenic air separation units (ASU) and CHP capacity present on-site (Cioli, Schure, & Van Dam, 2021), (Botlek Europoort, 2021). In the ASU's, liquefaction of atmospheric air followed by multi-column distillation and separation based on different boiling points occurs in order to produce pure oxygen, nitrogen and a small amount of argon. The process is fully electric and therefore does not emit CO_2. The produced gases are transported by pipeline or truck (Botlek Europoort, 2021). The adjacent Lyondell site would require around 200 kt/yr oxygen for the PO/TBA process and additionally hydrogen (Yong & Keys, 2021).

Steam is also supplied by Air Products, currently estimated at 1.3 PJ/y, although Lyondell is currently self-sufficient. At the Merseyweg the CO_2 emissions originate from the boilers present, mostly natural gas. In 2017, Air Products received 0.3 PJ refinery gases from Esso/ExxonMobil Refinery and around 0.4 PJ waste fuel from LyondellBasell (EEA, 2017).

The initiative Porthos in Rotterdam, capturing and transporting CO_2 in order to store it under the North Sea, is a collaboration between Air Products, Air Liquide, Shell and ExxonMobil (Porthos, 2020). For Air Products a short-term decarbonisation option is CCS for its HYCO4 in combination with Porthos for the Botlekweg site. Installations present at the Merseyweg could potentially be fuelled by blue hydrogen to replace the natural gas, connection to the planned H-vision hydrogen backbone would be required.

Alternatively, the steam demand can be partially covered by e-boilers, sourcing electricity from CO_2-free energy sources. Long term decarbonisation options include electrolyser projects, producing green hydrogen instead of the production of blue hydrogen via SMR. Air Products is not involved in any electrolyser projects in Rotterdam, but recently invested in a large-scale electrolyser plant in Saudi Arabia of 2GW (Gasworld, 2021).

2.2.4 AVR Rijnmond

The AVR Rijnmond waste processing facility is located at the Professor Gerbrandyweg 10, Botlek-Rotterdam. Around 1970 the AVR was nearing bankruptcy and the government bought most of the assets. Since 2014 the AVR is part of the Cheung Kong Group (AVR, 2017).

The AVR Rijnmond is specialized in the processing of waste water, industrial waste water, paper residuals, municipal waste, hazardous waste and industrial waste (Botlek Europoort, 2020b). Separation and recycling of the incoming waste, such as plastics and metals, is also facilitated by AVR. The total capacity of waste that can be incinerated by AVR Rijnmond is 1314 kt/yr and the estimated composition is indicated in Table 2.4 (Rijkswaterstaat, 2021).

Besides the CO_2 that is released (1723 kt/yr) during the waste incineration originating from fossil components, heat and electricity are valuable co-products that can be delivered to surrounding companies. The heat (including steam and residual heat) produced by AVR Rijnmond on a yearly basis is 4.1 PJ and the generated electricity is 1.69 PJ (Rijkswaterstaat, 2021). Although the AVR is a net producer of energy, the incoming waste water streams require certain purification processes. The natural gas use of the AVR is related to these water purification processes or to start up the furnaces. The AVR Rijnmond has 31.4 MW installed electric power and 120 MW thermal power (De Leeuw & Koelemeijer, 2022).

AVR Rijnmond currently delivers steam to Tronox Pigments and Lanxess (previously Emerald Kalama Chemicals) via the steam pipeline. Cabot is also connected to the steam pipe initiative and similarly supplies steam (AVR, 2019). Nobian delivers NaOH to AVR (Bedrijvenpark Botlek, 2021).

Table 2.4
AVR material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Mixed municipal waste	Input	830	n/a	(Rijkswaterstaat, 2021).
Industrial waste	Input	27	n/a	(Rijkswaterstaat, 2021).
Industrial waste, not dangerous	Input	20	n/a	(Rijkswaterstaat, 2021).
Residual fermentation	Input	9	n/a	(Rijkswaterstaat, 2021).
Separation residuals	Input	322	n/a	(Rijkswaterstaat, 2021).
Dangerous waste, non-specified	Input	92	n/a	(Rijkswaterstaat, 2021).
Remaining waste	Input	10.7	n/a	(Rijkswaterstaat, 2021).
Total amount of waste	Input	1314	n/a	(Rijkswaterstaat, 2021).
Electricity	Output	n/a	1.69	(Rijkswaterstaat, 2021).
Heat (steam + waste heat)	Output	n/a	4.10	(Rijkswaterstaat, 2021).
- of which steam	Output	n/a	1.20	(AVR, 2019)
Scope 1 CO_2 emissions (fossil and biogenic)	Output	1723	n/a	(Emissieregistratie, 2019)
Fossil based CO_2 emissions	Output	620	n/a	Average 36% of total emissions

AVR Rijnmond has a significant amount of CO_2 that is released during the waste incineration process. A possible decarbonisation approach could be CO_2 capture with connection to the Porthos and OCAP infrastructure (see the sections on Alco and Shell). The SDE++ covers the non-profitable part for CCS and is based on the avoided fossil part of CO_2 that would otherwise be emitted. The fossil part of the waste incineration facilities is estimated on a national scale to be 36% of the total emissions and this percentage has remained constant over the past few years. With the current regulations, CCS would be almost three times more expensive for waste incineration plants since the subsidy will only cover 36% of the avoided emissions.

For indirect reduction of CO_2, which could also be applied simultaneously with CO_2 capture, a viable option is the expansion of the steam pipeline currently present around AVR and Cabot, and the extension of residual heat to surrounding urban areas. WarmteLinQ is a project that aims to distribute the residual heat originating from the Rotterdam port to surrounding urban areas in the province of South Holland. AVR Rijnmond could provide this residual heat (WarmtelinQ, 2022).

2.2.5 Alco Energy Rotterdam B.V

Alco is a large scale bioethanol producer, located at the Merwedeweg 10 at Europoort-Rotterdam. Alco Energy Rotterdam B.V is a cooperation of the Alco Group and Van den Avenne Commodities, founded in 2010. For a more detailed description of the technologies and processes, see chapter 2 of the MIDDEN report 'Decarbonisation Options for the Dutch Biofuels Industry' (Khandelwal & Van Dril, 2020).

Alco Energy has a combined heat and power facility on-site (48 MW) (Khandelwal & Van Dril, 2020). The natural gas feed for the CHP, boiler and dryers is estimated to be 6 PJ/yr. The steam generated by the CHP on site (110 tonne/hr) is annually 2.5 PJ. The electricity produced by this CHP is partly used for the production process (0.6 PJ/yr), the remaining electricity (0.9 PJ/yr) is sold to the grid (Khandelwal & Van Dril, 2020).

The raw material for this bio-refinery consists of maize. The process technology that is used at Alco Energy to convert the maize into bioethanol consist out of dry milling and fermentation process. The main product Alco Energy produces is bioethanol with an annual production capacity of 379 kt. The coproduct is dried distilled grain with soluble (DDGS), annual production of 360 kt, commonly used for animal feed. Additionally, 300 kt/yr of biogenic CO_2 is produced, around 100 kt/yr of this CO_2 is used as fertilizer in horticulture, mostly in the summer season. It is transported to greenhouses in the Westland by the OCAP pipeline, a subsidiary of Linde Gas Benelux (Khandelwal & Van Dril, 2020; OCAP, 2021). The CO_2 is transported with a capacity of 42 tonne/hr. The Shell refinery also supplies CO_2 to OCAP.

Table 2.5
Alco Energy material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Maize	Input	1137	n/a	(Khandelwal & Van Dril, 2020)
Natural gas (for CHP, boilers, dryers)	Input	n/a	6.0	(Khandelwal & Van Dril, 2020)
Bioethanol	Output	379	n/a	(Khandelwal & Van Dril, 2020)
DDGS	Output	360	n/a	(Khandelwal & Van Dril, 2020)
Biobased CO_2 emissions	Output	300	n/a	(Khandelwal & Van Dril, 2020)
Scope 1 fossil CO_2 emissions	Output	344	n/a	(NEa, 2019)
CHP steam generation	Output	n/a	2.5	(Khandelwal & Van Dril, 2020)
CHP electricity generation	Output	n/a	1.5	(Khandelwal & Van Dril, 2020)

For the reduction of Scope 1 CO_2 emissions and decarbonisation of Alco, the replacement of natural gas for steam generation is the obvious first step. Using waste heat, heat pumps or e-boilers could accommodate temperature requirements for the process. Removing both biobased and fossil based emissions with post combustion carbon capture and storage via Porthos would provide a net CO_2 sink. Alco is currently working on increasing its capacity for biobased CO_2 delivery to horticulture. The horticulture sector prefers biobased CO_2 instead of fossil based, currently delivered by Shell Pernis.

2.2.6 Lyondell Chemie Nederland

The US Lyondell Chemical Company merged with Basell Polyolefins in 2007 to form LyondellBasell. LyondellBasell is one of the largest chemical companies worldwide and has three production facilities in the Netherlands, two located in the Port of Rotterdam and one in Moerdijk. The company also has a transport terminal in Europoort connecting to the Rotterdam production sites with pipelines (Lyondellbasell, 2020). For a more detailed description of the technologies of the Botlek and Maasvlakte site, see the report on Decarbonisation Options for large volume organic chemicals production, LyondellBasell Rotterdam (Yong & Keys, 2021).

The site located at Theemsweg 15 Botlek is known as Lyondell Chemie Nederland B.V., built in 1972 (Yong & Keys, 2021). Lyondell Chemie produces propylene oxide (PO) and tert-butyl alcohol (TBA), both can be internally processed into several products or sold to external parties. PO is a pre-cursor for propylene glycol, propylene glycol methyl ether (PGME) and butanediol (BDO), while TBA is a pre-cursor for methyl tertiary butyl ethyl (MTBE), ethyl tertiary butyl ether (ETBE) and co-product tert butyl hydroperoxide (TBHP). The products of Lyondell Chemie are mainly intermediate chemicals, used by other companies to create a wide range of applications. Some examples of final products are cosmetic products, textiles, packaging for food and paint and coating applications.

In 2015 the most recent addition to the site were two on-site steam boilers to provide steam for the production processes, fuelled mainly by natural gas and other waste gases (115 MWth each).
In the table the annual production capacities and feedstock capacities are reported (Yong & Keys, 2021; Port of Rotterdam, 2016). The mixed butane feedstock, obtained from external parties, is isomerised to isobutane, one of the main raw materials for this production site. The propylene is

similarly acquired from external parties and the propylene oxide feedstock is supplied by the Maasvlakte LyondellBasell site. Oxygen for the PO/TBA production is supplied by a third party which is located adjacent to the Lyondell Chemie Botlek site (Yong & Keys, 2021). Supply of synthesis gas for the BDO process, consisting out of carbon monoxide and hydrogen, is also supplied by the same third party. The remaining isobutylene that is required for the MTBE/ETBE process that is not produced on-site is supplied by external parties.

Table 2.6
Lyondell Chemie Nederland Botlek site material and energy overview

	In/out	Capacity kt/yr)	Energy (PJ/yr)	Source
Mixed butane	Input	510	n/a	(Yong & Keys, 2021)
Propylene	Input	180	n/a	(Yong & Keys, 2021)
Oxygen	Input	200	n/a	(Yong & Keys, 2021)
Carbon monoxide	Input	40	n/a	(Yong & Keys, 2021)
Propylene oxide	Input	240	n/a	(Yong & Keys, 2021)
Hydrogen	Input	5	n/a	(Yong & Keys, 2021)
Methanol	Input	185	n/a	(Yong & Keys, 2021)
Steam use, optimised	Input	n/a	7.0	(Yong & Keys, 2021)
Electricity use	Input	n/a	0.9	(Yong & Keys, 2021)
Propylene Oxide (PO)	Output	250	n/a	(Port of Rotterdam, 2016)
Propylene Glycol (PG)	Output	80	n/a	(Port of Rotterdam, 2016)
PGME	Output	90	n/a	(Port of Rotterdam, 2016)
TBHP	Output	12	n/a	(Port of Rotterdam, 2016)
MTBE/ETBE	Output	400	n/a	(Port of Rotterdam, 2016)
Gasoline grade TBA	Output	589	n/a	(Port of Rotterdam, 2016)
Isobutylene	Output	100	n/a	(Port of Rotterdam, 2016)
1,4-butanediol (BDO)	Output	126	n/a	(Port of Rotterdam, 2016)
Allyl Alcohol (AA)	Output	16	n/a	(Port of Rotterdam, 2016)
Methyl propanediol (MPD)	Output	20	n/a	(Port of Rotterdam, 2016)
Scope 1 CO_2 emissions	Output	322	n/a	(NEa, 2019)

Air Products has steam boilers and a CHP on the Merseyweg 8, located adjacent to the Lyondell Chemie Botlek site. This CHP (total capacity of 95 MW_e, 225 t/h steam) can produce steam for Lyondell Chemie and the electricity is consumed by Air Products or fed into the grid. Currently only the boilers generate steam for the local network. In addition, Lyondell Chemie receives steam and electricity from Eurogen C.V. Rotterdam Rozenburg (total capacity of 88 MW_e, 270 t/h steam). Waste streams are sent back to Eurogen C.V. (gas) and Air Products (liquids) to serve as fuel for the CHP's (Yong & Keys, 2021). Lyondell Chemie's steam supply provided by external parties can be substituted by its own steam generation, it is estimated that since the installation of the two steam boilers (each 115 MW_{th}) the plant is capable of being self-sufficient (Yong & Keys, 2021).

The energy consumption of the Lyondell Chemie Botlek site is based on the production capacities and ingoing streams (Yong & Keys, 2021). The total steam use (optimized) is 7.0 PJ/yr and electricity consumption is 0.9 PJ/yr. Waste fuel consumption were calculated to be around 5 PJ per year. The annual Scope 1 CO_2 emissions for the Botlek site correspond with 322 kt. The majority of these emissions can be attributed to its on-site steam generation.

In order to reduce these Scope 1 emissions and decarbonize the site, an alternative method for steam generation must be found. Lyondell Chemie imports the required steam or generates the steam on-site. Because of mostly moderate process temperatures, a logical decarbonisation option would be e-boilers with sufficient capacity. Another possibility is the combustion of blue hydrogen for high temperature steam generation. An important aspect is the production of residual gases and liquids, currently combusted in the boilers or exported. A connection with H-vision utilizing residual gases for the blue hydrogen production seems possible. Alternatively, in the future residuals could be exported and processed in central specialized facilities with carbon capture and storage or usage. Bio-based feedstocks such as bio-based polyethylene and bio-based polypropylene provide further decarbonisation options.

2.2.7 Cabot B.V.

The site's history goes back to 1959 when Ketjen Carbon built the site located at the Botlekstraat 2. Ketjen Carbon merged with Cabot Corporation and in 1981 Cabot took over completely and named the company Cabot B.V. Ever since 1995 Cabot B.V. is the only carbon black manufacturer in the Netherlands (Cabot, 2021).

Cabot B.V. uses an incomplete feed combustion, also known as the furnace black process, to produce the carbon black. The site has four production units with 6 reactors in total, manufacturing different grades of carbon black (Abdallas Chikri & Wetzels, 2020). A more detailed description of the processes can be found in the MIDDEN report 'Decarbonisation Options for the Dutch carbon black industry' (Abdallas Chikri & Wetzels, 2020). Annual production capacity of carbon black is 80 kt/yr (Bedrijvenpark Botlek, 2021). Product applications for carbon black are pigments, reinforcement filler, UV protector in rubber products, plastics, the printing industry and coatings. The application in tyres has the largest market share.

The main raw materials for the furnace black process are liquid hydrocarbons, natural gas as fuel and air. Petrochemical oils are commonly used for this process although any aromatics with high ring numbers are suitable, these aromatics will lead to an increase in carbon black product. Greenhouse gas emissions of 227 kt/yr can be accounted to the combustion of natural gas and tail gas. The tail gas is separated from the carbon black product and further used for the production of steam/electricity (70% of total tail gas) or as fuel in dryers/boilers (30% of total tail gas) on site (Abdallas Chikri & Wetzels, 2020). The flue gases are released to the atmosphere. Cabot has a steam turbine (CHP) to produce electricity and consequently is self-sufficient in electricity needs.

Table 2.7
Cabot material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Liquid hydrocarbons (Petrochemical oils)	Input	146	5.9	(Abdallas Chikri & Wetzels, 2020)
Natural gas for process	Input	n/a	0.6	(Abdallas Chikri & Wetzels, 2020)
Natural gas, other uses	Input	n/a	Pm	n/a
Total input (process + product)	Input	n/a	6.5	n/a
- Thermal energy process	Input	n/a	3.37	(Abdallas Chikri & Wetzels, 2020)
- Feedstock energy use	Input	n/a	3.2	(Abdallas Chikri & Wetzels, 2020)
Tail gas for steam/power	Input	n/a	1.06	(Abdallas Chikri & Wetzels, 2020)
Tail gas for other uses	Input	n/a	0.46	(Abdallas Chikri & Wetzels, 2020)
Electricity use	Input	n/a	0.14	(Abdallas Chikri & Wetzels, 2020)
Carbon black	Output	80	n/a	(Bedrijvenpark Botlek, 2021)
Produced tail gas	Output	n/a	1.52	(Abdallas Chikri & Wetzels, 2020)
Exported steam (Linde Gas, Kemira)	Output	n/a	0.51	(Abdallas Chikri & Wetzels, 2020)
Generated electricity	Output	n/a	0.14	(Abdallas Chikri & Wetzels, 2020)
Scope 1 CO_2 emissions	Output	227	n/a	(NEa, 2019)

The energy consumption of the Cabot site is based on the annual carbon black production. Annual electricity consumption is 0.14 PJ and is fully covered by the steam turbine on site, producing 0.336 PY/yr of steam for internal consumption. The thermal energy consumption for the black furnace process amounts to 3.37 PJ/yr. This includes 0.66 PJ from complete combustion of natural gas in the reactor and 2.70 PJ from the incomplete oil combustion in the reactor. The tail gas produced during the reaction process is used for the boilers (27 MWth) and dryers, total of 1.52 PJ/yr. Cabot is connected to the Botlek steampipe since November 2019 and delivers steam to Linde Gas Benelux (40 bar) and Kemira Rotterdam (11 bar) with a total of 0.512 PJ/yr (Abdallas Chikri & Wetzels, 2020), (AVR, 2019). The AVR Rijnmond and Cabot furthermore deliver steam to Tronox (Van Dril, Koelemeijer, & Van Dam, 2021).

Currently, plasma technology for the electrification of the furnace is developed, which directly splits hydrocarbons into carbon and hydrogen. It has been tested and scaled up but still needs further development and is not expected to be operational before 2030. For the short-term decarbonisation, CCS seems the only option, combined with connection to the Porthos system. It is unclear which specific CCS technology is most suitable. Post combustion capture can be combined with oxy-fuel combustion of the tail gas, for CCS with pre-combustion, the tail gas has to be converted into blue hydrogen when connected to the Porthos project. Cabot can further decarbonise and decrease the Scope 1 emissions by electrification of the current boilers and dryers. An extension of the existing steam pipeline system could further influence the activities of Cabot. A plant for recycling of carbon black from used tyres is now initiated on the Chemelot site.

2.2.8 Nobian

In 1961 AkzoNobel founded its third mercury electrolysis plant for the chlor-alkali production at the Welplaatweg 12, Rotterdam-Botlek (Scherpbier & Eerens, 2021). In 2018 The Carlyle Group took over AkzoNobel Speciality Chemicals and launched the company under the name Nouryon (Nouryon, 2018). In May 2021, Nouryon announced that the industrial chemicals section would proceed under the name Nobian, remaining under the ownership of The Carlyle Group and GIC (Nouryon, 2021). For a more detailed description of the processes, see the report on Decarbonisation Options for the Dutch Chlor-alkali Industry (Scherpbier & Eerens, 2021)

Nobian currently has a production capacity of 640 kt/yr of chlorine and an additional independent chlor-alkali plant will be operational in 2025 at the Botlek site. The production capacity of this expansion is projected to be 75 kt/yr of chlorine. This plant provides a baseload supply of chlorine when the existing one is out of operation. This can avoid the transport of chlorine by train since the two plants can operate independently (Personal communication, 2021) (Scherpbier & Eerens, 2021). Chlorine and caustic soda are raw materials for many chemicals like EDC for PVC production, ECH for epoxy resins and for many applications including the food and pharmaceutical industry. The chlorine related material streams can be seen in the figure in Section 3.3.3 since Nobian is at the heart of the chlorine-cluster present in Botlek (Bedrijvenpark Botlek, 2020).

The process technology used is the membrane electrolysis of salt using water, two main products are chlorine and caustic soda also known as lye, NaOH. Co-products are high purity hydrogen and a small amount of hydrogen chloride (Scherpbier & Eerens, 2021). Most of the hydrogen is sold as feedstock, but part of it is used as fuel gas in the energy system of Nobian and Shin-Etsu. The process can be divided into several sub-processes including steam generation, caustic soda preparation, brine preparation, electrolysis and hydrogen/chlorine/caustic soda processing.

The Scope 1 CO_2 emissions for the year 2019 are reported to be 109 kt, most of the emissions for Nobian Botlek can be accounted to steam generation with boilers and a cogeneration unit. However, part of the steam and electricity required is not generated on-site and therefore not accounted for in the direct Scope 1 emissions. The required electricity that is not covered by the on-site generation is supplied by the grid. Shin-Etsu, located adjacent to the Nobian site, requires high temperature steam and is producing low temperature steam. Nobian delivers their high temperature steam to Shin-Etsu and approximately half of the energy equivalent is delivered back as low temperature steam. All of the steam required by Nobian is either delivered by Shin-Etsu or produced on-site from natural gas.

