FINAL REPORT

Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam

  

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On behalf of:
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0 Summary

The *Paris Agreement* adopted in December 2015 by 195 countries (UNFCCC 2015) makes it very clear that the world needs to take significant steps towards decarbonising the global economy and energy systems until the middle of the century. The agreement requires countries to intensify their respective strategies and policies towards this aim.

Future global and EU decarbonization policies will affect the industrial cluster at the Port of Rotterdam, as the bulk of the port's economic activities focuses on trading, handling, converting and using fossil fuels, i.e. fossil carbon. This makes the port's businesses particularly vulnerable to global and European decarbonization efforts, as the stepwise phasing out of fossil resources is at the very core of any decarbonization strategy. Furthermore, with annual CO_2 emissions of well over 30 million tonnes, the port area is one of the major European hot spots of GHG emission and therefore bears a particular responsibility to actively contribute to European GHG emission reduction efforts.

Therefore, already in 2007, the Port Authority set an ambitious goal of reducing the emissions of the port and its industrial complex by 50% by 2025 and by 60% by 2030, compared to 1990 levels as part of the *Rotterdam Climate Initiative* (Port of Rotterdam Authority 2011). Furthermore the Port Authority commissioned the Wuppertal Institute for Climate, Environment and Energy to conduct a study on *Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam*, in order to explore the consequences of global decarbonisation for the port's industrial cluster and to identify possible scenarios on how the port could prepare for such a future and prepare for a pro-active stance towards deep decarbonisation.

For this purpose, four different scenarios (one "business as usual" and three decarbonisation scenarios) are developed, describing how the port's industrial cluster could look like in 2050 in case of ambitious decarbonization efforts globally and in Europe, and to what extent the cluster might contribute to GHG mitigation. The decarbonisation scenarios cover different levels of ambition as well as different technological strategies for decarbonisation.

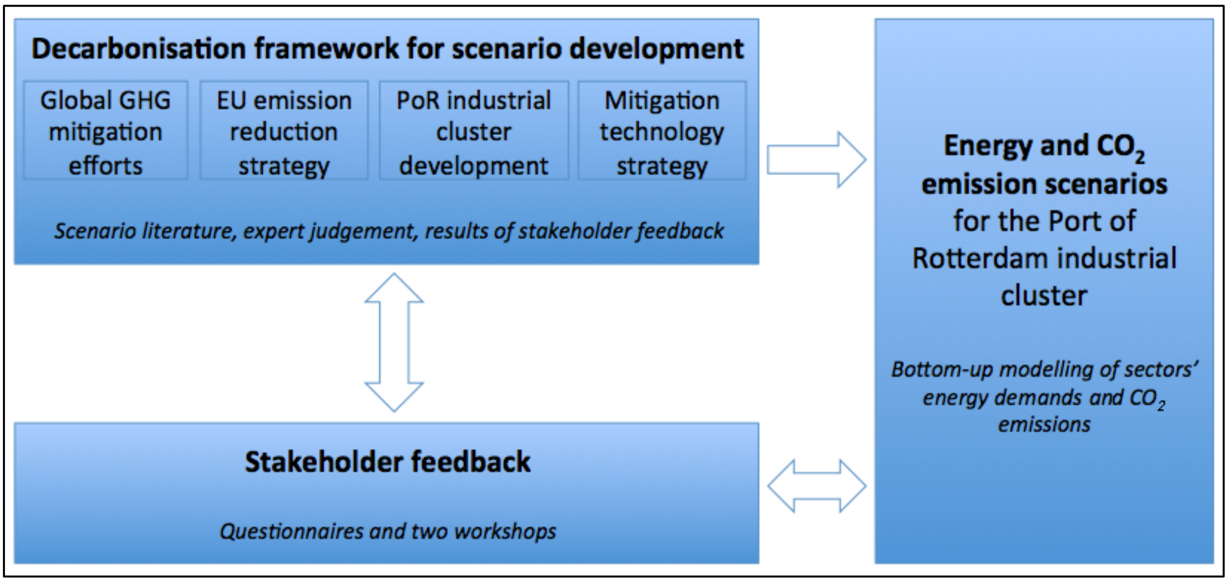
While the actual future developments of the port's industrial cluster can and will most likely be quite different from the developments laid out in these scenarios, the scenarios are intended to help broaden today's thinking on potential future developments of the port's industry in a decarbonizing world. By thinking in an open and unrestricted way about the future, the Port Authority together with its industries and possibly other stakeholders can increase their capabilities to be prepared for potential future developments – so as to better tackle the challenges ahead and to fully exploit the opportunities awaiting. As the port's industry profits from its cluster structure, it is logical to prepare for the future jointly – even if individual companies will also pursue separate strategies. As a first step towards such a joint process, this study was developed in interaction with Port of Rotterdam stakeholders from industrial companies as well as civil society.

The process of scenario development is depicted in Figure S1. First, a framework for the scenarios of the port's industrial cluster was determined: An overview of recent global GHG mitigation and decarbonisation targets and respective EU GHG emission reduction strategies

provided information for deriving assumptions about the future developments of the business environment for the companies within the port's industrial cluster. The assumptions about the future EU GHG emission reduction strategies were mainly based on an analysis of available European decarbonisation scenarios. According to these scenarios (which we refer to in this study as our "framework scenarios"), considerable changes are expected in the coming decades particularly in the transport and power generation sectors. This will have strong effects on the production of fuels and electricity in the port and on the technologies and energy carriers used. Plausible economic visions for the industrial cluster were derived based on the business environments foreseen by the framework scenarios. Potential "low carbon" technologies were selected in the scenarios based on literature and a survey among the port's industrial stakeholders.

Building on these steps, four energy and CO_2 emission scenarios for the Port of Rotterdam industrial cluster were developed and quantitatively modelled (one business-as-usual scenario and three CO_2 mitigation scenarios). The results were intensively discussed with stakeholders in two workshops and refined based on the feedback received from the stakeholders.

Figure S1: Steps taken in developing the scenarios for the port's industrial cluster



It needs to be mentioned that – although this study is limited in scope to the industrial activities and to the related territorial emissions in the port area – it is obvious that the huge up- and downstream flows and transports of resources, energy and products that are linked to the industrial as well as logistics activities also have significant impacts on global GHG emissions and resource depletion. Via their influence on these flows and the linked value chains, the port and its industries hold an important lever for climate mitigation outside of their territorial boundaries. These options should also be systematically explored in the future and should be included in an overall decarbonisation strategy for the port.

Global and European decarbonisation strategy as framework condition

This study highlights the challenges that the Port of Rotterdam area will likely face in the coming decades as global and European decarbonization efforts intensify. That the EU and other nations around the world will strengthen their efforts to combat climate change is probable, as this will be needed if the international community's climate change mitigation targets laid out in the Paris Agreement are to be reached. In a decarbonizing world, however, the port's industrial cluster will most likely not be able to retain its current form in the decades to come. Instead, some elements of the current cluster, specifically refineries and unabated fossil fuel power generation, will become less relevant over time as a result of changes in regulation and market demand associated with global and European decarbonization efforts.

Reducing GHG emissions by 80 to 95% compared to 1990, as the EU intends to do by 2050, will require a transformation of the European economy. As almost 80% of total GHG emissions in Europe are energy-related, radical changes are especially required in regard to how energy is supplied and consumed.

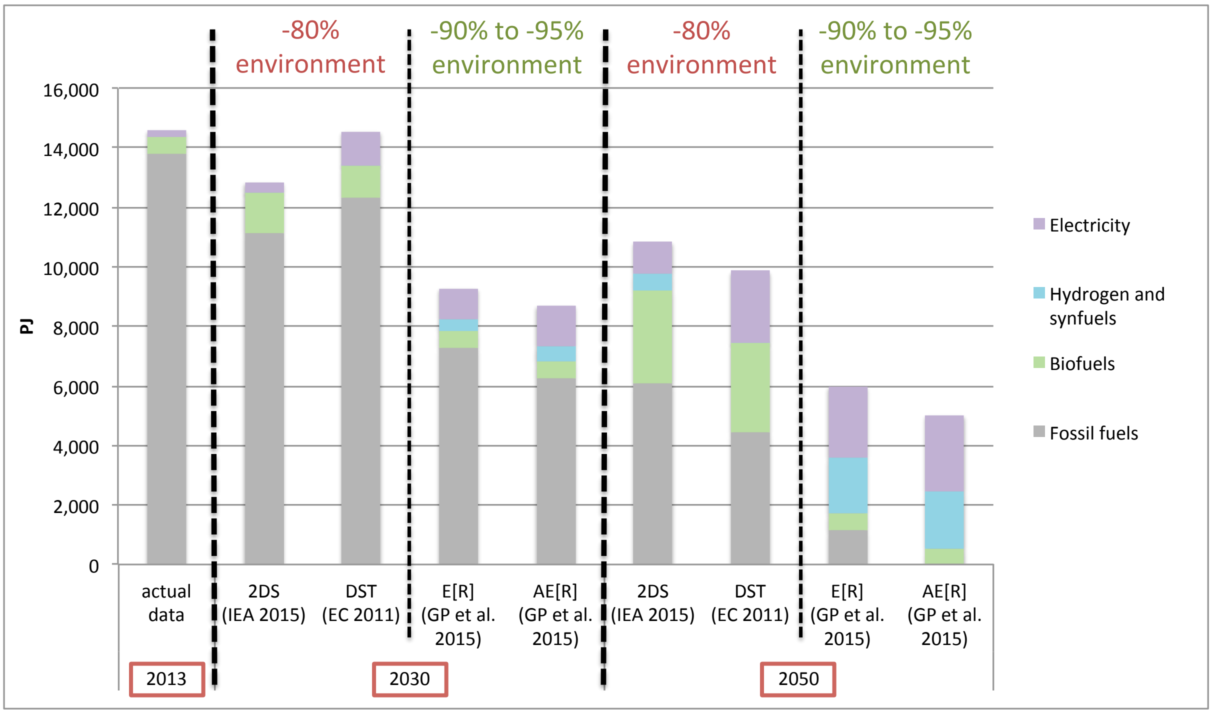
To better understand the changes that are needed in energy demand and supply in Europe and the likely consequences on the market environment for the industrial cluster in the Port of Rotterdam area, we have analysed four framework scenarios that describe energy-related CO_2 emission reductions of 76 to 100% until 2050 (relative to 1990) for Europe. These four framework scenarios were combined to two archetypical frameworks for the EU, one achieving an 80% emission reduction relative to 1990 and the other one achieving a more ambitious 90 to 95% reduction.

From an analysis of the framework scenarios it becomes clear that particularly the changing demand for fuels in the European transport sector (see Figure S2) as well as the expected changes in Europe's electricity mix are very significant already in the "minus 80%" but particularly in the "minus 90 to 95%" scenarios and that they are most relevant for the future market environment of the port's current industrial cluster.

Expected changes in the European transport sector

Should European decarbonization efforts until 2050 achieve only the lower end of the EU's long-term target range – an 80% GHG emission reduction vs. 1990 – the transport sector's fossil fuel demand would still be of considerable size by the middle of the century. In this case, the generally favourable conditions for refineries at the Port of Rotterdam might allow them to continue to operate at only modestly reduced output compared to today. An increasing share of their output would continue to supply a relatively stable petrochemicals production in the port's cluster. However, this would require the port's refineries to be able to increase their market share in a declining European fuel market.

Figure S2: Final energy demand by source in the European transport sector between 2013 and 2050 (in PJ)



Sources of data: EEA 2016, IEA 2015, EC 2011, Greenpeace et al. 2015.

In case of highly ambitious European decarbonization efforts – achieving emission reductions of 90% or more by 2050 vs. 1990 – fossil fuel demand in the transport sector would be minimized by the middle of the century. Some limited refinery capacities could still be present in this scenario, as there would be a small remaining demand for hydrocarbon products. However, it is difficult to assess whether the production of these refinery products would indeed take place in Rotterdam in the future.

Even if the refineries were to eventually cease production, the study's decarbonization scenarios show that the production of chemicals in the port area could nonetheless continue beyond the middle of the century. Base chemical production at the port could switch from using mineral oil products as feedstock to natural gas liquids or it could be radically transformed so as to rely on plastic waste as feedstock in a closed carbon cycle approach. Sustainably produced biomass on the other hand is a scarce resource that will likely be needed as a feedstock for low carbon fuel. Small volume but high-value biomass-based speciality chemicals could nevertheless be an interesting field of business in the future at the port.

Expected changes in the power generation sector

Unabated fossil-fuel electricity generation is likely to be completely or largely phased out by 2050 in case of ambitious decarbonization efforts in Europe. This study's decarbonization scenarios sketch several ways on how to deal with the fossil fuel power plants currently operating at the port, especially the two new coal-fired power plants on the Maasvlakte. These could be equipped with CCS technology, if the various challenges faced by this technology can be overcome in the next ten to twenty years.

However, in a highly ambitious European decarbonization environment, the life-cycle GHG emissions even of coal-fired CCS plants will be too high. This study suggests that if sufficient amounts of sustainable and suitable biomass can be made available at the port at acceptable costs, the power plants could be converted to eventually run entirely on biomass and waste with the CO_2 captured and the heat utilized with the help of a heat grid. Due to the limited amount of sustainable biomass available globally and the possible need to use this potential to substitute fossil fuels in other applications, its use in the power generation sector may only be justifiable if “negative” emissions can be achieved by using CCS technology. Furthermore, renewable electricity generation from wind turbines and solar PV systems can and should play an increasing role in the port area in the years and decades ahead.

Three future visions of the Port's industrial cluster in a decarbonised world

Based on the challenges of the different decarbonisation pathways for the businesses of the Port's industrial cluster and the different possible technological developments in these framework scenarios, three very different scenarios for the development of the industrial cluster are developed. They combine the potential future pathways of the port’s refinery, chemical and power and heat generation industries to create three plausible pathways that are consistent with the respective regulatory, market and technology developments assumed.

The first decarbonisation scenario, "Technological Progress" (TP), assumes that Europe reduces its GHG emissions by 80% by 2050 compared to 1990. The scenario focuses on strong technological progress, with only moderate structural changes in energy and transport systems. In this scenario, technologies assumed to be successfully exploited by the port’s industrial cluster are CCS for power plants and parts of the refineries as well as a fast implementation of best available technology.

The other two decarbonisation scenarios in contrast assume that the EU aims for a more ambitious 90 to 95% GHG emission reduction until 2050 and that respective policies are enacted. In regard to key decarbonisation technologies, the "Biomass and CCS" scenario (BIO) assumes that large amounts of biomass can be supplied sustainably and will be used in the port for power generation as well as for feedstock for refineries and the chemical industry. Successful exploitation of technologies such as CCS are assumed as in the TP scenario. Furthermore, Fischer-Tropsch fuel generation plays an important role in this scenario, allowing the port to become a key cluster for the production of synthetic fuels in Western Europe.

The "Closed Carbon Cycle" scenario (CYC) on the other hand assumes that the future EU energy system will be almost completely based on renewable electricity, which will supply heat as well as hydrogen for the synthetic generation of feedstock for the chemical industry as well as the remaining small rest of fuels in the transport sector, with the carbon required for the chemicals stemming from recycled waste. Technologies particularly needed for the port’s industrial cluster in this scenario are water electrolysis and gasification or pyrolysis to capture carbon from waste, as well as technologies for the production of base chemicals from syngas.

The "Technological Progress" (TP) scenario

EU-wide, the TP scenario is characterized by continuous efforts to decrease CO_2 emissions. The ETS scheme is tightened and significant measures are taken at the EU and at national levels to expand renewable electricity generation and to improve energy efficiency in all sectors, including in industry and transport. For the transport sector, alternative propulsion schemes with battery and fuel cells achieve high market shares, leading to significantly lower demand for fossil fuels. Carbon Capture and Storage (CCS) is successfully implemented at an industrial scale in the EU.

The industrial cluster of the Port of Rotterdam will only see gradual structural changes in this scenario, mainly a decrease in refinery capacities (which is expected to occur in the BAU scenario as well). Despite this decrease, however, the scenario assumes that the remaining refineries in the port will be able to keep Rotterdam's market share stable in the declining fuel market, against the direct "competition" in Western Germany.

Regarding investment choices, best-available technology (BaT) will be widely implemented due to favourable economic and regulatory conditions for energy efficiency. Furthermore, renewables-based electricity will be used for heat generation as well as for hydrogen production at modest scale.

Power plants as well as large industrial emitters in the port area will invest in carbon capture technology. However, despite the port area's advantageous geographical location in regard to CO_2 storage, a key challenge of the TP scenario will be to realize the required CCS infrastructure. Aside from technical, economic and public acceptance challenges, which all are assumed to become solved in the TP scenario, the long-term viability of the CCS infrastructure cannot be taken for granted. If climate policy will aim for GHG emission reductions beyond 90%, coal firing – even when equipped with CCS – might turn out to be a dead end, at least if the power plants cannot be converted to run entirely on biomass.

The "Biomass and CCS" (BIO) scenario

In the BIO scenario, it is assumed that the EU sets clear, credible and tight long-term GHG reduction targets. Energy-related emissions in the EU by 2050 approach almost zero in this scenario. Strong and effective instruments, like a carbon tax, provide long-term certainty to investors about the costs of emitting CO_2 and at the same time the implementation of CO_2 grids and CO_2 storage sites is supported. CO_2 pilot grids are built from the 2020s on.

Renewable electricity is developed all around Europe, realizing a very high share of the technical potential and thereby achieving a market share of nearly 100% in 2050 in electricity generation. The remaining thermal power plants will not be fired with fossil fuels anymore, as capture rates below 100% and life-cycle emissions of the fuels do not allow for a complete avoidance of GHG emissions, which would be necessary in the scenario. Therefore, after 2040 the thermal units connected to a CO_2 grid are converted to biomass- and waste-fired units, also delivering high-temperature heat. The firing of biomass and the respective CO_2 storage provides the opportunity to realise *net negative* emissions.

Heat and mechanical energy is delivered by electricity in this scenario. Power-to-heat, water electrolysis and the electrification of transport are therefore crucial technologies to decarbonize the overall energy system, which will have a high impact on the port's industrial cluster, particularly in the long run.

A main challenge of this scenario is the sustainable and affordable sourcing of biomass in a world where sustainable biomass is restricted and in high demand. Although the actual logistics of delivering biomass are favourable due to the port location. A second challenge is the assumed need for high investments in synthetic fuel production facilities and the resulting need for capital-intensive water electrolysis capacity. However, synthetic fuel production is not a necessary part of the petrochemical cluster. Synthetic waxes could also be imported (e.g. from the Middle East and/or North Africa) and simply be converted to fuels at the port.

The "Closed Carbon Cycle" scenario (CYC)

With a GHG emission reduction target of minus 90 to 95%, which means almost full decarbonization of the energy system, the climate policy framework is similar to the one in the BIO scenario. However, this scenario assumes that CCS will not turn out to be an economically viable and sustainable solution, and that it will not be possible to source very high amounts of sustainable biomass.

The CYC scenario provides a vision of an industrial cluster that does not rely on CCS but still keeps the value chains of basic industry at the port. Without the CCS option, fossil feedstock needs to be kept in a circular system with different stages of product use and a recycling option for the carbon content (e.g. by gasification of the waste) at the very end of product use. In this scenario, Rotterdam – with its unique location within Western Europe – would still be the hub for fuels and fuel pre-products and would remain a fully vertically integrated cluster of chemical production.

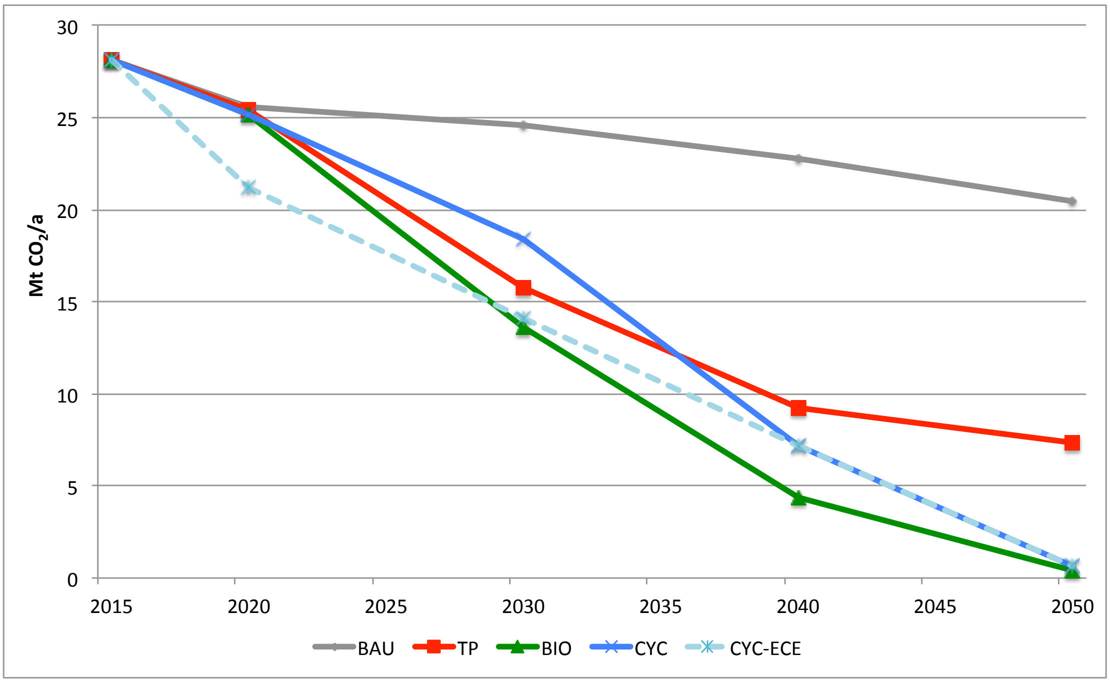
The CYC scenario is a very attractive scenario in regard to the ecological impacts. The port area is a front-runner in this scenario for a circular and almost carbon-neutral economy. It has, however, the most far-reaching impacts on the cluster's structure. Massive and simultaneous investments in different kinds of production stock are required to make this vision technically viable. With the closing of refineries and the steam cracker in the early 2030s, there is a need to substitute existing structures with methanol-based feedstock (or something similar), with the platform product derived from waste and renewable hydrogen. Experience with this technology should already be gained prior to 2030. For fuel supply for aviation and marine transport, the imported crude oil is substituted by the import of Fischer-Tropsch wax.

The CYC scenario is described in two variants: The main scenario assumes the final closure of coal-fired power plants in the mid-2030s, which could be in line with European scenarios achieving GHG emission reductions of about 90% by 2050 (compared to 1990). A variant of this scenario (CYC-ECE) describes the development in case of an earlier closure of coal-fired power stations at the port in 2019/2025, reflecting recent political discussions in the Netherlands focusing on achieving national GHG emission reductions targets for the years 2020 and 2030.

Comparison of the scenarios' CO_2 emissions

All scenarios show a sharp short-term decline of CO_2 emissions by 2020 (compared to 2015), which can be attributed to the closing down of two 40-year old coal-fired power plant units by the end of 2016 (see Figure S3). These closures will reduce annual CO_2 emissions by roughly 6 million tons compared to emissions in 2015. This will, however, be partly compensated for by the Moerdijk steam cracker, which is assumed to soon resume full operation, as well as Exxon's new hydrocracker, which will require additional hydrogen production (leading to additional CO_2 emissions). The only short-term difference between the scenarios can be seen in the CYC-ECE, in which it is assumed that one of the recently built *new* coal-fired power plant units will be closed down already in 2019.

Figure S3: Comparison of CO_2 emissions of the port's industrial cluster in the four scenarios and the scenario variant



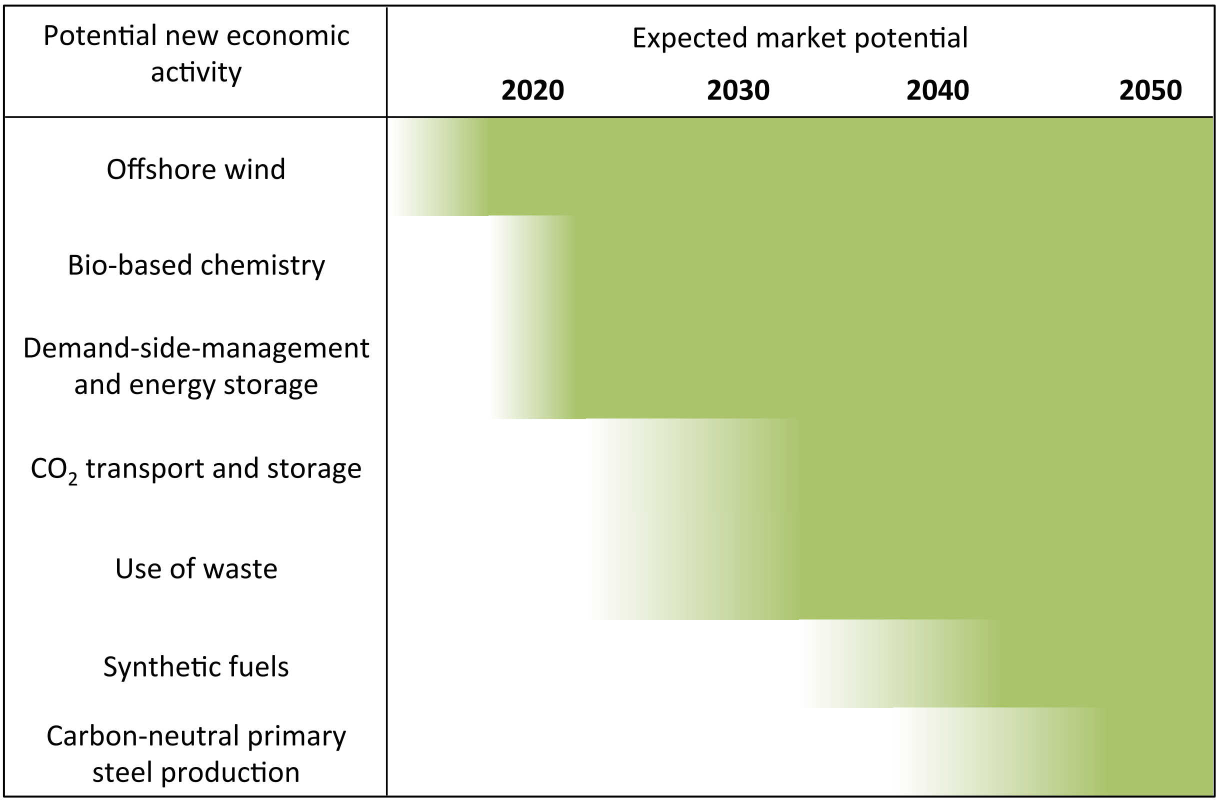
Source: WISEE Model results

In the BAU scenario there will be no further considerable cuts in emissions after 2020. Emissions will remain stable until 2030 and will gradually decline afterwards due to technical improvements and declining refinery production. In contrast, the BIO scenario shows the fastest decline in emissions, due to the adoption of CCS, combined with a high-efficiency path and the large-scale conversion to biogenic fuel and feedstock supply as well as electricity generation and a partial closing down of refinery capacity. Finally, in the CYC scenario, emission reductions occur slightly slower than in the BIO scenario as it takes more time to provide completely CO_2-neutral hydrogen and steam based on renewable electricity (imports), because emission reductions here indirectly depend on the decarbonisation in the EU electricity supply. However, if it is assumed that one of the recently commissioned coal-fired power plants will be closed down by 2019 already, due to national GHG emission reduction policies (as depicted in the scenario variant CYC-ECE), emission reductions in the port area would be comparable to those in the BIO scenario.

Potential new industries in the decarbonisation scenarios

The study also looks at the opportunities arising from global and European decarbonization for industrial production at the port that go beyond the existing industrial cluster. In particular, several industries and activities that may sooner or later gain importance in a decarbonizing European economy and that would also profit significantly from being located at a seaport or even specifically at the Port of Rotterdam are briefly discussed. These are offshore wind, bio-based chemistry, demand-side-management and energy storage, CO_2 transport and storage, use of waste for a closed-carbon cycle economy, synthetic fuel production and carbon-neutral primary steel production. As Figure S4 shows, these potential industries can be expected to become relevant at different time scales. While the offshore wind industry and the bio-based chemical industry already play a relevant role in the port, other industries may become relevant around or beyond 2030.

Figure S4: Expected market potential of possible new economic activities by time period in a future in which Europe pursues ambitious GHG emission reduction efforts



The production of bio-based chemicals and fuels is widely expected to be an important element of a low-carbon future, as biomass provides the only natural source of carbon. Due to the presence of several companies already active in this area, the port of Rotterdam as an industrial cluster is already in a good position to profit from an expected future increase in the relevance of bio-based chemistry as an important and innovative field.

As large electricity consumers, the port's industries have significant potential to adapt their electricity demand to supply. The port’s industries could benefit from becoming major providers of electricity demand flexibility. New types of electricity demand foreseen mainly in the chemical sector (and especially in the CYC scenario), like electrolysis and electric steam generation, are generally suitable to be operated flexibly, with higher demand at times of low electricity prices and lower demand at times of high prices.

CO_2 capture and transport is already practised in the port area (as part of the OCAP pipeline) and the area is also involved in plans to build a pilot CCS project that aims to store CO_2 from a coal-fired power plant in depleted offshore gas fields. Rotterdam is therefore in an favourable position to develop CCS as a business case. At a first step, some of the port area's sites with high CO_2 emissions (e.g. coal-fired power plants) would need to be connected to a dedicated infrastructure. This infrastructure could later become part of a logistic hub that channels CO_2 towards the North Sea. The port area could potentially become a technology and service provider for companies or regions aiming to join the CCS infrastructure.

Hydrogen and synthetic fuels (or *synfuels*) like methanol – produced with renewable electricity – could play a significant role in the transport sector by 2050. In such a future, the port would be well-suited to become a major producer, as its existing delivery infrastructure for fossil transport fuels could be used, while the required carbon and hydrogen could be sourced via ship. Hydrogen could also be produced from electricity at the port, provided the already strong interconnection to the electricity grid is further expanded.

Due to the high CO_2 emissions of current primary steel production processes, steel production may need to radically change in a decarbonising world. Electricity-based production processes such as melt reduction with hydrogen or electrowinning would require greenfield investments and would allow the choice of location of new steel generation to be economically optimised. In such cases, the transport costs of the ore as well as the availability of bulk hydrogen and electricity would become major factors for determining the location of such new plants. Compared to other (landlocked) European sites, the Port of Rotterdam area may well have favourable characteristics for such new steel generation plants.

Ambitious future climate policies would put much more pressure on achieving a circular economy. As described in the CYC scenario, this would include the recycling of the carbon embedded in industrial and municipal waste streams by producing syngases to be used in the production of synthetic feedstock for the chemical industry. Due to its existing petrochemical cluster and the favourable logistical opportunities, the port is in a good position to profit from such potential future activities.

The Port Authority would be well advised to continue to observe the prospects of these new industries and activities and it may want to investigate in more detail the precise conditions that each industry and activity would need to be successful, their respective potential interactions with the existing industrial cluster and promising measures to help attract the industries and activities to the port once the time for investments has come.

Conclusion and recommendations

The potential future industrial clusters of the Port of Rotterdam as well as the potential new industries described here heavily rely on successful research, development and demonstration of new and partly disruptive technologies in energy supply, in the chemical industry and in other sectors. The companies at the port as well as the Port Authority itself are encouraged to take an even more active role in the respective research and innovation processes and to co-operate in this regard as far as possible. Such an active and joint approach offers the potential to foster innovation and also helps to better identify promising pathways for the port. It may result in competitive advantages over other industrial clusters that are less innovative. Such a more active role in research need not be restricted to technical research but can also cover innovation strategies as well as the development of possible business models.

This study's scenarios can only be a first step in developing decarbonization pathways for the industrial cluster of the Port of Rotterdam. One of the key recommendations to the Port Authority is to initiate a Decarbonization Roadmap process in close collaboration with the port's industry. Such a process could help to identify in more detail the conditions that would be required for the port's industry to continue to play an important role in (and for) a decarbonizing Europe. Another key recommendation to the Port Authority is that it should attempt to win financial, regulatory and other support from the Dutch government and the EU for making the port area a flagship region for industrial decarbonization. The Port Authority could emphasise that the port area's good geographic conditions (e.g. CO_2 storage sites nearby; low transport costs for internationally traded goods, including biomass) and strong international visibility make it well-suited to function as a flagship region.

A Decarbonization Roadmap process as well as a close eye on the promising future industries and activities in a decarbonizing environment would help the Port Authority to take on an active role in shaping the port industry's future in a regulatory, market and technology environment that is likely to change much more dynamically over the years and decades to come than in the past. Furthermore, winning government and EU support for making the port area a flagship region for industrial decarbonization would enable the Port Authority and the port's industry to take earlier and more ambitious steps towards the long-term target of full decarbonization.

Global GHG mitigation efforts		EU emission reduction strategy		Development of the port area's industrial cluster					Strategies and emissions		Scenario name
Global GHG emission reduction efforts until 2050	Relative change in global GHG emissions by 2050 (vs. 2010)	European GHG emission reduction efforts until 2050	Change in Europe's domestic GHG emissions by 2050 (vs. 2010)	Key changes in the market environment by 2050 as relevant to the port area's current industrial cluster	Strategy of the port area's industrial cluster	Economic activity in 2050 (vs. today): Refineries	Economic activity in 2050 (vs. today): Chemical production	Economic activity in 2050 (vs. today): Power generation	Key mitigation strategies	Change in the port area's CO_2 emissions by 2050 (vs. 2015)	
Weak (Countries do not implement Paris Agreement)	+20 to +50%	**Minimal** (GHG emission reductions mostly the result of technological developments and policies focusing on other goals, e.g. reducing import dependency)	-30 to -40%	• Decrease in demand for oil refining products	• Efforts focus on keeping the cluster in its current form	↘	→	↘	• (slow) adoption of BaT	-30%	**BAU**
Strong (Countries make great efforts in order to implement Paris Agreement)	-40 to -70%	**Strong** (Europe contributes to global efforts at the lower range of its "fair share" contribution)	-80%	• Strong decrease in demand for fossil transport fuels • Phase-out of unabated coal power generation	• Efforts focus on keeping the cluster in its current form	↘	→	↘	• rapid adoption of BaT • some power-to-heat (P2H) • coal CCS	-75%	**TP**
		Very strong – Significant use of biomass (Europe contributes to global efforts at higher range of its "fair share")	-90 to -95%	• Demand for fossil fuels virtually zero • Phase-out of coal power generation • *BIO:* Large amounts of sustainable biomass available on the world market • *CYC:* No biomass, but large amounts of carbon-free power and/or H_2 available	• Oil is used as feedstock for chemicals • Today's new large power plants continue to operate using biomass & CCS	↓	→	↘	• rapid adoption of BaT • P2H • biomass CCS	-98%	**BIO**
		Very strong – Efforts to achieve closed carbon cycle (Europe contributes to global efforts at higher range of its "fair share")			• Recycled plastics are used as feedstock for chemicals	↓	→	↓	• rapid adoption of BaT • P2H • recycled plastics for chemicals	-98%	**CYC**

1 Introduction

The *Paris Agreement* adopted in December 2015 by 195 countries (UNFCCC 2015) as well as the *Elmau declaration* of the G7 leaders from June 2015 (G7 Heads of State 2015) make it very clear that the world needs to take significant steps towards decarbonising the global economy and energy systems until the middle of the century, and that countries are determined to do so.

Limiting the increase in the global average temperature to well below 2° C over pre-industrial levels means that global GHG emissions need to peak very soon and emissions in industrialised countries need to be reduced by as much as 80 to 95% by the middle of the century compared to 1990 levels (IPCC 2014). The EU has set itself this target range of reducing its GHG emissions by 2050 (EC 2009). Given the industrialised countries' current almost complete reliance on fossil energy carriers, this means that significant changes will come about in all parts of the economy and particularly the energy systems worldwide.

Global and EU-wide decarbonization policies will also affect the industrial cluster at the Port of Rotterdam, as the bulk of the port's economic activities focuses on trading, handling, converting and using fossil fuels, i.e. fossil carbon. This makes the port's businesses particularly vulnerable to global and European decarbonization efforts, as the stepwise phasing out of fossil resources is at the very core of any decarbonization strategy. Furthermore, with annual CO_2 emissions of well over 30 million tonnes, the port is one of the major European hot spots of GHG emission and therefore bears a particular responsibility to actively contribute to European GHG emission reduction efforts.

Therefore, already in 2007, the Port Authority set an ambitious goal of reducing the emissions of the port and its industrial complex by 50% by 2025, compared to 1990 levels as part of the Rotterdam Climate Initiative (Port of Rotterdam Authority 2011, Rotterdam Climate Initiative 2009). The fact that since then emissions in the port area have increased substantially and that the current targets do not yet reflect recent international decisions on long-term climate change targets and overall decarbonization, the Port Authority commissioned the Wuppertal Institute for Climate, Environment and Energy to conduct a study on *Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam*. This study aims to focus on learning about the possible challenges as well as chances for the port‘s industrial cluster, if there will indeed be ambitious climate mitigation efforts in Europe and globally in the coming decades. For this purpose, four different scenarios are developed, describing what the port's industrial cluster could look like in 2050 in case of ambitious decarbonization efforts globally and in Europe, and to what extent the cluster might contribute to GHG mitigation.

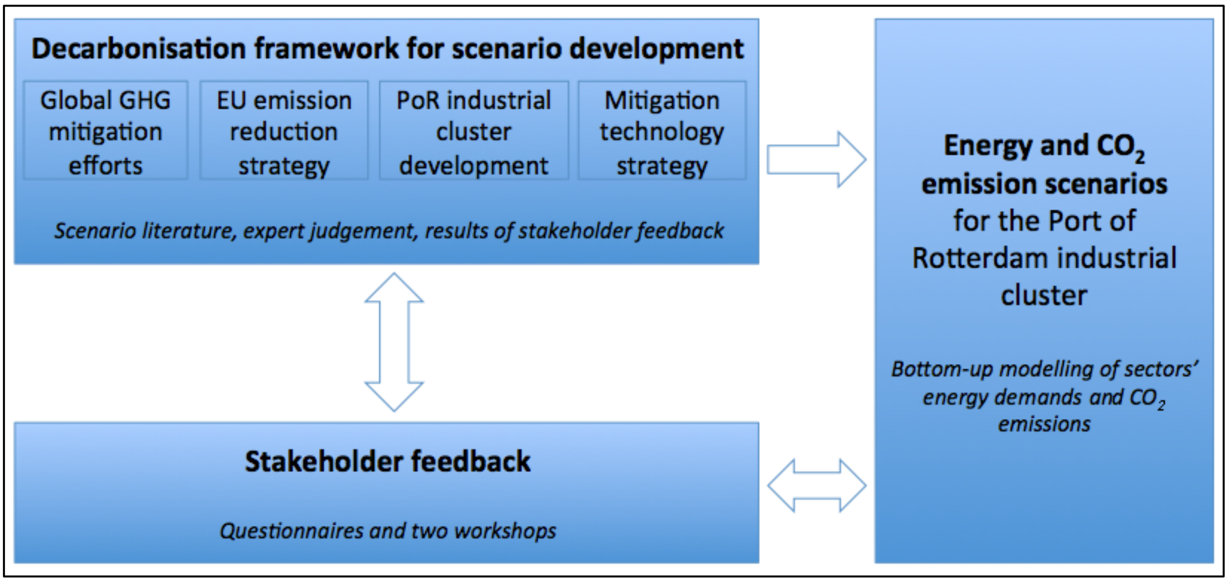
This study's task is therefore to think through the consequences for the Port of Rotterdam area if the world and Europe will indeed pursue ambitious climate protection efforts in the years and decades to come. Consequently, ambitious global and European climate change mitigation efforts until 2050 are a fundamental assumption of this study, although one can obviously not be certain that such efforts will indeed be made.

In this study we use a *scenario approach* which is meant to be a way to help decision makers at the port as well as other stakeholders in the area be better prepared for future developments. Each of the scenarios developed within this report describes a conceivable development for the port area until the year 2050. This scenario approach enables thinking about and preparing for possible future developments that would bring about major changes to the area's industrial cluster in the years and decades to come. Experts from the Port Authority, the port's industries, as well as societal stakeholders were involved in our study and collaboratively, four energy and CO_2 emission scenarios for the port's industrial cluster were developed. One of the scenarios captures a business-as-usual development, while the three other scenarios describe different possible developments in a decarbonising world.

The aim of the study and the scenarios is not to determine any "appropriate" emission reduction targets for the port's area or its industrial cluster. Instead, the scenarios represent pictures of future industrial development at the port that are consistent with the assumed global and European developments.

To derive the scenarios, a stepwise approach has been taken (see Figure 1). First, the results of global as well as European GHG mitigation scenarios are compared with regards to their potential consequences for the businesses of the port's industrial clusters. Consequences include the expected changes in the electricity generation mix (e.g. phase out of coal and/or new investments into carbon capture and storage technologies) as well as the changes in the transport sector which will lead to a significant decline in European demand for fossil transport fuels, directly affecting the demand for refinery products. Secondly, the European decarbonization scenarios are analysed with regards to the technological characteristics of their respective decarbonization strategies. These may be, among others, a focus on the use of biomass if biomass is assumed to be available in a sustainable manner and in sufficient quantities, or a wide-reaching electrification of energy systems and a conversion of chemical feedstock to synthetic fuels.

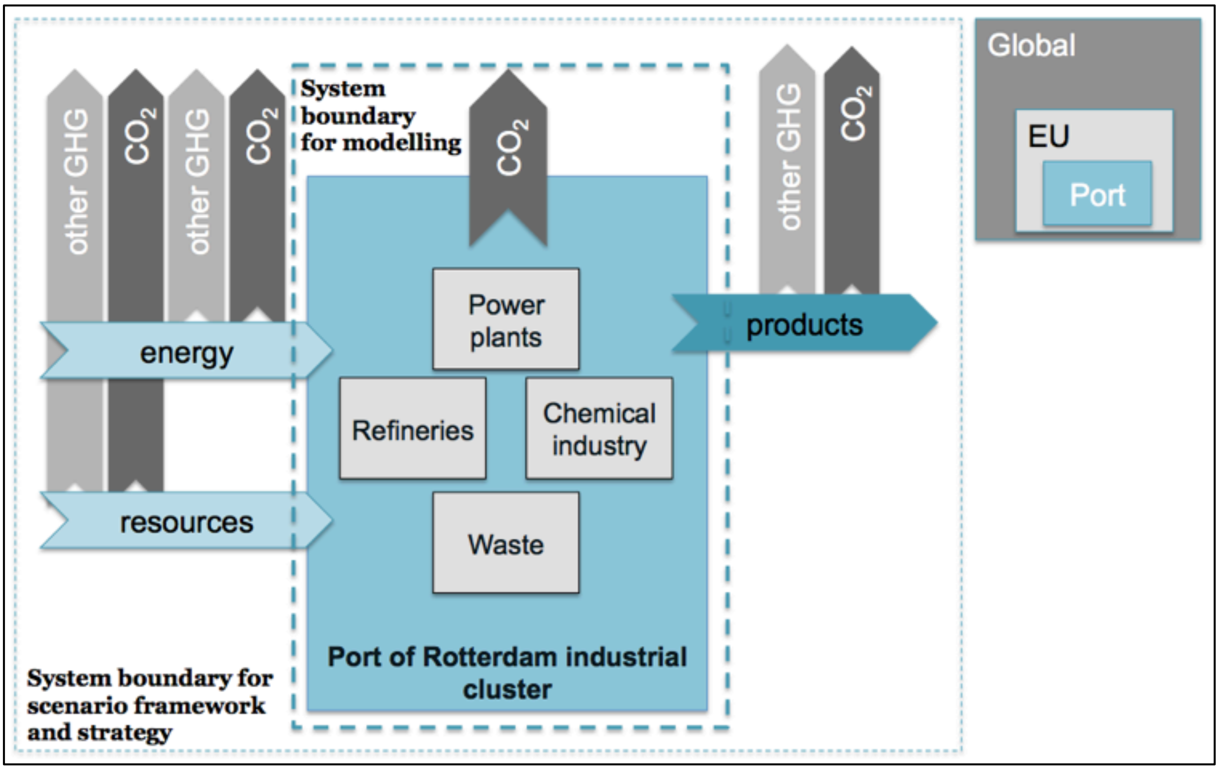
Figure 1: Steps taken in developing the scenarios for the port's industrial cluster



Based on these first two steps, plausible future industrial clusters for the port have been designed and reproduced in a technologically detailed model. The model verifies the technological feasibility of the future industrial clusters and calculates their respective CO_2 emissions. The different clusters depict possible future developments by taking into account the persistence of the existing stock of assets, including its technical and economic lifetime as well as foreseeable changes in the markets for the cluster's core industries such as refineries and power plants. The technological mitigation strategies of the port's industries are in line with the overall technological strategies assumed for the respective decarbonization scenario. In a final step, the different future clusters are implemented in the model, so that energy flows, GHG emissions and necessary technologies and infrastructures can be quantified.

The scope of the study as well as the bottom-up energy and emission model is the area or territory of the Port of Rotterdam, with a focus on its large CO_2 emitters (see Figure 2). These large emitters are found within the port's industrial cluster consisting of refineries, chemical industry, power plants and waste incineration. Other activities at the port area are less relevant for the territorial GHG emissions of the port (see Figure 3 in Chapter 2 below) and have therefore not been modelled quantitatively.[1]

Figure 2: System boundary for the modelling of the port's industrial cluster and its CO_2 emissions



[1] It should be noted that CO_2 emissions of the transport sector become highly relevant if emissions beyond the port area's territory are regarded, i.e. if not only intra-port traffic but also the inbound and outbound traffic of the port are taken into account. The Port Authority therefore intends to study the possible future developments of the transport sector in a decarbonization environment (as well as the port's potential to shape these developments) in a separate report.

The analysis considers the port's industrial cluster as an integral part of the EU and of European as well as global decarbonization trends. The industrial cluster contributes in a significant way to European GHG emissions, mainly through energy-related CO_2 emissions from the industrial activities performed at the port. These emissions are taken into account and are quantified in the study. But the port's industrial cluster also depends on future trends, particularly regarding the demand for its products but also the prospective supply of (renewable) resources. This dependency is taken into account in the formulation of the different scenarios. Finally, via the resources it uses and the products it delivers the cluster also has (complex) indirect effects on other GHG emissions downstream and upstream the value chains. These are not covered in this study.

In the following Chapter 2, the current status of the port's emissions is provided and four framework scenarios depicting different global as well as EU decarbonization trends are described. Based on these framework scenarios, the driving forces that will influence the emergence of future industrial clusters at the port are described.

Next, Chapter 3 describes the developed scenarios for the port's industrial cluster, including the technological strategies, necessary investment trajectories and quantitative results on future energy, emission and resource flows. Further, possible new industrial developments for the port are discussed. Here industries are taken into consideration that probably will experience strong growth under ambitious decarbonization policies and for which the port could offer competitive advantages as a location under such circumstances.

Chapter 4 then derives recommendations for the government, the Port Authority and the industrial enterprises at the port, from the scenario analysis. Finally, Chapter 5 concludes the study and recommends further steps and research.

More detail on the multi-criteria and stakeholder-judgement based selection of technologies, the stakeholder workshops as well as the model used for the quantitative analysis is provided in the study's Appendix.

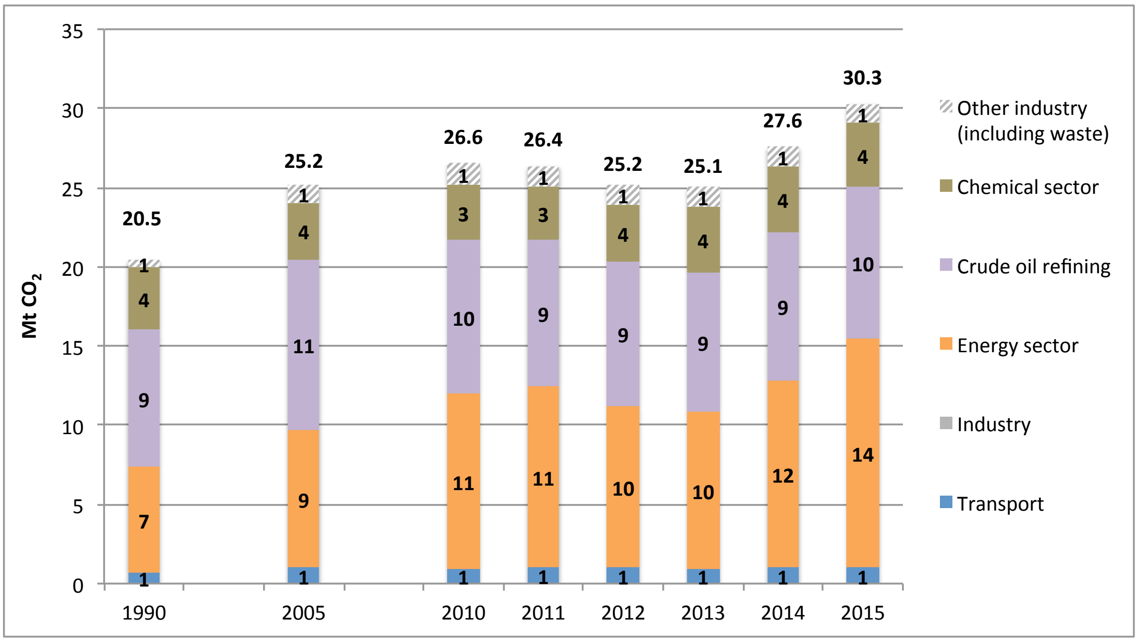
2 What is the challenge?

2.1 The Port of Rotterdam area and its CO_2 emissions since 1990

The Port of Rotterdam is the largest seaport in Europe with an annual throughput of around 465 million tonnes in 2015. The port area stretches over 40 kilometres from the City of Rotterdam to the Maasvlakte 2 area, which projects into the North Sea. The port area includes about 6,000 ha of industrial sites. Overall, more than 90,000 people are employed in the port area, about 20,000 of those in the port's industry. (Port of Rotterdam Authority 2016)

The port's industrial cluster is made up to a great extent of companies operating in the energy- and CO_2-intensive sectors of oil refining, chemical manufacturing and power and steam generation. In 2015, the area's CO_2 emissions totalled 30.3 Mt (see Figure 3) and made up 18% of the Netherlands' total CO_2 emissions[2]. Figure 3 shows the port area's CO_2 emissions for the years 1990, 2005 and 2010 to 2015. CO_2 emissions grew by 48% between 1990 and 2015.

Figure 3: Annual CO_2 emissions in the Port of Rotterdam area from 1990 to 2015 (in Mt)



Notes: No official statistics for the port area's transport emissions exist. For this figure, the sector's emissions in the port area are therefore estimated to be 50% of transport emissions for the entire region of Rotterdam.

Sources of data: DCMR (2008) for 1990 and 2005 and personal communication with DCMR via email in September 2016 for 2010 to 2015.

2 Non-CO_2 greenhouse gases make up only about 1% of Rotterdam's total GHG emissions (personal communication with DCMR via email in June 2016) and are therefore not analysed in this report.

3 This goal was already committed to by the Port of Rotterdam in 2007, as part of the Rotterdam Climate Initiative (Rot-

In the *Port Vision 2030*, released in 2011, the Port Authority emphasized its goal of reducing the CO_2 emissions of the port and industrial complex by 50% by 2025 compared to 1990 levels.[3] By 2030, the Port Authority aims to reduce these emissions by an additional 10 percentage points, to minus 60% compared to 1990 levels (Port of Rotterdam Authority 2011). These targets were originally assumed to be reached to a great extent through the use of Carbon Capture and Storage (CCS) technology. However, persistently low emission allowance prices in the EU Emission Trading System (EU-ETS) as well as the failure of most of the originally planned CCS demonstration projects to be realized make it unlikely that CCS will deliver large scale emission reductions already by 2025.

A main reason for the massive growth in emissions between 1990 and 2015 was the increase in electricity and steam generation from fossil fuel sources. The energy sector's CO_2 emissions in the port area more than doubled between 1990 and 2015, growing from 6.6 Mt to 14.5 Mt. Emissions from the chemical sector and from crude oil refining also increased slightly, as economic output grew over the years, offsetting emission-reducing effects of higher efficiency.[4] Looking only at the more recent years shows that CO_2 emission grew strongly (by 21%) between 2013 and 2015. The main reason for this growth was that two new coal-fired power stations owned by Engie (previously GDF Suez) and E.ON became operational during this period.

The decarbonization scenarios for the Port of Rotterdam's industrial cluster introduced in Chapter 3 also include industrial activity in the Moerdijk port area, as the industrial complex in Rotterdam has strong ties to the industrial complex in Moerdijk. Table 1 shows the development of CO_2 emissions in Moerdijk as accounted for in the EU Emission Trading System (EU ETS). Moerdijk's CO_2 emissions from large industrial source covered under the EU ETS totalled just over 2 Mt in 2015, mainly from the chemical industry and the power and heat sector. CO_2 emissions declined by 1 Mt between 2013 and 2015, mainly because the steam cracker operated by Shell in Moerdijk experienced technical problems in 2014 and 2015 and was not in operation for much of these two years.

Table 1: CO_2 emissions in Moerdijk as accounted for in the EU ETS from 2008 to 2015 (in Mt)

	2008	2009	2010	2011	2012	2013	2014	2015
TOTAL	**2.7**	**2.6**	**2.9**	**2.8**	**2.7**	**3.0**	**2.4**	**2.0**
of which bulk chemicals	*2.0*	*1.9*	*2.1*	*2.1*	*2.0*	*2.4*	*1.9*	*1.3*
of which power & heat	*0.7*	*0.6*	*0.7*	*0.7*	*0.6*	*0.6*	*0.4*	*0.6*

Source of data: http://ec.europa.eu/environment/ets/oha.do

[3] This goal was already committed to by the Port of Rotterdam in 2007, as part of the Rotterdam Climate Initiative (Rotterdam Climate Initiative 2009).

[4] One reason for growing emissions from the refinery sector were stricter regulations on transport fuel emissions over time, requiring higher energy use (and accompanying CO_2 emissions) in refining to reduce the fuels' SO_2 and NO_x levels.

2.2 Future GHG emission reductions and related changes to the market environment

2.2.1 Global and European emission reductions until 2050 in line with the Paris Agreement

In December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal at a UN conference in Paris (UNFCCC 2015). The deal, referred to as the *Paris Agreement*, aims to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". In order to achieve this goal, governments agreed that global greenhouse gas emissions need to peak as soon as possible and that rapid emission reductions would be required thereafter. Furthermore, according to the agreement, a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases needs to be achieved in the second half of this century.

Before the Paris conference, most countries submitted national climate action plans, so called Intended Nationally Determined Contributions (INDCs). While the sum of mitigation contributions laid out in these plans are not yet enough to keep global warming below 2°C, the agreement stipulates that these climate action plans are to be updated regularly. A "global stocktake" to be undertaken every five years is foreseen to inform countries on their common progress towards the long-term target and to support them in increasing their national mitigation targets over time.

Scenarios of global greenhouse gas emissions reviewed by the IPCC in its latest Assessment Report (AR5) (IPCC 2014) suggest that global emissions in the year 2050 will need to be about 20% to 65% lower than in 1990 for global temperature rise to "likely" remain below 2°C over the course of the 21st century. The range within these scenarios mainly reflects differences between their emission pathways (as it is the *cumulative* emissions over time that determine the atmospheric concentration of GHG) and related assumptions about if and to what extent technologies will eventually be available and deployable that can extract CO_2 from the atmosphere.

However, there are reasons to assume that the world will need to aim for the more ambitious end of this emission reduction range until 2050 to have a good chance to reach its long-term climate target as agreed upon in the Paris Agreement:

- The scenarios reviewed by the IPCC are several years old and mostly assume more ambitious early mitigation action (e.g. from 2010 on) than actually took place in recent years. Higher past emissions mean emissions will need to be lower in the future to reach a specific temperature target.
- The scenarios are unlikely to limit global temperature rise to 1.5°C. Not enough such ambitious emission scenarios were available to the IPCC for its AR5 to analyse their implications, but obviously global emissions will need to be lower in such scenarios compared to those scenarios that are only compatible with the 2°C target.

- Most of the scenarios assume that at least in the second half of the century technologies will be available to extract CO_2 from the atmosphere. The future prospects of these technologies are highly uncertain though and if they cannot be utilized to a significant extent, emission reductions by 2050 will need to be stronger.

It can therefore be assumed that global emissions in the year 2050 will need to be at least 50% to 60% below 1990 emissions in order to hold global average temperature "well below" 2 °C, as aimed for by the Paris Agreement. Due to much higher per capita emissions in 1990 (and the related higher mitigation potential), industrialised countries are expected to need to reduce their CO_2 emissions more strongly than the global average over the period of 1990 to 2050, in order to contribute fairly to global mitigation effort in line with the 2°C target. According to the climate science literature, global GHG emission reductions of 50% until 2050 would require developed countries to reduce their emissions by about 85% to 90%. This would result in similar per capita emissions and abatement costs for developed and developing countries by 2050 (den Elzen et al. 2013).