Nobian has a natural gas fired CHP on-site (85% efficiency, 70 MW_{th}) to supply part of the required heat and electricity for the process and can function as back-up supply (Scherpbier & Eerens, 2021). Furthermore, two boilers are present at Nobian, one (60 MW_{th}) running partly on hydrogen originating from electrolysis and on residuals coming from the Shin-Etsu oxychlorination process (Personal communication, 2021). The second boiler (50 MW_{th}) is a flexible boiler that can correct the fluctuations if the first boiler is out of operation. The energy demands for the current plant are based on the chlorine production capacity of 640 kt/yr, normalized for the chlor-alkali industry (Scherpbier & Eerens, 2021).

Table 2.8
Nobian material and energy summary

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Salt	Input	1024	n/a	(Scherpbier & Eerens, 2021)
Water	Input	1472	n/a	(Scherpbier & Eerens, 2021)
Steam use (net)	Input	n/a	1.2	(Scherpbier & Eerens, 2021)
Fuel consumption	Input	n/a	2.3	(EEA, 2017; NEa, 2019)
Electricity use	Input	n/a	5.50	(Scherpbier & Eerens, 2021)
Chlorine	Output	640	n/a	(Scherpbier & Eerens, 2021)
Hydrogen	Output	17.9	2.1	(Scherpbier & Eerens, 2021)
Caustic soda	Output	723	n/a	(Scherpbier & Eerens, 2021)
HCl	Output	0.12	n/a	(Scherpbier & Eerens, 2021)
Steam production	Output	n/a	1.9	(EEA, 2017; NEa, 2019)
Scope 1 CO_2 emission	Output	109	n/a	(NEa, 2019)

The specific situation in Botlek is currently more optimized than the literature figures. Based on NEa emissions (NEa, 2019) and the Large Combustion Plants database (EEA, 2017), we assume fuel consumption of 2.3 PJ/yr, consisting of 1.7 PJ/yr natural gas, 0.45 PJ/yr hydrogen and 0.15 PJ/yr oxychlorination residuals. Total gross steam production is estimated at 1.9 PJ/yr, of which more than half is first transported for EDC production at Shin-Etsu, from which low pressure steam is returned to Nobian.

In order to reduce the Scope 1 emissions, Nobian can electrify the remaining steam demand. Electric boilers are deemed to be possible, the biomass boiler option was explored and SDE++ subsidy was awarded but Nobian did not choose to build it. Nobian could also benefit from external steam supply from the AVR fed steampipe or other sources with moderate temperatures. Since Nobian is an expert in the electrolyser field, they are involved in several green hydrogen electrolyser projects. Several projects are currently in different stages of development. These include Djewels-1 (20 MW, Delfzijl), Djewels-2 (40 MW, Delfzijl), H_2ermes (100 MW, Amsterdam) and H2.50 (250 MW, Maasvlakte) are four electrolyser projects initiated by Nobian.

2.2.9 Almatis B.V.

Almatis B.V. Netherlands was founded in 1967, being the first plant of Almatis located in Europe, and is located at the Theemsweg 30 in Botlek-Rotterdam. Almatis B.V. produces high-quality raw materials based on alumina (Al_2O_3) for the refractory, ceramic, steel, plastic, paper and chemical industries (Almatis B.V., 2021). The production capacity of Almatis is 125 kt/yr for tabular alumina (TAB) and co-product calcium aluminate cement (CAC) (DCMR, 2020b).

The process technology used at Almatis is a CAC rotary oven, fired on high-caloric natural gas at high temperatures, resulting in high NOx emissions (DCMR, 2020b). The annual electricity use is estimated at 0.08-0.1 PJ and the high-caloric gas use at 0.2-0.4 PJ based on the annual CO_2 emissions. Main focus for Almatis is the reduction of NO_2 emissions (0.19 kt/yr) as opposed to the reduction of direct CO_2 emissions (18 kt/yr).

The alumina feedstock is supplied by ship and stored in terminals in Botlek. Final products are either shipped overseas or transported by train through Europe (Almatis B.V., 2021). Almatis B.V. has no other reported connections with companies in Botlek. The decarbonisation options for Almatis for Scope 1 emissions will mainly involve the optimization of the CAC oven and the substitution of the natural gas by low carbon gas. No further decarbonisation options, like electric furnace technology, were explored for this company.

Table 2.9
Almatis material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Alumina feedstock	Input	Pm	n/a	n/a
High-caloric natural gas	Input	n/a	0.2-0.4	Calculated
Electricity demand	Input	n/a	0.08-0.1	Estimated
Tabular alumina	Output	125	n/a	(DCMR, 2020b)
Calcium aluminate cement (CAC)	Output	60	n/a	(DCMR, 2020b)
Scope 1 CO_2 emissions	Output	18	n/a	(Emissieregistratie, 2019)
NO_2 emissions	Output	0.19	n/a	(Emissieregistratie, 2019)

2.2.10 Biopetrol Rotterdam B.V.

Biopetrol Industries AG (Biopetrol) built their third biodiesel production facility at Royal Vopak Terminal, located at the Welplaatweg 108 in Botlek-Rotterdam (VOPAK, 2006; Khandelwal & Van Dril, 2020). Rotterdam is the centre of the vegetable oil market and therefore a strategical location for Biopetrol (Petrochem, 2006). Biopetrol Rotterdam B.V. is a joint venture between the trading company Glencore Agriculture (60%) and Argos (40%) (DGAP, 2010). For a more detailed description of the processes, see Chapter 2 of the report 'Decarbonisation Options for the Dutch Biofuels Industry' (Khandelwal & Van Dril, 2020).

The annual production capacity at Biopetrol Rotterdam for biodiesel is 400 kt and for glycerol 60 kt, the glycerol by-product is used for pharmaceutical grade purposes and the biodiesel for transport fuels (Khandelwal & Van Dril, 2020). For this plant, the bio-based feedstock mainly consists out of rapeseed oil and sunflower oil. Other raw materials are methanol and water and function as feedstocks for the production of glycerol. The biodiesel is produced via the transesterification process with a closed water loop to minimize the water usage. Steam required for the process is generated on-site by natural gas boilers in addition to natural gas fired dryers (Khandelwal & Van Dril, 2020). The greenhouse gas emissions (Scope 1) are 36 kt/yr of CO_2 (NEa, 2019). The vast majority of these emissions can be attributed to the natural gas usage, estimated to be 0.60-0.65 PJ annually for the Biopetrol plant. More than half of the total natural gas is used for generating steam and the remaining part is used for drying purposes (Khandelwal & Van Dril, 2020). Biopetrol Rotterdam B.V. is relatively unlinked and there are no major connections reported, material or energy based, in the public domain.

Table 2.10
Biopetrol Rotterdam material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Rapeseed oil and sunflower oil	Input	380	n/a	(Khandelwal & Van Dril, 2020)
Methanol	Input	34	n/a	(Khandelwal & Van Dril, 2020)
Water	Input	9500	n/a	(Khandelwal & Van Dril, 2020)
Electricity use	Input	n/a	0.04 - 0.045	(Khandelwal & Van Dril, 2020)
Steam use	Input	n/a	0.60 - 0.65	Calculated, based on NEa (2019)
Biodiesel	Output	400	n/a	(Khandelwal & Van Dril, 2020)
Glycerol	Output	36	n/a	(Khandelwal & Van Dril, 2020)
Scope 1 CO_2 emissions	Output	36	n/a	(NEa, 2019)

Decarbonisation options for Biopetrol Rotterdam are mainly focused on the natural gas use for steam generation. An electric boiler would be the plausible alternative. Substitution of natural gas by blue hydrogen in the boilers and drying sections can provide also a viable short-term solution, which would require connection to a hydrogen grid. Alternatives for the drying section could be further explored.

2.2.11 Cargill B.V.

Cargill was founded in 1865 in the United States by William Wallace Cargill. In 1959 Cargill B.V. expanded their business to the Netherlands as a commodity trading operation and acquired the Botlek plant in 1984 from Brinkers, located at Welplaatweg 34. The Botlek site mainly operates in the oil and fat food sector (Altenburg & Schure, 2021). For a more detailed description of the processes, see Chapter 2 of the report 'Decarbonisation Options for the Dutch Vegetable Oil and Fat Industry' (Altenburg & Schure, 2021).
The products of Cargill Botlek include palm oil, palm kernel oil and coconut oil, mainly for the food industry. Other markets for these products are animal feed, energy or oleochemical purposes. After increasing the production capacity in 2005 the annual production capacity is 1000 kt of oil in total. The distribution of oil fractions is unknown, however it is reported that in 2005 the palm oil production increased with 300 kt/yr and the coconut and palm kernel oil increased with 200 kt/yr (Industrielinqs, 2005). The main raw materials for Cargill Botlek are vegetable palm oil and water. The process technologies used to convert the crude palm oil into final oil are the refining stage and oil modification stage. The temperatures present for the vegetable oil processing are above 280 degrees and require steam, supplied by a natural gas fired boiler (15 MWth). The sodium hydroxide (NaOH 50% in water) is used during the refining stage and supplied by Nobian (Bedrijvenpark Botlek, 2020).

Table 2.11
Cargill material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Vegetable oil[a]	Input	1045	n/a	(Altenburg & Schure, 2021)
Water	Input	700	n/a	(Altenburg & Schure, 2021)
NaOH	Input	2.9	n/a	(Altenburg & Schure, 2021)
Electricity use	Input	n/a	0.17	(Altenburg & Schure, 2021)
Heat use	Input	n/a	0.52	(Altenburg & Schure, 2021)
Natural gas use	Input	n/a	0.44	Calculated
Vegetable oil product[a]	Output	1000	n/a	(Altenburg & Schure, 2021)
Scope 1 CO_2 emissions	Output	25	n/a	(NEa, 2019)

[a)] Palm oil, coconut oil and palm kernel oil is processed, palm oil is main product

The greenhouse gas emissions are 25 kt/yr of CO_2, reported by NEa in 2019. Energy consumption of the total palm oil production process is 684 MJ/tonne palm oil based on literature, resulting in 0.69 PJ in total per annum for the Botlek site (Altenburg & Schure, 2021). However, based on the lower actual emissions, the site is 20% more energy efficient, or not using its full capacity.

Decarbonisation options for Cargill are focused on the steam generation originating from natural gas. Since the steam is required at relatively high temperatures, solely electric boilers might not be sufficient. Instead of utilizing natural gas for the high temperature steam, biogas or hydrogen could be suitable as fuel. A biogas boiler can potentially utilize residual streams from oils and fats as fuel, but residual flows mostly find higher value purposes. Recently, Cargill signed a Corporate Power Purchase Agreement (CPPA) with Vattenfall for 10 years of 2.9 TWh annually of green electricity harvested by wind parks (Vattenfall, 2021). By signing this agreement, 90% of the total electricity use of Cargill corporate is generated in a sustainable manner.

2.2.12 Climax Molybdenum B.V.

Located at the Theemsweg 20 Botlek- Rotterdam, Climax Molybdenum started production in 1965 and the main products consist out of technical molybdic oxide, ammonium dimolybdate, sulfuric acid and pure molybdic oxide (Climax Molybdenum, 2021; Climax Molybdenum, 2010). Molybdenum is a metal that is commonly used in products for cars, wind turbines, dietary supplements or added to stainless steel.

The molybdenum concentrate, collected at the mines, is heated in a floor oven at high temperatures (500-650 °C) to produce molybdenum oxide (IMOA, 2021). The sulphur is roasted from the concentrate and converted into sulphuric acid at the sulphuric acid plant with a capacity of 58 kt/yr (Climax Molybdenum, 2010). No complete production capacities of molybdenum oxide are reported for the Botlek site. According to CBS, national imports of unroasted molybdenum ore average to around 30 kt/yr. The capacity of the chemically purified part of molybdenum oxide is 9 kt/yr (Staatscourant, 2013).

In 2019 the NEa reported 11 kt/yr of CO_2 emissions. It is likely that these emissions originate from the oven heat generated and therefore from natural gas and/or gas oil usage. Climax Molybdenum signed the IRBC agreement in 2019 concerning the metal sector. The IRBC agreement encourages reporting and exchange of knowledge between businesses, benefitting everyone while identifying, mitigating, preventing and remediating risks and violations to people and the environment (Climax Molybdenum, 2019).

Table 2.12
Climax Molybdenum material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Molybdenum concentrate	Input	pm	n/a	n/a
Natural gas/gas oil for oven	Input	n/a	0.1-0.2	calculated
Sulphuric acid	Output	58	n/a	(Climax Molybdenum, 2010)
Molybdenum oxide	Output	9	n/a	(Staatscourant, 2013)
Scope 1 CO_2 emissions	Output	11	n/a	(Emissieregistratie, 2019)

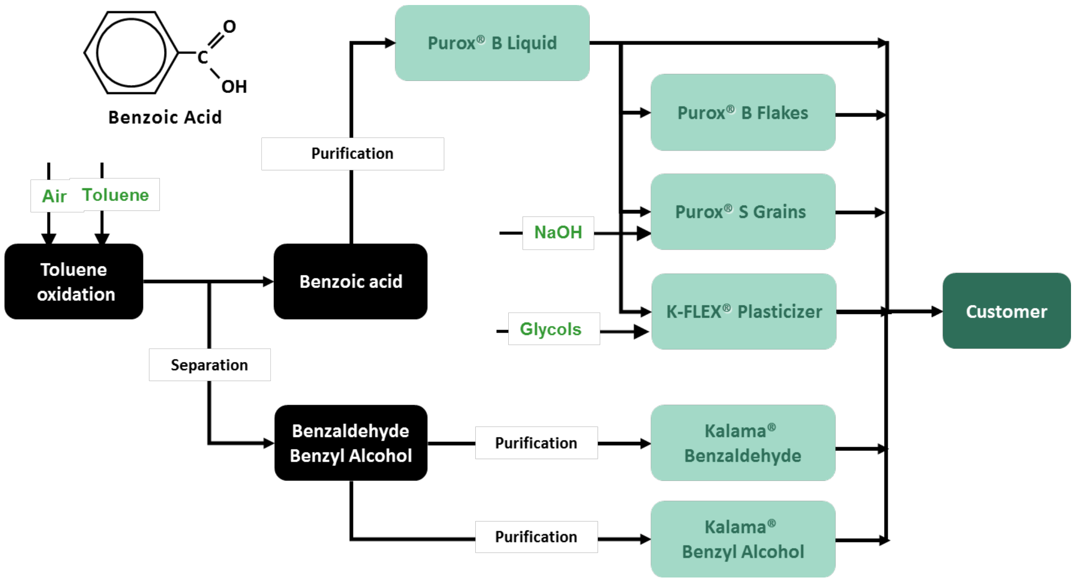
Decarbonisation options for the Scope 1 emissions of Climax Molybdenum are mainly focused on the substitution of natural gas and gas oil for the boilers. The oven operates at high temperatures, limiting the possibilities for electrification. An alternative fuel for the boilers is hydrogen, which requires a connection to the hydrogen infrastructure.

2.2.13 Lanxess (former Emerald Kalama Chemical)

The former Emerald Kalama Chemical was acquired by Lanxess AQ in August of 2021 (Lanxess, 2021). The site was founded in 1962 at the Montrealweg 15 and was previously owned by DSM and DOW Chemical for the production of phenol. Emerald Kalama Chemical took over in 2010 and shifted the focus on the production of raw materials for the food and care industry. The annual production capacity for benzoates is 191 kt and for benzaldehyde 60 kt is reported (Provinciaal Blad, 2019). Common product applications are antioxidants, conservation purposes, fragrance and taste purposes as well as the animal feed industry (Botlek Europoort, 2020).

The main feedstock for Lanxess is toluene which undergoes an oxidation with air. The annual production capacity of toluene oxidation products is around 200-250 kt (DCMR, 2020a). Other raw materials for the tuning of chemicals downstream are NaOH and glycol. The products of partial toluene oxidation are a mix of benzoates and co-products water and CO_2. The mix of benzoates is further processed and extensively distilled in order to separate the benzoic acid, benzaldehyde, benzyl alcohol and sodium benzoate.

Figure 2.6
Lanxess Botlek process overview



Lanxess emitted 74 kt/yr of greenhouse gas CO_2 in 2019, reported by NEa. Approximately 90% is a direct result of fuel combustion (natural gas or process residual) and 10% is a result of process emissions (Personal communication, 2021). The old steam boiler built in 1976 (46 MW) is currently running on a mix of process residual and natural gas due to the significant process residual decrease over the years (approximately 75%) (DCMR, 2020a). In order to eliminate the use of natural gas to generate steam, a new boiler (30 MW) is constructed to solely run on process residual or potentially blue hydrogen in the future (Personal communication, 2021). The process residual (20 tonne/day) cannot be processed by AVR due to cobalt being present, resulting in the dependency on the boiler to process the residual stream until there is a feasible alternative (DCMR, 2020a). Three more heating installations are present at Lanxess, two thermal oil boilers (16 MW each) and a process air heater (5.5 MW). The water that is co-produced during the oxidation of toluene undergoes an anaerobic and aerobic water purification, resulting in fermentation gas. Consequently, this fermentation gas (10% of total input) is used for the thermal oil boilers in addition to natural gas (90% of total input) (Personal communication, 2021). The benzoic acid purification installation on-site has doubled the pure benzoic acid production. Furthermore, four compressors are providing the toluene oxidation reactors with compressed air (Botlek Europoort, 2020).

The toluene is supplied by an underground pipeline originating from Vopak Chemiehaven terminal, receiving the toluene by shipping oversea (Botlek Europoort, 2020). Previously, the toluene was supplied by ExxonMobil but this connection no longer exists since ExxonMobil utilizes the toluene internally. The NaOH (24%) supplied by Nobian is used for the tuning of chemicals downstream in the process (Bedrijvenpark Botlek, 2021). Lanxess is connected to the steam pipeline since 2013 and has a contract with AVR concerning the steam supply. The steam pipe delivers steam (39 bar overheated, 400 °C) to Lanxess and the steam is lowered to 35 bar saturated on-site (DCMR, 2020a); (Personal communication, 2021).

Table 2.13
Lanxess material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Toluene	Input	200-250	n/a	Estimated
NaOH, glycol	Input	pm	n/a	n/a
Natural gas for steam	Input	n/a	0.75	Calculated, based on NEa (2019)
Fermentation gas for steam	Input	n/a	0.03	Calculated, based on NEa (2019)
Residuals for steam	Input	n/a	0.33	Calculated, based on NEa (2019)
Steam from AVR	Input	n/a	0.7	Estimate
Total steam for process	Input	n/a	1.6-1.8	Calculated
Benzoates	Output	191	n/a	(Provinciaal Blad, 2019)
Benzaldehyde	Output	60	n/a	(Provinciaal Blad, 2019)
Process residuals	Output	7.9	n/a	(DCMR, 2020a)
Scope 1 CO_2 emissions	Output	74	n/a	(NEa, 2019)

In 2040 Lanxess aims to be CO_2-neutral and is therefore very driven to decarbonise. Lanxess is examining more than 60 options to tackle the decarbonisation plant-wide. Electrification is not seen as a viable option due to the benzoic acid being present in pipelines, benzoic acid solidifies below a certain temperature and therefore the temperature must be kept above 145 °C (Personal communication, 2021). Using hydrogen as fuel instead of natural gas for the boilers is regarded more viable, for instance blue hydrogen produced from the process residual. Another investigated decarbonisation option is to optimize the use the heat of the reactors since the oxidation of toluene is exothermic.

Furthermore, the residual stream can be possibly 30% reduced by further hydrogenating of benzyl benzoate. Toluene will remain the main raw material, benzene is the alternative although that is not preferred considering the working conditions. Biobased toluene would be an alternative, this option is also explored by Lanxess. However, biobased toluene supply is expected to be limited on a short-term notice (VNCI, 2021).

2.2.14 Hexion Inc. (Westlake Chemical, Bakelite Synthetics)

Until recently, Hexion Inc. owned two production sites in Botlek and Pernis, one located at the Chemiestraat in Botlek and one larger production site at Shell Pernis. The Pernis site owned by Hexion was formerly part of Shell, acquired by Hexion in 2000 (Hexion, 2020a). In October 2021 the epoxy department of Hexion Pernis was acquired by Westlake Chemical Corp. The department of Versatics Acid Derivatives will continue under Hexion Versatics Acid Derivatives at Pernis and Moerdijk (De Brauw, 2021).

The Hexion Botlek site was acquired by Bakelite Synthetics and the formalin production (140 kt/yr) will no longer be Hexion's business (Greenwood, 2021), (Port of Rotterdam, 2016). Around 5 kt of annual CO_2 emissions are reported for the former Hexion Botlek site. For the process, externally supplied methanol is both dehydrogenated and partly oxidized for conversion to formaldehyde. Formaldehyde is a gaseous chemical intermediate which is used in a variety of applications, for example in resins, polyols, MDI and BDO. Formalin is a solution of formaldehyde in water.