This reduction requirement is in line with the European Union's declared objective of reducing its greenhouse gas emissions by 80-95% by 2050 compared to 1990 (EC 2009).[5]

This project assumes that policy makers and societies around the world will take adequate and ambitious steps in the coming years and decades to realize the vision laid out in the Paris Agreement. Under this assumption, the global and European economies and especially their energy supply and demand will undergo radical transformations within the next 35 years. These transformations would also affect the industrial cluster at the Port of Rotterdam in a substantial way. The report at hand aims to explore the potential consequences for the cluster – including challenges and opportunities – if the world and Europe will indeed pursue ambitious climate mitigation efforts in line with their long-term targets and commitments.

Before discussing several scenarios for the area's industry until the year 2050 in Chapter 3, it is important to think about how the market environment for the port's industrial cluster will change in case of ambitious global and European climate change mitigation efforts. The following sections will take a closer look at how the European economy and especially its energy system are expected to change from now until the middle of the century if Europe is indeed going to realise its target of reducing GHG emissions by 80 to 95% until then. The focus will be on the expected developments that are most relevant for the port's industrial cluster.

2.2.2 Changes in the market environment for the port's industry in a decarbonizing Europe

Reducing GHG emissions by 80 to 95% by 2050 will require a transformation of the European economy. As almost 80% of total GHG emissions in Europe are energy-related, radical changes are especially required in regard to how energy is supplied and consumed. To better understand the changes that are needed in energy demand and supply in Europe and the likely consequences on the market environment for the industrial cluster in the Port of Rotterdam

[5] In 2014, the EU's emissions were 23% lower than in 1990 (EEA 2015).

area, we have analysed four framework scenarios that describe energy-related CO_2 emission reductions of 76 to 100% until 2050 (relative to 1990) for Europe. These four framework scenarios are from three studies that have been released in recent years by different institutions. Table 2 provides an overview of the four scenarios and shows that these are in line with the range of GHG emission reductions according to the current political targets (either 80% or 90 to 95% GHG emission reductions vs. 1990).[6]

Table 2: Overview of the four analysed European climate change mitigation scenarios

Name of the study	Publisher	Framework scenario	Scope of Europe as considered in studies	CO_2 emission reduction by 2050 (energy-related, vs. 1990)	Scenario taken as an example for a/an...
Energy Technology Perspectives 2015	IEA (2015)	2DS	EU-28	76%[a]	80% GHG reduction in Europe by 2050
Energy Roadmap 2050	European Commission (EC) (2011)	Diversified Supply Technologies (DST)	EU-27	82%	
Energy [R]evolution - A Sustainable World Energy Outlook 2015	Greenpeace et al. (2015)	Energy [R]evolution (E[R])	OECD Europe	92%	90 to 95% GHG reduction in Europe by 2050
		Advanced Energy [R]evolution (AE[R])	OECD Europe	100%	

[a] *Also includes process-related CO_2 emissions from the industrial sector.*

While the range of energy-related CO_2 emission reductions by 2050 in these four framework scenarios is larger than the EU's target range of 80 to 95% GHG emission reductions, all four scenarios may be in line with this target range as there is uncertainty regarding the extent that other GHGs can be reduced in the future. Especially for energy scenarios that aim to be in line with highly ambitious GHG emission reductions of 90% or more, their energy-related emission reductions are widely believed to need to be proportionally greater than overall GHG emission reductions. The reason for this is that very deep reductions of some non-energy related GHG emissions in the future (especially from the agricultural sector and from some industrial processes like cement production) are thought to be impossible or extremely expensive. Therefore, the energy-related CO_2 emission reductions of 92% (E[R] scenario) and

[6] As the fourth row shows, the three studies each consider a slightly different scope of Europe, which means that the studies do not cover exactly the same countries. Especially the Greenpeace et al. study considers more European countries than the other two studies do (with the difference in population in 2012 about 10%). This should be kept in mind when looking at the following comparisons of the four scenarios. However, the differences in scope do not affect the key insights gained from the analysis.

100% (AE[R] scenario) by 2050 described by the two scenarios from the Greenpeace et al. study might well be in line with about 90% and 95% total GHG emission reductions, respectively.

Two of the framework scenarios (2DS and DST) describe energy system changes that would likely allow the EU to meet the lower end of its long-term GHG reduction target, while the other two framework scenarios (E[R] and AE[R]) describe more radical energy-related emission reductions that would likely be compatible with the upper end of the EU's long-term target. As the four framework scenarios cover both ends of the EU's target range, together they provide a good indication of possible future developments if the EU is to meet its long-term emission reduction target and, in doing so, is to contribute adequately to international climate change mitigation efforts.

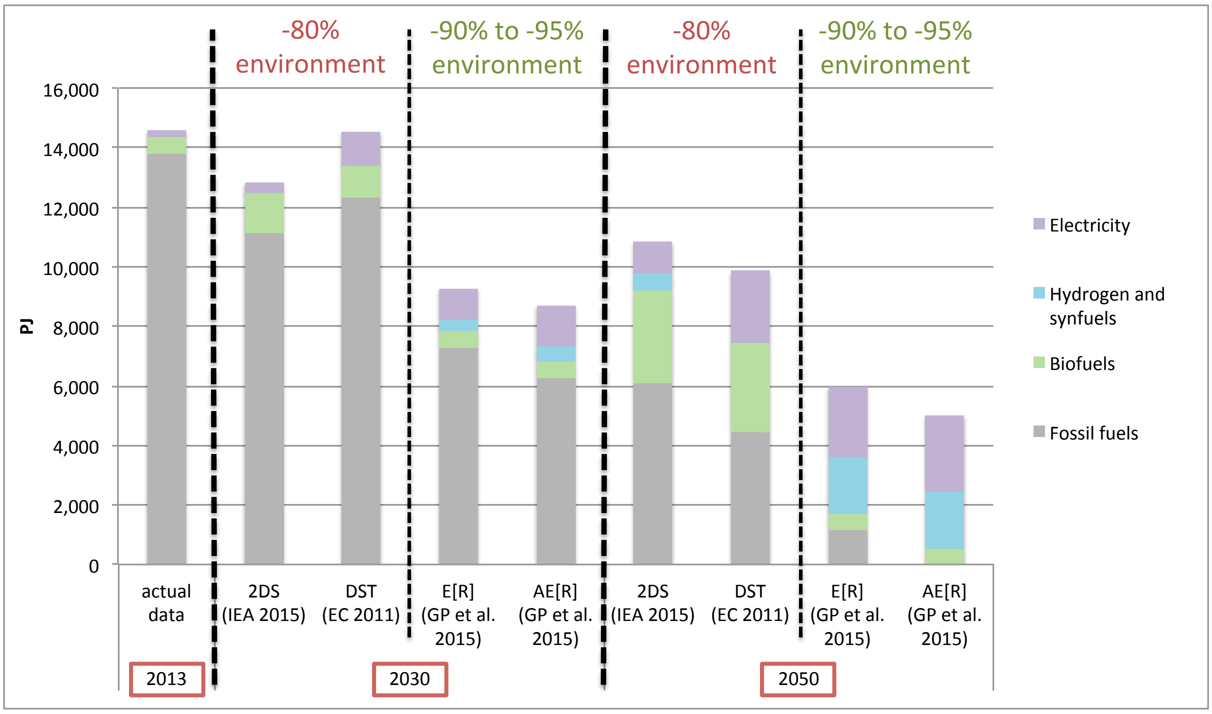
The following discussion of the four framework scenarios focuses on the developments that are most relevant for the future market environment of the port's current industrial cluster:

- Expected changes in demand for fuels in the European transport sector
- Expected changes in the final energy demand mix of the industrial sector
- Expected changes in Europe's electricity mix

Expected changes in demand for fuels in the European transport sector
As the following Figure 4 shows, energy demand in the transport sector declines in all mitigation framework scenarios in the coming decades. This is the case even though all scenarios expect an increase in passenger and freight transport activity until 2050. More efficient vehicles and a modal shift in both passenger and freight transport towards less energy-intensive means of transportation (e.g. from road to rail)[7] are key reasons for the decline in energy demand. The increased role of battery-electric vehicles and fuel-cell vehicles contributes to final energy demand reductions, as the efficiency of electric motors is considerably higher than that of combustion engines.

[7] In the DST scenario, for example, the share of aviation in passenger transport activity in the EU (expressed as person kilometres travelled) is assumed to increase more modestly than in the study's reference scenario. The share of aviation increases from 9% in 2010 to 13% in 2050, while it increases to 15% in the reference scenario. At the same time, the share of rail transport increases from 7 to 10% during the same period in the DST scenario, while it increases to only 8% in the reference scenario.

Figure 4: Final energy demand by source in the European transport sector between 2013 and 2050 (in PJ)



Sources of data: EEA 2016, IEA 2015, EC 2011, Greenpeace et al. 2015.

The sum of the contribution to final energy demand of alternative fuels (i.e. electricity, biofuels and hydrogen/synfuels) is similar in all scenarios by 2050, amounting to between 4.800 and 5,400 PJ. However, the relative role of each type of alternative fuel is assessed differently in the scenarios. The two scenarios on behalf of Greenpeace et al. assume that much less biofuels but considerably more hydrogen and synfuels are used than in the other two scenarios. And the IEA's 2DS scenario uses much less electricity than the other three scenarios.

In the two Greenpeace et al. scenarios, considerable amounts of hydrogen and (in the AE[R] scenario) synfuels are generated from renewable-based electricity by 2050. In these scenarios even a large part of the road freight transport is electrified, using both batteries as well as overhead catenary trucks, enabling high shares of direct electricity use in the transport sector.

As not only final energy demand decreases but the contribution of alternative fuels (biofuels, hydrogen/synfuels and electricity) increases strongly at the same time, the role of fossil fuels in the transport sector is declining rapidly, especially post-2030. That said, in a -80% environment, fossil fuels may still play a relevant role in the transport sector by the middle of the century, with the two scenarios 2DS and DST describing contributions by fossil fuels in 2050 that equal about 30% (DST scenario) to 45% (2DS scenario) of today's value. In a minus 90 to minus 95% environment, however, fossil fuels are not expected to still play a relevant role in the transport sector. Fossil fuels are either completely phased out (AE[R] scenario) or their use is reduced to less than 10% of today's value (E[R] scenario)[8].

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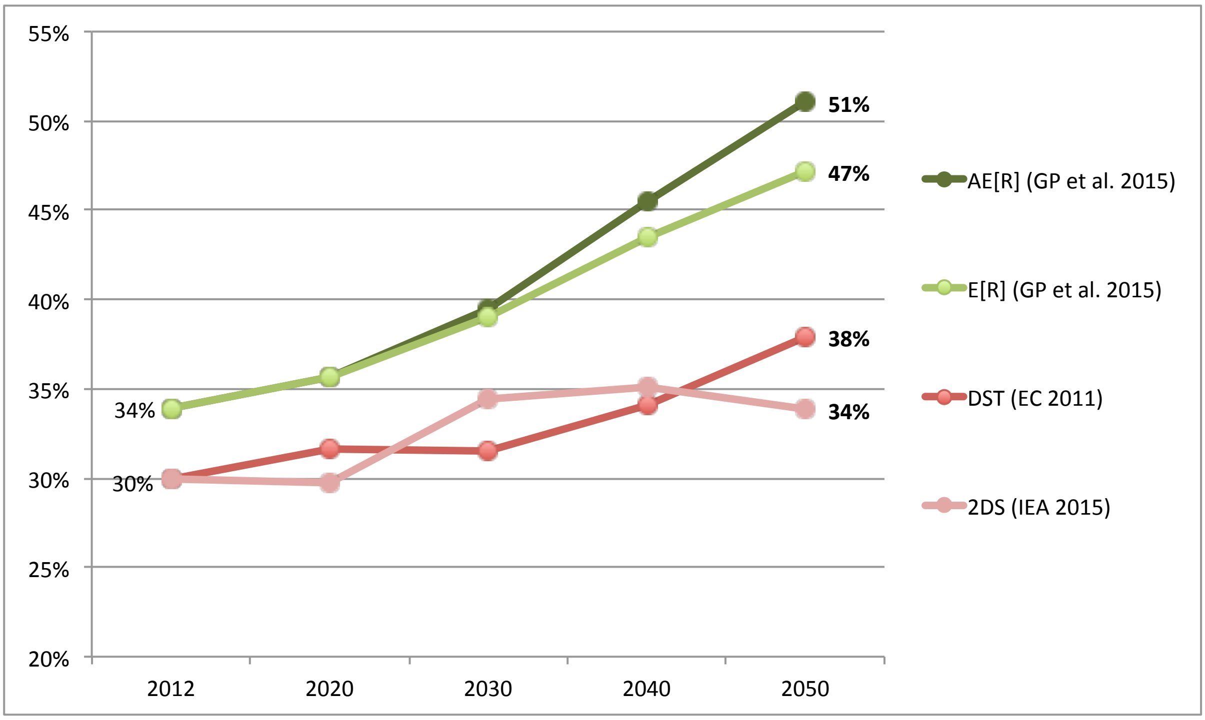
[8] It should be noted that the two Greenpeace et al. scenarios do not include energy demand from international (i.e. out of EU) marine shipping and international air transportation. The authors suggest that this demand could be met by a combination of more biofuels and synfuels, the latter of which would require additional renewable electricity generation.

As a look at the values for the year 2030 in Figure 4 shows, the two pairs of scenarios also differ in regard to short- to medium-term reductions in the use of fossil fuels in the transport sector. While fossil fuel use is only slightly lower in 2030 compared to today in the 2DS and DST scenarios, its use is already roughly halved compared to today in the E[R] and AE[R] scenarios.

Expected changes in the final energy demand mix of the industrial sector

The final energy demand mix in the industrial sector in 2030 and especially in 2050 differs considerably from one scenario to the other. However, there is agreement between all analysed mitigation scenarios that electricity will play an increasingly important role in the sector's final energy demand in the future (see Figure 5). Electricity's share increases from 30% in 2012 to 34 to 38% in 2050 in the two scenarios describing a -80% environment. In the two scenarios describing a -90 to -95% environment, the share increases more strongly, from 34% to 47% (E[R] scenario) and 51% (AE[R] scenario).[9] More ambitious mitigation scenarios tend to have higher shares of electricity in the industrial sector (as well as in other sectors), as in these scenarios there is a greater need to substitute fossil fuels with electricity from low- or zero-carbon sources in processes where this type of substitution is possible.

Figure 5: Share of electricity in final energy demand of the industrial sector between 2012 and 2050 (in %)



Sources of data: IEA 2015, EC 2011, Greenpeace et al. 2015.

A main reason why the share of electricity increases only moderately in the 2DS scenario is that unlike all other scenarios discussed here, this scenario assumes that carbon capture and

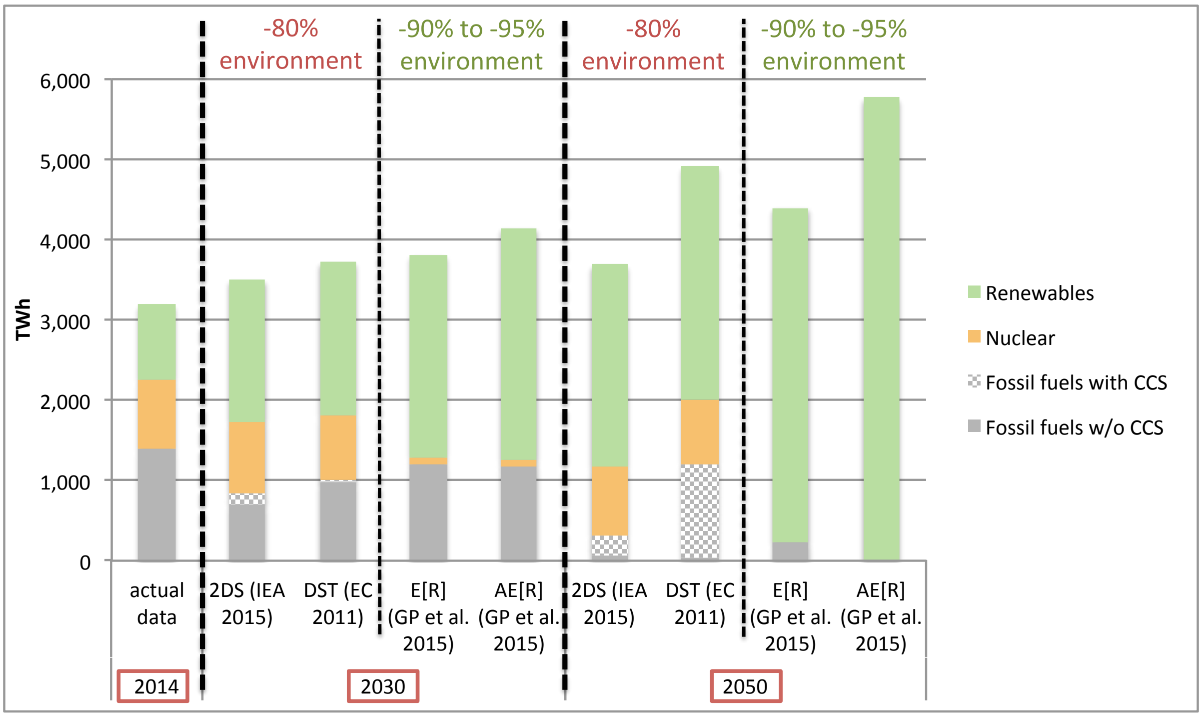
[9] The higher share of electricity in the Greenpeace et al. scenarios in the year 2012 compared to the respective value provided by the other two scenarios is mainly due to differences in distinguishing the industry sector from the other sectors of the economy.

storage (CCS) technology will be used to reduce not only CO_2 emissions from power plants, but also from industrial facilities. Therefore, in this scenario there is less pressure to substitute fossil fuels with electricity or other low-carbon sources in the industrial sector.

Expected changes in Europe's electricity mix

The following Figure 6 compares gross electricity generation by source in all four analysed scenarios. Electricity generation is expected to increase in all scenarios. This increase is the result of higher electricity demand caused by economic growth but also by the aforementioned need to substitute fossil fuels with electricity in the energy demand sectors, for example through the use of electric cars, heat pumps and power-to-heat applications. As a result, electricity demand increases, even though all scenarios assume more rapid improvements in the energy efficiency of traditional electric appliances.

Figure 6: Gross electricity generation in Europe by source between 2014 and 2050 (in TWh)



Sources of data: Eurostat 2016, IEA 2015, EC 2011, Greenpeace et al. 2015.

Despite the increase in total electricity generation, generation based on fossil fuels is expected to decline in all scenarios. Increasing power generation from renewable energy sources, especially from wind and solar energy, more than compensate the decline in power generation from fossil fuels and (in the case of the E[R] and AE[R] scenarios) nuclear power. While power generation from unabated fossil fuelled power plants in the scenarios is only about 10 to 50% lower than today in the year 2030, power generation from these plants has either ended or is very small by 2050 in all four scenarios. The share of unabated fossil fuel power generation declines in the scenarios from 43% in 2014 to 0 to 5% in 2050, virtually all of it coming from natural gas-fired power plants (as opposed to coal-fired power plants).

According to the scenarios, coal-fired power generation in a decarbonizing Europe can only play a role by the middle of the century if the plants are equipped with CCS technology. The two scenarios depicting a -80% world assume that natural gas and coal power plants with CCS technology will indeed be built, mainly from around 2030 on, with much more capacity built in the DST scenario than in the 2DS scenario. The two scenarios depicting a -90% world do not assume that CCS power plants will be built, with the assertion that “costs, effectiveness and environmental effects of CCS are highly speculative”.

It can be argued that by the middle of the century at least new coal-fired CCS plants will be difficult to reconcile with efforts to reduce overall GHG emissions by around 95% or more, as remaining life-cycle GHG emissions of power generated from coal CCS plants are too high. Even when it is assumed that a very high share of the plants’ CO_2 emissions (e.g. 99%) could be captured and stored, relevant amounts of upstream emissions accrue during coal mining. In addition, CCS is associated with concerns about the possibility of long-term leakage of the CO_2 stored and storage capacities may become a limited resource.

Demand for and supply of petrochemicals in a decarbonized world
Global demand for petrochemicals is widely believed to continue to grow strongly in the coming decades (IEA 2013, Cefic 2013, VCI 2013), with future growth rates in Europe expected to be smaller than in the rest of the world. There is considerable uncertainty in regard to the volumes that the petrochemical industry will produce within Europe in the future. While European production volumes of other chemical subsectors, like specialty chemicals and consumer chemicals are widely believed to grow in the future, the future prospects of the petrochemical industry in Europe are viewed as more uncertain, as other regions of the world might be viewed as more attractive for new investments in production facilities.

According to a study for the chemical industry’s European trade association (Cefic 2013), the future production of petrochemicals in Europe is uncertain, even when assuming that the world reduces its GHG emissions by 50% between 1990 and 2050. In that case, Europe’s petrochemical production (expressed in real monetary terms) may go down by about 15% between 2010 and 2050, if there will be no convergence of climate mitigation policies around the world. However, production values may also grow strongly (by about 50%) in that period, if policies are chosen that ensure a level playing field for the global manufacturing industry by introducing a uniform global carbon price. Because of this uncertainty, we make the simplifying assumption for all our scenarios in Chapter 3, that the volume of petrochemical production in Europe will remain roughly flat over the coming decades and so will the production in the Port of Rotterdam area.

3 What is the vision?

3.1 Scope of the Port of Rotterdam scenarios and model-based scenario building

Sectoral and regional scope of the scenarios

As shown in the Introduction, the scope of this study's energy and GHG modelling is the territory of the port area (incl. Moerdijk) and the direct CO_2 emissions which occur within this area. Emissions during the extraction of resources processed at the port and of use of the port's products also have an impact on the GHG emissions of the whole chain, but are not quantified here. This approach is justified as is it is not the main aim of the study to derive a quantitative GHG target for the port but to sketch viable future industry clusters which might emerge in the port under different socio-political and regulatory environments. For these potential future clusters, respective CO_2 emissions are quantified.

The sectoral system boundary of analysis is restricted to electricity generation, waste incineration and the petrochemical cluster within the Rotterdam port area (including Moerdijk). The port area forms a complex cluster with many interlinkages and value chains. However, the bulk of GHG emissions can be attributed to a small number of GHG and energy intensive resource and product flows.

From system analysis to model-based scenario building

Before developing the scenarios, the port's energy system was analysed in detail. As there are no energy statistics available for the port area, the energy system was modelled for the base year (2015), taking the following capacities into account:

- Electricity generation units (in MW_{el}; > 70 units)
- Refinery processes (in t/a; > 30 units)
- Number of petrochemical processes (in t/a; > 40 units)

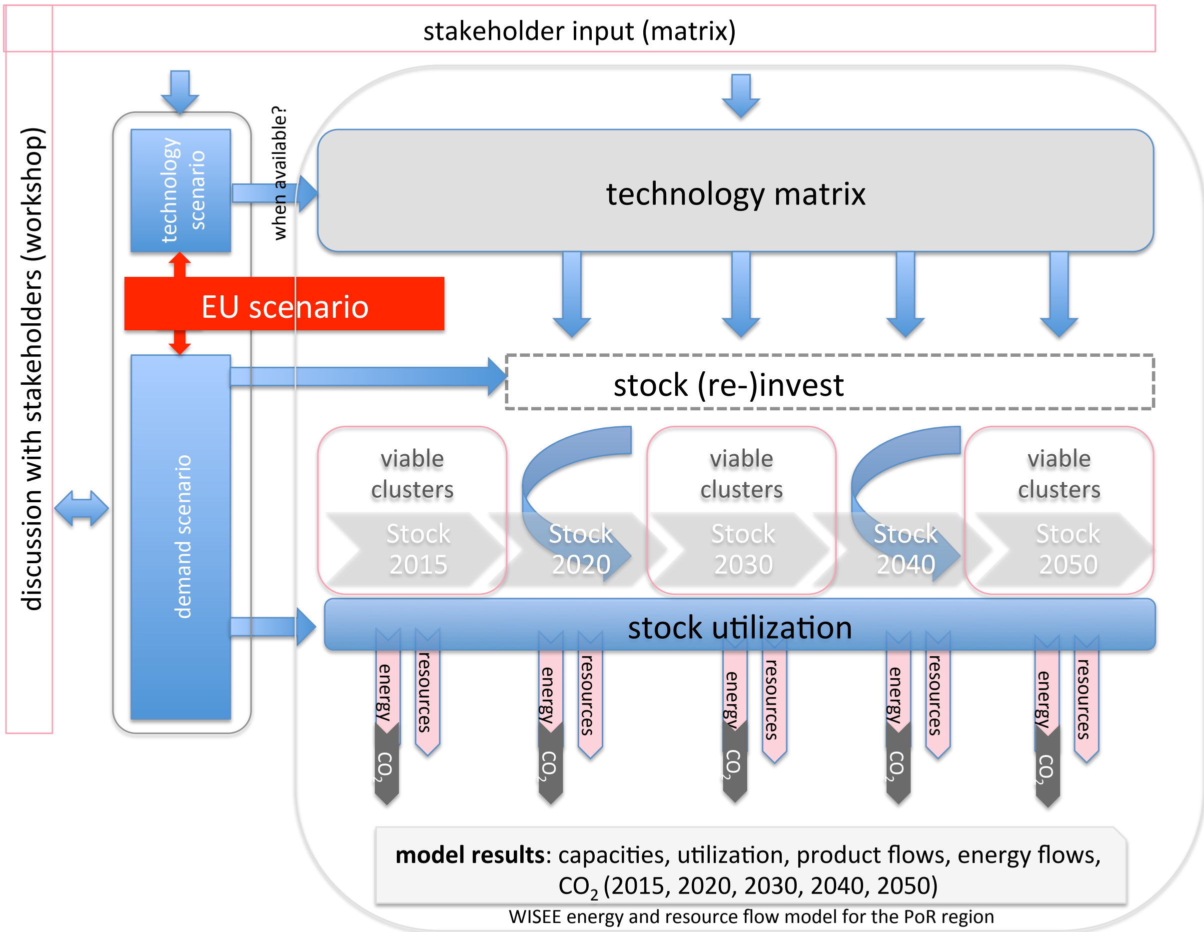
The specific energy and resource demand of the processes was derived from literature and the results were validated with data from the European Emission Trading System (EU ETS), which provides site or plant specific data on annual CO_2 emissions in the form of time series.

Refinery utilization was modelled using an optimization procedure. The dispatch of the different kinds of processes (ADU, VDU, FCC, cokers, visbreakers, hydrocrackers, reformers and hydrotreating units) was modelled for all five Rotterdam refineries and the Vlissingen refinery. The total results (for all six Dutch refineries) could be validated with the data on refineries in the Dutch energy balance.

Based on the system analysis for the base year, the scenarios were built by combining a backcasting and a forecasting approach: The starting point to build industrial clusters in the port area for the year 2050 were European energy and emission scenarios (see Chapter 2). The European scenarios provide time series on the volume and structure of transport fuel demand, the pathway of investments in renewable electricity generation capacities (like on- and offshore wind, PV, geothermal energy etc.), the primary energy use and the sectoral CO_2 emissions (see Chapter 2 for details). The EU scenario results were broken down to the relevant markets, especially the transport fuel markets. The assumed transport fuel demand for all scenarios is documented in Appendix D.

The 2050 clusters were designed taking into account the EU scenario framework as well as the available technologies according to a technology matrix and local potentials for application (see Figure 7). The technology matrix was designed by the Wuppertal Institute and stakeholders commented on the applicability of technologies. Following the stakeholder feedback, the technology matrix was amended and key technologies were discussed on two stakeholder workshops held in June 2016.

Figure 7: Schematic diagram of the model used to develop the scenarios



The clusters that were built were tested with Wuppertal Institute's WISEE energy and emission system model in regard to technical feasibility, energy demand and emission reduction potential (backcasting). Future refinery dispatch was modelled with the optimization tool mentioned above. The clusters were assessed to be viable as long as their net energy demand is in line with overall energy supply and as long as the industries at the port area contribute sufficiently to CO_2 mitigation. As a next step, the pathways to the future clusters were analysed, taking the lifetimes of existing stock, future demand of products (especially transport fuels) and the investment cycle into account (forecasting). The analysis focused on the question whether necessary reinvestments were in line with the pathways to future viable clusters.

For the intermediate scenario years 2020, 2030 and 2040, energy demand, resource demand and CO_2 emissions were calculated in the model, testing compatibility with the overall system in regard to energy use and CO_2 emissions. The pathways were analysed subsequently to detect challenges (investments needed) and to define decision windows. 2050 clusters were rejected if a plausible pathway could not be found.

Preliminary 2050 clusters and scenario results were discussed with stakeholders in two scenario workshops in June 2016 (see Appendix C for details), the scenarios were subsequently adapted to take comments and suggestions from stakeholders into account.

Future clusters and pathways as well as selected quantitative results will be presented in the following sections. At first, the current characteristics of the industrial cluster is briefly described. After that, all four scenarios modelled – Business as Usual (BAU), Technological Progress (TP), Biomass and CCS (BIO) and Closed Carbon Cycle (CYC) are described in a separate section each. The chapter concludes with a comparison of scenario results and a discussion on future possibilities of the port to attract new industries and activities.