Table 2.14
Hexion Pernis overview material and energy

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Propylene	Input	60-70	n/a	Based on reaction stoichiometric
Chlorine	Input	180-200	n/a	Based on reaction stoichiometric
Acetone	Input	45-50	n/a	Based on reaction stoichiometric
Phenol	Input	150-160	n/a	Based on reaction stoichiometric
Nonene	Input	pm	n/a	n/a
Steam use	Input	n/a	2-3	calculated
Electricity use	Input	n/a	0.2-0.4	calculated
Epichlorohydrin (ECH)	Output	100	n/a	(Port of Rotterdam, 2016)
Bisphenol A (BPA)	Output	190	n/a	(Port of Rotterdam, 2016)
Liquid epoxy resins (LER)	Output	170	n/a	(Port of Rotterdam, 2016)
Cardura glycidyl ester	Output	20	n/a	(Port of Rotterdam, 2016)
Versatic Acids™ and Derivatives	Output	90	n/a	(Port of Rotterdam, 2016)
Scope 1 CO_2 emissions	Output	32	n/a	(NEa, 2019)

At the Pernis site, epichlorohydrin (ECH) is made in a three-step process (Elzenga, 1993). In the first stage, allyl chloride is produced from propylene and chlorine at high temperature <300° with large residual flows of dichloropropene, dichloropropane and hydrochloric acid. In the second stage allylchloride with and hypochlorite are reacted to produce dichlorohydrin. In a combined hydrolysis/rectification unit, the dichlorohydrin is further reacted with $Ca(OH)_2$ to ECH with by-products water and $CaCl_2$.

Raw material inputs for Hexion Pernis are based on reaction stoichiometric and it is expected that the actual intake of raw materials is higher, mostly due to high yield losses in the ECH process (Bell, et al., 2008). Around 90% of the produced ECH is used for the production of LER, the remaining 10% is used for the Cardura production process. Nobian is responsible for the chlorine supply and the propylene is currently supplied by Shell Chemie.

For the bisphenol A (BPA) production process at Pernis, phenol is supplied by ship from abroad and reacts with acetone (Process Economics Program, 1982). For the most part, the produced BPA is used internally (60%) to produce liquid epoxy resin (LER) and the remaining BPA is purified and sold for various purposes (40%) (Epoxy Europe, 2015). LER is produced via the two step reaction of ECH and BPA and consists out of the standard monomer BADGE with several isomers. Main applications of LER consist out of thermo-hardeners for cars, wind turbines, electronics or buildings. Versatic Acid Derivatives are used for high-performance coating applications (Hexion, 2020). Furthermore, Hexion Pernis produces a range of versatic acids, using nonene as a building block (Hexion, 2020). Versatic Acids can be the end-product and sold to customers, at Hexion the Versatic Acids partly react with ECH to form Cardura.

During the production process of LER there is brine released in the waste water, this is currently discharged via the Shell Bio water purification plant towards the harbour. A possible circular option would be to recycle this brine towards Nobian, the Watermining initiative led by TU Delft is exploring this option (Watermining, 2021). Nobian can potentially utilize this left-over brine instead of mining new salt required for their chlorine production process. A major obstacle remains the purity of the brine and the significant distance (8 km) between Hexion and Nobian, coherent with substantial investment costs. Another co-product that is created during the ECH process is hydrogen chloride, this is transferred to Shin-Etsu (Bedrijvenpark Botlek, 2020).

The Pernis site's Scope 1 emissions amount to 37 kt CO_2/yr and Scope 1 & 2 emissions together are 220-230 kt/yr. The Scope 1 emissions include a steam boiler and furnaces. The total steam demand includes process steam as well as steam for the compressors. The compressors are the biggest units utilizing steam, around 0.6-0.9 PJ/yr, in addition to the steam required for the processes around 2.0 PJ/yr. The steam is mostly imported from the Shell steam system. The vast majority of the Scope 1 and 2 emissions originate from natural gas or refinery gas from the Shell Refinery, used as fuel for the steam production, followed by electricity generation and compressed air. Electricity demands of Hexion Pernis are similarly covered by Shell Pernis.

Decarbonisation options for the Scope 1 emissions of Hexion Pernis mostly focus on the steam usage. Substituting the current boilers by electric boilers is a bigger investment in comparison to substituting natural gas with e.g. biogas or hydrogen. This is however influenced by the price of hydrogen or biogas compared to electricity. The compressor on-site (28-35 t/h, input steam 0.6-0.9 PJ/yr) is now powered by steam and the biggest steam user on-site. This compressor can be electrified with an engine of approximately 5 MW. Hexion is also exploring the use of a 100 °C water purge flow for upgrading to steam with mechanical vapour recompression (MVR) technology to recycle waste heat and improve energy efficiency. Most of the projects initiated by Hexion are heavily dependent on Shell and projects in the Botlek region, H-vision or Porthos in particular. Shell can also potentially produce 'green' steam from the planned biofuel plant, which could also reduce Scope 2 emissions of Hexion by using 'green steam'. In combination with Porthos, post-combustion CCS could also be applied to the furnaces present.

2.2.15 Shell Pernis

Shell, previously named Royal Dutch Shell and N.V. Koninklijke Nederlandse Petroleum Maatschappij (KNPM), started their refinery activities for the gasoline production in 1902 in Waalhaven. In 1936 the gasoline production site re-located at the Vondelingenplaat 601, Pernis. This is where the current refinery and chemical complex is located. Shell Pernis is the largest refinery in Europe and one of the largest worldwide. Connected are large chemical facilities (SNC, see next paragraph) on site and in Moerdijk. Over the years, part of the petrochemical installations at Pernis were sold to other chemical producers such as Hexion and Shin-Etsu. For a more detailed description of the processes, see Chapter 2 of the MIDDEN report 'Decarbonisation Options for the Dutch Refinery Sector' (Oliveira & Schure, 2020).

The crude oil capacity Shell Pernis can process yearly is 21,000 kt. In the table below the reconstructed inputs and outputs can be seen for Shell Pernis, based on the MIDDEN report about refineries (Oliveira & Schure, 2020). Refining processes present at Shell include: atmospheric distillation, vacuum distillation, catalytic reforming, alkylation, fluidized bed catalytic cracking, hydrocracker, hydrotreating, thermal cracking, visbreaking, solvent deasphalting and gasification/hydrogen production (Oliveira & Schure, 2020). On site, there is also an SMR hydrogen plant (hydrogen manufacturing unit, HMU), and Air Liquide's Pergen CHP for steam and power generation. Shell Pernis is closely linked in terms of energy with the Shell Nederland Chemie Pernis site, Hexion Pernis and Shin-Etsu. For naphtha and several basic chemicals Shell Pernis is connected to the Shell Nederland Chemie site in Moerdijk as well. Shell Nederland Chemie Pernis converts product streams of the refinery into products such as propylene, MTBE and polyether polyols. Furthermore, Shell Pernis has pipelines directed to the Maasvlakte and Europoort terminals to receive the crude oil from overseas.

Shell Pernis operates several natural gas fired gas turbines to provide steam for the processes on-site. This on-site CHP has a thermal input capacity of 502 MW_{th}, requiring around 10 PJ of natural gas input yearly according to the European list of large combustion plants (LCP) (EEA, 2017). The gas turbine connected to the crude oil distillation of 59 MW_{th} has an annual natural gas demand of 0.9 PJ. Shell has several crude furnaces on-site, fired by refinery gases, total input capacity of 484 MW_{th} (EEA, 2017). The accumulated input of refinery gases for these furnaces is 9.7 PJ/yr in 2017 (EEA, 2017). Smaller units below 50 MW_{th} are not reported in the LCP list.

Below in the table the reconstructed balance of Shell Pernis is presented. It should be noted that these numbers are based on open literature value concerning the process units, obtained from the MIDDEN-report. The report of Oliveira and Schure mentioned the hydrogen production via gasification (104 kt/yr), production via hydrotreating and catalytic reforming (77 kt/yr) and the SMR producing hydrogen (49 kt/yr).

Table 2.15
Material and energy overview of Shell Pernis

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Crude oil	Input	21000	900	(Oliveira & Schure, 2020)
Hydrogen for processes	Input	275	33	Calculated
Steam use in processes	Input	n/a	15-21	(Oliveira & Schure, 2020)
-imported from Pergen	Input	n/a	10-12	Calculated
-own generation	Input	n/a	10-12	Calculated
Electricity use in processes	Input	n/a	3-7	(Oliveira & Schure, 2020)
Total fuel gas and natural gas energy use in final processes	Input	n/a	29-31	(Oliveira & Schure, 2020)
Total fuel gas for furnaces	Input	n/a	14-16	(EEA, 2017)
Total fuel gas for CHP	Input	n/a	2-3	(EEA, 2017)
Fuel gas for Hexion and SNC	Input	n/a	1	This report
Pergen natural gas	Input	n/a	11-13	(EEA, 2017)
Natural gas feedstock for HMU	Input	n/a	3	Estimated
Fuel gas feedstock for HMU	Input	n/a	12	Estimated
Oxygen feed for gasifier (SGHP)	Input	800	n/a	(Shell, 1997)
Refinery oil products	Output	20000	n/a	Calculated based on (Oliveira & Schure, 2020)
Fuel gas production	Output	700	30	Calculated based on (Oliveira & Schure, 2020)
Steam to SNC chemicals	Output	n/a	3	(Block, Gamboa Palacios, & Van Dril, 2020)
Steam to Hexion, etc.	Output	n/a	3	This report
Scope 1 CO_2 emissions	Output	4264	n/a	(NEa, 2019)

Nameplate hydrogen production capacity according to Oliveira and Schure (2020) was 211 kt. Hydrogen consumption in several process units was accumulated, and is now estimated at 275 kt/yr. The hydrogen production capacity for the gasification unit (SGHP) is currently estimated at annually 150 kt; the hydrogen by product of the catalytic reforming unit is 75 kt/yr and the HMU 49 kt/yr.

The Pergen VOF site, owned by Air Liquide, supplies Shell Pernis with steam in addition to their on-site steam generation units, annually around 11 PJ. The 400 kt/yr CO_2 that is captured from the gasifier and transported to Linde Gas for the OCAP application and for a Linde CO_2 liquification plant is included under Shell's emissions in the NEa. The annual CO_2 emissions for Shell can be allocated to process emissions as well as steam generation. At Pernis, the refinery supplies steam and refinery gas to Hexion, Shell Nederland Chemie and Shin-Etsu, which represents a strong dependency.

For the short-term decarbonisation Shell is involved in several big projects. Firstly, the Porthos initiative that will transport and store the CO_2 underneath the North Sea. The Gasification Hydrogen Plant (SGHP) will be directly connected to Porthos. Thus, it can achieve more than 1 Mt reduction of CO_2, but still accommodate the 400 kt horticulture summer peak demand. The current thinking is that the supply to horticulture can partly be accounted for by administrative swapping with biobased CO_2 from Alco to be stored in winter. Furthermore, for heating the refinery furnaces, the refinery gases can be first converted to blue hydrogen using an ATR in the H-vision project. Shell is a partner of Porthos and project partner in H-Vision. CCS could also be applied to the other SMR based hydrogen manufacturing unit (HMU). It is unclear whether this unit will be connected to the CO_2 capture and storage infrastructure, or whether its hydrogen may be replaced by green hydrogen, or how the emissions are dealt with otherwise.

Other decarbonisation plans may include electrification, installation of e-boilers and heat pumps on-site, and replacing steam driven compressors with electric drives all with the intent to drive down the use of steam generated by natural gas.

Shell is currently investing in a biofuels plant to be located on the Pernis east side that produces 820 kt/yr of biofuels. It is to be operational in 2024, indicating a more fundamental decarbonisation measure replacing fossil feedstock (Shell, 2021). This factory uses different kinds of pre-treated oils and fats, residuals from food processing and agriculture and soy and rapeseed oil crops. The installation is also flexible on the output side, producing biodiesel, bio jet fuel and bio naphtha. The biogenic CO_2 that is released during this process can be captured and transported via the Porthos pipeline, storing it underseas or connected to the OCAP. The plant will produce green transport fuels, using low carbon hydrogen and can possible also deliver renewable steam.

For the supply of green hydrogen a 200 MW electrolyser plant on the Maasvlakte is developed, to be ready in 2025. This plant is fed by the Shell and Eneco owned offshore wind park Hollandse Kust Noord (Shell Nederland, 2020). With this plant, 50-60 tonnes/day hydrogen is produced to substitute fossil based hydrogen at the Pernis refinery (Shell Nederland, 2020a). To obtain policy support for such projects, the windfarm that feeds the electrolyser should be connected and newly built, so not a windfarm that has been operational for several years ('additionality criterion').

2.2.16 Shell Nederland Chemie Pernis (SNC)

Shell Nederland Chemie (SNC) Pernis is located on the Shell Pernis refinery site. Originally, Shell chemicals expanded on the Pernis site and due to the lack of space expanded to Moerdijk in 1969 (Wong & Van Dril, 2020). SNC Moerdijk, at around 25 km distance, is connected with underground pipelines to the Shell refinery, enabling the exchange of feedstocks, residual streams and products. In this report the chemical production site of SNC Moerdijk will not be evaluated.

The Pernis petrochemical cluster includes both the refinery and chemical sites, covering a total area of 5.5 km^2 (Shell Chemicals, 2021). Additionally, the Shin-Etsu PVC plant and Hexion Pernis are located at the Pernis site and were previously owned by Shell. Shell Chemicals is established in the Netherlands since 1929, quickly followed by the construction of the refinery at Pernis in 1936 (Block, Gamboa Palacios, & Van Dril, 2020). In 1959 the chemical branch continued under the new name Shell Nederland Chemie (SNC). For a more detailed description of the processes, see Chapter 2 of the report 'Decarbonisation Options for Large Volume Organic Chemical Production, Shell Pernis' (Block, Gamboa Palacios, & Van Dril, 2020).

Table 2.16
Shell Nederlandse Chemie Pernis material and energy overview (Block, Gamboa Palacios, & Van Dril, 2020).

Main products	Capacity (kt/yr)	Process	Feedstock	Feedstock (kt/yr)	Additional inputs	Final Energy (PJ/yr)
Propylene	280	Distillation P-P splitter	Propane/ propylene (P-P) mix[2]	307	-	0.12
Various Hydrocarbon solvents	820	Distillation and hydrogenation	Hydrocarbon mix[3]	604	Hydrogen	0.34
Isopropyl alcohol (IPA)	150	Propylene hydration	Propylene	78	Water	1.12
Methyl Isobutyl Ketone (MIBK)	35	DMK reaction	Acetone (DMK)[4]	38	Hydrogen	0.47
Di-isobutyl Ketone (DIBK)	5	DMK reaction	Acetone (DMK)[3]	5.7	Hydrogen	0.07
Methyl Isobutyl Carbinol (MIBC)	2.5	MIBK hydrogenation	MIBK	2.3	Hydrogen	0.03
PO-Glycol ethers (POGE's)	247	PO etherification	Propylene oxide (PO)[5]	150	Methanol, ethanol	0.35
Methyl Tertiary Butyl ether (MTBE)	170	Reaction of isobutane and methanol	Raffinate 1 (C4's)[6]	94	Methanol	0.54
Secondary Butyl Alcohol (SBA)	105	Sulphuric acid hydration of n-butane	Raffinate 2[7]	85	Water, sulphuric acid	0.54
Methyl Ethyl Ketone (MEK)	90	SBA de-hydrogenation	SBA	88	-	0.39
Polyether Polyols	200	PO etherification	Propylene oxide (PO) / Ethylene oxide (EO)	191	Glycerine, sorbitol, sugar	0.24
Styrene acrylonitrile (SAN) polyols	50	SAN polymerisation	PO, Styrene, acrylonitrile	48	Macromer	0.12

2 The C3 mixture is imported from Shell Refinery Pernis.

3 Hydrocarbon mixture is imported from Shell Refinery (Naptha, C5 cuts), Shell Rheinland (Germany) and Shell Qatar Gas to Liquid (GTL) plants.

4 The acetone (DMK) is imported from external companies

5 Imported from SNC Moerdijk

6 Imported from SNC Moerdijk

7 Raffinate-2 is the by-product of MTBE, after treatment of Raffinate-1

The total energy use for these processes amounts to 4.4 PJ/year, subdivided in 3.1 PJ steam, 0.5 PJ hot oil, 0.4 PJ electricity and 0.2 PJ fuel gas. Most of the energy needs for SNC Pernis is supplied by the adjacent refinery. This also is assumed for the hydrogen supply, which is estimated to be less than 10 kt.

An important product for the surrounding companies is the propylene flow from the refinery processes, further separated by SNC Pernis. Propylene production from steam cracking in Moerdijk amounts to supply another 500 kt/yr. Propylene is feedstock for the propylene oxide production at SNC Moerdijk, for SNC's own IPA plant, for the epichlorohydrin production at Hexion Pernis and also for Lyondell. The propylene oxide produced at SNC Moerdijk is transported to SNC Pernis and utilized for the POGE and polyols production.

The annual CO_2 emissions for the SNC Pernis site amount to only 36 kt/yr since most of the energy is provided by the refinery steam generation and hot oil systems, resulting mainly in Scope 2 emissions. Half of the Scope 1 emissions originate from the fuel combustion in the furnaces and the remaining part originates from the combustion of residual gases (Block, Gamboa Palacios, & Van Dril, 2020). The refinery supplies SNC Pernis with some fuel gas to fire the furnaces and incinerators. Most of the energy demand in SNC Pernis processes originates from heating requirements on relatively low temperatures, from less than 100 °C to 300 °C, only MEK requires around 500 °C.

Similarly to Hexion Pernis, Shell Chemie Pernis depends heavily on the Shell refinery energy system for decarbonisation. For the residuals combustors, CCS seems to be the ultimate decarbonisation option. Shell is already customer in the Porthos initiative for CCS and in OCAP for CCU. Since the majority of the energy demand is relatively low and medium temperature steam, electrification by installing e-boilers is deemed feasible. Also, the steam turbine in the IPA process could be replaced by an electric motor drive of around 5 MW.

2.2.17 Esso Nederland B.V. Refinery

Esso Nederland B.V. is a subsidiary of the American ExxonMobil Corporation. The refinery was built in 1958, located at the Botlekweg 121. Over the years the plant has undergone several renovations, a visbreaker, flexicoker, cogen (CHP installation) and hydrocracker were added. The hydrocracker on site was extended and adjusted based on the changing demands from the industry and customers. ExxonMobil chemicals is closely linked and adjacent to the refinery with the Rotterdam aromatics plant (RAP) and the Rotterdam plasticizers plant (RPP). At some distance in Europoort Rotterdam is the connected oxo-alcohols plant (ROP). The basic information in this section is derived from MIDDEN studies (Advani & Van Dril, 2020; Oliveira & Schure, 2020).

Due to the increased hydrogen demand following the hydrocracker extension, in 2010 Air Products built their hydrogen facility at the ExxonMobil Rotterdam Refinery site (Air Products, 2012). This 300 tonne/day SMR plant uses refinery gas from ExxonMobil refinery and natural gas, delivering hydrogen and steam to the refinery. The hydrogen SMR uses on average 60-70% of refinery gas input, and additionally uses natural gas. ExxonMobil also has an older hydrogen production facility on site. The cogen (CHP) on-site uses high-calorific gas (HJG) to produce electricity and steam. The electricity generated covers around half of the site demand. Steam is generated from the CHP (3.9 PJ/yr), from boilers fired by mixes of refinery gas and low calorific gas (LJG) (4 PJ/yr), from the Air Products SMR (2.3 PJ/yr), and additionally from all kinds of furnace waste heat.

The refining processes at the Rotterdam refinery are installations for atmospheric distillation, vacuum distillation, catalytic reforming, hydrocracking, hydrotreating and a flexicoker. The feedstock

for the Rotterdam refinery exists out of crude oil with an annual input of 9140 kt, and other fractions are also processed, to an estimated total input of 10.5 Mt (Oliveira & Schure, 2020). In Table 3 the in- and outputs of the refinery and the integrated Rotterdam Aromatics Plant (RAP) can be seen. A relatively large share of the products are sold to the petrochemical sector (steam crackers, aromatics). For a more detailed description of the processes, see the report, chapter 2 on Decarbonisation Options for the Dutch Refinery Sector (Oliveira & Schure, 2020).
The throughput of the hydrocracker can be optimally utilized to produce more synthetic lube oil, diesel and jet fuel and less gasoline or non-synthetic lube oil (HaskoningDHV, 2015).

Table 2.17
Esso Nederland -ExxonMobil Refinery Rotterdam + RAP material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Crude oil	Input	9140	400	(HaskoningDHV, 2015)
Heavy oil fractions	Input	882	35	(HaskoningDHV, 2015)
Naptha/gasoline/gasoline components	Input	392	18	(HaskoningDHV, 2015)
Raw chemicals for RAP[a]	Input	1767	n/a	(HaskoningDHV, 2015)
Hydrogen	Input	166	20	(HaskoningDHV, 2015)
- from Air Products	Input	105	12.7	Calculated
-own SMR (WSP)	Input	26	3.1	(Oliveira & Schure, 2020)
-reformer byproduct	Input	~50	4.2	(Oliveira & Schure, 2020)
Steam generation for processes	Input	n/a	20	(Advani & Van Dril, 2020)
-from CHP and boilers	Input	n/a	8	(Advani & Van Dril, 2020)
-from Air Products	Input	n/a	2	(Advani & Van Dril, 2020)
-from various processes	Input	n/a	10	(Advani & Van Dril, 2020)
Electricity use in processes	Input	n/a	2.1	(Advani & Van Dril, 2020)
Total fuel gas/natural gas energy use in processes incl. RAP	Input	n/a	19	(Advani & Van Dril, 2020)
-Total fuel gas/natural gas energy use in larger refinery processes	Input	n/a	14-15	(Oliveira & Schure, 2020)
-Total fuel gas/natural gas demand for hydrogen production via SMR	Input	n/a	3	Calculated
LPG	Output	496	n/a	(HaskoningDHV, 2015)
Naptha/gasoline/gasoline components	Output	2178	n/a	(HaskoningDHV, 2015)
Diesel and kerosene	Output	5818	n/a	n/a (HaskoningDHV, 2015)
Basic oil	Output	1016	n/a	(HaskoningDHV, 2015)
Aromatics[b]	Output	1399	n/a	(HaskoningDHV, 2015)
Sulfur	Output	128	n/a	(HaskoningDHV, 2015)
Cokes	Output	105	n/a	(HaskoningDHV, 2015)
Fuel gas	Output	1206	39[c]	(HaskoningDHV, 2015)
-energy for furnaces	Output	n/a	16	(Advani & Van Dril, 2020)
-for steam generation/CHP	Output	n/a	10	(Advani & Van Dril, 2020)
-to own SMR (WSP)	Output	n/a	3	Calculated
-to Air Products SMR	Output	n/a	10	(Advani & Van Dril, 2020)
Steam use for refinery processes	Output	n/a	9	Estimated
Steam to RAP	Output	n/a	10	(Advani & Van Dril, 2020)
Steam to RPP	Output	n/a	0.4	(Advani & Van Dril, 2020)
Scope 1 CO_2 emissions Refinery	Output	2373	n/a	(NEa, 2019)
Scope 1 CO_2 emissions RAP	Output	453	n/a	(NEa, 2019)

a) The input of raw chemicals is related to the inputs of the RAP production site.

b) The aromatics produced can be allocated to the RAP production site.

c) Based on (Advani & Van Dril, 2020), appendix. This is a mix of gas flows with different calorific values.