3.2 The port’s industrial cluster today

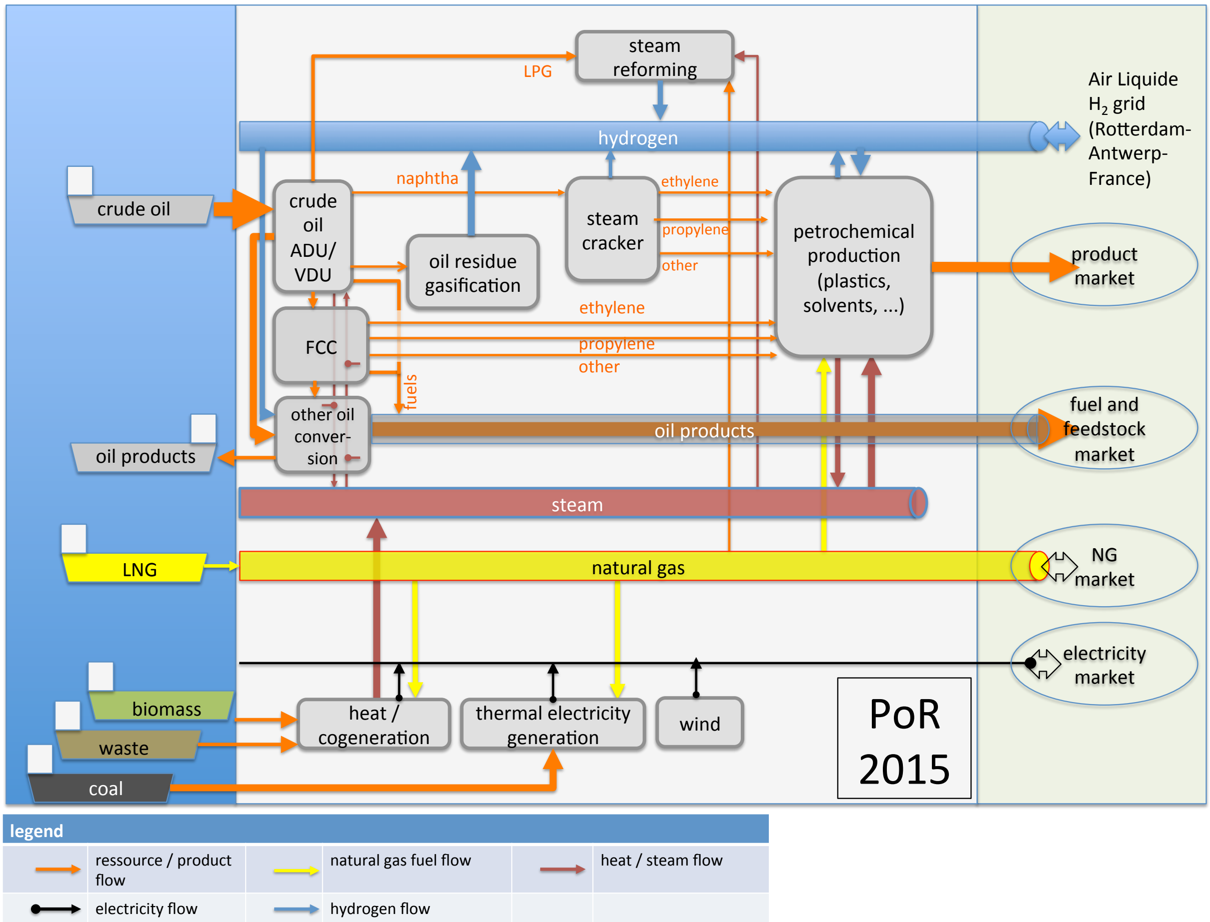
Figure 8 shows Rotterdam’s industrial cluster in a highly aggregated form. It is schematic and focuses only on the most relevant processes that were analysed with the model that was used for scenario building. The figure will be presented later on in adapted forms again in the respective scenario sections to show the 2050 clusters.

The port area is represented in the figure by the grey shaded area at the centre of the figure. It can be seen that there are three different main value chains connected to energy:

- fuel production
- chemicals production
- electricity production

The first two chains are strongly interlinked and are both based on crude oil as a feedstock.

Figure 8: Schematic diagram of Port of Rotterdam's industrial cluster in 2015



Rotterdam is Europe's most important crude oil hub and also the site with the highest capacities in crude oil refining in Europe. Rotterdam's five refineries deliver fuels and feedstock to different markets. On the one hand, there is a market which can be supplied easily by road tankers (because of short distances) and an existing pipeline for petroleum products. This market comprises geographically the Netherlands, Luxemburg and three (south-)western federal states of Germany[10]. The product pipeline from Rotterdam to southern Germany delivers crude oil, fuels and naphtha to the fuel market, to inland refineries (in the Western German Rhine-Ruhr area) and to inland petrochemical sites (Rhine-Ruhr, Frankfurt and Ludwigshafen).

On the other hand, there is an important market for bunker fuels at the port itself. Sea as well as inland waterway vessels bunker their transportation fuel there. A third market for oil products is offshore export. Currently there is an imbalance between the gasoline/diesel ratio in the European fuel market and the European refinery capacities: European refineries are relatively old and traditionally have a strong gasoline dedication, but the fuel market in the EU has shifted more and more to diesel since the 1980s. Therefore, there currently is a shortage of

10 North Rhine-Westphalia, Rhineland-Palatinate and Hesse.

middle distillate and a surplus of gasoline capacities, resulting in a lot of export of gasoline from the EU to the U.S. and East Asia, which have different gasoline/diesel ratios in their markets. While single refinery operators at the Port of Rotterdam have adapted to the situation, this imbalance still holds true for the aggregate cluster of the five Rotterdam refineries.

Another market for refinery products is the downstream petrochemical industry cluster at the port itself. Steam crackers and fluidized-bed crackers (FCC) processing the refinery product naphtha or other crude products respectively to platform chemicals like ethylene, propylene and aromatics are the connection between refineries and the petrochemical industry. The oil companies operate their own petrochemical plants at the port and a lot of other global players are part of the petrochemical value chain within the port area.

Crude oil refining and processing as well as hydrogen production and steam cracking are responsible for the bulk of direct CO_2 emissions of the petrochemical industry at the port. There are other downstream production lines which are energy intensive and lead to indirect CO_2 emissions in the electricity or heat supply sector. The most energy intensive of these are regarded in the model together with the main processes from the refineries (see Appendix E for details).

Further, Rotterdam is also a site of massive production of electricity and steam in cogeneration. The refineries operate their own cogeneration plants. Furthermore, the Rotterdam port area is the most important site of coal-fired power plants in the Netherlands. Two new units with a total capacity of 1,870 MW_{el} have started operation just recently and will replace two older units with a combined capacity of 1,000 MW_{el}, which are scheduled for decommissioning in 2017.

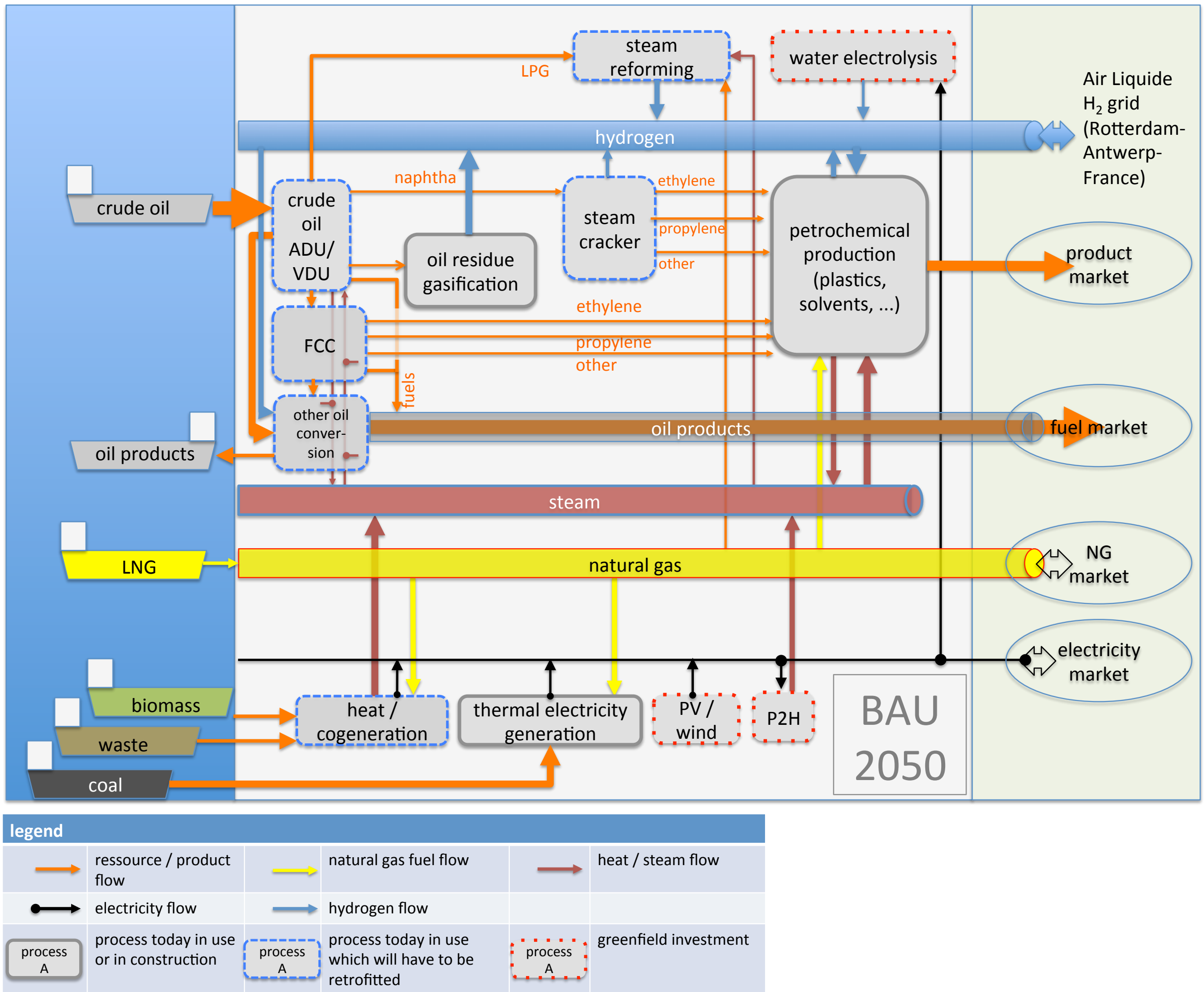
Most of the electricity produced at the port is supplied not for the demand of the port area itself but for the Dutch (and European) electricity market. This has a strong impact on the territorial GHG balance of the port area: coal-fired power units are the largest single emitters of CO_2 at the port.

3.3 BAU scenario

The BAU scenario assumes that there will be no significant future climate policy measures in Europe going beyond the currently implemented policies.[11] As a consequence, industrial players at the port are assumed not to invest in innovative low carbon technologies. Nevertheless, there will be on-going investments to improve efficiency in the course of retrofits and reinvestments within the regular investment cycles using currently available or expected future technological standards.

[11] The BAU scenario mainly serves as a reference point for the other scenarios. We believe it is highly unlikely that no significant additional climate policies will be enacted in the future.

Figure 9: Schematic diagram of Port of Rotterdam's industrial cluster in 2050 (BAU scenario)



Electricity generation and energy infrastructure

The two coal-fired power plant units commissioned in the 1970s will cease to operate in the next years. This will – as a singular effect – lead to a major cut in CO_2 emissions of the port compared to 2015 levels. The two new coal-fired units (of 1.9 GW) will be in operation until the end of their technical lifetime, which will be reached after the year 2050. However, the extension of renewable electricity generation in the European electricity market, which also takes place in the BAU scenario (albeit slower than in the other scenarios), leads to slightly declining utilization rates of conventional power plants. This means that for the coal-fired units, which are currently operated 5,000 h/y, utilization slowly decreases to 4000 h/y until 2050. The relatively low CO_2 prices in the ETS do not provide sufficient certainty for investments in a CCS pilot in the Rotterdam area.

To maintain steam generation for the industrial cluster, gas cogeneration plants are retrofitted. Due to rising efficiency in industry, the stock of power and heat generation plants at the port will be smaller in 2050 than today, but of a similar structure. Power-to-heat and a small amount of electrolysers at the port support the power and cogeneration plants to flexibly operate in an electricity market with higher shares of intermittent sources than today.

The number of wind turbines within the port area increases and existing turbines are retrofitted, leading to an increase of existing capacities by 220 MW until 2030 and by another 120 MW until 2050, reaching a total capacity of 597 MW in 2050.

However, due to the decommissioning of some old fossil fuel-fired power plants and lower utilization in the long term there is a reduction of total electricity generation within the port area by 25% by 2030 compared to today's (modelled) generation and by 50% in the long term (2050).

Refineries

Rotterdam's refineries are facing severe competition within Western Europe (s. van den Bergh et al. 2016). In the BAU scenario, two of five refineries that are integrated into the petrochemical cluster of the port will survive, while the other three will not be reinvested and will be phased out between 2020 and 2030. The remaining refinery capacities will be retrofitted and upgraded to deliver a higher share of middle distillates compared to naphtha/gasoline. This implies additional investments in vacuum distillation units and cokers (or similar deep conversion technologies like Shell's Hycon process) and the closing of gasoline-dedicated fluidized-bed crackers (FCC). One FCC which is operated to optimize propylene yield (with lower gasoline yield) will remain operational in the BAU scenario until 2050 (see Figure 9). Hydrogen demand rises strongly after 2020 due to the processing of heavier and sourer crude oils as well as tighter sulphur content standards for oil products. Additional hydrogen demand results in higher process-related emission of steam reforming.[12] Water electrolysis – as an alternative to steam reforming – phases in during the 2040s and is used to balance out the electricity market rather than to decarbonize industry. Its shares in hydrogen supply remain low.

In spite of lower refining capacities and the shift to middle distillates, naphtha production at Rotterdam will be sufficient to meet the demand of hydrocarbons in the naphtha steam cracker of the petrochemical industry (see below).

Petrochemical industry

The petrochemical cluster of Rotterdam/Moerdijk does not change in structure compared to today. It should be stressed that this is a (justified) assumption for the scenario building and not a prediction. The main purpose of this scenario is to function as a reference for the developments in the other three scenarios, in which the existing cluster is assumed to have to cope with the challenges posed by changing regulation and market demand.

So in the BAU scenario, the production stock is reinvested in line with the investment cycle and best-available technology is used (as specified by regulating authorities).

Around the year 2030, the Moerdijk steam cracker is reinvested using best-available technology. This investment is necessary to maintain the cluster's vertical integration. As the Rotterdam area is connected with other petrochemical production sites by product pipelines, inland waterways and sea shipping, the steam cracker reinvestment is not necessarily an imperative

[12] In the process of steam reforming, natural gas or LPG (hydrocarbon) molecules are split up into hydrogen and CO_2. In the BAU scenario there is no sink to use the relatively pure CO_2 from steam reforming.

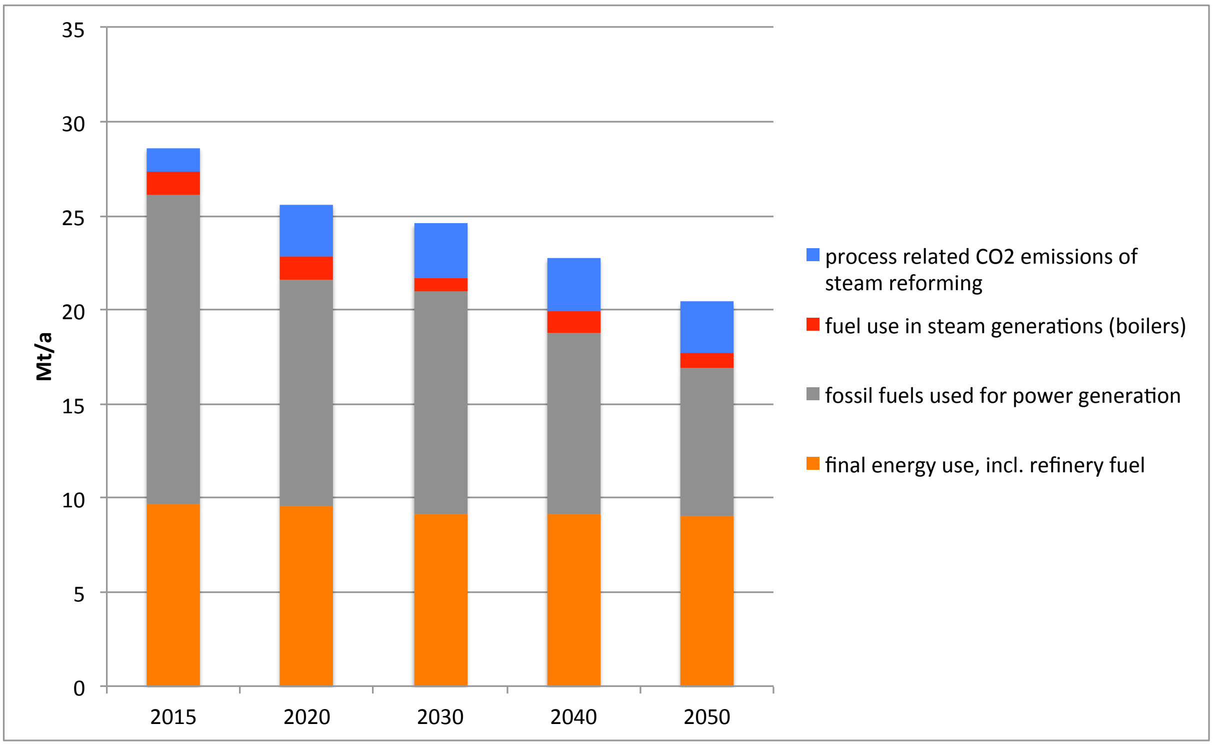
to hold up downstream petrochemical production, but it is necessary to maintain the level of vertical integration. Outsourcing of steam cracking would mean that the cracker feedstock naphtha would have to be exported and the cracker products (olefins and aromatics) would have to be imported again. So keeping steam cracking "in-house" is a reasonable strategic investment for a viable cluster.

Energy demand and emission levels in the BAU scenario

As in all other scenarios, CO_2 emissions peak in the year 2016. Due to the phase-out of old coal power plant units in 2017, CO_2 emissions in 2020 will be 11% lower than in 2015. Between 2020 and 2030, emissions are reduced by a further 4 percentage points due to the closing of refinery capacities and efficiency increases through the retrofitting of existing stock.

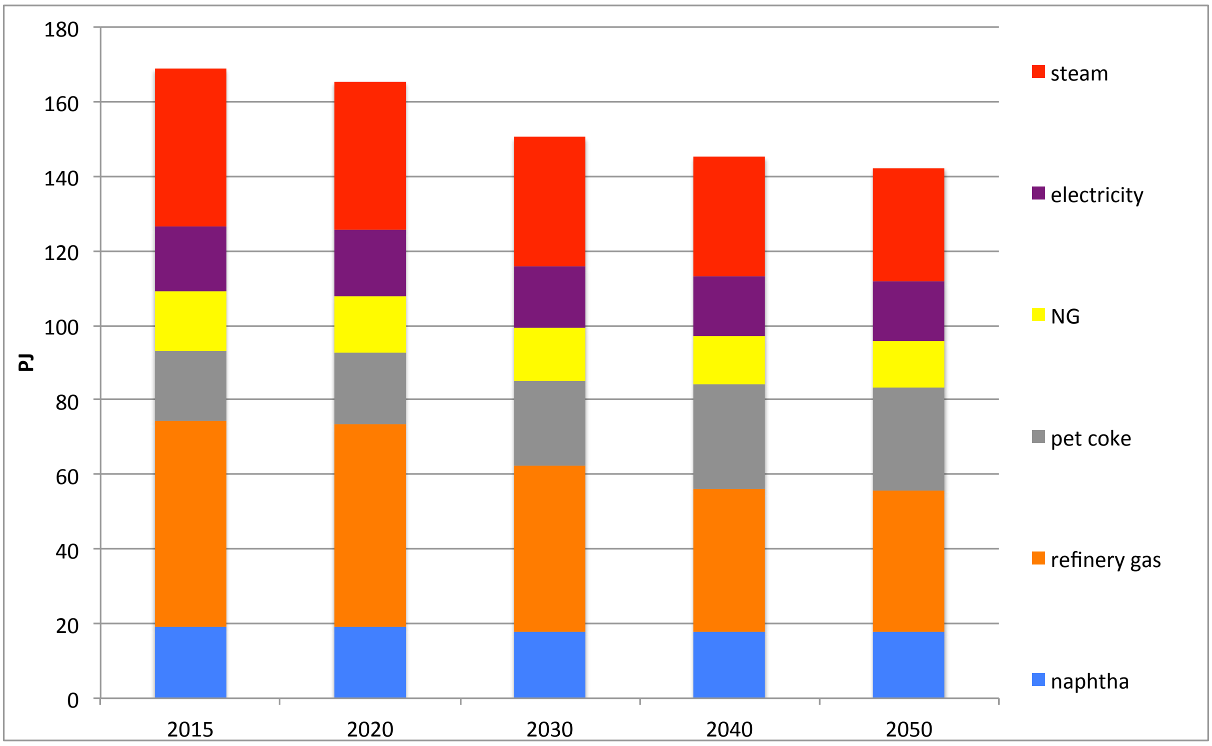
In the last two decades of the BAU scenario, emission reductions can be attributed to reductions in power generation from fossil fuel power plants and efficiency increases in final energy use. However, additional hydrogen demand of refineries and its production from fossil fuels compensate some of the reductions achieved.

Figure 10: CO_2 emissions in the BAU scenario (Mt/a)



Source: WISEE Model results

Figure 11: Fuel use in refineries and the petrochemical industry (BAU scenario)



Source: WISEE Model results

Scenario-specific challenges

The BAU scenario extends trends from the past and does not assume any radical changes in the future. Despite this, there are still scenario-specific challenges in the BAU scenario. This is particularly relevant for investment decisions, as industry and power plant owners need to take into account that climate policy might still change due to increasing climate risks. Therefore industry may be inclined to delay retrofit investments or even the complete reinvestments of production lines like the steam cracker at Moerdijk.

The assumed closing of a part of the refinery capacity in Rotterdam during the 2020s is a probable development, as the closed refineries are not aligned with the foreseeable market developments within the EU (shrinking transport fuel demand and higher shares of middle distillates[13]). In spite of this capacity reduction, Rotterdam will still be able to keep up its market share in the shrinking fuel market. The closure of a part of the refineries is not a threat to the petrochemical cluster as a whole as the closed plants are not directly integrated with petrochemical production at the site.

However, keeping up all refinery capacity could be a possible development under BAU circumstances as well. This would probably mean that some of the inland refineries (with petrochemical integration in the Western German Rhine-Ruhr area) or some of the refineries at the

[13] „Diesel gate“ seems to alter the short (and perhaps mid term) fleet policy of car manufactures in favour of gasoline (hybrid) cars instead of diesel combustion engines. This development however does not affect the more fundamental trends of growing freight and air transport and stable or even shrinking car mileage within the EU, which will dominate in the mid to long term, resulting in a shift from gasoline to middle distillate (diesel, kerosene) demand.

British or French coast would need to be closed. Such a development would then require much more reinvestment and additional upgrade investments at the port site.

Even in the BAU scenario, power plant operators face difficulties to run their fossil coal power plants and cogeneration plants with high utilization (as they do today) because of increasing shares of renewable generation in the European electricity market and increasing prices for emission allowances in the EU ETS scheme.

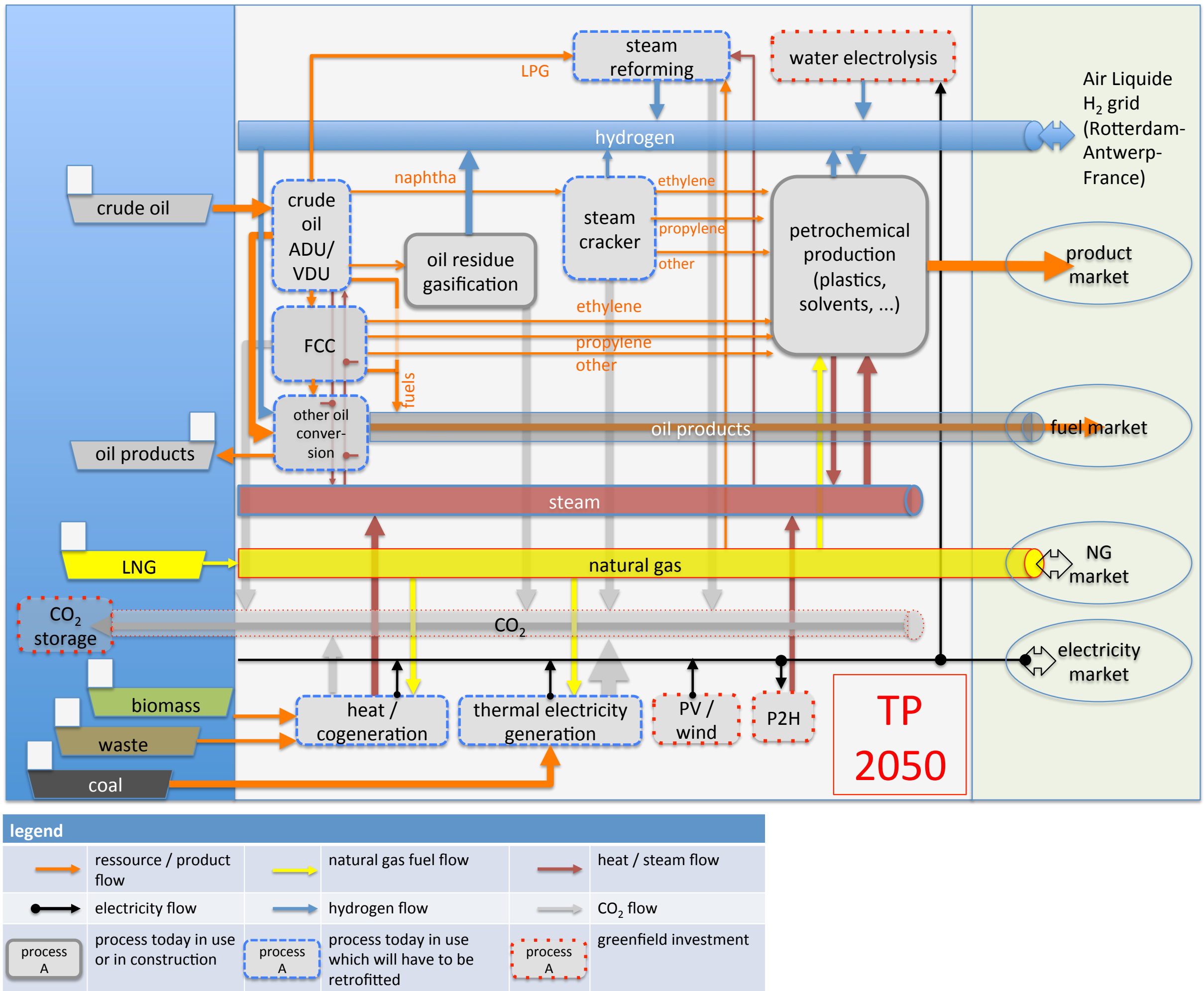
3.4 TP scenario

EU-wide, the TP scenario is characterized by a continuous decrease in CO_2 emissions. The ETS scheme is tightened to achieve the lower end of the EU's GHG reduction target of minus 80% by 2050 (vs. 1990) and significant measures are taken at the EU and at national levels to expand renewable electricity generation and energy efficiency in industry and transport. For the transport sector, alternative propulsion schemes with battery and fuel cells are supported by all EU member states, resulting in a significantly lower demand for fossil fuels by the middle of the century.

Carbon Capture and Storage (CCS) is successfully implemented at an industrial scale in several places in the EU. The technology and the storage of CO_2 in offshore deposits beneath the sea floor are accepted by the civil society in the Netherlands. The EU and the Dutch government establish a regulatory framework providing security to investors to build and operate CO_2 pipeline systems and storage capacities.

From the perspective of the Port of Rotterdam, its industrial cluster will not undergo more significant structural changes in the TP scenario as compared to the BAU scenario. However, the adoption rate of best-available technology (BaT) is higher than in BAU and CCS plays an important role. Power plants as well as large industrial emitters with good access to CO_2 grids (as in the port area) will invest in carbon capture technology and will be connected to the CO_2 pipeline networks that is assumed to be developed in the TP scenario (see Figure 12).

Figure 12: Schematic diagram of Port of Rotterdam's industrial cluster in 2050 (TP scenario)



Electricity generation and energy infrastructure

Renewable electricity generation in the port area will be significantly ramped up. Additional wind turbines within the port area as well as retrofitting of existing turbines add 280 MW additional capacity by 2030 and an additional 70 MW by 2050 (total capacity of 605 MW in 2050). New PV power plants in the port area exploit the existing and additional future potential of rooftops and in the Slufter on the Maasvlakte. In the TP scenario, national policy as well as framework conditions in the port area enable the installation of PV plants with a total capacity of 950 MW_{peak} until 2050.

As in all other scenarios, the two coal-fired power plant units commissioned in the 1970s cease to operate between 2015 and 2020. As in the BAU scenario, the two new coal-fired units (with a combined capacity of about 1,900 MW) are operated until the end of their technical lifetime, which will be reached after the year 2050. In the TP scenario however, power plant operators and the Port Authority succeed in realizing a pilot carbon capture plant at the beginning of the 2020s which is connected to an offshore storage deposit in the North Sea (see the box below on *Coal use in power plants and Carbon Capture and Storage*). The pilot plant initially captures 13% of the total emissions of Rotterdam's two new coal-fired plants.

A stable ETS framework, rising CO_2 prices and support from the national government encourage companies and the Port Authority to plan the expansion of the CO_2 grid to collect all major CO_2 sources within the port area (including Moerdijk). Authorities only permit new power plants and major retrofits if the power plants use CO_2 capture technology.

Due to this policy, existing gas-fired (heat demand driven) cogeneration power plants get retrofitted with carbon capture technology during the late 2020s. The two big coal-fired units are completely retrofitted with capture technology in addition to the pilot CCS plant until 2030 and will be operated with a stable utilization rate of 5,000 h/y thereafter.

Newly built peak load gas turbines at the port help to stabilize the electricity market. Their utilization is relatively low (1,250 h/y) and they are not equipped with carbon capture technology.

Due to higher shares of renewable electricity, power-to-heat and water electrolysers gain higher importance in the TP scenario compared to the BAU scenario.

Box: Coal use in power plants and Carbon Capture and Storage

Two coal-fired power plant units have gone online on the Maasvlakte in recent years, with a combined capacity of 1,870 MW_{el}. They have higher efficiencies and are more flexible compared to older units but are still more emission-intensive than natural gas power plants. Assuming an electrical efficiency of 45% and 5,000 full load hours, they emit around seven million tonnes of CO_2 a year. This is equal to almost a quarter of the port's current total CO_2 emissions.

According to European energy scenarios that aim to be in line with European GHG emission reductions of 80% by 2050 compared to 1990 (see Chapter 2), coal-fired power generation can only play a role by the middle of the century if the plants are equipped with CO_2 capture technology. Other energy scenarios following a minus 90% to minus 95% path do not regard CCS as an option and consider a phase out of coal-fired power plants at around 2030.

In the context of coal's climate impact and ahead of the climate negotiations in Paris at the end of 2015, the Dutch parliament passed a plan to phase-out all Dutch coal power plants until 2020 in order to protect the climate and improve air quality. The plan, which was supported by one party of the ruling coalition, was recently discussed in the cabinet.

The plan challenges power plant operators who have just recently started operation of their plants. In our decarbonization scenarios, two ideas are discussed on how to transform the two new units on the Maasvlakte to become compatible with future developments characterized by strong decarbonization efforts: One idea is to convert the power plants to biomass-fired plants (see the box below on *Biomass use in the BIO scenario and the sustainable biomass potential*), the other one is to equip both plants with CCS technology.

CCS has been discussed for a long time and Rotterdam seems to be in a comparatively good position to realize a CCS pilot. There are plans to build a CO_2 capture plant on the Maasvlakte, which would capture about a quarter of the emissions of the 1,070 MW_{el} coal-fired unit. The CO_2 captured in the plant is supposed to be transported via pipeline to an offshore deposit in the North Sea and stored there in a former natural gas field with a capacity of 8 Mt. Near to the field there are other possible deposits with a storage capacity of 100 Mt altogether (TNO 2011). The total technical potential to store CO_2 in the Netherlands has been estimated to be 3,000 Mt (Koornneef et al. 2008).

As carbon capture would be a retrofit to an existing facility, only post-combustion technology can be considered. This technology generally achieves capture rates of about 90%, but leads to a decrease in energy efficiency of 20-25% (or about 10%-points). Together with an additional efficiency decrease of 1.5%-points caused by the fact that in this case the carbon capture technology needs to be retrofitted, the plants' technical efficiency can be assumed to decrease from 45% to 33.5%.Taking into account the additional energy demand required for the capture process, net 14% of the CO_2 emissions are still emitted to the atmosphere.

The plans for a CCS demonstration project at one of the new coal-fired power plants on the Maasvlakte have not been successfully implemented because of the still expensive technology and the very low CO_2 prices in the EU emission trading system in recent years.

In the Netherlands, public acceptance is lacking for onshore storage of CO_2, but transport from the port to an offshore deposit is considered less critical. On the other hand almost all CCS pilots all over the EU have been abandoned in recent years due to high costs, low CO_2 and electricity prices and missing public acceptance.

So the realization of a CCS pilot is still a challenge even given the good starting position the port has. Even if the pilot can be realized, a scale-up would be needed afterwards to cover the full 1.9 GW of capacity. Further expansion of electricity generation from renewables and increasing costs for storage operation could however make investments in CCS retrofits unattractive. On the other hand, a scale-up could perhaps profit from the adoption of the technology in other countries and the learning made there.

If a full scale coal (and gas) power plant CCS system were to be established at the port, the CO_2 grid would have to be extended at least to the other Maasvlakte coal unit (of 800 MW). The subsequent inclusion of refineries (as assumed in the TP scenario) would additionally require a major (onshore) extension within the port area. Including Moerdijk (as also assumed in the TP scenario) would require a further onshore extension, with the pipeline running through or close to residential areas.

In the long term, however, climate policy itself could impose risks to the coal-fired plants and related CCS investments: In a minus 90% to minus 95% environment, the capture rates are not sufficient to fully decarbonize the electricity sector. To keep the plants in operation under such a scenario, a fuel switch to biomass and/or waste is an option, however requiring further retrofit invests (as assumed in the BIO scenario). A further financial risk is that some institution needs to take over the responsibility of operating and long-term monitoring the offshore CO_2 storage site(s) for at least several hundreds of years to fulfil the requirements of the Dutch legal framework for CCS.

Refineries
Development of refinery capacities in the TP scenario is very similar to BAU, i.e. the closing of outdated refineries takes place in the 2020s. The remaining Rotterdam refineries succeed in expanding their market shares. As the "competing" refinery sites within the narrow pipeline market area[14] are also very competitive and highly vertically integrated, this could mean that Rotterdam increases exports by ship to France or the UK, which do not have comparable petroleum- and petrochemicals-integrated refinery sites.

Refineries are retrofitted and upgraded during the 2020s and 2030s – in a similar way as in the BAU scenario. Additionally, fluidized bed crackers (FCC) and cokers, which have relatively and absolutely high CO_2 emissions due to the process-related burning of carbon-rich pet coke, are equipped with carbon capture technology and connected to the port's CO_2 grid. The same holds true for the steam reforming facilities, which deliver relatively pure CO_2 streams and can therefore be connected to the CCS system with comparatively little effort.

As in the BAU scenario, hydrogen demand of crude oil refining increases sharply. Related CO_2 emissions are abated by the use of CCS and the higher share of water electrolysis in hydrogen generation at the port.

Petrochemical industry
Due to shrinking gasoline demand, decreasing naphtha production at Rotterdam remains sufficient to meet the demand of hydrocarbons in the naphtha steam cracker for petrochemicals production.

Therefore, unlike the decrease in refinery capacities, the petrochemical cluster of Rotterdam/Moerdijk does not change in structure or in the degree of vertical integration as compared to today. This means that the production stock is reinvested according to the investment cycle and best-available technology is used. As companies retrofit parts of their plants regularly and efficiency investments are more profitable than in the BAU scenario due to higher assumed CO_2 prices, efficiency improvements are significantly stronger than in the BAU scenario.

Around the year 2030, the Moerdijk steam cracker will be reinvested using an advanced technology (with new furnace materials and gas turbine integration, see Ren 2009). The cracker will be built "carbon capture ready" and will be connected to the CO_2 grid as soon as the grid is extended to the Moerdijk site.

Energy demand and emission levels in the TP scenario
CO_2 reductions between 2015 and 2020 can be attributed to the closing of the two old coal-fired power units. Between 2020 and 2030 the closing of old refineries and the phase-in of CCS have the greatest impact. Due to the full implementation of CCS, the CO_2 emissions within the port area will drop sharply by more than 60% between 2020 and 2040. In the last

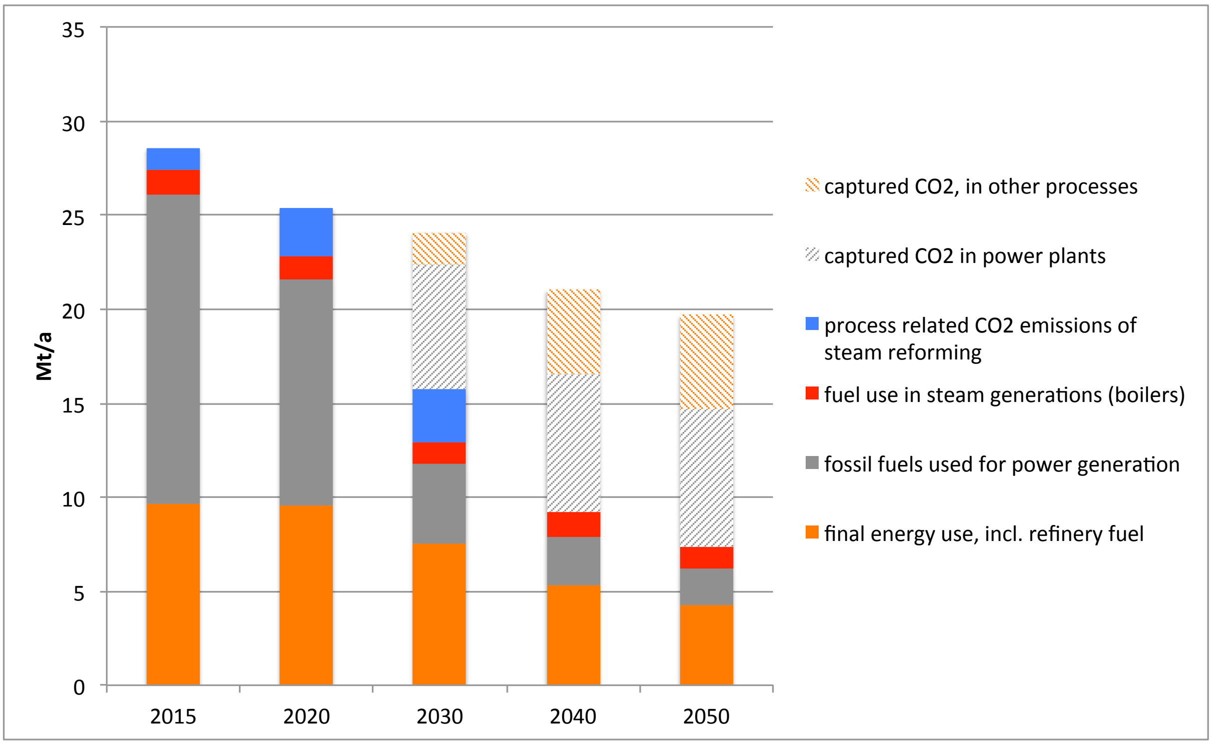
[14] The „pipeline market area" consists of the area which can be supplied by road tankers and/or pipelines. The competing sites are Wesseling, Cologne and Gelsenkirchen in Western Germany, which are directly connected to the Port of Rotterdam via a crude oil and product pipeline. They are also integrated in petrochemical clusters. The nearby petrochemical cluster of Antwerp is also strongly vertically integrated, but it is not connected via a fuel (product) pipeline to Rotterdam.

decade, the closing of some old natural gas power plants and increased efficiency in the petrochemical industry due to retrofits and reinvestments result in a further reduction of CO_2 emissions of 1.9 Mt/a.

However, the amount of captured CO_2 is substantial: Around 250 Mt of CO_2 need to be captured and stored between 2022 and 2050. 87 Mt of this can be attributed to refineries and the steam cracker and 166 Mt to the coal- and gas-fired power plants. The amount of 250 Mt exceeds the storage potential of deposits close to the shore (estimated to have a storage volume of about 100 Mt, see the box above on *Coal use in power plants and Carbon Capture and Storage*), so the CO_2 grid needs to be extended significantly in the mid-2030s to other Dutch deposits, e.g. former gas fields in the north of the Netherlands.

Overall, CO_2 emissions of the port's industrial cluster are reduced by 74% compared to 2015 levels in the TP scenario. This is in line with the GHG emissions reductions assumed to be undertaken by the EU as a whole in this scenario (-80% by 2050 compared to 1990, which is about -75% compared to 2015 emissions). This is the case even though the market share of the port's refineries are assumed to increase compared to today.

Figure 13: CO_2 emissions in the TP scenario (Mt/a)

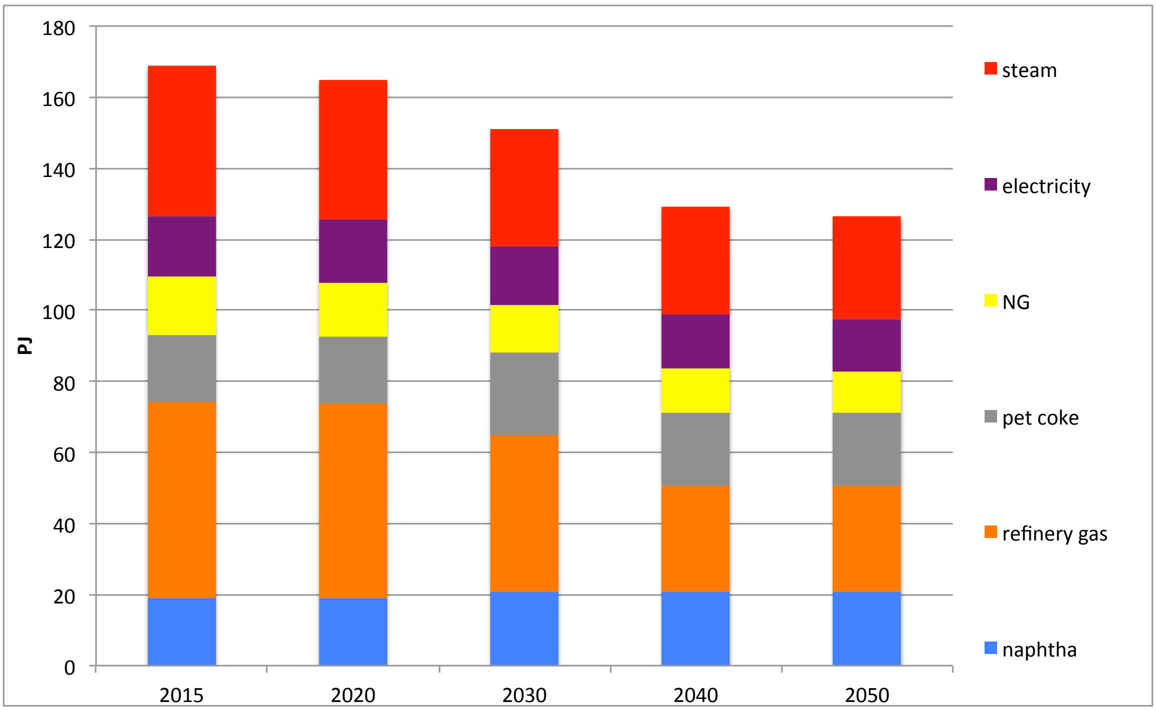


Source: WISEE Model results

Fuel use in refineries and petrochemical industry decreases due to the closing of old refineries and to efficiency improvement. The higher use of naphtha compared to BAU is due to the thermal energy demand of carbon capture in the steam cracker, which cannot be fully compensated by higher efficiency of other parts of the cracker.

In spite of significant efficiency gains, electricity use in the TP scenario is only slightly lower than in the BAU scenario. The high electricity demand of carbon capture again partly compensates higher efficiency in other applications (e.g. chlorine electrolysis).

Figure 14: Fuel use in refineries and the petrochemical industry (TP scenario)



Source: WISEE Model results

Scenario-specific challenges

The key challenge of the TP scenario is to realize the CCS infrastructure. It is a big advantage of the port's geographical location that the proposed CCS pilot project does not depend on the construction of an onshore CO_2 pipeline, which means a relatively high probability of getting the pilot realized. If the pilot were to be realized, other carbon capture elements could be added and the grid could be extended successively. On the other hand, the long-term viability of the CCS infrastructure cannot be taken for granted. If climate policy takes the sustainable path and aims for GHG emission reductions beyond 90%, coal firing – even when equipped with CCS – may turn out to be a dead end. Retrofitting the plants to enable them to run on 100% biomass may be a way out of this dead end, but bears economic and political risks of its own (see the discussion of the BIO scenario below).

Another challenge is the realization of higher market shares in the fuel market. The direct "competitors" in Western Germany have similar advantages as the Rotterdam site as they can be supplied via pipeline from the Rotterdam port and are similarly vertically integrated. The Gelsenkirchen site is equipped to cope with heavier oils (coker) and to produce high shares of middle distillates, while Shell's Rhineland refinery at Cologne/Wesseling has large aromatics production facilities. However, it is the port's main advantage that its industry can export fuels easily and at low costs by vessel. In addition, the port area is in a better position geographically to make use of CCS technology.

3.5 BIO scenario

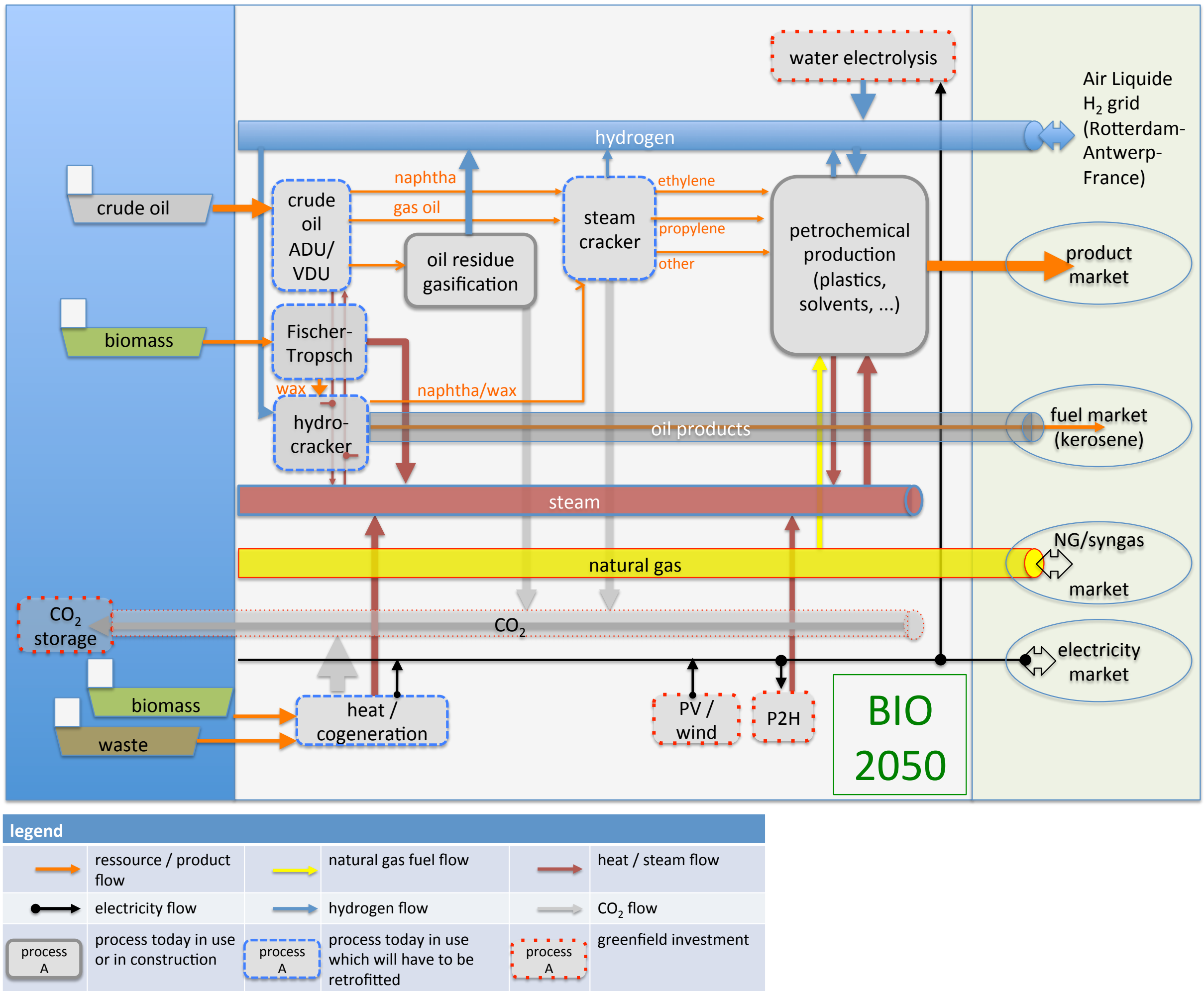
In the BIO scenario (as in the CYC scenario, see below) the EU sets clear, credible and tight long-term GHG reduction targets. While in the TP scenario, GHG emissions within the EU are assumed to be reduced by about 80% by 2050 compared to 1990, the respective emissions reductions in the BIO scenario (and the CYC scenario) are assumed to be stronger, reaching 90 to 95% and necessitating even stronger climate policy measures in Europe. Policy makers are successful at implementing strong and effective instruments, like a carbon tax, giving long-term certainty to investors about the costs of emitting CO_2. Governments support the implementation of CO_2 grids and storages. Pilot grids are built in Europe's most favourable regions from the 2020s on.

Renewable electricity is developed all around Europe, realizing a very high share of the technical potential. Renewables achieve a market share of nearly 100% in 2050 in electricity generation (see Chapter 2). The remaining thermal power plants cannot be fired with fossil fuels anymore, as capture rates below 100% and life-cycle emissions of the fuels do not allow for a complete avoidance of GHG emissions, which would be necessary in the electricity sector in order to achieve total GHG emission reductions of 90% and beyond (see Chapter 2). Therefore, after 2040 the thermal units connected to a CO_2 grid are converted to biomass- and waste-fired units, also delivering high-temperature heat. Other thermal units are closed. The firing of biomass and the respective CO_2 storage provides the opportunity to realise *net negative* emissions. However, (sustainable) biomass resources are scarce globally and competition for these resources is hard (see Box below).

Energy-related emissions by 2050 approach almost zero in this scenario. Fossil resources cannot be burnt anymore but either need to be used in a circular economy or any CO_2 emissions accruing after the end of the product's lifetime need to be stored. Therefore, waste incineration needs to be coupled with CCS, too.

Heat and mechanical energy is delivered by electricity. Power-to-heat, water electrolysis, synthetic fuel and chemicals production as well as battery cars and cable lorries are therefore crucial technologies to decarbonize the overall energy system, with a high impact on the port's industrial cluster.

Figure 15: Schematic diagram of Port of Rotterdam's industrial cluster in 2050 (BIO scenario)



Box: Biomass use in the BIO scenario and the sustainable biomass potential

In the BIO scenario, biomass is considered a valuable feedstock that is utilised in two ways, for the production of fuel and in the power sector.

First, a decarbonized transport sector still requires hydrocarbon fuels for some means of transportation that cannot (easily) run on electricity or hydrogen, namely heavy road transport, shipping and aviation. Methane, methanol or Fischer-Tropsch based fuels are discussed as adequate fuels providing high energy density. Carbon is required to produce these kinds of synthetic chemical energy carriers. Climate-neutral carbon needs to be derived from sustainable biomass or waste or extracted from the atmosphere – as capture and storage of CO_2 from mobile sources is not a viable option.

Second, biomass can be used in the power sector, as well. Apart from delivering carbon-neutral energy, it could also be a means to achieve net negative emissions: If biomass firing *and* storing of the respective CO_2 (Bioenergy & CCS, BECCS) could be realized, net negative emissions would be achieved. This makes BECCS a potential option to compensate for past

GHG emissions or for emissions from activities like agriculture, for which a complete avoidance of emissions is unlikely even in the long term.

In the BIO scenario, it is assumed that by 2050 approximately 1.8 Mt or 28 PJ of dry biomass will be used annually in the (formerly coal-fired) power plants – which will be converted to 100% biomass-firing together with CCS (so called BECCS) by then. Further, by the year 2050, 7 Mt (108 PJ) of dry biomass will be required annually for gasification to Fischer-Tropsch fuels which will be used as feedstock for the chemical industry. Due to the requirements of gasification and co-firing in regard to biomass characteristics, the most suitable biomass resource is wood in both cases. The total annual demand would sum up to about 8.8 Mt of wooden biomass by 2050.

The question is whether such an amount will be sustainably available for energetic and feedstock use in the Netherlands, given the growing demand for biomass from other world regions and purposes and the need to reserve enough agricultural land for the production of food crops.

Several studies exist that evaluate the biomass potential in different world regions. Recently, a meta analysis of studies has been conducted by the German Renewable Energies Agency (Zeddies et al. 2014). This meta analysis makes clear that an evaluation of biomass potential and especially a comparison of different studies dealing with the topic is difficult. Within the field of biomass, several distinctions and assumptions need to be made, as the different categories of biomass – for example forestry biomass (forest wood, scrap wood, farmed wood, etc.), agricultural biomass (energy crops from dedicated farming, by-products from food & feed production etc.) and waste biomass (waste wood, agricultural wastes, domestic waste, industrial waste) – each have their specific sources and characteristics and need to be regarded separately.

In many studies, different categories of biomass are summed up and are not provided separately. As the conversion technologies (gasification, co-firing, biofuels production, heating, electricity generation, etc.) exhibit different performance characteristics when using different feedstock, it is not possible to work with this sum of overall biomass without making relevant assumptions. It is therefore not useful to compare an overall biomass potential e.g. of the Netherlands to the projected 136 PJ of wood demand for feedstock and power plants in the Port of Rotterdam.

Most available studies estimate the technical potential, meaning the amount of biomass that can technically be used, e.g. the amount of energy crops that can grow on a given acreage (usually the acreage that is not used for food & feed production) and under the given framework conditions as to specific yield, which depends on the world region. However, the technical potential does not take into account which agricultural product would achieve the most revenue for the farmer and will therefore likely be produced (economical potential). Evaluation of the economic potential is rather difficult, as it needs to be based on the (global) market for all agricultural and related energy products (e.g. bio fuels).

In political discussion, biomass use is confronted with much critique in terms of its perceived or actual lack of sustainability. Biomass use in EU's fuel market has already been restricted for this reason. For long term scenarios it is therefore important to only take into account the *sustainable* potential. Sustainable biomass is produced or provided without harming people and the environment, i.e. it is produced without extending the use of intensified agriculture, without violating inhabitants' rights to use their land (most relevant in some developing countries) and without causing significant amounts of "hidden" emissions of greenhouse gases, e.g. through so-called indirect land use changes (iLUC).

Thus, for a first robust assessment of the required amount of wood biomass in the Port of Rotterdam in the BIO scenario in 2050 (136 PJ per year), only studies taking broad sustainability criteria into account should be considered.

A study looking only at global *forestry* biomass potential is Schweinle et al. (2010). The authors provide a range of 29 to 45 EJ/a – the lower level of 29 EJ representing the sustainable potential. (Thrän et al. 2010) come to similar conclusions: the global technical potential of wood for energy use is estimated at 36 EJ when taking enhanced environmental and nature conservation restrictions into account (the reference year of that study is 2020). The International Renewable Energy Agency (IRENA) has estimated the biomass potential to be 94 EJ to 148 EJ in the year 2030 over all categories. Just over 20% of this is from wood – resulting in roughly 20 EJ to 30 EJ. So, a range of 20 EJ to 36 EJ can be considered a robust estimate for the global "sustainable" potential of wood biomass, given the currently available evidence.

In order to get a rough estimate what these numbers mean in relation to the 136 PJ of biomass needed for biofuels and BECCS in the port of Rotterdam, the population of the Netherlands in relation to the global and European population is looked at. The population of the Netherlands or the EU (17/507 million people) currently represents about 0.2%/6.9% of today's world population. The 136 PJ required in the BIO scenario for biofuels and BECCS power generation represent between 0.45% to 0.68% of the 20 EJ to 30 EJ as derived above. This suggests that the need for sustainable biomass in the port's industrial cluster in the BIO scenario exceeds the "fair share" that could be assigned to the Netherlands and represents about 7 to 10% of the EU's total share in global sustainable biomass potential.