The annual steam demand for the refinery processes is 9 PJ and total electricity use 2.1 PJ/yr. The refinery is self-sufficient regarding heat demand, using the produced fuel gases internally for furnaces, generation of steam via boilers or CHPs and hydrogen production. The refinery has only minor needs for natural gas in specific applications. Greenhouse gas emissions peaked in 2019 at 2373 kt/yr of CO_2 and originate mostly from thermal combustion processes (around 70%) and the remainder can be allocated to cracking, coke gasification and other process emissions. Fuel gas and steam are delivered to ExxonMobil RAP and ExxonMobil RPP, and some fuel gas to Air Liquide.

The furnaces and hydrogen production are responsible for a large chunk of the annual Scope 1 emissions. Relatively pure flow capture of CO_2 can be applied to the hydrogen production facility (and the Air Products hydrogen facility) with transport to Porthos. ExxonMobil is also studying post-combustion capture at its SMR (WSP). ExxonMobil is a partner in the Porthos initiative and H-vision, providing realistic short-term decarbonisation options. H-vision aims to collect the refinery gases at an autothermal reformer (ATR) located at the Maasvlakte; the produced blue hydrogen will afterwards be transported back to the refineries to serve as fuel for furnaces.

Additional short-term substantial reduction (0.2-0.3 Mt) could be achieved by several energy efficiency and electrification projects. An extension of the electricity network could be required for electrifying shaft equipment and potentially e-boilers although this reduction potential is minor compared to the Porthos and H-vision plans. Furthermore, ExxonMobil has been active in initiatives for waste heat supply in district heating projects. Developing these projects encounters lengthy and complicated decision processes of multiple stakeholders.

2.2.18 ExxonMobil Chemicals

ExxonMobil founded the refinery (Esso Refinery) in 1958 which produced materials for the aromatics production sector. A few years later, ExxonMobil built their own Rotterdam Aromatics Plant (RAP) on the refinery site and later on expanded with the Rotterdam Oxo-alcohol Plant (ROP) and Rotterdam Plasticizers and Intermediates Plant (RPP) (Advani & Van Dril, 2020). The RAP plant and RPP plant are located adjacent to the refinery, the ROP plant is located in Europoort (15 km distance to refinery). For a more detailed description of the processes present at RAP, RPP and ROP, see the MIDDEN report, chapter 2 on Decarbonisation Options for ExxonMobil Chemicals Rotterdam (Advani & Van Dril, 2020).

ExxonMobil Chemicals RAP

The Rotterdam Aromatics Plant (RAP) owned by ExxonMobil is operational since 1963 and located at Botlekweg 121. The aromatics plant utilizes the output of the Esso refinery and third party supply of steam cracked naphtha and aromatic concentrates from catalytic reformers (ExxonMobil, 2015). Important process steps include the hydrogenation of steam cracked naphtha, several separation steps based on difference in boiling points, crystallization, centrifugation and catalytic conversions in the presence of hydrogen. ExxonMobil RAP receives its hydrogen from the refinery hydrogen grid.

Table 2.18
ExxonMobil RAP energy and material in- and outputs (Advani & Van Dril, 2020)

	In/out	Amount (kt/yr)	Energy (PJ/yr)	Product applications
Steam cracked naptha / aromatic concentrates / olefins	Input	1510	n/a	n/a
Hydrogen[a]	Input	20	n/a	n/a
Fuel gas from refinery	Input	n/a	3	n/a
Steam from refinery	Input	n/a	10	n/a
Electricity	Input	n/a	1	n/a
Orthoxylene	Output	149	n/a	Feedstock for phthalic anhydride production, coatings and plastics
Paraxylene	Output	775	n/a	For production of TPA and DMT, polyester fibres, PET bottles
Cyclohexane	Output	282	n/a	Manufacturing of cyclohexanone, solvent for paints, resins, varnish. Used for production of nylon6 and nylon6.6
Benzene (mostly intermediate)	Output	832	n/a	Plastics, resins, synthetic fibres, lubricants, dyes, pesticides, gasoline, glues, adhesives, cleaning products and paint
Toluene (mostly intermediate)	Output	301	n/a	Paints, rubbers, plastic, lacquers, glues, adhesives, nail polish remover, resins, hardeners and lacquers
Residual stream[b]	Output	151	n/a	n/a
Scope 1 CO_2 emissions (2019)	Output	453	n/a	n/a

a) Hydrogen supplied by the refinery system

b) Residual stream is sent back to the adjacent refinery

The RAP CO_2 emissions are reportedly 453 kt/yr (NEA, 2019). The vast majority of the emissions originate from the furnaces that combust refinery gas (both LJG and HJG). The refinery, RPP and RAP are closely linked and share their utilities.

ExxonMobil Chemicals RPP

The Rotterdam Plasticizers and Intermediates Plant (RPP) is also located in the Botlek area at Welplaatweg 2, adjacent to the refinery. The site was constructed in 1978 and is similarly to the RAP closely linked with the refinery concerning steam supply and fuel gas. The main output of the RPP site are plasticizers with an annual production capacity of 420 kt. Plasticizers make 'hard' plastics soft and pliable, commonly applied in textile, cables, wallpapers, carpeting, furniture and footwear flexibles. The production site can be divided into two sections, the phthalic anhydride (PAN) section and plasticiser section.

In the PAN section the ortho-xylene supplied by the adjacent ExxonMobil RAP undergoes an oxidation reaction to produce phthalic anhydride (Advani & Van Dril, 2020). The pure phthalic anhydride is either stored in product tanks or directed to the plasticiser plant. During the oxidation step the undesired maleic anhydride is formed, resulting in significant CO_2 process emissions, around 90% of the total emissions of the RPP plant (27 kt/yr) (NEa, 2019). The phthalic anhydride produced in the PAN section functions as feedstock for the plasticiser section, producing the plasticizers (420 kt/yr). Plasticizers are produced by esterification of C9-C13 oxo-alcohols, supplied by the ROP plant or external tank terminal, with phthalic anhydride. Alcohol is removed from the plasticizers during the process and stored in tanks for reuse. The plasticiser products are delivered to third parties by trucks or via pipelines. Nitrogen is required during the dewatering step and delivered by third parties utilizing underground pipelines (Advani & Van Dril, 2020)

Table 2.19
ExxonMobil RPP energy and material in- and outputs (Advani & Van Dril, 2020)

	In/out	Amount (kt/yr)	Energy (PJ/yr)	Product applications
Steam use from refinery	Input RPP	n/a	0.4	n/a
Electricity	Input RPP	n/a	0.1	n/a
Ortho-xylene	Input PAN section	66	n/a	n/a
Oxygen	Input PAN section	pm	n/a	n/a
Phthalic anhydride	Output PAN section	70	n/a	Preparation of the anthroquinone dye quinizarin, production of plasticizers such as Vestinol 9 DINP (diisononyl Phthalate)
Maleic anhydride	Output PAN section	minor	n/a	n/a
Phthalic anhydride	Input plasticiser	70	n/a	n/a
Oxo-alcohols	Input plasticiser	306	n/a	n/a
Plasticisers	Output plasticiser	420	n/a	Flexible PVC products for automotive industry, flexible PVC products, wire and cable application, electrical wire insulation, coatings and food contact applications.
Scope 1 CO_2 emissions (2019)	Output RPP	27	n/a	n/a

ExxonMobil Chemicals ROP

This Rotterdam Oxo-alcohol plant (ROP) is located at Merwedeweg 21 and belongs to ExxonMobil since 1982, prior to that the plant was owned by AkzoNobel (Nobian). At the ROP, olefins are converted to a variety of oxo-alcohols consisting out of iso-octyl alcohol, isononyl alcohol, isodecyl and undecyl alcohol and a residual stream (Advani & Van Dril, 2020). These oxo-alcohols are used as raw material for the plasticiser production at RPP and are delivered by pipeline. The oxo-alcohols not utilized by RPP are shipped to third parties.

Raw materials for the ROP consist out of C7-C10 olefins and synthesis gas delivered by Air Liquide. Olefins are desulfurized and consequently converted into aldehydes and oxo-alcohols via oxonation. Further separation and purification include hydrogenation, distillation columns and crackers to obtain oxo-alcohols. Annual CO_2 emissions reported by NEa amount to 54 kt and process emissions are assumed to be negligible. The energy used in the ROP consists out of natural gas and residual gas use for the steam boilers and electricity.

Table 2.20
ExxonMobil ROP energy and material in- and outputs (Advani & Van Dril, 2020)

	In/out	Amount (kt/yr)	Energy (PJ/yr)	Product applications
Olefins C7-C10	Input	292	n/a	n/a
Syngas	Input	91	n/a	n/a
Net steam use	Input	n/a	1.0	n/a
Electricity use	Input	n/a	0.1	n/a
Oxo-alcohols	Output	345	n/a	Production of plasticizer, acrylates, acetate, resins, solvents, glycol ethers, lubes and blending into gasoline.
Residuals	Output	38	n/a	n/a
Scope 1 CO_2 emissions	Output	54	n/a	n/a

Decarbonisation of the RAP and RPP plants is closely linked with the decarbonisation of the adjacent Esso refinery. Relatively pure flow CCS is applicable on the hydrogen production facilities. The partnership with Porthos and H-vision provides viable options for ExxonMobil to utilize the refinery gasses in the production of blue hydrogen, which can also be used by the RAP, RPP and ROP.

For further decarbonisation of the steam system, demand could be reduced by electrification of the low temperature processes with e-boilers. Process emissions and emissions from combustion of the various residual flows still have to be addressed by post combustion CCS technology.

2.2.19 Huntsman Holland

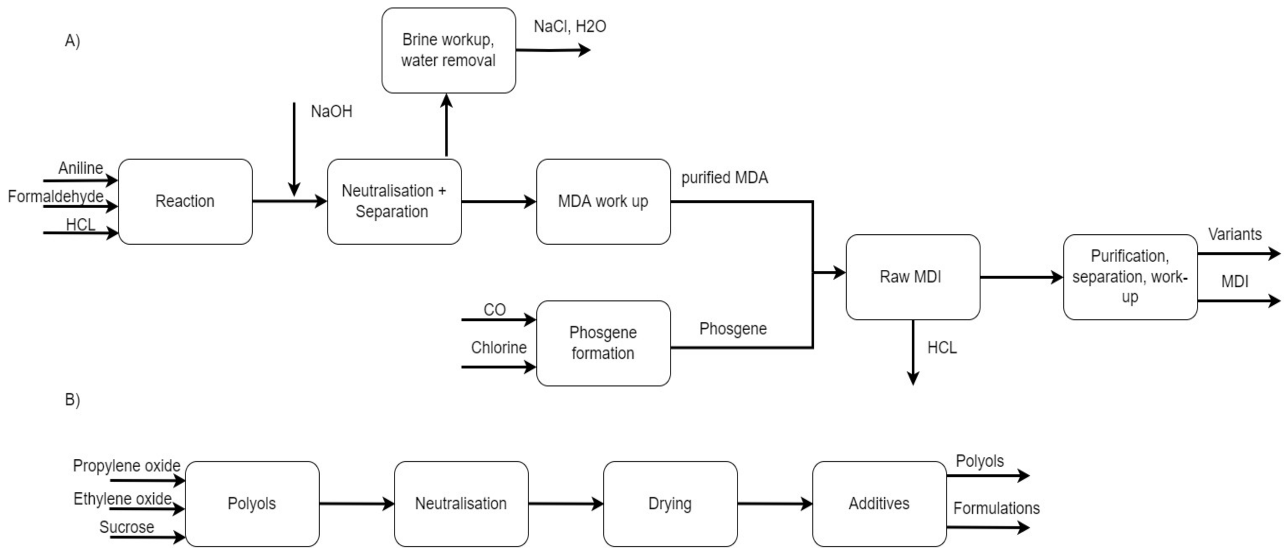
Huntsman Holland is located at the Merseyweg 10 together with Air Liquide and Ducor. The site adjacent belongs to Lyondellbasell Chemie. The site was built in 1961 and formerly owned by ICI, in 1999 Huntsman acquired the site and their core business includes the production of intermediate products for the polyurethane industry (Botlek Europoort, 2020c). Key product is MDI (methyleendifenyldi-isocyanaat), a precursor for polyurethane foams. The polyurethane foams are mainly used in construction, packaging, thermal insulation, furniture, bedding and transportation. MDI can also be used for the production of binders, adhesives and coatings.

The annual production capacity is 420 kt of MDI and variants (155 kt). Huntsman furthermore produces polyols (70 kt) and formulations (30 kt) (Port of Rotterdam, 2016). For the production of MDI, hydrochloric acid, aniline and formalin react to 4,4'-Methylenedianiline (MDA, also known as DADPM) (Huntsman), (RVO, 2012). The aniline is imported from abroad (Plastics Today, 2008). Sodium hydroxide is added to neutralize the MDA and separate the brine from MDA. Phosgene is produced by passing carbon monoxide and chlorine gas over a catalyzed bed. The purified MDA and phosgene react to raw MDI and several purification and separation steps are performed in order to achieve the end products MDI and variants (Falcke, et al., 2017).

The polymerization polyol production process requires raw materials propylene oxide, ethylene oxide and initiator alcohols are glucose, glycol, sorbitol or amines (Huntsman) (Block, Gamboa Palacios, & Van Dril, 2020). A wide range of polyols are produced along with formulations.

Below, in Figure 2.7, both production sections for Huntsman are depicted. The MDI process is the main energy consumer compared to the polyol production processes.

Figure 2.7
Huntsman production steps



In A) the MDI and variants production route is visible, in B) the polyol production steps. Adapted from (Huntsman; RVO, 2012).

According the DCMR emission registration, the annual CO_2 emissions are only 0.25 kt/yr (DCMR, 2019a). It is apparent that Huntsman Holland outsources most of the required utilities such as steam and electricity. The energy demands of the Huntsman site are estimated to be 2.0-3.0 PJ/yr of steam and 0.3-0.8 PJ/yr of electricity.

Huntsman is closely linked with several surrounding companies. All of Huntsman raw materials are currently produced by surrounding companies in the Botlek, resulting in a two-sided dependency. In the chlorine cluster, Huntsman receives NaOH and chlorine from Nobian. The by-product HCl is sent back to Nobian and Shin-Etsu in order to minimize the waste of chlorine (Bedrijvenpark Botlek, 2020). The steam demand is covered by Air Liquide, located on-site with Huntsman, operating the Eurogen and Enecal CHP. Air Liquide also provides the carbon monoxide (CO), formaldehyde can be sourced from Bakelite Synthetics (Botlek) or Caldic (Europoort).

Huntsman uses its private steam network to deliver steam and/or electricity to Invista, Lucite, Ducor Rozenburg and Wilmar Oleochemicals, passing through the steam that is supplied by Air Liquide. Huntsman is the largest consumer of the incoming steam and electricity compared to the other companies present at the former ICI site. Lyondell Chemie, adjacent to Huntsman, produces ethylene oxide and propylene oxide that can serve as raw materials in the polyol production process. There is no steam exchange between Lyondell Chemie and Huntsman. Located near the Huntsman Holland site is the Central Wastewater Treatment Botlek owned by Evides Industriewater, processing the waste water from Huntsman (EuropoortKringen, 2021).

Table 2.21
Huntsman Holland material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
HCl catalyst	Input	pm	n/a	n/a
Aniline	Input	475	n/a	reaction stoichiometric[b]
Formaline	Input	75[a]	n/a	reaction stoichiometric
Chlorine	Input	326	n/a	reaction stoichiometric
Carbon monoxide	Input	145	n/a	reaction stoichiometric
Ethylene oxide, propylene oxide, sucrose for polyols	Input	pm	n/a	n/a
Steam use	Input	n/a	2.0-3.0	Estimate
Electricity use	Input	n/a	0.3-0.8	Estimate
MDI	Output	420	n/a	(Port of Rotterdam, 2016)
Polyols	Output	70	n/a	(Port of Rotterdam, 2016)
Variants	Output	155	n/a	(Port of Rotterdam, 2016)
Formulations	Output	30	n/a	(Port of Rotterdam, 2016)
HCl	Output	335	n/a	reaction stoichiometric
Scope 1 CO_2 emissions	Output	0.249	n/a	(Emissieregistratie, 2019)

a) formaldehyde weight is used

b) 90% overall yield assumed

Huntsman hardly emits CO_2 directly, is not part of the EU ETS and neither subject to the Dutch CO_2 taxation. Indirectly, carbon costs are involved in the steam and electricity pricing. Short-term decarbonisation targets for Huntsman include the decarbonisation of electricity and steam (Scope 2). In 2021, Huntsman applied for a permit to install two e-boilers with the combined capacity of 50 MW (DCMR, 2021). The scope-2 emissions related to steam generation by Air Liquide can therefore be reduced, however Huntsman will still be dependent on Air Liquide for part of the steam supply.

Other decarbonisation options include the substitution of propylene oxide and ethylene oxide (PO/EO) with biobased PO/EO, depending on the availability in the Botlek. In 2019/2020 Huntsman made an contractual agreement with a green electricity supplier that covers all of their electricity needs from the external grid. The long term decarbonisation focus for Huntsman is on the circularity of their core products, focusing on the end-use of the products that are produced. Recycling of products can potentially become a new department for Huntsman in 2050, decreasing the annual production capacities. The recycling of the released brine is currently not attractive for Huntsman, due to the high purity demands and pipeline investment costs.

2.2.20 Tronox Pigments Holland

The site is located at Prof. Gerbrandyweg 2 and has been operational since 1962 and was previously owned by Kerr-McGee (Tronox Pigment Holland, 2021). In 2000 Tronox acquired the site and is currently the sole producer of titanium dioxide pigment in the Netherlands. The titanium dioxide is produced using the chloride process to separate the titanium from its ores (Tronox, 2017; ICIS, 2021). The titanium is mined in South Africa and Australia (RSI Technology Channels, 2017). Titanium dioxide is widely used in coatings, construction, plastics, paper, inks and paint due to its white pigment.

The annual production capacity is 90 kt and important raw materials include titanium ores, petroleum cokes and chlorine (Port of Rotterdam, 2016). Tronox is dependent on the chlorine supply by Nobian in Botlek, otherwise the production process ceases when stored capacity is depleted. The production process is divided into two sections, firstly the titanium ores enter the chlorination reactor where cokes are added and chlorine gas is blown into the reactor at relatively high temperatures of 800-1000 °C (Watertalent, 2021a; Bordbar, Yousefi, & Abedini, 2016; Huizinga, Verburgh, Matthijsen, & Crijns, 1992). The desired product $TiCl_4$ is formed amongst other metal chlorides and further purified before the oxidation (air/oxygen) occurs to create TiO_2..The chlorine is released during oxidation and recycled back to the chlorination step (Watertalent, 2021a). In a second plant, the Finishing Plant, the TiO_2 is used and further processed into the customer demands. During the chloride process hydrogen chloride and metal chlorides are produced as by-product. Steam is used for drying and finishing.

The annual Scope 1 CO_2 emissions for Tronox Pigments Holland amount to 84.6 kt. In the chloride process the carbon enters via petroleum cokes so part of the annual emissions are process emissions (assumed to be 80% of total Scope 1 emissions). The remaining part of emissions are assumed to be correlated to the on-site steam generation and therefore originate from natural gas (20% of total Scope 1 emissions).

Tronox is involved in the chlorine-cluster that is present in the Botlek area. Furthermore, the adjacent AVR Rijnmond and Cabot are connected to the steam pipeline and supply Tronox with steam (Manders, 2013; Technisch Weekblad, 2008).