If only the EU is considered as a source of biomass, the potential disparity is getting more obvious: according to (EEA 2013), between 600 PJ and 1,100 PJ of wood can be sustainably utilised for energy purposes in the EU in 2030. This would mean that the share of the required 136 PJ for biofuels from Rotterdam would be as high as 12% to 23% - while today the Netherlands' population is about 3.3 % of the EU population.

However, it needs to be added that these considerations do not take into account the fact that Rotterdam supplies more than the domestic Dutch market with kerosene and road diesel in the BIO scenario, but also exports fuels according to today's market share. Regarding the use of biomass for BECCS power generation it could furthermore be argued that Rotterdam is one of the best-suited site for the application of this technology in Europe. Consequently, this may be another reasons to accept a higher-than-average share of sustainable biomass use in the Rotterdam port area.

Nevertheless, a sustainable and fair supply of sufficient biomass as required in the BIO scenario cannot be taken for granted. In a future world characterised by increasingly strict climate policy measures, demand for sustainable biomass can be expected to increase considerably, as biomass can be used to decarbonize a broad range of applications. Consequently, the price of biomass could rise significantly compared to today, making it unclear whether the biomass use as foreseen in the BIO scenario will indeed be economical for the port's industrial cluster. Furthermore, it is unclear whether the *maximum* potential for sustainable biomass, as discussed in the literature, will indeed be fully realised in the future. The coincidence of uncertain biomass supply (or uncertainty about its costs) and uncertainty about the viability of CCS technology (see box above on *Coal use in power plants and Carbon Capture and Storage*) makes the BIO scenario depend on several developments that are as of today quite uncertain.

Electricity generation and energy infrastructure

Expansion of renewable generation capacities in the port area is even stronger than in the TP scenario, with an additional capacity of wind turbines of 320 MW by 2030 compared to today and another net additional 30 MW installed between 2030 and 2050 (total capacity: 602 MW in 2050). The potentials of solar PV are also realized earlier and faster. Facade-integrated PV systems become a standard technology in the BIO (and CYC) scenario from 2035 on and are integrated into the building envelope as part of regular retrofit measures. Therefore, in addition to the capacity of 1,000 MW_{peak} on rooftops of buildings and in the Slufter on the Maasvlakte, an extra capacity of 40 MW from facade-integrated PV will be realized by 2050.

As in the BAU and TP scenarios, the two new coal-fired units (with a combined capacity of 1,900 MW) are operated until the end of their technical lifetime. As in the TP scenario, in the BIO scenario a pilot carbon capture plant (at one of Maasvlakte's coal-fired units) is realized in the 2020s and is connected to an offshore storage deposit in the North Sea. This is the starting point for a larger CO_2 infrastructure, which will be expanded after 2030 and which will transport the complete CO_2 emissions from both coal-fired power plants as well as CO_2 from other sources at the port. Due to the stricter GHG mitigation targets after 2030, the port's coal-fired power stations are re-equipped with technology to fire biomass and waste and to couple out steam into a high-temperature heat grid. Maasvlakte becomes the starting point of such a heat grid, connecting the power stations with most of the industrial plants within the area (including Moerdijk).

In the BIO scenario, incentives to collect all CO_2 sources in the area are even stronger than in the TP scenario. Power plant operators together with refineries and petrochemical industry develop a CO_2 grid connecting the remaining CO_2 hot spots (including Moerdijk's steam cracker).

Almost 100% renewable electricity generation and the need to decarbonize the energy system increase the importance of power-to-heat and water electrolysers, both as a means to supply zero emission process heat and hydrogen and as flexible consumers of fluctuating renewable electricity. By 2050, 100% of heat and steam in the port area is supplied by biomass/waste-

CHP (from Maasvlakte), electrical boilers, furnaces or other electrical heating. Industrial waste heat is almost completely used within the sites or fed into a high-temperature heat grid with different levels of temperature and pressure. Feed-in of heat is of special importance in regard to the production of synthetic fuels, which are exothermal processes allowing huge amounts of excess heat to be transported to heat consumers via the grid. The total heat generation of cogeneration plants and waste heat supplied to the grid are sufficient to supply the whole port area – at least in a yearly net balance and without taking different temperature levels into account.[15]

Refineries

In the BIO scenario (as in the CYC scenario, see below) there is a clear roadmap for phasing out fossil fuels from the markets for ground-based transport. Nevertheless, there is still the need to supply hydrocarbon fuels for aviation and shipping. Also, the petrochemical industry still needs hydrocarbons to produce plastics, solvents and other products.

Whereas production of motor fuels for transport – where carbon capture is not technically and economically feasible in the use-phase of the product – has to rely on climate-neutral carbon from the atmosphere, e.g. from biomass, many hydrocarbon chemical products can also become part of a circular system, where the fossil carbon is recycled after the use of the product.

In the BIO scenario, these options are reflected at the port's industrial cluster by

- a Fischer-Tropsch (FT) plant producing synthetic fuel from biogenic hydrocarbons and additional hydrogen from water electrolysis and
- a conventional small scale oil refinery producing feedstock for steam cracking and subsequently supplying the petrochemical industry.

With the FT capacities assumed in the BIO scenario, Rotterdam can keep up its market share in kerosene and diesel production but will not produce methanol shipping fuel. It is assumed that the latter fuel can be produced more economically in the Middle East and North Africa region with comparatively lower electricity generation costs to run water electrolysis (see the box below on *Waste-based chemicals production*).

The existing refinery capacities are not retrofitted in this scenario with the exception of one single refinery that will be retrofitted and down-scaled during the 2030s to supply the remaining steam crackers' feedstock demand.

Petrochemical industry

Due to the reinvestment of the refinery and the Moerdijk cracker, the petrochemical cluster is still vertically integrated and technically viable. When retrofitting the steam cracker, it needs to be split up into different lines capable of processing light and heavy naphtha as well as gas oil and wax. The efficiency of gas oil steam cracking is worse than the performance of naphtha steam cracking. Production stock is retrofitted regularly and efficiency potentials are joint-

[15] Economic analysis and dimensioning of the grid would require a deeper analysis of the different temperature levels and of the temporal resolution of heat load and waste heat.

ly developed by companies within the cluster to exchange heat, steam and gases (hydrogen, oxygen etc.) in an optimal way.

Energy demand and emission levels in the BIO scenario
CO_2 mitigation between 2015 and 2020 can (as in the other scenarios) be attributed to the closing of two old coal-fired power units. Between 2020 and 2030, the closing of refineries (more than in the TP scenario) and the phase-in of CCS have the greatest impact.

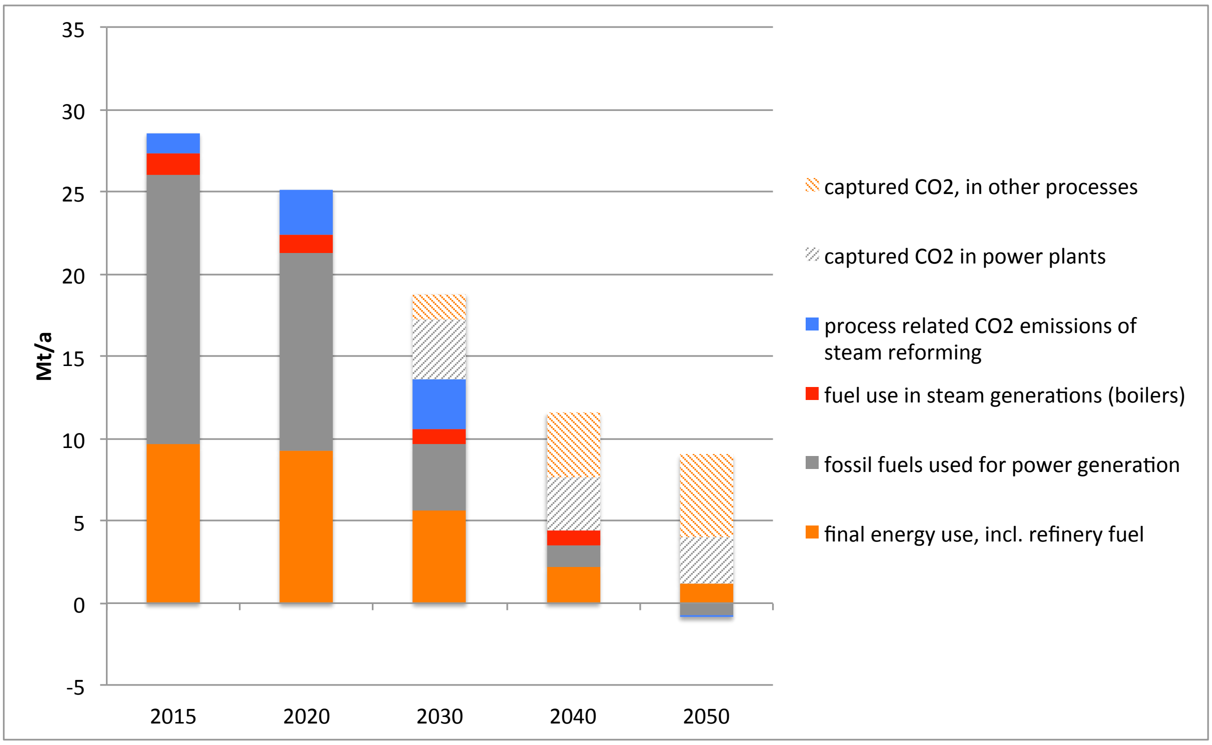
Due to the full implementation of CCS, the shift to biomass/waste firing (with negative emissions for biomass) and the carbon-neutral supply of hydrogen by water electrolysis, the CO_2 emissions within the port area drop sharply by more than 80% between 2020 and 2040.[16] In the last decade, the shift from coal-firing to biomass/waste-firing and increased efficiency in the petrochemical industry result in a further cut of CO_2 emissions by 4 Mt/a.

The amounts of captured CO_2 to be stored are lower than in the TP scenario: Around 158 Mt of CO_2 (compared to 250 Mt in the TP scenario) needs to be captured and stored during the full period of CCS application between 2022 and 2050. 80 Mt can be attributed to refineries and the steam cracker and 78 Mt to the coal- and later biomass/waste-fired power plants. The difference to the TP scenario is due to the phase-out of steam reforming and the shift to more hydrogen-rich fuels in the power plants as well as the decommissioning of the gas-fired co-generation plants (instead of equipping them with carbon capture as in the TP scenario). Again, the assumed storage deposits in relatively close proximity to Rotterdam (with a combined capacity of about 100 Mt) do not suffice to absorb the full amount of emissions. So the offshore CO_2 pipeline needs to be expanded in the early 2040s to other deposits in the North of the Netherlands.

Net negative emissions from fuel use in power plants account for the fact that CO_2 from biomass is stored. The net negative emissions from biomass are balanced with those emissions from (fossil-derived) waste-firing which are not captured (due to an assumed capture rate of only 90%). The grey bar in 2050 represents the net value of the two effects.

[16] It should be noted that in this report we do not assign any CO_2 emissions from biomass burning, as these emissions have been extracted from the atmosphere during biomass growth. Any additional lifecycle emissions from biomass, e.g. resulting from fertilization, transport or processing of biomass are difficult to quantify (especially dynamically until 2050) and are not considered and reported here.

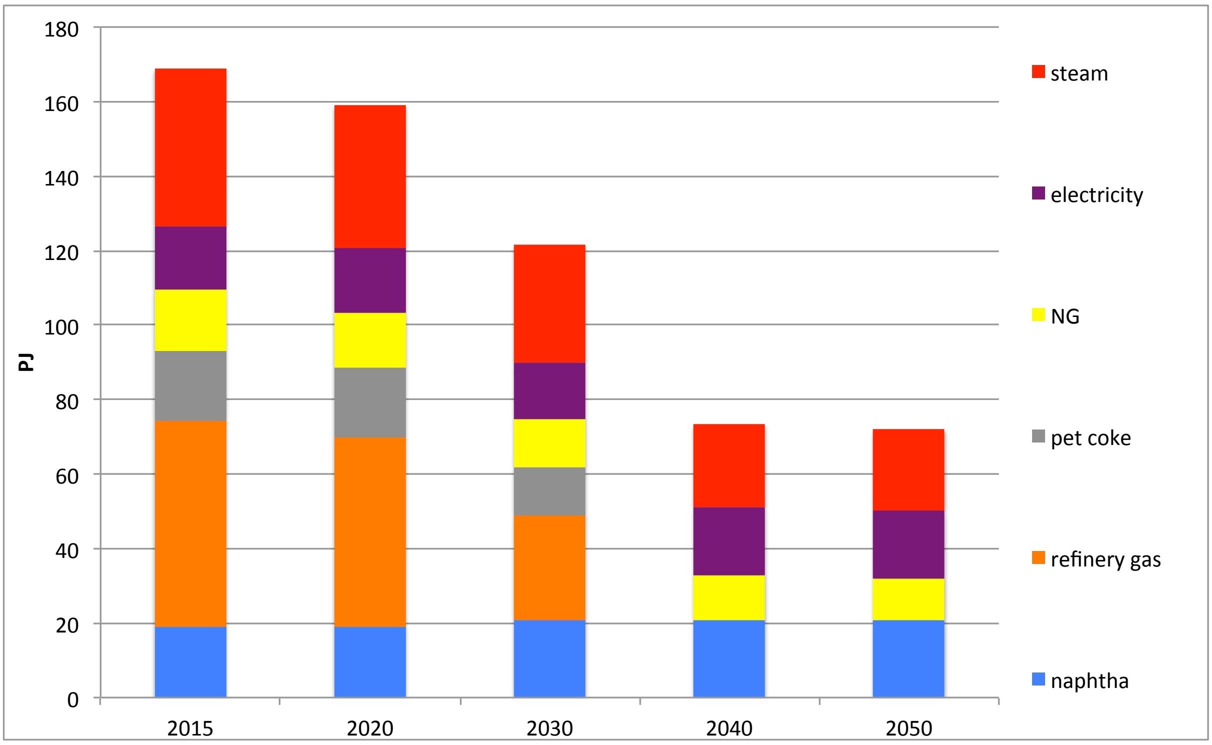
Figure 16: CO_2 emissions in the BIO scenario (Mt/a)



Source: WISEE Model results

Fuel use in refineries and in the petrochemical industry are reduced by more than half within the port area by 2040 compared to 2015. Refineries and most of the petrochemical industry use electricity to produce heat or use high-temperature heat from the grid. Some natural gas fuel for petrochemical products is still used in 2050 in the scenario, which could be substituted by synthetic methane (not regarded in the scenario). As the structural changes will take place before 2040, only marginal changes in the energy demand structure occur in the last decade of the scenario.

Figure 17: Fuel use in refineries and the petrochemical industry (BIO scenario)



Source: WISEE Model results

Scenario-specific challenges

Mid-term challenges in the BIO scenario are similar to those of the TP scenario (see above). In the long term and in a -90/-95% world, CCS technology needs to be combined with biomass in order to enable sufficiently deep emission reductions. The physical supply of biomass can be achieved quite easily in a port but economic availability and particularly the sustainability of a huge amount of seaborne supply could turn out to be a challenge in a world where sustainable biomass is restricted and in high demand (see the box above on *Biomass use in the BIO scenario and the sustainable biomass potential*).

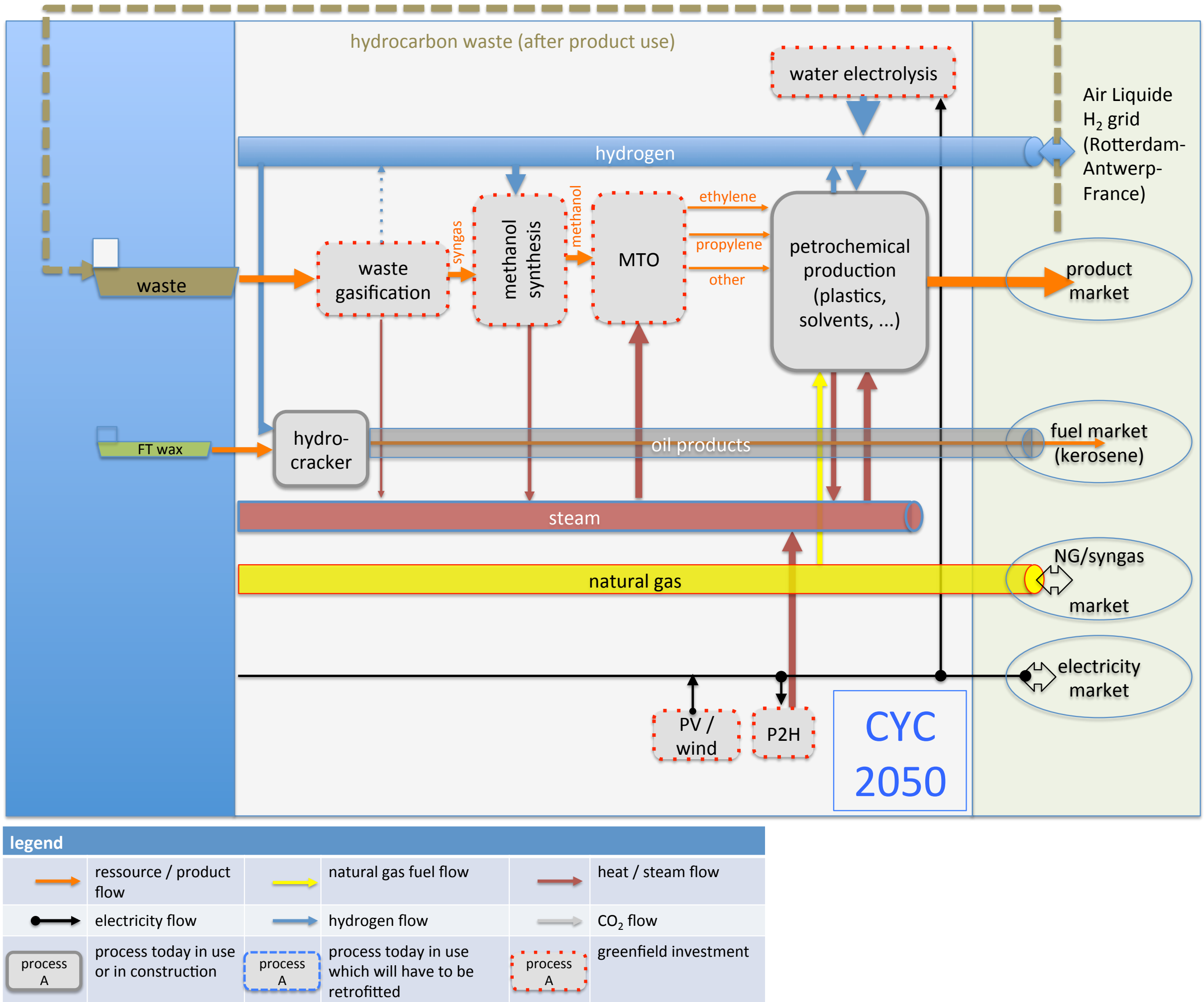
A second challenge is the need for high investments in synthetic fuel production facilities and the resulting need for capital-intensive water electrolysis capacity. It needs to be stressed that synthetic fuel production is not a necessary part of the petrochemical cluster, although it is a good complement to it providing heat and additional feedstock. An alternative strategy – still keeping part of the value chain within the port area – could be to import synthetic waxes from the assumed Fischer-Tropsch plants in the Middle East and North Africa region and to produce only the fuels at the port (see also CYC scenario below).

3.6 CYC scenario

In the Closed Carbon Cycle scenario (CYC), the climate policy framework is similar to the one in the BIO scenario, with a GHG emission reduction target of 90 to 95%, which means almost full decarbonization of the energy system. However, as discussed above, CCS could eventually fail as an economically viable and sustainable solution, particularly if it will not be possible to source very high amounts of sustainable biomasses.

The CYC scenario provides a positive vision of an industrial cluster that does not rely on CCS but still keeps the value chains of basic industry at the port. Without the CCS option, fossil feedstock needs to be kept in a circular system with different stages of product use and a recycling option for the carbon content (e.g. by gasification of the waste) at the very end of product use (see the box below on *Waste-based chemicals production* for details). In this scenario Rotterdam – with its unique location within Western Europe – would still be the hub for fuels and fuel pre-products and would still be a fully vertically integrated cluster of chemical production.

Figure 18: Schematic diagram of Port of Rotterdam's industrial cluster in 2050 (CYC scenario)



Electricity generation and energy infrastructure
The expansion of renewable electricity generation is identical to the pathway described for the BIO scenario (see above).

With no CCS available, the coal-fired units cannot be operated economically. Biomass-firing (without the option of net negative GHG emissions) is not an attractive option because limited biomass potential is favoured to be used in the production of transport fuels and some chemicals. Therefore coal-fired units generally only achieve few utilization hours within the European electricity market in the late 2020s and the remaining and newest ones (i.e. the two new plants on the Maasvlakte) are closed during the 2030s.

Without the CCS option, gas-fired cogeneration plants will also not be retrofitted anymore. Therefore, after 2040 there is no more cogeneration at the port to provide steam. With 100% renewable electricity generation, power-to-heat (combined with large heat storages) becomes the main solution to produce steam at the port. An additional option is to use geothermal heat. A recent study on behalf of the Port of Rotterdam Authority identified a geothermal heat potential amounting to 600 MW at a level of 165 °C within the port area in a depth of 5,000 meters. In the CYC scenario – with a great net demand of steam – it is assumed that there will be several drillings within the area feeding a heat grid (with a constant temperature level). The temperature level can be raised if necessary at the point of actual heat demand with power-to-heat technology. By using geothermal heat from 2030 on, the need to use power-to-heat to provide carbon neutral steam can be significantly reduced. Electricity demand for power-to-heat will still be high, reaching 2 TWh in 2040 and 5 TWh in 2050.

However, further research is needed on the optimal combination of heat grids, power-to-heat, industrial waste heat, storages and geothermal heat in a future industrial cluster.

Hydrogen supply is another focal point of analysis. In the CYC scenario the synthetic production of olefins requires large amounts of hydrogen, as the hydrogen content of plastic waste can only be used to a degree of 70% in the gasification process (see the box below on *waste-based chemicals production*). The installation of electrolysers takes place mainly during the 2030s, so at a still quite early stage of technology development. Following the model calculations, electrolysing capacity of 2.3 GW would be needed to supply methanol and other hydrocarbon production at the port. The electricity demand for the electrolysis would be as high as 40 TWh in the year 2050.

Existing steam reforming capacities (of the closed) refineries can be used as a complementary supply during the early 2030s, but will then be closed due to their process-related emissions.

Refineries
Hydrocarbon fuel supply is not a major business model of the port area anymore from the 2030s on. The last refinery is closed during the 2030s. Instead, companies at the port shift to the processing of semi-finished products (wax) and finishing of fuel. The relatively new hydrocracker at the port (commissioning scheduled for 2018) could be used to crack imported waxes from Fischer-Tropsch plants at the Middle East and North Africa region, producing middle distillates and some naphtha.

Petrochemical industry
The petrochemical cluster's vertical integration is maintained in the CYC scenario. The existing oil-based production stock is replaced by a methanol infrastructure in the scenario, providing a platform to produce olefins (methanol to olefins, MTO) or aromatics (MTA).

Without oil-based feedstock and after the closing of refineries and the steam cracker, the petrochemical cluster within the port area relies on waste as a core resource base (see the box below on *Waste-based chemicals production* for details). Plastic waste like polyethylene (PE) or polypropylene for instance provides exactly the right atomic structure (C_nH_{2n}) needed to produce olefins. When 100% of the carbon from waste is to be recovered during the gasification process (prerequisite for decarbonization) hydrogen recycling rates will not exceed 70% in today's known processes (Brems et al. 2013). To compensate for the loss of 30% of the hydrogen, the missing H_2 is provided by water electrolysis. Additional H_2 losses (i.e. the reduction of H_2 to H_2O) occur in the production of olefins from methanol.

As in the BIO scenario, production stock is retrofitted regularly and efficiency potentials are jointly developed by companies within the cluster to exchange heat, steam and gases (hydrogen, oxygen etc.) in an optimal way.

Box: Waste-based chemicals production

With the banning of landfill within the European Union, recycling (especially of plastics) and waste incineration have become the dominating procedures of waste treatment in Europe. Industrial waste residues from crude oil processing, varnish or other material rich of hydrocarbons are mostly used as a fuel in industrial CHP or in cement ovens. Municipal waste is treated in waste incineration plants.

The petrochemical industry uses pyrolysis or gasification to make use of hydrocarbon residues. Since 1989 Shell is operating an oil residue gasification plant at its Rotterdam Pernis site producing hydrogen.

The main products of gasification of hydrocarbons are carbon monoxide (CO) and hydrogen (H_2). The actual yield depends on the pureness of oxygen (pure oxygen can be supplied as a by-product by water electrolysis) and the reaction conditions (temperature and pressure). A part of the hydrogen is oxidized.

To optimize hydrogen output, the water gas shift reaction can be applied, processing the CO with steam to create additional hydrogen.

$CO + H_2O \rightarrow H_2 + CO_2$

The Pernis plant is dedicated to produce as much hydrogen as possible to supply the refinery's needs.

If, on the other hand, there is a need for carbon monoxide, the water gas shift reaction can be left out. Carbon monoxide is part of syngas and is needed to produce methanol or other synthetic fuel in a Fischer-Tropsch plant. A gasification dedicated to CO has the advantage of integrating all carbon into valuable syngas and producing no CO_2. In this way (fossil) carbon contained in waste products can be recycled and be kept in the product stock.

However, CO dedicated syngas production leads to a hydrogen “loss” of approximately 70% (i.e. oxidation and building of H_2O, see Brems et al. (2013), which can be “refreshed” by hydrogen from water electrolysis. Methanol dedicated syngas requires a higher proportion of hydrogen molecules than provided by hydrocarbon waste, requiring further hydrogen.

The methanol synthesis is based on the following two reactions:

3) $CO + 2H_2 \rightarrow CH_3OH$

4) $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Both reactions are highly exothermic, i.e. they produce great amounts of waste heat.

A methanol-based economy has long been discussed in the context of a coal-based economy following the two phases of oil crisis in the 1970s. The classic work of Friedrich Asinger (1986) describes a chemical and fuel industry based on coal-based methanol. In the recent years methanol has gained attendance again in the context of discussion around a circular economy with methanol based on renewable hydrogen and CO_2.

Since the 1970s, methanol-based olefin (and aromatics) production has been developed and there are now various technologies commercially available (e.g. by former Lurgi, UOP and ExxonMobil). All technologies have high steam demand, which exceeds the respective waste heat stream of methanol production. The supply of steam (besides high hydrogen demand) is a major challenge in a low carbon industry relying on renewable energy only. Steam supply could be a disadvantage of the Rotterdam site compared to locations in the Middle East or North Africa, for example, that could rely on steam produced from concentrated solar energy.

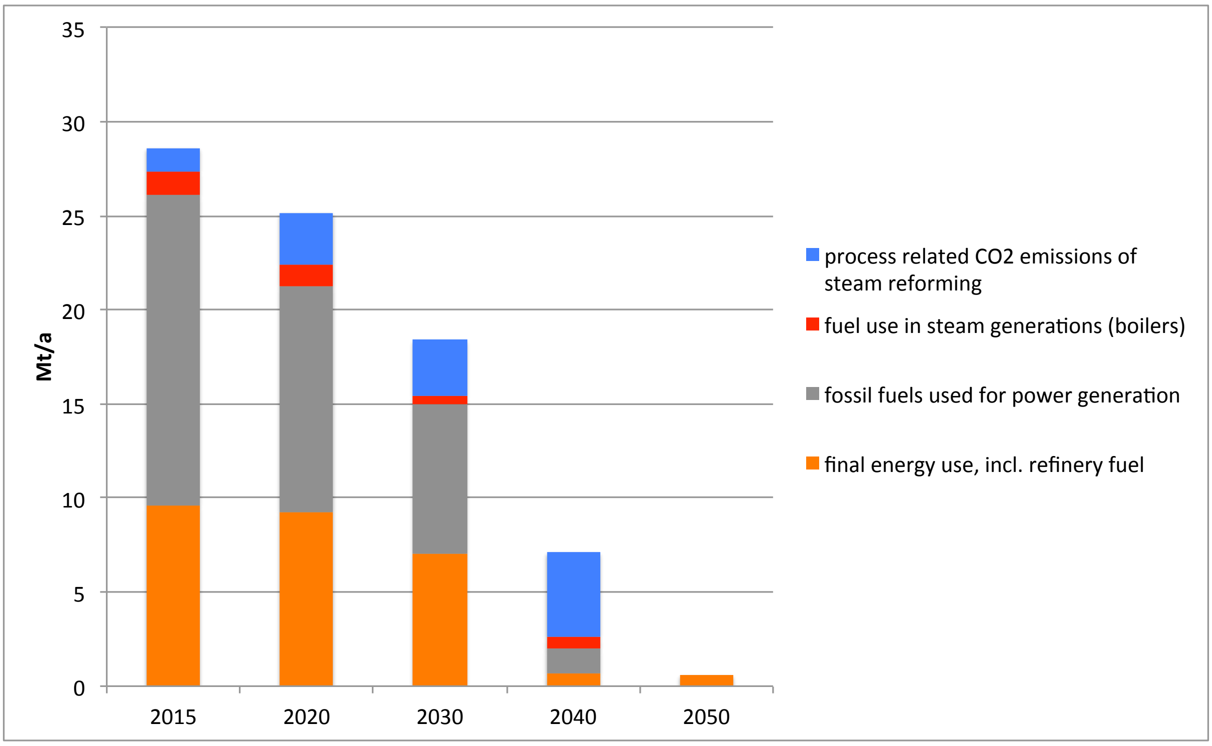
There are, however, products which cannot be kept in the cycle: Propylene-based solvents degrade during the use phase of the product, the constituent carbon degrades to CO_2. In a carbon-neutral economy, in which (net) fossil fuel CO_2 emissions have to be avoided, solvents need to be produced either based on biomass or on CO_2 that is extracted from the atmosphere.

In the CYC scenario, we assumed a waste input of 2.6 Mt with an energy content of 50 PJ to produce 5.2 Mt of CO and 32 PJ of H_2. An additional 100 PJ of hydrogen is required to produce 5.9 Mt of methanol. The amount of methanol is needed to produce 910 kt of ethylene and 1,600 kt of propylene – approximately equal to today’s production at the cluster.

It needs to be stressed that the energy demand of recycling only the building molecules is much higher than that of direct recycling of plastics. The latter should therefore be favoured in those cases, where the quality of the recycled plastics is sufficient. Furthermore, other ways of recycling plastics, like from polyethylene to ethylene (monomer recycling) should also be further researched, so that in the future different recycling processes for different types of plastics and needs will be available.

Energy demand and emission levels in the CYC scenario
Until the year 2020, the CYC scenario does not differ from the BIO scenario and the differences in the CO_2 emissions in the year 2030 reflect the fact that the CCS pilot is operational in BIO, whereas it is not in the CYC scenario. After 2030, the CYC scenario's CO_2 reductions are due to refinery closings on the one hand and a massive restructuring of the basic chemicals production and the use of (renewable) power-to-heat in the petrochemical industry on the other hand.

Figure 19: CO_2 emissions in the CYC scenario (Mt/a)

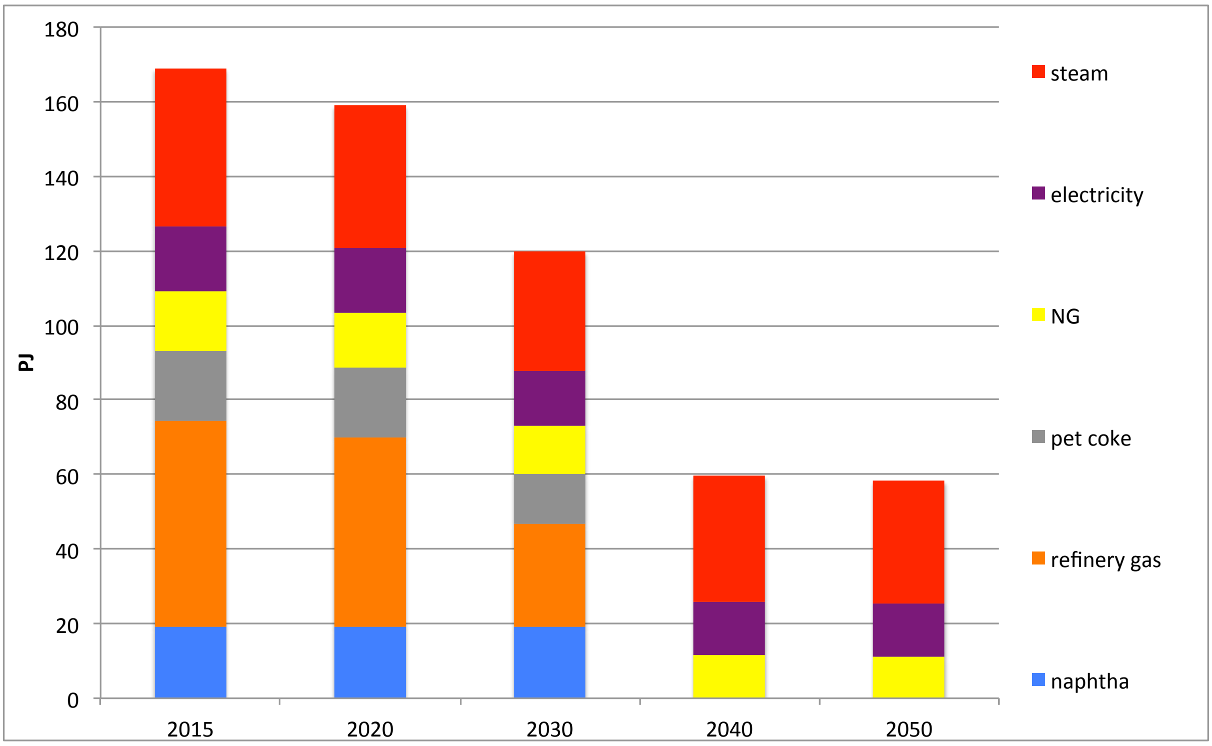


Source: WISEE Model results

Fuel use in refineries and the petrochemical industry is cut by 70% within the port area between 2015 and 2040. The petrochemical industry uses electricity to produce heat or uses (electricity-based) high-temperature heat[17] from the grid. Some natural gas fuel for petrochemical products is still used in the scenario by 2050, which could be substituted by synthetic methane (not regarded in the scenario).

[17] The use of geothermal heat would be an additional option – as discussed above.

Figure 20: Fuel use in refineries and the petrochemical industry (CYC scenario)



Source: WISEE Model results

Scenario-specific challenges

The CYC scenario is a very attractive scenario in regard to the ecological impacts. The port area is a front-runner in this scenario for a circular and almost carbon-neutral economy.

However, it needs to be stated that this is the scenario with the most far-reaching impacts on the cluster's structure. Massive and simultaneous investments in different kinds of production stock are required to make this vision technically and ecologically viable. With the closing of refineries and the steam cracker in the early 2030s, there is a need to substitute existing structures with methanol-based feedstock (as is assumed in the scenario) or something similar, with the platform product (e.g. methanol) derived from waste and renewable hydrogen. Experience with this technology should already be gained prior to 2030.

The loss of one part of the value chain in fuel production may lead to the perception that this scenario is not attractive in regard to geostrategic or industry-strategic implications. However, today's import dependency in regard to crude oil for aviation and marine fuel is only substituted by another one – the import of Fischer-Tropsch wax. And energy for cars (electricity and hydrogen) is in this scenario completely produced within the European Union – without any import dependency – outweighing the lost part of the chain.

The CYC scenario – with an assumed phase-out of coal power plants in the 2030s – is not consistent with 2015 decision by the Dutch parliament, which urged all Dutch coal power plants to be closed by 2020 (see box "Coal use in power plants and Carbon Capture and Storage"). A recent study (CE Delft 2016) analysed the macroeconomic costs of different CO_2 mitigation measures to achieve the Dutch 2020 GHG reduction target and highlighted that closing down one or two of the three modern coal power plants would be the most cost-efficient solution. Furthermore, the CYC scenario may not be in line with a similar decision by the Dutch parliament from September 2016, which demanded the government to pursue a 55% GHG emission reduction target for the year 2030, requiring all coal power plants to be closed by then. We therefore added a variant to the CYC scenario, assuming the closing down of Uniper's 1,000 MW unit in 2019 and Engie's 800 MW unit in 2025. This CYC scenario variant is called *early coal exit* (**CYC-ECE**) and is shown in the following section in some figures comparing CO_2 emissions in the different scenarios.

3.7 Comparison of the four pathways

In this section, the different assumptions and results of the scenarios are wrapped up and compared. The following table provides an overview of the different approaches in building the four scenarios.

Global GHG mitigation efforts		EU emission reduction strategy		Development of the port area's industrial cluster					Strategies and emissions		
Global GHG emission reduction efforts until 2050	Relative change in global GHG emissions by 2050 (vs. 2010)	European GHG emission reduction efforts until 2050	Change in Europe's domestic GHG emissions by 2050 (vs. 2010)	Key changes in the market environment by 2050 as relevant to the port area's current industrial cluster	Strategy of the port area's industrial cluster	Economic activity in 2050 (vs. today)			Key mitigation strategies	Change in the port area's CO_2 emissions by 2050 (vs. 2015)	Scenario name
						Refineries	Chemical production	Power generation			
Weak (Countries do not implement Paris Agreement)	+20 to +50%	**Minimal** (GHG emission reductions mostly the result of technological developments and policies focusing on other goals, e.g. reducing import dependency)	-30 to -40%	• Decrease in demand for oil refining products	• Efforts focus on keeping the cluster in its current form	↘	→	↘	• (slow) adoption of BaT	-30%	**BAU**
Strong (Countries make great efforts in order to implement Paris Agreement)	-40 to -70%	**Strong** (Europe contributes to global efforts at the lower range of its "fair share" contribution)	-80%	• Strong decrease in demand for fossil transport fuels • Phase-out of unabated coal power generation	• Efforts focus on keeping the cluster in its current form	↘	→	↘	• rapid adoption of BaT • some power-to-heat (P2H) • coal CCS	-75%	**TP**
		Very strong – Significant use of <u>biomass</u> (Europe contributes to global efforts at higher range of its "fair share")	-90 to -95%	• Demand for fossil fuels virtually zero • Phase-out of coal power generation • *BIO:* Large amounts of sustainable biomass available on the world market • *CYC:* No biomass, but large amounts of carbon-free power and/or H_2 available	• Oil is used as feedstock for chemicals • Today's new large power plants continue to operate using biomass & CCS	↓	→	↘	• rapid adoption of BaT • P2H • biomass CCS	-98%	**BIO**
		Very strong – Efforts to achieve <u>closed carbon cycle</u> (Europe contributes to global efforts at higher range of its "fair share")			• Recycled plastics are used as feedstock for chemicals	↓	→	↓	• rapid adoption of BaT • P2H • recycled plastics for chemicals	-98%	**CYC**

In the following Figure 21, the results of the model-based back- and forecasting scenario development are described in a very condensed way, showing on a time scale the key investments that need to be made in the respective scenarios.

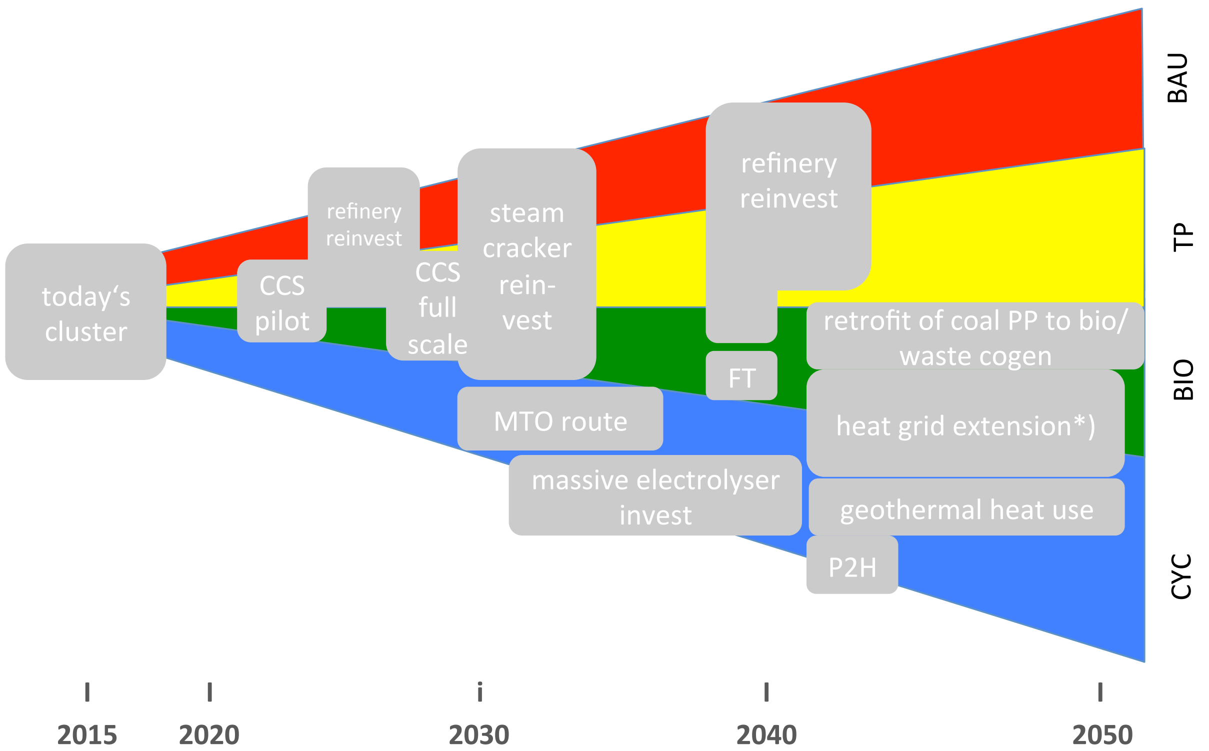
The figure indicates that the TP and BIO scenarios require a fast adoption of the CCS pilot to be able to keep the two new coal-fired units online. If the fuel market changes only marginally, as is assumed in the BAU and TP scenarios (with electric mobility needing more time to be widely adopted), refinery reinvestments would be due during the 2020s in order to maintain the port's market shares in the European fuel market. According to the authors' estimates, a steam cracker would need to be reinvested at around 2030. This reinvestment would be necessary to maintain vertical integration of the petrochemical cluster (if there is no replacement by alternative routes as sketched in the CYC scenario).

Radical decarbonization of the transport sector, as is assumed in the BIO and CYC scenarios, is provided by a shift to battery cars, hydrogen driven fuel cell cars and cable lorries. Shipping, aviation and heavy road transport fuel is provided by synfuels based on renewable hydrogen and non-fossil carbon. We assume methanol for shipping and Fischer-Tropsch kerosene and diesel to be the fuels that will need to be supplied. European (and Rotterdam) refinery capacities are adjusted respectively.

For GHG mitigation in thermal power stations and for some other processes in refineries and petrochemicals production, a scale-up of CCS will be necessary in the decade form 2030 to 2040 in the BIO and TP scenarios – based upon learning from the CCS pilot plant assumed to be important in these scenarios. During the 2030s, the respective pathways of the TP and BIO scenarios diverge: In the TP scenario, sustained demand for fossil fuels induces refinery reinvestments (as in the BAU scenario), whereas in the BIO scenario fuel supply is switched to Fischer-Tropsch (FT) based synfuels derived from biomass and hydrogen. In the BIO scenario, a significant retrofit of the thermal power stations is required after 2040, as all of the stations need to be converted to allow waste- and biomass-firing and to connect them to the heat grid to supply high-temperature heat for the cluster. Combining an extensive heat grid with heat storages and with the use of waste heat, the supply of high-temperature heat can be optimized.

The CYC scenario differs strongly from the other scenarios. There will neither be reinvestments into refineries or steam crackers, nor retrofits of power plants. The main reason for this is the fundamental restructuring of hydrocarbon supply, which is switched between 2030 and 2040 from mineral oil-based to renewable feedstock-based technology, requiring investments into methanol to olefins technology (MTO). Almost in parallel, massive investments in electrolysers will be needed to supply renewable-based hydrogen to methanol synthesis, feeding the MTO process. Process heat demand will probably be supplied by decentralised power-to-heat technology (P2H) to decarbonize the cluster.

Figure 21: Key (re-) investments to be taken in the four scenarios over time



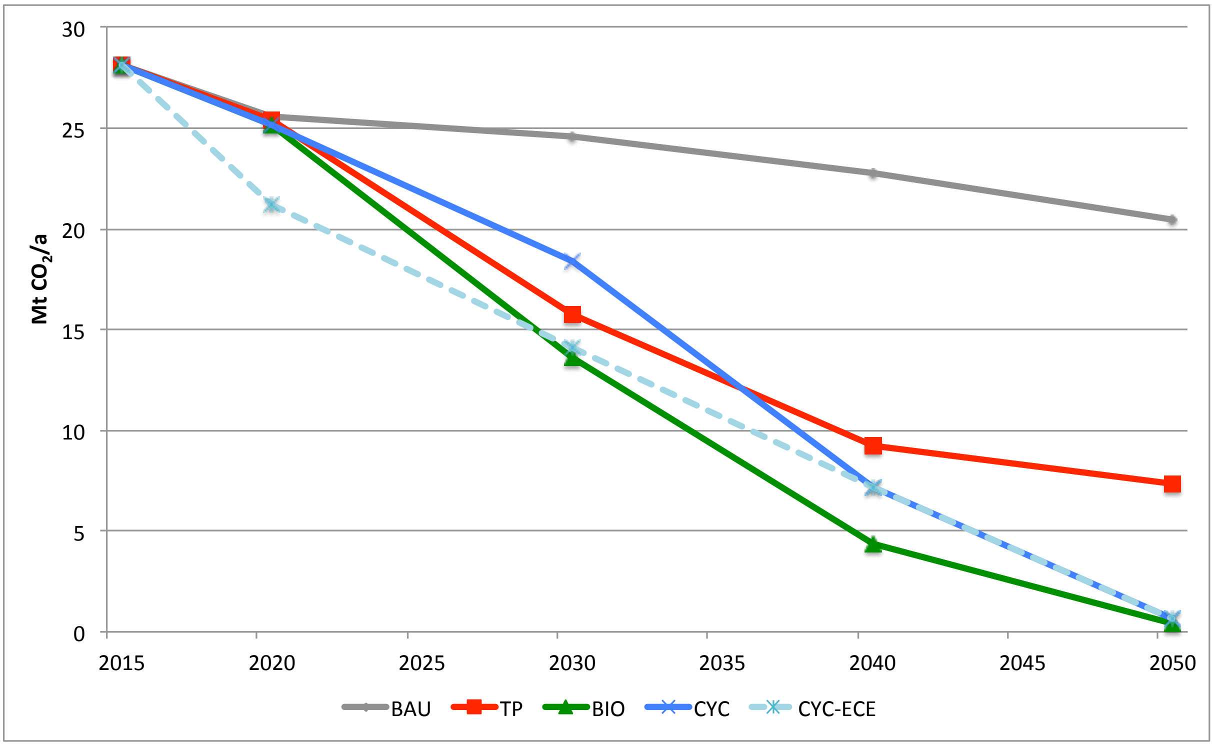
*) Heat grid extension is an option also relevant in the short- and mid-term in all scenarios. Linking single sites to optimize CHP utilization and to facilitate the exchange of surplus heat between sites is therefore reasonable. In the BIO and CYC however, there is a need to invest in a massive network covering the whole industrial cluster.

The development of CO_2 emissions in the four scenarios is shown in the following Figure 22.

All scenarios show a sharp short-term decline of CO_2 emissions by 2020 (compared to 2015), which can be attributed to the closing down of two 40-year old coal-fired power plant units by the end of 2016. These closures will reduce annual CO_2 emissions by roughly 6 million tons compared to emissions in 2015. This will, however, be partly compensated for by the Moerdijk steam cracker, which is assumed to soon resume full operation, as well as Exxon's new hydrocracker, which will require additional hydrogen production (leading to additional CO_2 emissions). The only short-term difference between the scenarios can be seen in the CYC-ECE, in which it is assumed that one of the recently built *new* coal-fired power plant units will be closed down already in 2019.

In the BAU scenario there will be no further considerable cuts in emissions after 2020. Emissions will remain stable until 2030 and will gradually decline afterwards due to technical improvements and declining refinery production. In contrast, the BIO scenario shows the fastest decline in emissions, due to the adoption of CCS, combined with a high-efficiency path and the large-scale conversion to biogenic fuel and feedstock supply as well as electricity generation and a partial closing down of refinery capacity. Finally, in the CYC scenario, emission reductions occur slightly slower than in the BIO scenario as it takes more time to provide completely CO_2-neutral hydrogen and steam based on renewable electricity (imports), because emission reductions here indirectly depend on the decarbonisation in the EU electricity supply. However, if it is assumed that one of the recently commissioned coal-fired power plants will be closed down by 2019 already, due to national GHG emission reduction policies (as depicted in the scenario variant CYC-ECE), emission reductions in the port area would be comparable to those in the BIO scenario.

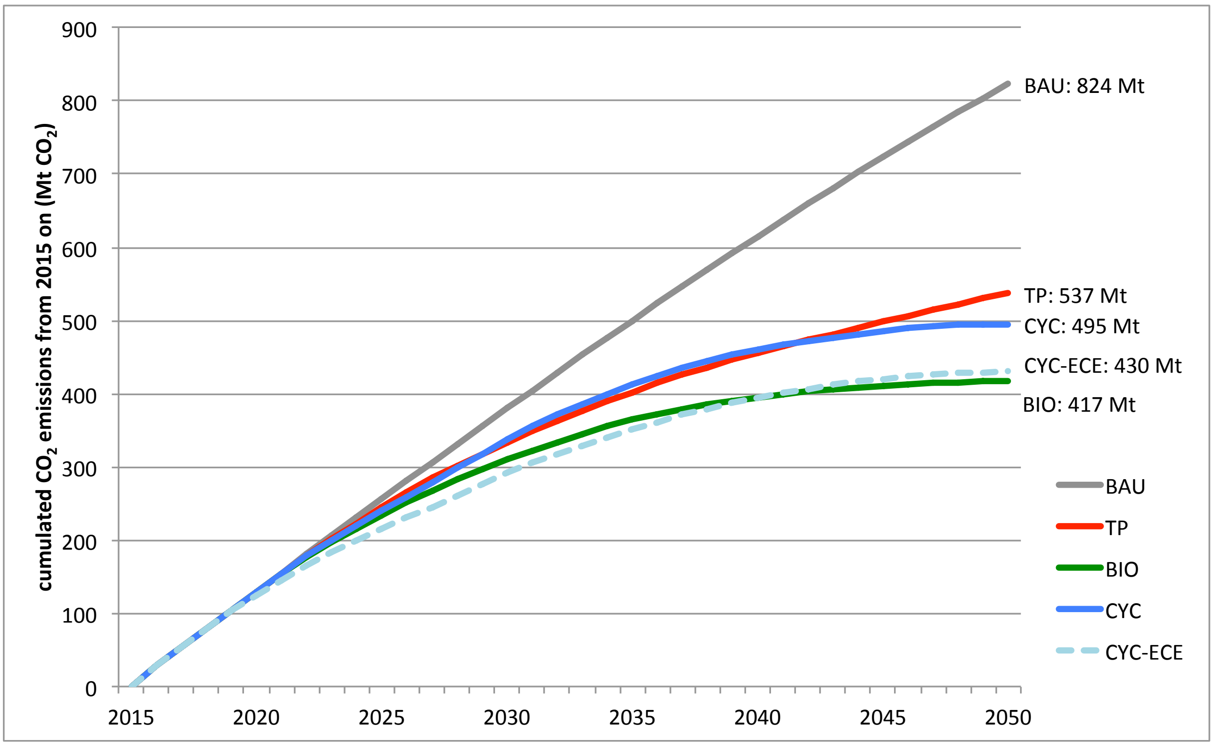
Figure 22: Comparison of net CO_2 emissions of the port's industrial cluster in the four scenarios and a scenario variant



Source: WISEE Model results

Figure 23 complements the picture by showing cumulative CO_2 emissions in the different scenarios over the period of 2016 to 2050. Compared to the emissions of a certain year, cumulative emissions are a better indicator for the actual climate burden of a scenario. As modelling covers only the base year 2015 and the four scenario years 2020, 2030, 2040 and 2050, CO_2 emissions for the years in between were derived by interpolation. However, the introduction of CCS was taken into account more precisely, by considering the actual year of connection of the CCS plants to the major power plants (2022 and 2029).

Figure 23: Comparison of cumulative net CO_2 emissions of the port's industrial cluster in the four scenarios and the scenario variant



Source: WISEE Model results

The ***BAU*** scenario – with only slight reductions of annual CO_2 emissions – shows an almost linear development of cumulative emissions. In this scenario, the mark of 400 Mt, which represents the total CO_2 budget of the two most ambitious scenarios (BIO and CYC-ECE), is fully used as early as 2030. Until the end of the scenario horizon the total amount is doubled, finally reaching a total of over 800 Mt of CO_2 emitted by 2050 – and continuously growing thereafter.

The ***TP*** scenario shows considerable reductions in the mid-term, as indicated by a flattening of the curve. However, it fails to approach zero additional emissions even in the long term. Cumulated emissions until 2050 are well above 500 Mt CO_2 in this scenario and the gradient of the curve is still high in the last years of the scenario horizon, indicating significant future emissions after 2050.

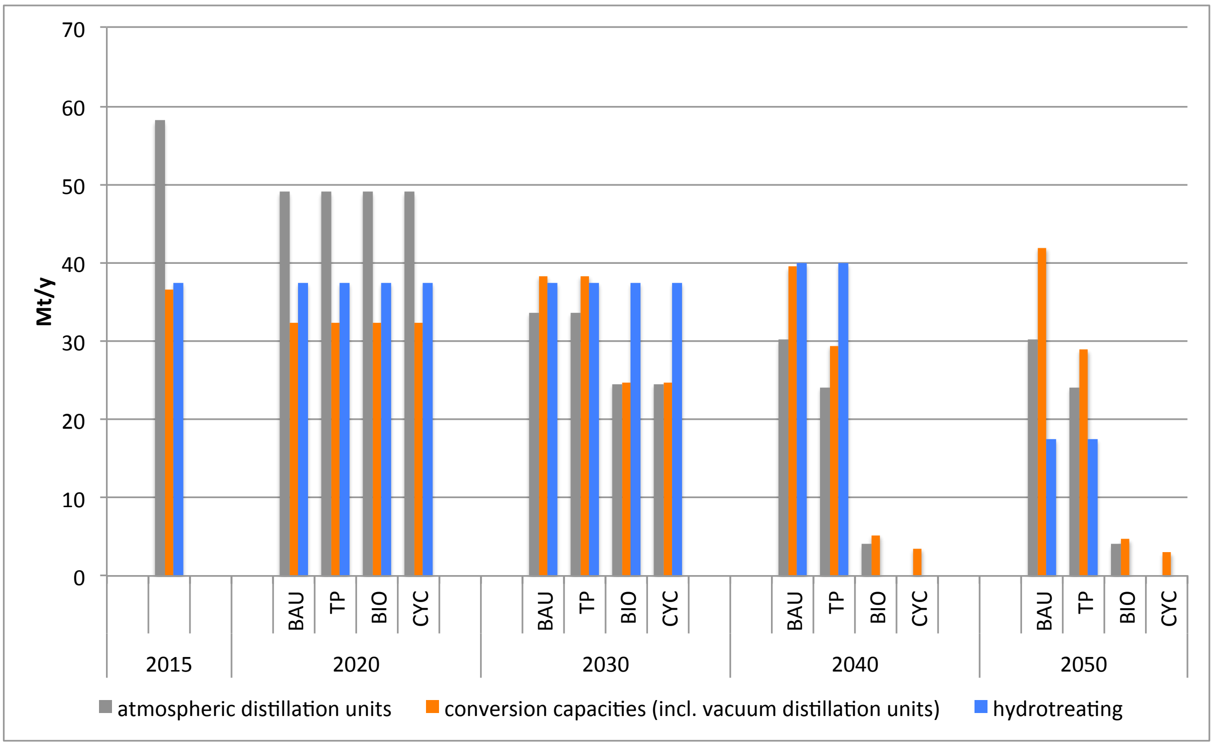
The ***BIO*** scenario leads to the lowest total amount of CO_2 emissions over the scenario period, with CO_2 emissions almost levelling off in the end, meaning that very little CO_2 will be emitted after 2050. However, the low total amount of net CO_2 emissions of 420 Mt will only be reached by the successful adoption of CCS and full conversion of the largest power plants to biomass, resulting in net negative emissions of biomass-firing in the overall balance. It was argued above that this scenario is built on *two* pillars (CCS and massive energetic use of biomass) and each of them might encounter difficulties in realizing them because of potential negative sustainability effects.

The development of cumulated emissions in the ***CYC*** scenario demonstrates that a long-term saturation of CO_2 emissions is also possible without CCS. In this case, however, the relative long use of the two new coal-fired power stations (in non-CCS form) in the scenario (until 2035) results in a higher total emission budget compared to the BIO scenario (500 Mt vs. 420 Mt), where emission cuts are realized earlier. This is not inevitable, of course, as the ***CYC-ECE*** scenario variant shows. With an earlier exit from coal-fired power generation, total cumulative emissions are almost similar to the BIO case. Both scenarios show that it would be possible to limit total future CO_2 emissions of the Port of Rotterdam industrial cluster to slightly more than 400 Mt.