Table 2.22
Material and energy overview Tronox Pigments

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Titanium ores	Input	100	n/a	90% purity TiO2
Chlorine	Input	160	n/a	calculated, incl. 80% recycled
Natural gas use for heating	Input	n/a	0.25-0.35	(NEa, 2019)
Petroleum cokes	Input	19	0.65-0.75	(NEa, 2019)
Steam imported from AVR	Input	n/a	0.6-0.7	(Technisch Weekblad, 2008)
Electricity imported	Input	n/a	0.1-0.2	Estimate
Titanium dioxide	Output	90	n/a	(Port of Rotterdam, 2016)
Recycled chlorine **Hydrogen chloride and metal chlorides**	Output	130 pm	n/a	20% loss assumed (Vynova, 2019)
Scope 1 CO_2 emissions	Output	84.6	n/a	(Emissieregistratie, 2019)

Decarbonisation strategies for Tronox could include CCS and the replacement of natural gas by blue hydrogen for the furnaces and/or boilers. Since the process occurs at relatively high temperatures (around 1000 °C), electrification might not be sufficient here. The feasibility of post-combustion capture of CO_2 on the furnace has not been specifically investigated, but seems the most logical option to also reduce the process emissions. This would require post combustion capture of the relatively pure flow of CO_2, and connection to Porthos.

2.2.21 Ducor Petrochemicals

Ducor Petrochemicals is located at the Merseyweg 24 in Rozenburg-Rotterdam, on-site with Huntsman and adjacent companies Wilmar Oleochemicals, Invista and Lucite International Holland. Ducor Rozenburg is the second largest producer of polypropylene after SABIC Geleen (Negri &

Ligthart, 2021). Ducor solely produces polypropylene (PP) with a production capacity of 200 kt/yr (Port of Rotterdam, 2016). In 1979 the plant was built by Basell and in 2007 the company merged with Lyondell. The company was acquired by DOMO, a big petrochemical company of Israel, and changed name in 2011 to Ducor Petrochemicals.

Ducor Rozenburg has three production lines that can produce different types of polypropylene resins and is connected to an efficient system of pipelines for the supply of feedstock and utilities (A. Negri, 2021). Polypropylene is semi-rigid, translucent plastic and has a high resistance to heat, electricity and chemicals. A major advantage is the ability to alter the product properties by changing the share of co-monomers during the polymerization process. The applications of polypropylene is therefore extensive, including the flexible and rigid packaging sector, household sector, building and construction sector and automotive sector.

Air Liquide supplies Ducor with electricity, steam and industrial gases via the Huntsman energy system. PP is produced with a gas phase process where the gaseous propylene, co-monomer, catalyst and hydrogen are mixed and compressed before the polymerization step. After polymerization, the resulting polymer powder is extracted at the bottom of the reactor and moved to a nitrogen degassing vessel to deactivate the catalyst. Afterwards, additives are added to the polymer mix and followed by drying, blending, degasification steps of the residual monomer. Based on average literature values and the MIDDEN report (Negri & Ligthart, 2021), the annual heat demands linked to the production capacity of 200 kt of PP are 0.12 PJ. Electricity demands are annually 0.26 PJ. Annual greenhouse gas emissions amount to 15.94 kt and are assumed to originate from flaring and incinerating waste flows (DucorChem, 2020).

Table 2.23
Material and energy overview Ducor

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Propylene	Input	~200	n/a	(Negri & Ligthart, 2021)
Hydrogen	Input	Pm	n/a	(Negri & Ligthart, 2021)
Co-monomer	Input	Pm	n/a	(Negri & Ligthart, 2021)
Heat use	Input	n/a	0.12-0.13	(Negri & Ligthart, 2021)
Electricity use	Input	n/a	0.24-0.26	(Negri & Ligthart, 2021)
Polypropylene	Output	200	n/a	(Negri & Ligthart, 2021)
Scope 1 CO_2 emissions	Output	15.94	n/a	(Emissieregistratie, 2019)

Decarbonisation for the Ducor site could include reprocessing of the flared gases and further optimization of other residual flows. Ducor is located near the planned hydrogen backbone which provides possibilities for the use of hydrogen instead of natural gas for steam generation on-site. In the future, mechanical or thermal recycling of plastics could significantly reduce the need for new plastics and thereby the production capacity. Another decarbonisation option for Ducor is shifting to biobased propylene, which is dependent on the availability of biobased propylene in the future.

2.2.22 Shin-Etsu PVC B.V.

Shin-Etsu PVC B.V. is a subsidiary of Shin-Etsu Chemical Co., one of the largest chemical companies in Japan. In 1999 Shin-Etsu Chemical Co. acquired two plants in Rotterdam, one located in Botlek adjacent to Nobian and one located at Pernis, on-site with Shell (Semeijn & Schure, 2020). The site located in Botlek at Welplaatweg 12 is producing 670 kt/yr vinylchloride monomer (VCM) and 80 kt/yr high purity 1,2-dichloroethane (Port of Rotterdam, 2016). The VCM is transported via the Multicore pipeline system to the site located at Pernis where the VCM feedstock is used to produce polyvinyl chloride (PVC) (Semeijn & Schure, 2020). PVC product applications include the construction sector, pipes, fittings, cables and flooring. It is a strong, lightweight, resistant to weathering and cost-effective product and therefore widely applied.

Shin-Etsu VCM, Botlek site

At the Botlek site, VCM is produced from the raw materials chlorine, ethylene and oxygen. Two processes are applied to produce the intermediate EDC, 1,2-ethylenedichloride. One method, the low temperature direct chlorination, uses ethylene and chlorine. In the other method, oxychlorination, the building blocks consist out of ethylene, hydrogen chloride and oxygen to produce EDC and water. Both are highly exothermic reactions and low temperature steam is produced using external heat exchangers. Nobian, located adjacent to the Shin-Etsu Botlek site, delivers their high temperature steam to Shin-Etsu Botlek and approximately half of that amount in energy terms is delivered back in the form of low temperature steam. The hydrogen chloride required for oxychlorination is supplied by Hexion and Huntsman. Chlorine and additional hydrogen are supplied by Nobian. Oxygen can either be pure oxygen or ambient air. Two recently replaced reactors are air fed and the third reactor is oxygen fed, the exact distribution is however unclear.

Heat generated in a large natural gas-fired furnace (80 MW_{th}) decomposes EDC at 500 °C into VCM and hydrogen chloride, an endothermic cracking process. This cracking step is the main source of the CO_2 emissions of 102 kt/yr for Shin-Etsu Botlek and responsible for 73% of the total emissions yearly (Semeijn & Schure, 2020; NEa, 2019). The EDC, hydrogen chloride and other by-products are separated by distillation and the VCM is neutralized with NaOH to remove any traces of hydrogen chloride. The NaOH is supplied by Nobian. Based on the report of Semeijn & Schure (2020) and the annual production capacity of 670 kt VCM, the annual energy demand for steam is around 0.94 -1.47 PJ, for electricity between 0.46 -0.54 PJ and natural gas around 2.01-2.08 PJ. The total energy demand for Shin-Etsu is between 3.4-4.1 PJ.

Table 2.24
Shin-Etsu VCM Botlek material and energy overview

	In/out	Capacity (kt/yr)	Energy (PJ/yr)	Source
Chlorine	Input	388	n/a	(Semeijn & Schure, 2020)
Ethylene	Input	308	n/a	(Semeijn & Schure, 2020)
Air[a]	Input	489	n/a	(Semeijn & Schure, 2020)
Oxygen[a]	Input	94	n/a	(Semeijn & Schure, 2020)
Steam use	Input	n/a	0.94 - 1.47	(Semeijn & Schure, 2020)
Electricity use	Input	n/a	0.46 – 0.54	(Semeijn & Schure, 2020)
Natural gas use	Input	n/a	2.01 – 2.08	(Semeijn & Schure, 2020)
VCM	Output	670	n/a	(Semeijn & Schure, 2020)
Scope 1 CO_2 emissions	Output	102	n/a	(NEa, 2019)

a) It is not clear how the distribution of input concerning air and oxygen is at Shin-Etsu, these values are therefore maximums.

Shin-Etsu PVC, Pernis site

At Shin-Etsu Pernis the VCM is used to produce PVC, polyvinyl chloride, via a polymerization reaction. Water is required as raw material and after polymerization the VCM is recovered and recycled to the polymerization step. There is still a large fraction of water present in the PVC product that is removed by mechanical- and thermal drying steps followed by fluidized bed drying and flash drying. The PVC production process does not require natural gas for heat demands and since the Pernis site is not registered in NEa emission database, it can be assumed that the process emits no CO_2. Furthermore, the Pernis site receives its utilities (electricity and steam) from third parties (Semeijn & Schure, 2020). Shin-Etsu Pernis consumes 1.1 PJ steam annually and 0.4 PJ electricity (Semeijn & Schure, 2020).

The decarbonisation of Shin-Etsu is mainly focused on the Botlek site since all of the Scope 1 emissions originate from that site. The main source of emissions of the Botlek site is the cracking furnace, fuel substitution by blue hydrogen can significantly reduce those Scope 1 emissions although the TRL is still low. Alternatively, the furnace can be replaced by a fully electrified furnace but this is paired with high investment costs. The natural gas fired burners installed in the cracking furnace emit CO_2 in the flue gas that can be captured by a post-combustion capture unit and connected to Porthos (CCS). The steam supply connected to the Scope 2 emissions can be further reduced, here Shin-Etsu depends on efforts of Nobian and Shell/Pergen/Air Liquide.

2.2.23 Terminals in Botlek

Several terminal companies are located in the Botlek with direct deep-sea access to the refineries and chemical plants. Their core business exists out of the storage of chemicals, trans-shipment of commodities like oil and chemicals from marine, road, rail and pipeline transport and sometimes the mixing or heating of chemicals in storage. A few of the bigger terminals are discussed shortly, however the terminals may not be key players in direct CO_2 reduction and are therefore not analysed in depth. Terminals and pipelines are crucial for the supply chain infrastructure but will most likely adapt to the customer demands and follow decarbonisation developments from customers (Van den Beukel, Van Geuns, Patrahau, & Rademaker, 2021).

Table 2.25
Terminals in Botlek

Terminal	Location	Storage capacity (m^3)	Products	Source
Rubis Terminal	Welplaatweg 26	161 000	Fuel oil, gasoil, diesel, chemicals, niche products	(VOTOB, 2021a)
Vopak Terminal Botlek	Welplaatweg 110	884 844	Petroleum products, chemicals	(VOPAK , 2021)
Vopak Terminal Laurenshaven	Montrealweg 25	923 818	Petroleum products	(VOPAK , 2021)
Vopak Terminal TTR	Torontostraat 19	326 066	Petroleum products, chemicals	(VOPAK , 2021)
Koole (Odfjell) Terminal Botlek	Oude Maasweg 6	1 622 000	Chemicals, mineral oil products, acids, biofuels, base oils	(Koole Terminals, 2021)
HES Botlek Tank Terminal	Montrealweg 151	510 000	Petrol, diesel, ethanol, MTBE, biofuels	(VOTOB, 2021)

The total Scope 1 CO_2 emissions for these 6 terminals is 40 kt in 2019 (NEa, 2019). Koole Terminal Botlek and Vopak Terminal Botlek contribute to the majority of the annual emissions, it is expected that these emissions arise from the heating facilities. Therefore, the emissions are assumed to originate from natural gas or oil combustion. Vopak Terminal Botlek is involved in the Multicore C.V. pipeline system in collaboration with Port of Rotterdam, explained further in section 3.2. The decarbonisation of the terminals is mainly focused on the heating facilities. Low temperature heat is expected to be delivered by a residual waste heat system or potentially e-boilers. Venting and flaring can be further reduced by reprocessing these gases.

2.2.24 Kemira Rotterdam

Kemira Rotterdam has two sites in the Port of Rotterdam, one located in Botlek and one in Europoort Moezelweg 151. The Botlek site is located at Botlekweg 175, between Cabot B.V. and AVR Rijnmond. Kemira Rotterdam B.V. is a subsidiary of Kemira Oyj, a Finnish company that specializes in sustainable chemical solutions for water intensive industries worldwide (Botlek Europoort, 2020a). The core business of Kemira Botlek exists out of the production of products for water purification. Annual production capacity of polyacrylamides, also known as chemical flocculants, is 150 kt for the Botlek site (Port of Rotterdam, 2016).

The chemical flocculants types consist out of cationic, anionic or non-ionic polyacrylamides (Kemira, 2021). Sludge conditioning is one of the key application of flocculants, accurate sludge conditioning can decrease the amount of sludge and cut costs for water treatment facilities. Cationic polyacrylamides are, among other applications, used for dewatering of sludge from biological processes. The anionic polyacrylamides are mostly used for water clarification and process water recycling, whereas non-ionic polyacrylamides are used in mining to improve throughput, enhance yield and optimize processes (Kemira, 2021).

The annual CO_2 emissions for the Botlek site amount to only 0.16 kt (Emissieregistratie, 2019) and Kemira is not registered in the ETS. For the chemical flocculants production small amounts of electricity and steam are required. Nobian delivers NaOH to Kemira Rotterdam and Cabot supplies Kemira with 11 bar steam (Abdallas Chikri & Wetzels, 2020).

There are no major decarbonisation options investigated for Kemira Botlek concerning the Scope 1 emissions. Decarbonisation can be achieved mostly indirectly with the steam and electricity supply.

2.2.25 Linde Gas Benelux

The headquarters of Linde Gas Benelux is in Schiedam and Linde has three sites in the Port of Rotterdam, located in Botlek, Pernis and Europoort. Linde is specialized in the cryogenic separation of air into oxygen, nitrogen and argon. Other competitors in this field are Air Liquide and Air Products. Linde’s site in the Botlek region, at Botlekweg 169, terminated their production of industrial gases in 2017 due to the outdated equipment and poor efficiency of the ASU (Cioli, Schure, & Van Dam, 2021). From the Cabot Botlek site, Linde Gas Benelux receives 40 bar steam and forwards the steam to Kemira at the Botlekweg 169 (Abdallas Chikri & Wetzels, 2020).

In Botlek, Linde Gas Benelux currently focusses on collecting of CO_2 and distribution by pipelines to the greenhouse horticulture areas north of the Rotterdam harbour, as part of OCAP. In 2013, the Linde Group acquired full ownership of the OCAP joint venture, previously co-owned by Stedin. OCAP delivers roughly 400 kt annually to the greenhouses in the Rotterdam and Amsterdam region, preventing the CO_2 emission equivalent from natural gas of 205 kt (Linde Gas, 2021). The CO_2 gas is supplied by the Shell Refinery Pernis and the bio-ethanol plant owned by Alco Energy Rotterdam. Bordering Shell Pernis, located at the Vondelingenweg 545, an OCAP compressor station owned by Linde is present. Adjacent to the Alco Energy bio-refinery in Europoort another Linde OCAP compressor station is positioned. Linde Gas Benelux is not accountable for the imported CO_2 emissions and therefore has no reported annual emissions.

2.2.26 Organik Kimya

The Rotterdam plant of Organik Kimya is located at Chemieweg 7, in Botlek. Since 1965 Organik Kimya has been manufacturing and trading polymer dispersions and currently has four production platforms worldwide. In 2007, the Rotterdam plant was acquired by Organik Kimya and the production of acrylic polymers began. Currently, the annual production capacity of acrylic polymers is 45 kt (Port of Rotterdam, 2016).

On-site Organik Kimya has its own water purification installation, in short WWTP, which was recently updated in 2019 (DCMR, 2019) . The waste water processing capacity was increased since the old installation could not handle the increased production capacity. Organik Kimya intends to further increase the production capacity in Rotterdam (Organik Kimya, 2019). At the same time, energy consumption is one of the main cost pillars in the production process so initiatives to reduce this energy consumption are highly stimulated. Organik Kimya claims it has been importing their energy from 100% renewable energy sources since 2017 for the Rotterdam Botlek site (Organik Kimya, 2019). Furthermore, the annual greenhouse gas emissions of CO_2 are zero. From these numbers it can be concluded that the Scope 1 and 2 emissions are close to zero, indicating that Organik Kimya is relatively far progressed in the decarbonisation of their process and energy demands. No connections to other companies were reported in open literature.

2.2.27 Wilmar Oleochemicals B.V

Wilmar Oleochemicals located in Rozenburg, Merseyweg 10, is part of the Wilmar Europe organization, a subsidiary of Wilmar International. The Wilmar facility is located on the Huntsman site, formerly owned by ICI (WaterTalent, 2021). Steam is delivered by Air Liquide to Huntsman, the majority of the utilities is consumed by Huntsman and a small fraction is forwarded to Wilmar, Invista and Lucite. The private pipeline system owned by Huntsman facilitates this distribution. Wilmar Oleochemicals is specialized in the production of plant based fatty alcohols and derivatives by hydrogenating methyl esters (WaterTalent, 2021). An important by-product is methanol. The end products of Wilmar are mostly used in the personal care or detergent products.
The Wilmar site is not registered in the ETS, the annual steam use and electricity use are minor compared to the utility use of Huntsman. Decarbonisation strategies are therefore not considered for Wilmar.

2.2.28 Invista

Invista is located at the Merseyweg 12, surrounded by Ducor, Wilmar, Lucite and Huntsman. In the 1990s, Domo and Invista were split off from ICI Holland (later Huntsman). Between these companies on the former ICI site there is an electricity network, flexicoker gas network, steam and heat network and industry /demi water network (ACM, 2009). Invista receives steam and electricity via Huntsman, originating from Air Liquide. The waste water originated from Invista is transported to the Centrale Afvalzuivering Botlek (CAB) owned by Evides (Bilfinger Tebodin, 2019).

Production of nylon 6.6 is 115 kt/yr, with nylon granulate being the main product of Invista (DCMR, 2020). In 2012 Invista extended their production site with a new nylon salt production facility. Nylon salt is made from adipic acid and hexamethylenediamine, after polymerization the nylon salt becomes nylon polymer. The nylon polymer is widely applicable in airbags, car parts, carpets, active wear, cycling and running gear (Engineeringnet, 2012).
Other product applications nylon polymers are plastics, automotive, electronics, industrial, electrical and consumer applications. The annual CO_2 emissions amount to 5.9 kt and originate partly from the use of natural gas (Emissieregistratie, 2019). Decarbonisation strategies are dependent on the steam and electricity supply, Scope 1 and 2, therefore dependent on Air Liquide and not further evaluated.

2.2.29 Lucite International Holland B.V

Lucite International Holland B.V. is located at the Merseyweg 16, Botlek, in between Invista and Huntsman. In 1936, ICI Acrylics (now Lucite International) began the first commercially viable production of acrylic safety glass. In 2009, the new owners became Mitsubishi Chemical Co Ltd (Lucite International, 2020). The facility in Botlek produces polymethylmethacrylates (25 kt/yr), also known as PMMA polymers, in a scale of colors and variants (DCMR, 2018; Port of Rotterdam, 2016).

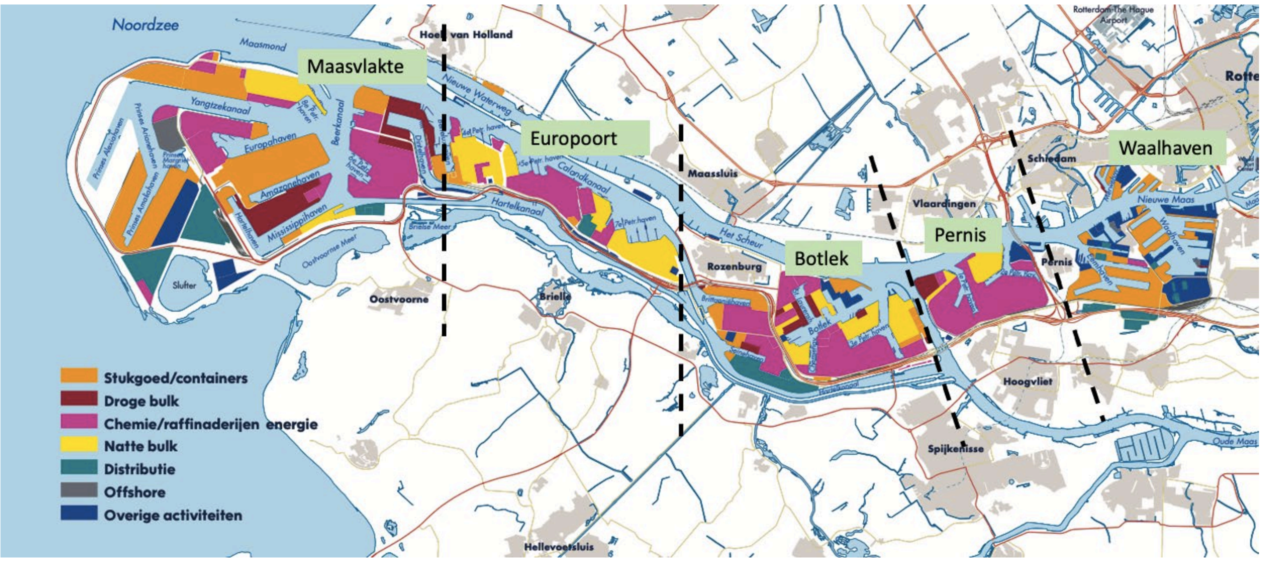
Lucite is specialized in the design, developing, manufacturing and selling of acrylics and acrylic based products. Lucite is not registered in the NEa or ETS, having zero CO_2 emissions. The site is dependent on the steam supply from Air Liquide, distributed via Huntsman to surrounding companies. Lucite's waste water is processed by the wastewater treatment plant (AWZI) owned by Huntsman (DCMR, 2020). Decarbonisation strategies were not evaluated for Lucite.

3 Cluster connections and characteristics

3.1 History of Botlek

The companies present in Botlek are part of the Port of Rotterdam area, both an important harbour as well as industrial area. The harbour has been there for centuries due to the strategical location at the Rhine river mouth, functioning as a gateway to Europe. Before 1900, several companies started to store their goods and gradually production sites were built around Waalhaven. The Pernis petroleum harbours were completed in 1933 and 1941. The Botlek plans were developed after 1947. Due to spatial constraints, the companies further expanded their production sites in Europoort, Moerdijk and the Maasvlakte (Port of Rotterdam, 2016).

Figure 3.1
Map of Port of Rotterdam



The harbour of Rotterdam with the variety of sectors indicated, image adapted from Port of Rotterdam report (Port of Rotterdam, 2020).

The construction of Botlek started in 1954 and most of the industrial sites were built in the period between 1960-1980 (Van Dril, Koelemeijer, & Van Dam, 2021). After the second world war, the petrochemical industry provided many opportunities and promised economic prosperity. DOW Chemical and Verolme were among the first companies that established their business in Botlek (ProIndustry, 2021). Nowadays, the Botlek area (24.73 km^2) is highly crowded with over 222 companies registered (Bedrijven.xyz, 2021). In this report, the evaluated companies are limited to the ones listed in Appendix A.

3.2 Current main infrastructure

The Rotterdam port area and Botlek are densely built with multiple companies, providing opportunities for the exchange of raw materials/products. The Multicore pipeline system is a collaboration between Port of Rotterdam and Vopak Chemical EMEA and is designed to transport chemicals and gases. The pipeline system exists out of a bundle of 4 pipelines and can be leased by third parties. Beginning in the Maasvlakte, the pipeline is extended all the way to the Pernis site where the Shell Refinery is located. Below, in Figure 3.2, the multicore pipeline in Botlek is depicted with the connected companies.

Figure 3.2
Multicore pipeline system

Multicore pipeline system present in Botlek and Pernis, adapted from Port of Rotterdam (Port of Rotterdam, 2016).

Table 3.1
Multicore pipeline system contents (Port of Rotterdam, 2016)

	Product	Possible purchaser
ExxonMobil ROP	Oxo-alcohols	ExxonMobil RPP
Air Products	Nitrogen, oxygen	ExxonMobil RPP (nitrogen)
Linde Gas Benelux	Carbon dioxide	OCAP
Shin-Etsu Botlek	Vinyl chloride monomer	Shin-Etsu Pernis
Shell Nederlandse Chemie Pernis	Isoprene extraction feed	Rubber production
Vopak Botlek	Various	Various

As mentioned, OCAP, the initiative led by Linde Gas Benelux, is supplying the horticulture in the Westland with CO_2 .The CO_2 demand from the horticulture and other sectors has been increasing over the past years and OCAP is able to expand (Tiersma, 2021). Currently, 400 kt/yr of CO_2 originating from Shell Pernis and biogenic CO_2 from ALCO is transported. The horticulture clients prefer biobased CO_2, and Alco is planning to expand its CO_2 capture and storage for this purpose. The demand for CO_2 is the highest in the summer by the greenhouse horticulture, a hybrid solution with seasonal CCS could therefore provide a solution. In the winter, the CO_2 can be stored underneath the North sea while the CO_2 is utilized in the summer. The growth of OCAP is in that sense dependent on the Porthos project, expansion is solely possible when the CO_2 can be stored in the winter time. The Porthos initiative is, in some ways, a threat to OCAP, since fossil based CO_2 deliveries by Shell and potential others remain accountable as emissions of the source industry. This implies that industry delivering to horticulture faces an opportunity cost comparable to the allowance costs minus Porthos storage costs. This will be passed on in the delivery price to horticulture.

In the Port of Rotterdam several other infrastructures developed over the years, including the electricity network, steam pipelines, CO_2 pipelines, residual heat pipelines and a hydrogen pipeline. In 2008 the subsidiary Stedin separated from Eneco Netbeheer and is responsible for the maintenance and installation of the electricity, steam and gas networks in the Port of Rotterdam (Stedin, 2021). Stedin is the network operator for the regions Den Haag, Utrecht, Rotterdam and the Port of Rotterdam.

Figure 3.3
Existing energy infrastructure, adapted from Port of Rotterdam report (Port of Rotterdam, 2019).

The Port of Rotterdam is well connected with surrounding areas and industries. Other important networks that reach far outside of Rotterdam are the propylene/ethylene network, industrial gases network and the oil network. Below are the three networks visible in Figure 3.4, 3.5 and 3.6.
In Botlek/Pernis there are more local networks present which will be discussed in the next paragraph (Section 3.3). The chlorine network, steam pipe initiative and other steam exchanges are examples of more local networks.

Figure 3.4
Crude oil and oil product pipelines, adapted from (Port of Rotterdam, 2016)

Figure 3.5
Ethylene and propylene pipelines, adapted from (Port of Rotterdam, 2016)

Figure 3.6
Industrial gas pipelines, adapted from (Port of Rotterdam, 2016)

3.3 Important connections and dependencies

In Botlek and Pernis the industry is highly intertwined in terms of feedstock and energy supply and demand. Before discussing several sub-clusters, it is important to note the difference between a connection and a dependency. When a company is dependent on another company, there will be significant consequences if one of them changes its process. For example, company A supplies company B with the main feedstock for their process, and company B aims to substitute its feedstock. If in that case company A is forced to stop its production; this is a strong dependency. If company A is able to find alternative customers for its product and can continue producing, there is a connection but no strong dependency. A connection can be seen as an optimization of the closely located independent plants from an economic perspective.

When transitions have to be achieved in clusters with strong dependencies, the simultaneous decision process is complicated. For an integral solution, some companies will benefit, while others will lose, and the latter ones may resist or frustrate the process. But if they simultaneously can find a satisfactory solution, they are able to cash in new cluster benefits after the transition.

Obtaining resources or utilities from nearby facilities is commonly preferred from an economic point of view. In this chapter, the main connections are mapped, but for the analysis the focus lies on the dependencies that may be affected by the transition plans.

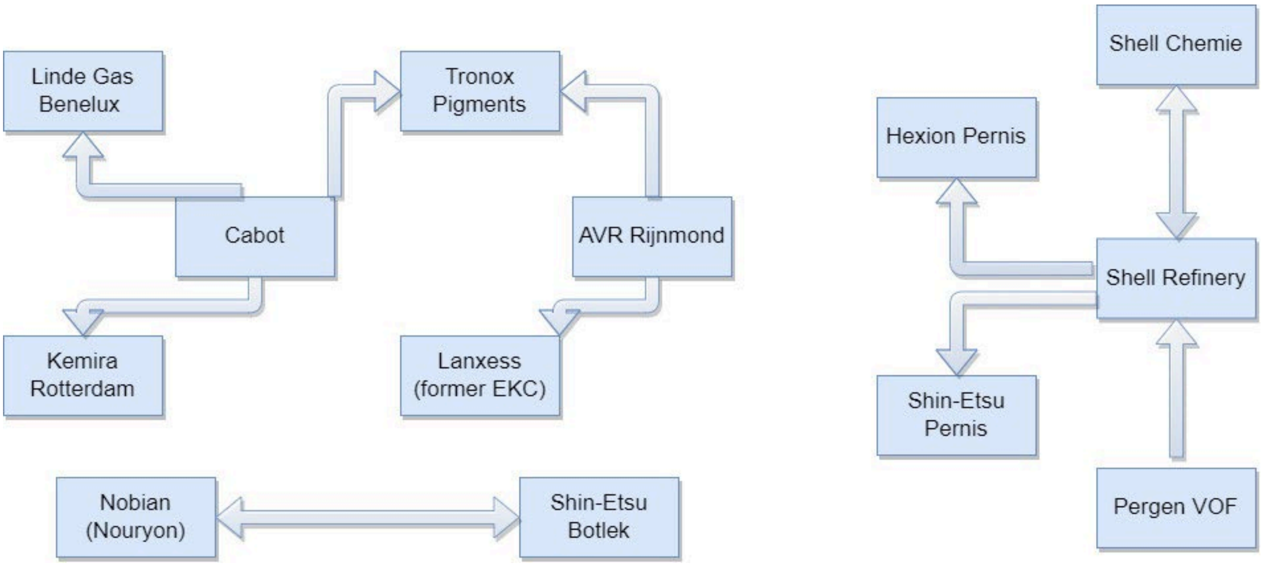
Physical dependencies are determined by the physical transport and storage possibilities. Dependency increases when commodities are hard to transport over long distances or hard to store, and the connected parties are captive, cannot switch to alternative supply or demand. Steam is an example of such a commodity. Further, gaseous commodities are less flexible than liquids.

Economic dependency is related to physical dependency, when transport costs significantly increase with distance, storage is expensive or the specific commodity has only one or two major suppliers or users. Institutional or regulatory dependencies can also be relevant. For example commodities like chlorine are hazardous to transport, residual flows have to be disposed of by controlled waste facilities, or storage is limited because of environmental risks.

3.3.1 Steam networks

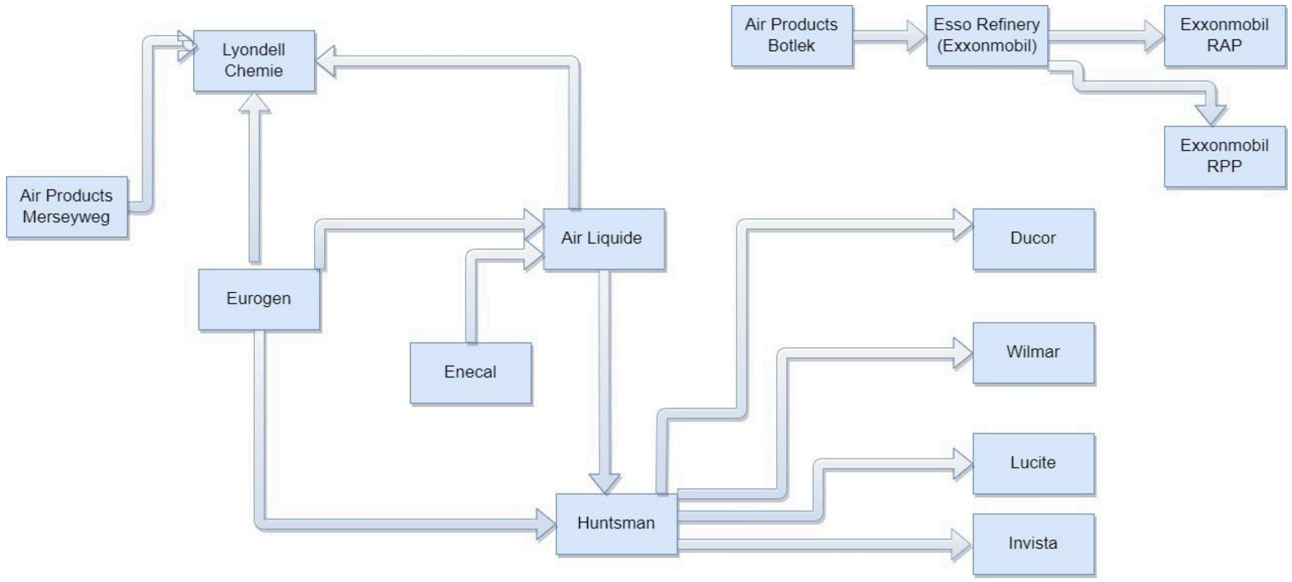
Steam networks mostly represent real dependencies between sites, although there are backup facilities for exceptional situations. The material and energy links described in Chapter 2 illustrate well-integrated steam connections. Below, in Figure 3.7, the steam sub-clusters are visualized. Cabot and AVR Rijnmond are the steam suppliers in the steam grid connected to several customers. Lanxess is becoming more dependent on the steam supply from AVR since Lanxess is currently reducing their own steam boiler capacities. The steam dependency between Shin-Etsu and Nobian is predominantly an optimization of residual heat streams. Nobian produces steam for Shin-Etsu and utilizes the returned residual stream from Shin-Etsu in its low temperature processes.
In the sub-cluster on the right, Shell Refinery Pernis is the main user of the supplied steam by Pergen VOF. Hexion Pernis, Shin-Etsu Pernis and Shell Chemie are all located on the Shell Refinery site and dependent on the steam supply.

Figure 3.7
Steam exchange in the Botlek-East



Two other sub-clusters can be identified in the Botlek/Rozenburg area, seen in Figure 3.8. Apart from industrial gases, Air Products Botlekweg delivers some steam to the Esso Refinery steam system which distributes the steam further to RAP and RPP. Air Products also has a steam system on the Merseyweg site, with a gas turbine and two boilers, delivering steam to Lyondell. However, Lyondell has also its own capacity and does not depend on this steam supply. Eurogen can also deliver steam to Lyondell, and residuals from Lyondell are combusted in the Eurogen CHP unit. The Air Liquide CHPs Eurogen and Enecal currently supply other sites with steam, Huntsman distributes the steam on its site via the private steam pipelines. Ducor, Wilmar Oleochemicals, Lucite and Invista are dependent on that steam supply for the execution of their processes.

Figure 3.8
Steam exchange in the Botlek-Rozenburg area



3.3.2 Hydrogen, carbon monoxide and syngas

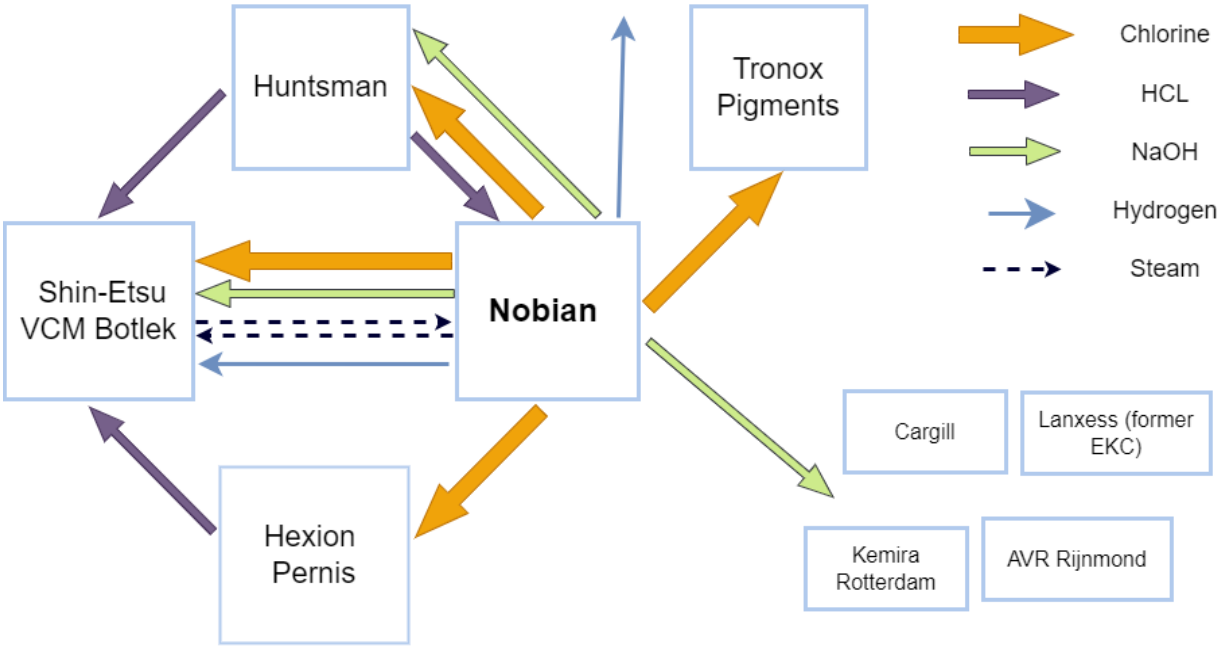
Real dependencies in this Botlek/Pernis cluster also include Air Liquide's hydrogen, carbon monoxide and syngas deliveries as feedstocks for other industries. Air Liquide has a separate industrial gas grid, but competitor Air Products is also potentially capable to deliver these gases. Air Products Merseyweg delivers oxygen and possibly hydrogen to Lyondell. The Air Products Botlekweg SMR unit is connected to the Esso Refinery, receiving refinery gases and converting them into hydrogen for Esso Refinery and ExxonMobil RAP, with steam as a by-product.

The bulky delivery contracts on these gases are long term, since hardware capacities and infrastructure have to be adjusted when deliveries change. Hydrogen is predominantly supplied by Air Liquide to Neste, Ducor Rozenburg and the BP refinery (Europoort), carbon monoxide is supplied to Huntsman and Lyondell, syngas to ExxonMobil ROP. This listing of connections and possible deliveries is not exhaustive, this inventory focuses on the real dependencies.

3.3.3 Chlorine cluster

In the chlorine cluster, Nobian is at the heart of the material exchange network. The annual chlorine production amounts to 640 kt, the four companies present in Botlek/Pernis that consume chlorine in their processes have the capacity for an annual intake of 900 kt. The companies are strongly linked to Nobian and dependent on the chlorine production capacity, the planned production capacity enlargement of 75 kt chlorine/yr can probably find enough demand by the connected plants. Due to the expansion of the chlorine production at Nobian, it is expected that the chlorine cluster will exist in its current form the upcoming years. Most material exchanges are optimized in the chlorine cluster, however there is still room for improvement. One example being the brine recycling towards Nobian instead of the continuous salt mining in the north of the Netherlands.

Figure 3.9
Chlorine cluster Botlek/Pernis adapted from (Bedrijvenpark Botlek, 2020)



3.3.4 Summary of important dependencies and players

Table 3.2
Summary of important dependencies and contributors

Companies involved	Type of dependency
Hexion Pernis, Shell Pernis, Pergen VOF, Shin-Etsu Pernis	Steam, refinery gases
The chlorine cluster; mainly Nobian, Huntsman, Shin-Etsu Botlek, Hexion Pernis, Tronox	Chlorine, HCL , NaOH
Esso Refinery, ExxonMobil RAP/RPP and Air Products Botlek	Refinery gases, hydrogen, steam
Air Products Merseyweg and Air Liquide	Competitive, in the industrial gases/hydrogen and steam markets
Air Liquide and Huntsman/ Ducor/Invista/Lucite/Wilmar Oleochemicals	Steam, electricity, industrial gases
AVR Rijnmond/Cabot and Lanxess/Tronox Pigments/Kemira/Linde Gas Benelux	Steam pipeline connection

4 Expected decarbonisation initiatives and future outlook

This chapter will evaluate the most promising projects in Botlek/Pernis and energy transition initiatives that are currently explored. At the end of this chapter two time horizons will be introduced. One short-term outlook for 2030 with reduction potentials regarding CO_2 emissions, natural gas use and electrification potentials. Decarbonisation strategies regarding the replacement of raw materials or different processes are discussed in the 2050 outlook. These evaluations were performed on the data collected from open resources such as MIDDEN reports and can be found in Chapter 2 of this report.

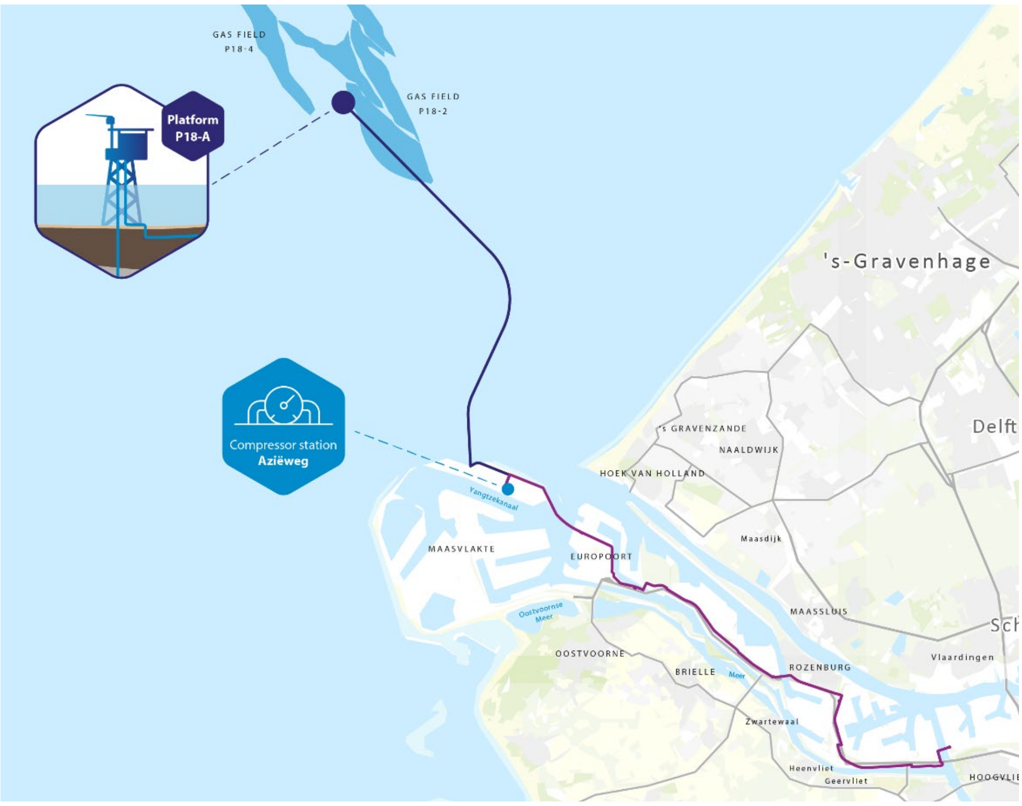
4.1 Current decarbonisation projects

4.1.1 Porthos and Aramis

The Dutch Climate Agreement for 2030 includes the important target of CO_2 emission reduction with 49% with respect to the 1990 level. For the industry sector this is equivalent to 14.3 Mt/yr of CO_2 (Porthos, 2021). A relatively straightforward solution would be to capture the CO_2 and to store it underground or utilize it for industrial purposes (CCS/CCU – note that CCU only ensures emission reduction if the CO_2 does not end up in the atmosphere by combustion later on). In the North Sea there is an abundance of depleted natural gas fields that can be filled up with CO_2 originating from the heavy industry located in Rotterdam. The storage of CO_2 undersea is a relatively quick fix for the industry and suitable for the short-term CO_2 emissions reduction targets. For long-term decarbonisation, companies have to invest in more sustainable decarbonisation strategies replacing fossil fuel consumption.

Porthos has the potential to store 2.5 Mt CO_2 annually for the first 15 years (Porthos, 2019). The project was initiated by the Port of Rotterdam Authority, EBN and Gasunie. Shell, ExxonMobil, Air Liquide and Air Products have successfully applied for an SDE++ subsidy in 2021, for an amount of up to 2.1 bln euro (depending on actual CO_2 prices in EU ETS). The pipeline collecting the CO_2 in the Rotterdam harbour area is planned to be 30 km in length starting at the Shell Pernis site. Built in the existing pipeline infrastructure it continues via Europoort to the Maasvlakte. The gaseous CO_2 will be compressed from 35 bar to a maximum of 130 bar at the centralized compressor station located at the Maasvlakte (Porthos, 2021). Porthos is currently awaiting the FID (Final Investment Decision) that is expected to be made in 2022. Once this final decision is made the construction work can start and Porthos is expected to be operational in 2024 or 2025.

Figure 4.1
Planned infrastructure Porthos adapted from the Porthos CO_2 project page (Porthos, 2021)



The four contracted suppliers of CO_2 are currently Air Products, Air Liquide, ExxonMobil and Shell (Porthos, 2021). CO_2 capture installations have to be built on-site prior to injecting the CO_2 to the Porthos pipeline. Currently, other companies are not able to join the Porthos initiative since the maximum storage capacity for the depleted natural gas field based on the upcoming 15 years is reached. A consortium with Gasunie, Shell, TotalEnergies and EBN is exploring the possibilities to expand their storage capacity by including other depleted natural gas fields or shipping the CO_2 abroad. This is also known as the Aramis project. The importance of Porthos does not solely rely on the capturing and storage of CO_2, it also facilitates the production of blue hydrogen and the establishment of a (blue) hydrogen hub.

Aramis is an initiative of EBN, Gasunie, TotalEnergies and Shell which includes an open access CO_2 transport system in the Rotterdam harbour area. This can be connected to Porthos, but can also facilitate CO_2 transported with ships. It includes a collection and compressor site on the Maasvlakte and transport pipeline to more remote North Sea platforms. It aims to transport and store another 5 Mt of CO_2 annually. Final investment decisions are expected in 2024 and the system should be operational well before 2030 (RVO, 2022).

The CCS projects introduce new dependencies on collective systems for transport and storage. When industries have invested in CCS as main reduction strategy, they have to make sure that storage is possible for a longer period.

4.1.2 H-vision and HyTransPort

The H-vision study on hydrogen for the Rotterdam area provides a perspective of production facilities for blue and green hydrogen, facilities for hydrogen imports and the required electricity and hydrogen infrastructure (H-vision, 2019a; H-vision, 2022). The first step in this vision is to produce low carbon blue hydrogen to substitute refinery gas as fuel in many refinery processes present in Rotterdam's industry. The residual gases from the refinery sector are to be used as feedstock for the blue hydrogen (95% purity) production process, along with some additional natural gas input (10%) (H-vision, 2022). The conversion is planned with autothermal reformers (ATR) situated separately from the refineries and well connected to the future CO_2 and hydrogen networks, most likely located on the Maasvlakte. By utilizing the residual gases produced by the refineries, H-vision provides a low carbon fuel solution in combination with CCS via Porthos, capturing the CO_2 at the source. Official partners of H-vision include Air Liquide, BP, ExxonMobil, Gasunie, Port of Rotterdam and Shell.

H-vision's first phase potential of carbon savings is around 1.7 Mt/yr, a significant amount compared to the annual reduction target for Dutch industry of 14.3 Mt (H-vision, 2022). The first hydrogen plant (ATR) has a capacity of 750 MW hydrogen, and is due in 2027. The perspective for development of H-vision has improved due to a positive advice of PBL on subsidies for this category of decarbonization technologies (H-vision, 2022a; PBL, 2022). A second 750 MW plant will double the CO_2 reduction capacity. The current potential of residual gases used for furnace heating in the Botlek/Pernis area is largely covered by a first 750 MW ATR. The ATR technology is preferred over the SMR for hydrogen production, primarily due to the higher turn down ratio of the ATR and therefore the improved flexibility. The required oxygen for the autothermal reforming can be supplied by ASUs located near the ATR, since transporting residual oxygen is difficult and costly.
The H-vision initiative for blue hydrogen from refinery gases benefits from the relatively short distances between the three major refineries: Shell, Esso and BP, combined with local CCS facilities.

H-vision's first step will leave the volume and process technology of the current refinery operations relatively unaffected. Because of the energy losses in the conversion process from refinery gas to blue hydrogen, the refinery energy balance will change. Additional natural gas supply, steam supply and efficiency improvements are necessary. New cluster dependencies will also materialize in the required collection grid for refinery gases and the blue hydrogen supply grid. Central operators for both Porthos and the H-vision system are needed, and the refineries will depend on those systems to reap the CO_2 reduction benefits of their on-site and off-site investments in the system.

The HyTransPort.RTM project is an initiative led by Port of Rotterdam Authority and Gasunie to construct an open access hydrogen pipeline (HyTransPort, 2022). The open access pipeline is essential in the realization of the Port of Rotterdam as a hydrogen hub. Companies present in Rotterdam are able to purchase from or supply to a green hydrogen system. The current planning is that the hydrogen pipeline will be operational around the end of 2024 or start of 2025. The Port of Rotterdam aims to have 2 GW of electrolyser capacity installed by 2030 and the hydrogen pipeline can distribute this green hydrogen (Brooks, 2021). Compared to H-vision, this pipeline is mainly intended for green hydrogen with an higher purity compared to blue hydrogen. The 24 inch pipeline can accommodate 1.5 mln Nm^3/h, around 1.2 Mt/yr hydrogen or 140 PJ at maximal continuous load (CES Rotterdam-Moerdijk, 2021).

4.1.3 Electrolyser initiatives

The Dutch government's goal for 2050 is to have all of the energy supply climate neutral, in other words indicating zero CO_2 emissions (Ministerie van Economische Zaken en Klimaat, 2020). Offshore wind is the most promising contributor for renewable energy sources. The current installed capacity (2.5 GW offshore wind power capacity) will increase in 2030 to at least 11 GW capacity (Government of the Netherlands, 2021); even further extension is being prepared. An important application for the green electricity from the offshore wind farms will be the conversion of electricity into green hydrogen. Conversion parks can be built near shore on locations where the off-shore power cables are landed, like the Maasvlakte. The conversion parks consist out of electrolysers, splitting water into hydrogen and oxygen, and hydrogen infrastructure connections. Several companies are involved in electrolyser projects to facilitate these conversion parks. Below, in Table 4.1, the biggest projects are mentioned.

The TRL of water electrolysis is high, although the electrolyser technology has yet to be scaled up since the technology has not been applied on industrial scale. The main difficulty however lies in the fluctuating availability of renewable energy from the offshore wind parks. The operation mode of the electrolyser can be continuous or follow the wind farms electricity supply (Mohammadi & Mehrpooya, 2018). Both have drawbacks: for the continuous mode, backup of thermal power generation is required to compensate for periods without wind. The emissions from this backup power generation have to be addressed if zero carbon hydrogen supply is required. If the electrolyser follows the electricity supply, the green hydrogen production is not continuous which can result in problems for the industrial processes. For continuous gas supply to industrial processes, hydrogen storage facilities would present a solution. Local storage of the green hydrogen to accommodate for the fluctuations is difficult on large scale, since the storage conditions are under high pressures and require expensive storage tanks. An alternative now considered would be the storage of hydrogen in salt caverns in the North-east of the Netherlands. This storage option is the more economic choice but requires a national infrastructure. Green hydrogen production and conversion parks are therefore part of the long term decarbonisation strategy.

Table 4.1
Overview of large electrolyser projects in Port of Rotterdam

Project	Location	Project period	Size and partners	Source
2 GW H_2 conversion Park	Maasvlakte/ Maasvlakte 2	2020-2050	150-250 MW (Shell) 250 MW H_2-Fifty (BP and Nobian)	(De Laat, 2020)
CurtHyl electrolyser	Port of Rotterdam	2020-2023	10 – 100 MW (Vattenfall, Air Liquide)	(De Laat, 2020)
Uniper	Maasvlakte (own site)	2021-2025	100MW (Uniper, Port of Rotterdam)	(De Laat, 2020)

4.1.4 Extensions of the Botlek steam pipe system

The current steam pipeline with AVR and Cabot as steam supplier might be expanding to other surrounding sites. Increased CO_2 and energy prices may unlock new economic potential. Conversations have been ongoing about the extension to the east-side where Lyondell and Huntsman are located and south to Nobian. Other companies are also interested in a connection to the steam pipeline although the negotiations remain complicated and time consuming.

4.1.5 WarmtelinQ

Port of Rotterdam and Gasunie are responsible for the WarmtelinQ project, aiming to utilize the residual heat from the Rotterdam industry in urban areas and greenhouse horticulture. The pipeline is planned between the Rotterdam harbour, Westland, The Hague and possibly Leiden. The avoided CO_2 emissions amount to 180 kt/yr, replacing local natural gas fired heating (CES Rotterdam-Moerdijk, 2021). At the end of 2021, the contractual agreement was made concerning the construction of the pipeline from Rotterdam to The Hague (WarmtelinQ, 2021). The decision about the extension to Leiden has yet to be made. The residual heat utilization is projected to be around 4.6 PJ/yr in 2030, originating mainly from Botlek and Pernis (CES Rotterdam-Moerdijk, 2021).

4.1.6 Various electrification and energy efficiency projects

Electric boilers increase the industries' operating flexibility and reduce the dependencies of the industry on steam supply from combined heat and power units. Moreover, e-boilers combined with gas boilers address the intermittency of renewable power generation for the medium term up to 2030. Several companies, including Huntsman and the CHP facilities owned by Air Liquide, have applied for the SDE++ subsidy concerning e-boilers substituting the steam supply demands. However, choosing for full scale electrification on the longer term will increase the dependency on external electricity supply from the network. A stable and 100% reliable power supply is important for many continuous chemical processes. The current choice for electrification also depends on the perspective for cost efficient long term supply, including well planned substantial network extensions (HBR; Tennet; Stedin, 2019).

An important energy efficiency technology concerns heat pumps, upgrading the low temperature waste stream to useful higher temperature streams (IndustrialHeatpumps, 2022). The mechanical heat pump can be widely applied on industrial scale, requiring electricity for powering of the compressor. Heat pumps are however not the main decarbonisation pillar for the majority of the companies. Some companies are involved in feasibility studies on heat pumps and mechanical vapor recompression.

Several sites in the area have plans for electrification of steam driven rotating equipment. Furthermore electrification of small heating or drying units provides relatively readily available decarbonisation possibilities. In general, energy efficiency projects are always of interest for companies, from an economic perspective as well as energy savings and CO_2 reduction perspective. With rising CO_2 and energy prices, the cost effective potential has increased. These individual projects can be implemented within the industry sites at convenient turnaround moments. Cluster connections are not affected by these implementations. For electrification projects, the electricity network and sufficient supply capacity is an important precondition for implementation.

4.2 2030 outlook

The data collected for the Botlek/Pernis area, described in chapter 2, were aggregated in a plausible baseline for 2030. For 2030, the main decarbonisation strategies include electrification, CCS/CCU and H-vision blue hydrogen for energy purposes. The use of green hydrogen for combustion instead of fossil fuel was not considered. Neither is the conversion of natural gas to blue hydrogen for energy purposes included. Based on open literature, information about the sites, interviews conducted with several companies and discussions with experts in this field an educated guess was made concerning the application of the most plausible decarbonisation strategies up to 2030. Both in literature and in the interviews, the dependency on infrastructure is stressed. Larger projects rely on new infrastructure, which is subject to decisions by public authorities and grid operators. They have to consider spatial availability, technical and staff capacity, regulation and policies. In the estimates this is taken into account.

The analysis was performed for the individual Botlek/Pernis companies, but reported here on a cluster level. Below, in Table 4.2, some important variables are seen, together with constants used in the configuration of the data

Table 4.2
Overview of the used variables and constants for 2030

Variables	Value	Unit/explanation	Source
E-boiler operational hours	4000	hours/yr	(PBL, 2022)
Share renewable electricity	70%		KEV (PBL, 2021)
Share gas fired electricity	30%		KEV (PBL, 2021)
Efficiency improvements on energy utilities	2%	Over period 2020-2030	Assumption
Efficiency improvements on final energy use combined with 3% incremental yield growth of current capacity	0%	Over period 2020-2030	Assumption
E-boiler efficiency	99%	steam/electricity	Assumption
Biomass boiler efficiency	85%	steam/biomass	Assumption
Gas boiler efficiency	87%	steam/(natural gas, hydrogen, fuel gas)	Assumption
MVR/Heat pump efficiency	400%	steam/electricity	Assumption
Electric motor or compressor	0.3	ratio power to steam replaced	Assumption
Electricity use for CO_2 capture	0.63	GJ electricity/tonne CO_2 captured and input in Porthos	(PBL, 2021a)
Steam use for pre combustion capture	1.13	GJ steam/tonne CO_2 captured	(PBL, 2021a)
Steam use for post combustion capture	2.41	GJ steam/tonne CO_2 captured	(PBL, 2021a)
Steam methane reforming (SMR)	1.42	natural gas or fuel gas input PJ/PJ hydrogen output	(Janssen, 2018)
Steam methane reforming (SMR)	0.03	electricity input PJ/PJ hydrogen output	(Janssen, 2018)
Steam methane reforming (SMR)	60%	share of pure CO_2 emissions	(Roussanaly, Anantharaman, & Fu, 2020)
Steam methane reforming (SMR)	40%	share of furnace CO_2 emissions	(Roussanaly, Anantharaman, & Fu, 2020)
Autothermal reforming (ATR)	1.20	natural gas or fuel gas input PJ/PJ hydrogen output	(Janssen, 2019)
Autothermal reforming (ATR)	0.05	electricity input PJ/PJ hydrogen output	(Janssen, 2019)
Autothermal reforming (ATR)	95%	share of pure CO_2 emissions	(Van Cappellen, Croezen, & Rooijers, 2018)

In this calculation simple generic assumptions on energy efficiency are based on 0.5% per year over 10 years amounting to 5%. For utilities and other energy conversions a 2% efficiency increase is assumed. Furthermore, the growth of final energy use in the current facilities remains constant but product output may increase incrementally by 3% on average, thus adding to energy efficiency. Specific adjustments are made, however. For the AVR and Shell Pernis refinery a decrease of 10% is assumed, based on reduction of combusted waste by 2030 and on the bio-refinery at Pernis substituting fossil based production. Overall, the remaining material and energy balances remain the same.

The share of renewable electricity and gas fired electricity was estimated to be 70%-30% on average for 2030 (PBL, 2021). This applies to the effects of the increased electricity demand for gas transportation and electrification of steam generation.

The decarbonisation strategies, CCS, electrification and H-vision were prominent in the interviews, and are therefore prominent in this analysis. For electrification, a distinction is made for e-boilers, electrification of compressors and the installation of heat pumps and MVRs. For e-boilers, a total capacity of 600 MW in 2030 is assumed. This is based on the revealed SDE++ applications in the interviews and a multiplication factor of around 3. The assumed load in 2030 is 4000 hours/yr (PBL, 2022). For conversion of steam driven compressors, a similar assumption is made based on the interviews of 75 MW replaced steam capacity. Heat pumps and MVR in the interviews were only mentioned as subject to further investigation, so a modest estimate is used for this category. CCS is either based on pure flow carbon capture or post-combustion carbon capture, depending on the source of CO_2 emissions. In the interviews, no full scale post combustion CCS projects were mentioned. In the calculation, a few specific projects are assumed. The residual gases that are currently used in the larger refinery furnaces[8] are assumed to be collected by H-vision, and converted to blue hydrogen with an ATR and CCS. This blue hydrogen is returned to the refinery and supplemented by natural gas for furnace heating. So, for the calculation it is assumed that the blue hydrogen originates only from the residual gas intake. As a result, no blue hydrogen intake is considered for smaller companies that cannot supply their own residual gases.

The base case 2030 is based on the interviews conducted, several MIDDEN reports and an educated guess on what the companies will do short-term. On average, the variables mentioned in Table 4.2 are used. The reader should be mindful that the numbers are subject to the assumptions mentioned, and would realistically show a large range when subjected to a rigid sensitivity analysis.

8 This is around half of the total amount of refinery gases currently produced. Refineries are already practicing full scale conversion of refinery gas to hydrogen for fuel product enhancement. These facilities can be directly connected to Porthos.

Table 4.3
Outcome of the calculation performed for the 2030 outlook

	Unit	Current	2030 outlook	Comment
CO_2 emissions Scope 1	Mt/yr	13.9[a]	8[b]	around 90% is CCS
Steam demand final	PJ/yr	63	65-68	mostly additional demand for CCS
Electricity demand final	PJ/yr	19	26	mostly additional demand for CCS/H vision
Electricity demand for steam generation	PJ/yr	0	9	mostly e-boilers
Electricity produced CHP		17	15	less running hours
Electricity net imported	PJ/yr	2	20	resulting effect
Natural gas total use	PJ/yr	84	88	calculated
- for additional imported power generation	PJ/yr	n/a	8	based on 30% gas fired
- less steam and CHP generation	PJ/yr	n/a	-6	replaced gas boilers and CHP but additional steam for CCS
- less final use	PJ/yr	n/a	-2	due to energy efficiency
- compensation for H-vision	PJ/yr	n/a	4	due to energy losses in ATR
Residual gases input processes	PJ/yr	57	38	diverted to H-vision
Residual gases input boilers and CHP	PJ/yr	16	9-10	diverted to H-vision
Residual gases into H-vision	PJ/yr	0	26	calculated
Hydrogen fuel use	PJ/yr	0	21	effect H-vision
Hydrogen feedstock use	PJ/yr	55	55	Production 71 PJ, export 16 PJ

a) Including around 1.1 Mton biobased emissions from AVR
b) Scope 1 including the effect of additional electricity supply, based on 30% gas fired and 70% low carbon

Out of the 40+ sites evaluated and present in Botlek/Pernis, 8 facilities are assumed to be directly or indirectly connected to the Porthos/Aramis infrastructure in 2030 and therefore apply CCS. The two refineries present in Botlek/Pernis that produce residual gases were assumed to be connected to the H-vision initiative, but chemical companies could also join.

For the 2030 base case scenario, the Scope 1 CO_2 emissions of 13.9 Mt could potentially decrease by 43% (5-6 Mt/yr) when accumulating the CO_2 reduction caused by electrification, CCS (Porthos/Aramis) and H-vision. Around 90% is caused by applying CCS and the utilization of the Porthos initiative and H-vision.

The total electricity increase is around 12- 15 PJ/yr, half of it is used for CCS, for compression and transportation by Porthos/Aramis, the other half is used for e-boilers and other electrification. Electricity for electrolysis is not yet part of this. Electricity export from the companies present in Botlek/Pernis will decrease, resulting from load reduction of the current CHP's.
In the calculations, the steam production is partly replaced by e-boilers, however the e-boilers require electricity that can be generated from renewable resources or gas fired sources. The shares of renewable and gas fired generation of the additional electricity are therefore decisive and heavily influence the total natural gas increase or decrease. Furthermore, some additional natural gas is

required for carbon capture and for compensation of the losses due to converting the refinery gases into hydrogen. The natural gas projection is therefore sensitive to the assumptions and the range varies significantly.

Residual gases that are currently consumed by processes on site, as fuel or for the firing of boilers/CHP's are partly directed to the ATR of H-vision. Approximately 24-25 PJ/yr of residual gases (around half to one third of the produced amount) is converted into blue hydrogen (17-21 PJ/yr). The first ATR that is planned on the Maasvlakte will have a capacity of 750 MW, the upper bound of 21 PJ/yr of hydrogen is equal to 741 MW and nearing that capacity limit.

4.3 2050 outlook

A quantified plausible future outlook for the long term is not attempted with the scope of this report. This depends on the success of decarbonization strategies, and also on the dynamics of industrial investments and disinvestments in the area. Therefore, this section includes a qualitative analysis on the most important issues in deep decarbonisation.

4.3.1 Refineries, fuel and carbon feedstocks production

Rotterdam is currently one of the largest fuel clusters worldwide. In the future, the offshore renewable electricity supply and green hydrogen production will increase substantially, but will most likely not satisfy the remaining carbon based fuel and feedstock demand. It is expected that the production capacities of the refineries will drop from 2030 onwards, due to the decreasing demand for transport fuel products (PBL, 2021). With this background, substantial efforts for CO_2 reduction on production sites are focused on the short-term, to achieve 2030 climate targets. Blue hydrogen can substitute the carbon based gases as fuel, and the major flows of CO_2 are addressed with CCS. In the long run, the increased green hydrogen capacity and possibly synthetic fuels can substitute fossil based fuels and feedstock. Another transition currently taking place in Botlek/Pernis is the development of biofuel refineries providing sustainable fuels. Shell is planning to build one in Pernis. Shell is also involved in an initiative with Enerkem to produce waste based jet fuel with a planned output capacity of 80 kt/yr (Enerkem, 2021). The process will use Shell's Fisher Tropsch technology. An investment decision is expected in 2022. These are the pathways to explore non-fossil or recycled carbon for future fuel and feedstock applications.

If Rotterdam remains a large fuel cluster in the European transport system, other types of fuels may become more important besides the biobased or waste based fuels. For instance, E-fuels are synthetic fuels that are produced with the use of green hydrogen and possibly CO_2 with technologies such as power-to-liquid, power-to-gas, power-to-X for synthetic fuels (Yugo & Soler, 2019). CO_2 would have to be sourced from existing processes or direct air capture. Examples of E-fuels are e-ammonia, e-diesel, e-methanol, e-methane and e-hydrogen. The production of E-fuels is currently more expensive and energy intensive compared to the biobased methanol and ethanol (Van Kranenburg, et al., 2021).

Rotterdam's position as one of the largest fuel producers worldwide therefore depends on the uptake of sustainable low carbon fuels and the transition of the current facilities. For future large scale fuel and feedstock production, Rotterdam will remain dependent on imports. It is uncertain how this will unfold, but it can be expected that the current production capacities will decrease significantly, with the remaining fossil based part requiring continued CCS. For the biobased part, CCS may also be a viable long term option in Rotterdam to provide future carbon sinks.

4.3.2 Residuals processing

Currently, next to the refinery gas emissions, the two refineries emit around 2 Mt of CO_2 from heavier residuals and process emissions[9]. Apart from the two refineries, around 10 chemical companies in the area also have residual flows that are combusted on or near the site, representing around 10 PJ of energy and 0.5-1 Mt of CO_2 emissions. For long run decarbonization, the on-site combustion of residual flows has to be addressed. For the main refinery sources, additional CCS with connections to Porthos or Aramis is plausible, even with biobased or waste based future feedstocks.

Projects such as H-vision deal with the refinery gases and collect similar gas mixtures to consequently convert into blue hydrogen. The infrastructure that will be put in place for H-vision, collecting and centralized processing the residual gases may remain of importance on the long term. Some chemical industries that produce residual gases currently may benefit from such an infrastructure. New biobased or waste based facilities will also produce residual gases, which can be applied for process heating. Centralised decarbonization of these gases within the Rotterdam cluster to avoid CO_2 emissions may also be an attractive option.

Liquid and solid residual streams are easier to handle, liquids can be stored on site and transported with relative ease compared to gases. In a long run zero emission future, these residuals will have to be processed in a sustainable manner, replacing current widespread combustion practices. Collection and central processing of the various carbon rich residuals, avoiding combustion emissions could be explored. Facilities like AVR could take up such a role. So for addressing the residuals issue the Rotterdam cluster may have an advantage.

4.3.3 Hydrogen

The cluster currently has a large production capacity for hydrogen of 600 kt/yr which is mainly used in fossil refinery processes. The use of hydrogen is expected to grow for biobased and waste based fuel production and possibly for synthetic fuels. For many chemical processes, hydrogen is also currently applied in hydrogenation and other processes. Using manufactured hydrogen as an energy source to replace carbon rich gases is currently too costly, but this is expected to change in future, with a fast growing worldwide supply of green hydrogen (Port of Rotterdam, 2020a). In the 2050 view, the full array of hydrogen supply modes and applications is expected to be operational in Rotterdam. The ambitious scenario set by Port of Rotterdam aims to handle around 20 Mt of hydrogen in 2050, over 30 times the current hydrogen throughput. Hydrogen can also be supplied by tanker in the form of ammonia or methanol. In the report, the realization of the hydrogen hub that can process around 20 Mt hydrogen annually is highly dependent on imported hydrogen. The offshore renewable electricity production near Rotterdam is not nearly enough for this ambition. On the long term, the worldwide availability of renewable energy is expected to increase and the production of green hydrogen will rise.

For hydrogen use in the industrial cluster it is important to guarantee a hydrogen supply at competitive cost. For feedstock purposes, it may replace current natural gas based SMR hydrogen production of 200 kt. Replacing the current hydrogen production fed by residual gases is not expected, as these gases will have to be converted again to blue hydrogen or syngas. Imported hydrogen will however not be a competitive option for installations already connected to CCS systems. So the 2030 solutions preferred in the cluster may stand in the way of green hydrogen

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[9] Main sources are the gasifier and catalytic cracker at Shell and the flexicoker at Esso.

supply for these current feedstock applications. New applications for hydrogen as a feedstock may welcome imported green hydrogen, but this potential demand is still tentative.

Heating applications in boilers and furnaces is a more concrete destination for green hydrogen, where heating cannot be served by direct electrification. The potential for heating in current higher temperature installations, and additional demand due to losses in H-vision may amount to 7-10 PJ. This would avoid the use of natural gas and reduce around 0.5 Mt of CO_2. This estimate excludes hydrogen use as a fuel in power generation and CHP's. The further penetration of either hydrogen or electricity for industrial heating depends on how the cluster steam and electricity infrastructure is developed. It has to be noted that also in de longer run, methane or natural gas used for syngas, carbon monoxide and carbon black production cannot be replaced by hydrogen and needs other solutions. Therefore, it can be expected that the SMR and ATR technology like at Air Liquide and Air Products will not disappear completely. For several companies, such as the AVR Rijnmond, Cabot and other cracking and chemical oxidation processes the oxidation of carbon is an unavoidable part of the chosen industrial activity. For decarbonisation, these sites have to apply either biomass and/or CCS or develop an alternative process. Electrification for these and other furnaces proposes technical difficulties. The TRL of specific electric furnaces and high temperature heating often is low and in the research phase, although it is deemed feasible by 2050 (ECN, 2018). A default decarbonisation option for these furnaces would be to install post combustion carbon capture units on the flue gases, capturing the CO_2 "end-of-pipe". Again, this may stand in the way of more sustainable long term solutions.

Oxygen
Air Liquide and Air Products are the main providers of industrial gases in Botlek/Pernis and it is expected that the demand of industrial gases will not decrease significantly, as several surrounding companies consume these goods. At present, the ASU's that produce oxygen are fully electrified and essential for the oxygen input of ATR's that produce hydrogen. Since the H-vision ATR's are planned on the Maasvlakte, a substantial demand for oxygen is expected there. Shipping the oxygen produced by the electrolysers on the Maasvlakte may at present be economically or technically unattractive, local ASU oxygen production might provide a short term solution here.

4.3.4 Electricity supply

CHP's in the area currently use 45-50 PJ of natural gas, and in the 2030 outlook around 6 PJ would be replaced, mainly by e-boilers. Additional flexible power generation may even lead to increased natural gas use. Complete substitution of this CHP capacity would require 40-45 PJ of carbon free electricity (around 1600 MW baseload capacity), replacing both power and steam output. The Rotterdam cluster energy strategy relies on offshore wind. It stresses the need for large network investments, but does not address the need for flexible carbon free backup capacity (HBR; Tennet; Stedin, 2019; CES Rotterdam-Moerdijk, 2021). The position of the current CHPs in Botlek/Pernis is uncertain and currently not favourable. E-boilers or blue hydrogen may be competing technologies for steam supply, renewable electricity will compete for power generation. On the other hand, flexible backup electricity demands are increasing and will continue to do so until 2050, creating new dependencies. The general consensus around CHPs is that the operational hours continue to decline for the upcoming years, in combination with increasing capacity of e-boilers (PBL, 2021). It however remains an important question whether or not the electricity network can handle both increased demand and the disappearance of CHPs. The current steam supply originating from these CHP's has to be partially covered with other methods if the CHP is operated flexibly. Electrification via e-boilers can be sufficient for the majority of the steam supply, either centralized or decentralized. SDE++ applications for e-boilers are already in place for several Botlek and Pernis facilities.

Further down the line, when imported hydrogen is readily available for energy purposes, low carbon hydrogen may be used in modified CHPs for flexible use and covering energy demands when the electricity prices are high. Some of the current CHPs have the flexibility to run on natural gas in combination with low carbon hydrogen. Pergen VOF (300 MW) and the CHP present on Shell's site (142 MW) are already mentioned as potential clients for blue hydrogen from the H-vision initiative (H-vision, 2019a). Without major modifications these CHPs can run partially on hydrogen, reducing the natural gas use in Pergen and the syngas use at Shell. The Enecal and Eurogen CHPs are not equipped to process the blue hydrogen, this will require modification of the CHPs or replacement.

4.3.5 Raw material substitution

For the large array of products from the chemical sector in Rotterdam, mostly feedstocks are required that contain carbon. In product applications such as plastics the use of carbon cannot be avoided. For these processes and products, two decarbonisation strategies are indicated to be applied without having major modifications to the processes and facilities. One is the use of biobased raw materials instead of fossil based raw materials. Implicitly this means that the availability of biobased materials must ramp up rapidly in the coming years. The other strategy entails the circular economy for carbon, which is expected to provide a solution. Collecting, recycling and purification are required to re-use carbon containing waste flows into products that contain carbon. Certain companies value this circular approach more than others, especially the ones with a specific application area can focus their recycling methods and technology better. Dependencies on raw material supply for the cluster in the long run are not analysed here as this involves global markets and a wide range of issues.

5 Discussion

In this chapter the most important observations are mentioned that originate from the quantitative analysis, the literature research as well as the interviews conducted. The main cluster difficulties that were encountered for Botlek/Pernis are dealt with in the last section.

5.1 Projects

- The Porthos and Aramis initiatives in Rotterdam become attractive as large scale and cost effective reduction options. The most concrete CCS plans for the area only include relative pure flows of CO_2, which can be effectively handled. The tax driven pricing of CO_2 may no longer be an adequate incentive for a more sustainable decarbonisation pathway, once connected to the CCS system. For 2050, a more profound and deeper decarbonisation of the industry is required, expanding beyond the CCS system.
- The only plan for an alternative industrial core process so far announced in the area is the Shell Pernis biofuels plant. The other industries are mostly focused on continuation of their current core processes. CO_2 capture or switching to a low carbon energy supply is the dominant decarbonization strategy. New initiatives, independent from existing industries, may have been missed in this report.
- Biobased and fossil based CO_2 are combined in the OCAP system and connected to Porthos. The biobased CO_2 currently is sourced from Alco, and in the future it can be sourced from other biofuels factories and from AVR. From a climate change perspective, sequestrating biobased CO_2 is just as effective as fossil based CO_2. This is not yet reflected in current climate policies. Rising decarbonisation targets set by the Dutch government thus may in future pose a threat to the OCAP initiative. Prices of OCAP CO_2 for horticulture thus have to exceed the societal benefits of storing this CO_2 underground.
- Converting refinery gases into hydrogen to use as low carbon furnace fuel, the first phase of the H-vision initiative, is accompanied by energy losses. How to compensate for these losses is important for the final reduction results.
  The CO_2 capture, gas conversion, cleaning and transport for H-vision and Porthos may require substantial amounts of baseload electricity, for 2030 in the range of 2-3 TWh for the area. E-boilers, other electrification and loss of cogeneration will also lead to 2-3 TWh of additional electricity demand. How much of this additional electricity is generated with fossil fuels is crucial for the 2030 reduction effect. There are currently no concrete plans in the area for carbon neutral baseload or flexible generation in 2030.
- Similarly, CO_2 capture will require additional steam and the conversion of residual gases in H-vision will require additional energy input to compensate conversion losses. This extra demand of 6-9 PJ of potential extra natural gas input may exceed the amount of natural gas saved with electrification.
- With the H-vision and HyTransport.RTM projects, the realization of a hydrogen grid within close proximity to Botlek/Pernis is nearing. The infrastructure has yet to be implemented, but can enforce the cluster benefits and cross-links.
- WarmtelinQ and the utilization of the industrial residual heat for district heating is not a priority for the industry. AVR is currently supplying surrounding urban areas with residual heat and recently the extension to The Hague was agreed upon. The potential residual heat available from mainly Botlek and Pernis represents a long term heat source for urban areas. Electrolysers on the Maasvlakte may also provide a substantial amount of residual heat in

future, and so will CO_2 compression units for Porthos. DCMR is exploring an approach for sourcing and collecting waste heat for the longer term.

5.2 Cluster observations

- A revised and optimized decarbonized cluster may not be achieved without an open design and planning process. Most of the strong dependencies are observed between refineries, industrial gases or steam suppliers and other smaller companies in Botlek/Pernis. In the future, it is however expected that the refineries have to drastically decarbonise and potentially scale down the fossil-based production capacity significantly. In parallel, production facilities for advanced biobased fuels and chemicals may be established in the same area, partially by the same companies. This will directly affect the attached utilities and hydrogen supply. Suppliers follow requirements of refineries and chemical industry clients and anticipate on potential future requirements. Gases and steam suppliers have to decide on investing in a range of new technologies like e-boilers, electrolysers, ATR's and gasifiers, including the required new infrastructure and adjustments to current assets. New cluster synergies can be developed, which will determine their competitive success. There is no overall planning of these facilities in the area, since there are also competition restrictions. Contracts are mostly bilateral and subject to competition. Larger investments are often joint ventures of the major stakeholders, that take lengthy iterative decision processes.
- The operational hours of the CHPs present in Botlek/Pernis are expected to decrease over the upcoming years, while the installation of e-boilers will partly replace this capacity. Once installed, these e-boilers will only operate when electricity prices are favourable, and this is highly uncertain. Power and gas prices fluctuate, and e-boilers will compete with new electrolyser capacity for the cheap renewable MWh. Therefore, in the analysis it is assumed that no full electrification of steam supply will take place by 2030, and the e-boiler load is estimated at 4000 hours by 2030. Furthermore it remains uncertain whether or not the electricity infrastructure can handle this hybridization of the boilers and CHPs and increasing demand for electricity.
- The SMRs, ATR and gasifier present in Botlek/Pernis are currently producing hydrogen, carbon monoxide and syngas. In combination with Porthos and H-vision these facilities can continue and produce blue hydrogen. Although in the 2050 outlook most of the hydrogen is expected to be based on electrolysis, the need for carbon monoxide and syngas will remain so the SMRs and ATRs are not expected to be completely replaced by electrolysers. Biomass or waste can be alternative sources of hydrogen, carbon monoxide and syngas, but this supply is limited.
- The current steam pipeline with AVR and Cabot as steam supplier might be expanding to other surrounding sites. Cross industry initiatives and concrete plans for further steam and waste heat optimization on sites and across site perimeters are lacking and cluster opportunities remain unaddressed.
- The heavily connected chlorine cluster appears to be relatively unaffected by the decarbonisation plans. The chlorine production capacity is scaling up by 2025 and the demand for the downstream product applications is still increasing every year, giving no indication of the cluster disappearing. Electrolysis performed by Nobian is already an electrified core process and the connected processes in the subcluster have relatively low CO_2 emissions.
- More than ten chemical sites located in Botlek and Pernis have special furnaces as direct sources of CO_2. Regularly, part of the CO_2 emitted is an inevitable reaction product. In order

to convert these furnaces to low carbon combustion, long and impactful development trajectories are needed. Due to the proximity to Porthos, post combustion CCS can be a faster and more cost effective option for this category of CO_2 sources.

- The residual gas flows and residual liquid streams are often dealt with on-site or processed by specialized waste facilities. After the maximum valorization of the streams, the majority of the flows is combusted on-site. These CO_2 emissions cannot be replaced by carbon free energy unless another sustainable destination is found. After completion of the planned Porthos and H-vision plans, residuals combustion emission still amounts to 2.5-3 Mt of CO_2 in the area. A collective construction in the cluster similar to H-vision could possibly work for other residual streams. For residual liquids the storage and transport is more applicable, in contrast with residual gases which have to be transported via pipelines. A more detailed insight to the residual flows is required to propose a realistic plan for their handling.

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Appendices

Appendix A

Below is the full list of all companies included in this project. The available CO_2 emissions (Scope 1) and addresses are reported as well.

Companies	Address	CO_2 emissions 2019	Source
Air Liquide-ATR	Merseyweg 10, 3197 KG Botlek-Europoort-Maasvlakte	107	(NEa, 2019)
Air Liquide-SMR	Merseyweg 10, 3197 KG Botlek-Europoort-Maasvlakte	Included together under AL-ATR	(NEa, 2019)
Air Liquide-SMR2	Merseyweg 10, 3197 KG Botlek-Europoort-Maasvlakte	808	(NEa, 2019)
Air products-Botlek	Botlekweg 127, Botlek Rotterdam	767	(NEa, 2019)
Air Products-Merseyweg	Merseyweg 8, 3197 KG Rotterdam-Botlek/ Boyneweg 10	87	(NEa, 2019)
Nobian	Welplaatweg 12, 3197 KS Rotterdam Botlek	109	(NEa, 2019)
Almatis	Theemsweg 30, 3197 KM Botlek Rotterdam	18	(Emissieregistratie, 2019)
AVR Rijnmond	Professor Gerbrandyweg 10, 3197 KK Botlek Rotterdam	1723 (fossil and biogenic)	(Emissieregistratie, 2019)
Biopetrol Rotterdam	Welplaatweg 108, 3197 KS Botlek Rotterdam	36	(NEa, 2019)
Cabot B.V	Botlekstraat 2, 3197 KA Botlek-Rotterdam	227	(NEa, 2019)
Cargill Refined Oils Europe	Welplaatweg 34, 3197 KS Botlek	25	(NEa, 2019)
Climax Molybdenum	Theemsweg 20, 3197 KM Botlek Rotterdam	11	(Emissieregistratie, 2019)
Lanxess	Montrealweg 15, 3197 KH Botlek-Rotterdam	74	(NEa, 2019)
Esso NL (ExxonMobil)	Botlekweg 121, 3197 KA Botlek Rotterdam	2376.3	(NEa, 2019)
ExxonMobil Chemical (RAP)	Botlekweg 121, 3197 KA Botlek Rotterdam	453	(NEa, 2019)
ExxonMobil Chemical (RPP)	Welplaatweg 2, 3197 KS Botlek Rotterdam	27	(NEa, 2019)
Hexion Inc. UK Ltd (Botlek)	Chemiestraat 30, 3197 KB Botlek Rotterdam	4.9	(Emissieregistratie, 2019)
Hexion B.V (Pernis)	Vondelingenplaat-Rotterdam	32.1	Nea2019
Huntsman Holland	Merseyweg 10, 3197 KG Botlek-Rotterdam	0.25	(Emissieregistratie, 2019)
Kemira Rotterdam BV	Botlekweg 175, 3197 KA Botlek Rotterdam	0.16	(Emissieregistratie, 2019)

Companies	Address	CO_2 emissions 2019	Source
Linde Gas Benelux Botlek	Botlekweg 169, 3197 KA Botlek Rotterdam	0	(Emissieregistratie, 2019)
Linde Gas Vondelingenplaat	Vondelingenweg 545, 3196 KK, Vondelingenplaat Pergen	0	(Emissieregistratie, 2019)
Lyondell Chemical	Theemsweg 15, 3197 KM Botlek Rotterdam	322	(NEa, 2019)
Koole 1 Terminals Rotterdam	Haven nummer 4040, Oude Maasweg 6, 3197 KJ Botlek-Rotterdam	18	(NEa, 2019)
Koole 2 Terminals Rotterdam	Haven nummer 4040, Oude Maasweg 6, 3197 KJ Botlek-Rotterdam	18	(NEa, 2019)
Organik Kimya	Chemieweg 7, 3197 KC Rotterdam-Botlek	0	(Emissieregistratie, 2019)
Rubis Terminal	Welplaatweg 26, 3197 KS Botlek Rotterdam	-	
Tronox Pigments	Prof. Gerbrandyweg 2, 3197 KK Rotterdam-Botlek	84.6	(Emissieregistratie, 2019)
Vopak Terminal Botlek	Welplaatweg 110, 3197 Botlek	4	(NEa, 2019)
Ducor- Rozenburg	Merseyweg 24, 3180 Rozenburg-Rotterdam	15.94	(Emissieregistratie, 2019)
Shin-etsu VCM	Welplaatweg 12, 3197 KS Botlek Rotterdam	102	(NEa, 2019)
ALCO Energy Rotterdam B.V	Merwedeweg 10, 3198 LH Europoort Rotterdam	344	(NEa, 2019)
Shell Nederland Chemie Pernis (SNC)	Vondelingenweg 601, 3190 GA Hoogvliet Rotterdam	36	(NEa, 2019)
Shell Refinery Pernis	Vondelingenweg 601, 3190 GA Hoogvliet Rotterdam	4358	(NEa, 2019)
Enecal	Corkstraat 46, 3047 AC Rotterdam/ Merseyweg 10	182.1	(NEa, 2019)
Eurogen	Merseyweg 10, 3197 KG Botlek Rotterdam	207.4	(NEa, 2019)
Pergen VOF	Vondelingenweg 601, Pernis	1238	(NEa, 2019)
Wilmar Oleochemical	Merseyweg 10, 3197 KG Botlek Rotterdam	0	(Emissieregistratie, 2019)
Invista B.V	Merseyweg 12, 3197 KG Botlek Rotterdam	5.95	(Emissieregistratie, 2019)
Lucite	Merseyweg 16, 3197 KG Botlek Rotterdam	0	(Emissieregistratie, 2019)
HES Botlek Tank Terminal	Montrealweg 151, 3197 KH Botlek Rotterdam	-	
Vopak Terminal Laurenshaven	Montrealweg 25, 3197 KH Botlek	-	
Vopak Terminal TTR	Torontostraat 19, Postbus 5040, 3197 XK Botlek Rotterdam	0	(Emissieregistratie, 2019)
ExxonMobil - ROP	Merwedeweg 21, 3198 LH Europoort Rotterdam	54.95	(NEa, 2019)
Shin Etsu PERNIS-PVC	Vondelingenweg 601, 3196 KK Vondelingenplaat	0	(Emissieregistratie, 2019)