The following figures show the respective model results for refinery capacities and refinery output at the port area. It needs to be stressed that only very limited data was available to validate the refinery output data for the base year 2015.[18]

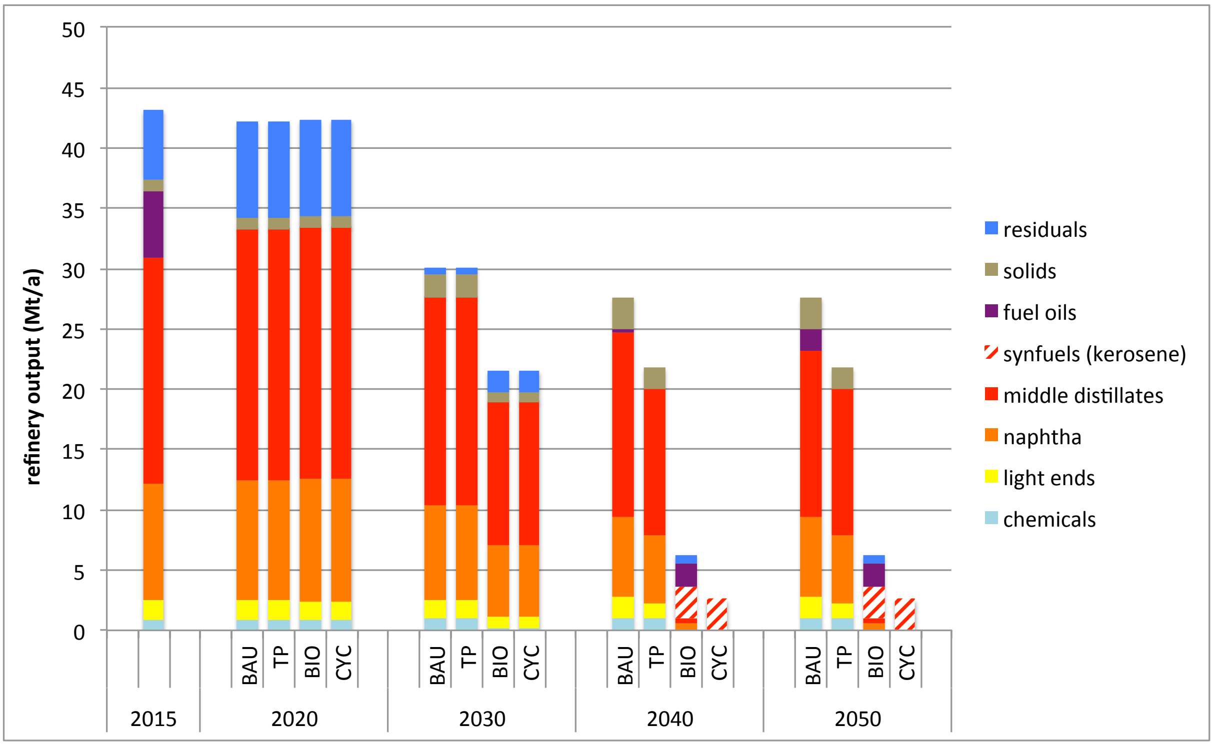
[18] Statistical data indicates that currently there is a high amount of import of heavy naphtha to the port, which is processed to gasoline and aromatics in catalytic reformers. In the refinery model, these kinds of value chains are not represented. For strategic reasons, some of the refinery capacity might also be kept in operation in spite of being in deficit. However, this cannot be accounted for in an optimization model.

Figure 24: Comparison of refinery capacities in the four scenarios



Source: WISEE Model results

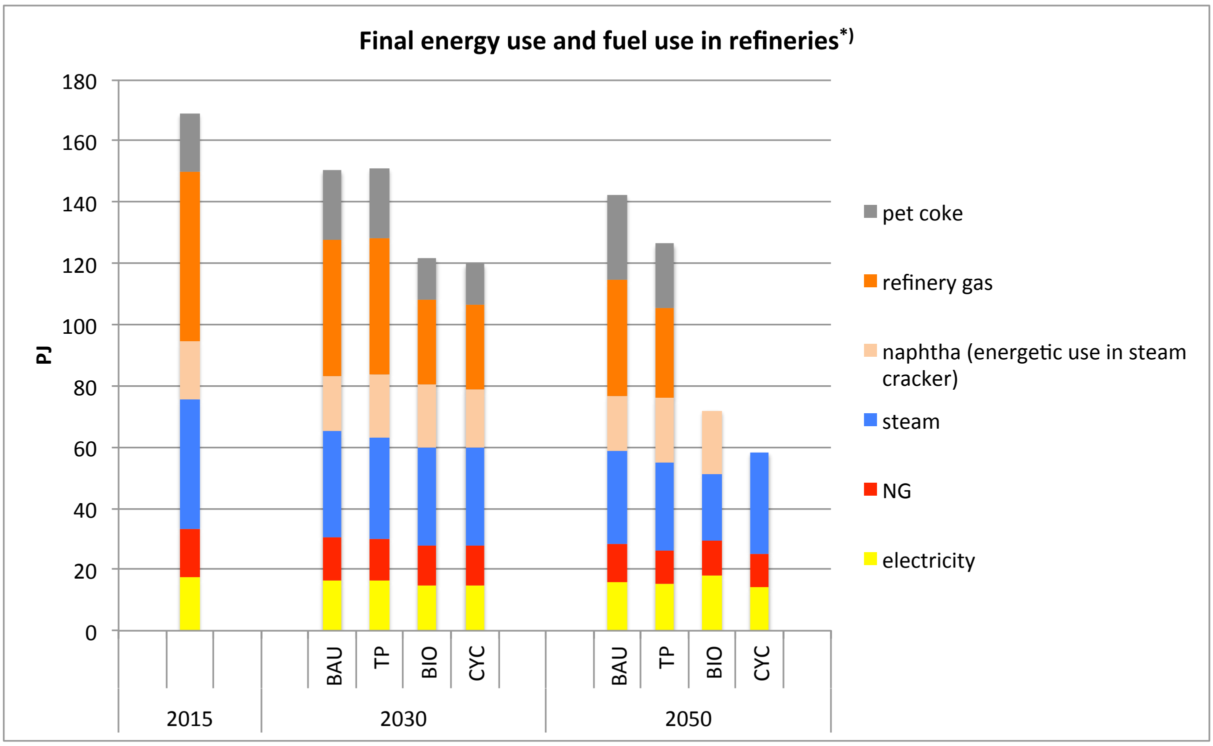
Figure 25: Comparison of refinery output in the four scenarios



Source: WISEE Model results

Differences in the level and structure of fuel use are shown in Figure 26. The differences mainly reflect differences in efficiency improvements (i.e. the pace of BAT adoption) and in refinery closing.

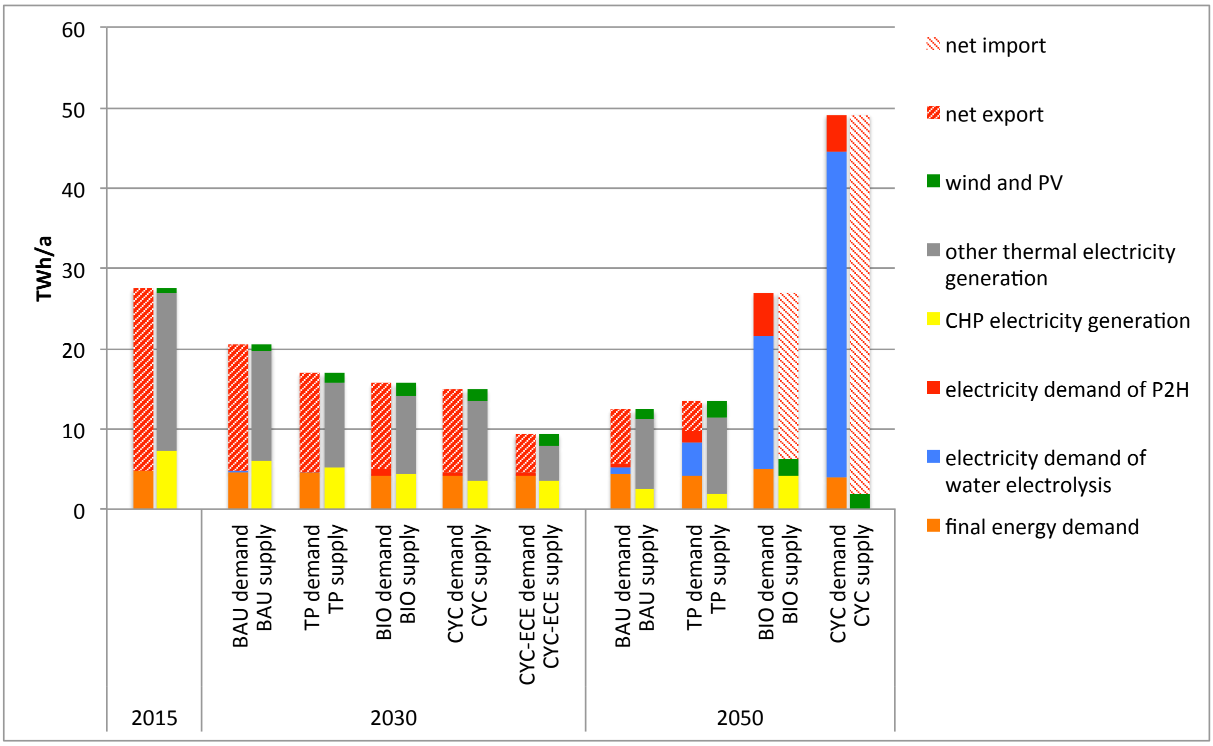
Figure 26: Comparison of final energy and refinery fuel use in the four scenarios



Source: WISEE Model results

Finally, Figure 27 shows the effects of decarbonization on the electricity balance of the port. Whereas a considerable net surplus is delivered to the electricity grid today, electrification reverses the situation in the future, making the port a net consumer of electricity in the long run. The amount of external electricity demand is very high, especially in the CYC scenario. Still, the demand even in the CYC scenario is well below the estimated potential for renewable electricity generation in the Netherlands as a whole until 2050. In the CYC scenario, the port area is the most important provider of hydrocarbon products within the country and can therefore claim a significant part of this potential. Furthermore, it should be noted that some of the electricity demand in the CYC scenario in 2050 (e.g. electrolysis and electric steam generation) could be managed in a way to maximise its temporal flexibility. The port's industrial cluster could thus contribute to optimising the use of the fluctuating electricity generation from wind and solar PV, while stabilising the Dutch and European electricity grid.

Figure 27: Electricity balances of the port's industrial cluster for the four scenarios in 2015, 2030 and 2050



export: annual electricity generation on the port territory exceeds consumption;
import: consumption exceeds production

Source: WISEE Model results

3.8 Potential new industrial activities at the Port of Rotterdam area

The four scenarios introduced above focus on the future development of the industries that currently make up the core of the port's industrial cluster, namely on refineries, chemical production and electricity and heat generation. As discussed above, some elements of the current cluster (refineries and unabated fossil fuel electricity generation) are expected to become less relevant over the coming decades as a result of regulatory changes and changes in market demand associated with the intensification of global and European decarbonization efforts. On the other hand, future changes in regulation and market demand are obviously also connected with new opportunities for investors, companies and regions. Several activities and industries that do not play a role in today's global economy or play only a minor role, are expected to become important and profitable in a decarbonized future.

This section discusses the prospects for some of these new activities and industries to become relevant in the Port of Rotterdam area between now and 2050. They were chosen based on the climate change mitigation scenario and technology foresight literature. Only those activities and industries that would seem to benefit from being located at a seaport or specifically at the

Port of Rotterdam are focused on. The following seven activities and industries have been identified as especially promising for the port's future:

- Offshore wind
- Bio-based chemistry
- Demand-side-management and energy storage
- CO_2 transport and storage
- Synthetic fuels
- Carbon-neutral primary steel production
- Use of waste

Offshore wind
All European climate protection scenarios expect a significant expansion of offshore wind power capacities in the years and decades to come. The Netherlands itself is currently planning to build several offshore wind farms in the North Sea. This growing industry offers a significant business opportunity for the Port of Rotterdam, as many elements of the offshore wind industry (e.g. assembly of wind turbines, their installation and operation and maintenance) profit considerably from being located at or near the shore. Further, the port area is also an important node in the electricity grid, so the area might be suited as one of the connection points of a future offshore high-voltage direct current (HVDC) grid to the onshore electricity system. This position could become increasingly important in the future, if plans to further develop the connections of the North Sea wind parks into a northwest European DC ring.

Significant steps to attract and grow offshore wind industry in the port area have already been made in Rotterdam recently, as manifested by the announcement of the *Rotterdam Offshore Wind Delta* in June 2016 by 15 CEOs of companies of the offshore wind sector. Furthermore, Sif Group and Verbrugge International are currently building a dedicated offshore terminal and a production site for monopiles on the Maasvlakte 2.

Bio-based chemistry
Bio-based chemistry is a wide field that includes the production of currently used 1st generation biofuels (made from energy crops from dedicated farming, e.g. biodiesel from rape seed) as well as 2nd (based on residues as straw and waste woods) and 3rd (based on new innovative biomass sources as algae) generation of biofuels and tailor-made specialty chemicals from biogenic sources as e.g. biopolymers. It is also linked to the topic of synthetic fuels, because CO_2 as feedstock is needed to produce these fuels.

Some companies in the Rotterdam port area already produce biofuels of the 1st as well as 2nd generation. Starting points for bio-based chemistry or biotechnology already exist in some of these companies. One example is the production of 1st generation biodiesel by Biopetrol Industries, which generates pharmaceutical glycerine as a co-product at the same time. With Abengoa, a player is based in Rotterdam that is engaged in the conversion of lignin as a feedstock to 2nd generation ethanol, although at the Rotterdam plant the process is operated based on cereals. Lignin can be used as a fuel and also as an important additive for the chemical industry to produce carbon fibre, solvents, adhesives etc. Abengoa is working on different utilisation routes for lignin to be used in their 2nd generation biorefineries. Already today, an existing plant producing NexBTL a 2nd generation biofuel is operated in Rotterdam by Neste. The process converts biomass via hydrogenation, deoxygenation and isomerization to pure hydrocarbons and (bio)propane. In contrast to the conventional biodiesel process for the production of fatty acid methyl ethers (FAME), the glycerine line is not applied. It is the dedicated goal of Neste to enhance the biomass feedstock from currently used vegetable oil and waste fats to a broader range of biomass raw materials and (in the longer term) to use not only biological, but also thermo-catalytic pathways to produce alternative transportation fuels. The company also aims to produce not only fuels for road and air transport, but also feedstock for bio-based chemicals. Neste has recently realised a new facility for the production of biopropane fuels at its refinery on the Maasvlakte.

The production of bio-based chemicals and fuels is widely expected to be an important element of a low-carbon future, as biomass provides the only natural source of carbon (aside from the possibility of extracting CO_2 from the atmosphere, which is energy intensive and expensive under current technical conditions). On the other hand, sustainable biomass is not an abundant resource. Therefore, the smart and innovative utilisation of biomass in the form of 2nd and 3rd generation processes will become increasingly important.

The port of Rotterdam as an industrial cluster is already in a good position to profit from an expected future increase in the relevance of bio-based chemistry as an important and innovative field:

- Well-known companies with the declared goals of becoming major players in the field of bio-based chemistry are already present at the port.
- A potential linkage to the production of synthetic fuels – another attractive new industry field – exists via the utilisation of CO_2 (from biogenic as well as industrial sources) as a building block.
- The port can serve as a hub for increasing imports of sustainable biomass feedstock from Europe and elsewhere.
- The existing chemical industry at the port might utilize some of the produced chemicals in order to "green up" their production route in the medium term, allowing for a better starting position in the market of specialty chemicals.

Demand-side-management and energy storage

The share of fluctuating electricity generation from onshore and offshore wind power, solar PV and ocean energy in overall electricity generation is widely expected to increase considerably in the coming decades. Most climate protection scenarios (e.g. IEA 2015, Greenpeace et al. 2015, EC 2011) assume that the share of these sources in EU electricity generation will increase from 11% in 2014 to somewhere between 40 and 65% by 2050. For the Netherlands, the climate protection scenario by Greenpeace et al. (2013) foresees a share of 66% of fluctuating electricity generation by the middle of the century. Such high shares of electricity generation from fluctuating renewable energy sources will pose technological challenges in regard to ensuring a stable supply of electricity as well as economic challenges in regard to maximising the value of the generated electricity. In the coming decades, markets for offering solutions to these challenges will likely grow in importance, and some of the solutions may be offered at the port area.

As large electricity consumers, the port's industries have significant potential to adapt their electricity demand to supply. The port's industries could benefit from becoming major providers of electricity demand flexibility. As mentioned in the previous section, new types of electricity demand foreseen mainly in the chemical sector (and especially in the CYC scenario), like electrolysis and electric steam generation, are generally suitable to be operated flexibly, with higher demand at times of low electricity prices and lower demand at times of high prices. Particularly heat and steam generation are typically well-suited to operate flexibly due to (typically) relatively low investment costs of heat generation as well as the possibility to take advantage of the storage capacities of existing heat and steam grids. Additional storage capacities for heat could be invested in, such investments are already today economically attractive in many district heating systems in Germany and Denmark and could be an option for the port.

For other electricity consumers such as hydrogen electrolysis flexibility typically comes at higher cost, as higher capacities of the electricity consuming processes would need to be installed compared to a more uniform operation. It is not possible to determine today whether the operational savings will be sufficient to allow for significant additional capacity investments.

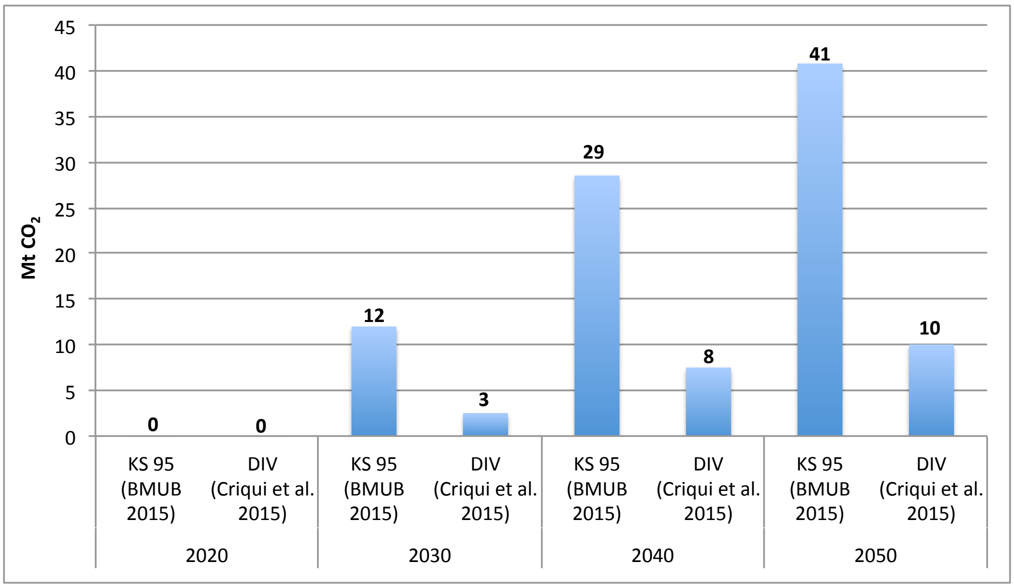
Additionally, it is possible that large-scale electricity storage plants might be located in the port area. Apart from battery storage (which has relatively small specific locational requirements), these could be compressed air storage power plants depending on the geology of the port. Typically salt domes or other underground caverns are needed. However, we are not aware of any studies on the availability of suitable reservoirs in the port area for storing large volumes of compressed air. Such studies would need to be made to be able to assess the future prospects of the port area for such storage facilities.

CO_2 transport and storage

Visions of the Port of Rotterdam becoming a central hub for transporting CO_2 from various European sources to CO_2 storage sites in the North Sea are not new. Although little progress has been made in Europe in recent years in further developing carbon capture and storage technology and related infrastructure, this does not necessarily mean that this option will not play a role in the coming decades. Due to technological challenges, uncertainties about future costs, questions in regard to public acceptance and declining costs of electricity generation from renewable energy sources, the prospects of a large-scale use of CCS technology for power generation in Europe have indeed become doubtful in recent years. However, achieving the internationally agreed-upon long-term climate targets will require an almost complete decarbonization by the middle of the century and will therefore require significant reductions of GHG emissions, including in all industrial processes, possibly reaching zero by the middle of the century or soon thereafter.

For some industrial activities, a complete avoidance of process-related emissions is either very expensive (e.g. in primary steel production) or technologically impossible (e.g. in cement production) from today's point of view. A complete shift from these materials to other, less emitting ones also seems to be unlikely. To prevent (most of) the emissions of these industrial activities from entering the atmosphere, carbon capture and storage (CCS) or carbon capture and use (CCU) may be the only viable options. Indeed, many climate protection scenarios for individual European countries assume that considerable amounts of CO_2 from industrial activities will be captured and stored in Europe by the middle of the century. Figure 28 shows the role of industrial CCS in two recent climate protection scenarios for Germany and France. Both scenarios assume that CCS will play a role in reducing CO_2 emissions of the industrial sector, while the technology will not play a role in reducing emissions of the power sector. CCS is expected to be phased in from 2025 on (French DIV scenario) and 2030 on (German KS 95 scenario), respectively.

Figure 28: Annually captured and sequestered CO_2 emissions (all from industrial sources) in two recent climate protection scenarios for Germany (KS 95) and France (DIV)



Sources: Data from BMUB 2015 and Criqui et al. 2015.

There are several reasons why Rotterdam is well suited to become a hub for collecting much of the CO_2 emissions potentially captured in Europe in the future and transporting them via pipeline to CO_2 storage sites in the North Sea:

- The fact that the port is a considerable source of GHG from large-point sources – at least today and in the mid-term (notably fossil fuel-fired power plants and refineries).
- The close proximity to Germany (and especially its industrial Ruhr area) and France as major potential sources of captured CO_2.
- The relatively close proximity to potential CO_2 storage sites (especially gas fields, but also saline aquifers at greater distance from shore) in the North Sea.
- The option to also use ships to transport CO_2 to the port or to storage sites in cases when pipeline transport is not a viable option.
- The significant experience with different kinds of gas networks the Netherlands and the port area has made in the past.

It therefore seems reasonable for the port to continue to observe the chances of such a hub becoming reality at some point in the future, and to talk to potential partners in the meantime. While considerable transport of CO_2 to Rotterdam appears to be unlikely in the next ten to fifteen years, given the technological challenges, the relatively high costs and the current prospects of low prices for CO_2 emissions allowances in the EU ETS, business opportunities for the port area may arise in the mid- to long-term (beyond 2030). For this to become reality, some CCS demonstration projects in Europe will probably need to be realized in the coming years, with the planned ROAD demonstration project obviously being of special importance for the port (see above).

Some of the CO_2 that may be transported through the Port of Rotterdam in the future may also be used by the port's industries, as they may need carbon as feedstock. This could be the case for the chemical industry as well as for the generation of synfuels, using hydrogen and CO_2 as a basis. In the scenarios developed here, however, the use of fossil carbon (e.g. from steel plants) to produce transportation fuels is not assumed as this eventually still results in net CO_2 emissions (after re-use of the CO_2 for fuels). This strategy would therefore not be in line with the requirements of a -90/-95% world.

Synthetic fuels

While fossil fuels will become less relevant in the transport sector in a world that pursues ambitious climate protection targets, CO_2-free or CO_2-neutral fuels will need to play a much larger role instead (see Chapter 2). The direct use of electricity is not seen as an option for all means of transport, especially not for aviation, maritime traffic and much of the road freight transport. Consequently, liquid or gaseous fuels will still be needed in a decarbonized world. Many decarbonization scenarios expect hydrogen and synthetic fuels (or *synfuels*) like methanol – produced with renewable electricity – to play a significant role in meeting energy demand from the transport sector by 2050 (see Chapter 2), as the potential for a sustainable production of biofuels is limited.

The Port of Rotterdam could attempt to become a major producer of synfuels in the future. It could use imported biomass or waste as well as the CO_2 it captures from local or regional sources (or that is transported from other regions or countries, see above) to produce synfuels at specialised facilities, using hydrogen as an additional feedstock. The hydrogen could either be produced locally, although that would create a huge additional demand for electricity, or it could be imported from other European or non-European regions via pipelines and/or ships. Where the hydrogen will come from will depend on the future competitive advantages of various world regions in producing electricity and/or hydrogen from carbon-free energy sources. In any case, the Port of Rotterdam would likely be a very suitable location for generating synfuels for several reasons:

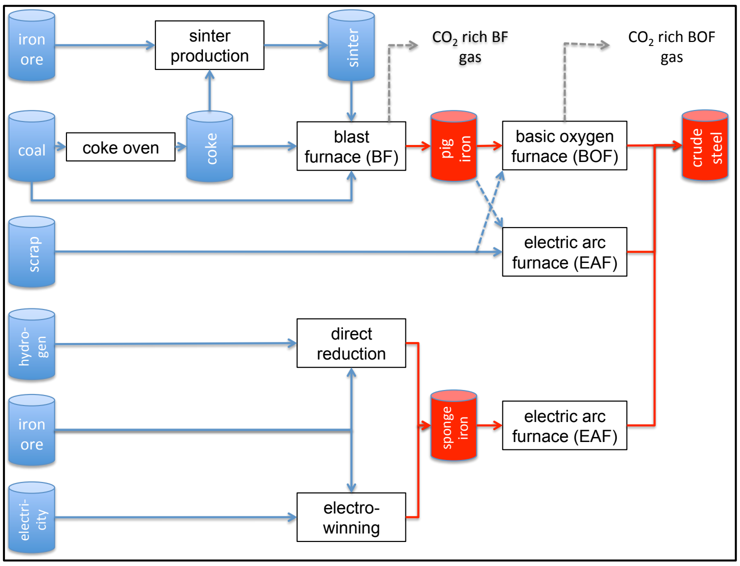
- Hydrogen could be imported via ships or via a hydrogen pipeline network, which already exists to some extent today. A local production of hydrogen from renewable electricity would likely require the connection of the port area to the Dutch and European electricity grid to be further expanded.

- The port could possibly use both, its existing fuel pipeline network and ships to deliver future synfuel products to the relevant markets.
- The carbon that is required to produce synfuels is either available from local industrial activity (CO_2) or it can be imported via ship (biomass) or pipeline (CO_2), the latter of which is also already available to some extent (*OCAP* pipeline)

Carbon-neutral primary steel production

Primary steel production is Europe's most emission intensive industry. The prevailing blast furnace/blast oxygen furnace route requires coal as a reduction agent for the processing of iron ore to crude steel (see Figure 29).

Figure 29: Different routes for primary steel production



Source: Own figure based on Quader et al. (2015).

Decarbonization of primary steel production requires either the carbon from diverse gas streams of an integrated steel mill to be captured, or alternatively a technology for carbon-neutral reduction of the iron ore. CCS technologies in primary steel production are expected to achieve CO_2 capture rates of about 80% when relying on the innovative smelt reduction technology, as tried out in a pilot plant in IJmuiden. Other systems like Top-Gas-Recycling at the blast furnace, which are dedicated to retrofit existing steel plants achieve lower capture rates. In a -90/-95% world, when these capture rates will not suffice to achieve emission reduction targets and/or if the CCS technology cannot be used for whatever reason, carbon-neutral reduction via direct reduction with hydrogen or electrowinning could be alternatives.

For steel companies, making investment in break-through-technologies such as melt reduction with hydrogen or electrowinning would have radical consequences. They would be unable to profit from their existing assets (blast furnaces, coke and sinter plants) at their existing production sites. Instead, greenfield investments would be required. The necessity of greenfield investment in turn would provide for larger flexibility in the decision of where to locate the new steel making capacities. This would allow the choice of location of new steel generation to be economically optimised.

Under such circumstances, the port would have a couple of advantages over inland sites:

- The iron ore could be disembarked directly from sea-going vessels at the steel plant, reducing transport costs considerably compared to inland sites. Rotterdam already has a big port infrastructure for the transhipment of iron ore.
- Hydrogen could be imported via ships or via a hydrogen pipeline network, which already exists to some extent today.
- Considerable amounts of electricity (for local hydrogen production or in the case of electrowinning) from carbon-free electricity generation in the Netherlands or other European countries could be made available if the electricity grid is further expanded.
- Crude steel could be easily shipped by vessels or trains to inland or coast-situated (existing) downstream production steps (hot rolling mills).

Use of waste
Waste is already today a relevant issue for the port. The petrochemical industry produces a lot of hydrocarbon waste, which is processed in waste incineration plants producing heat and electricity. Another way of treating waste is the production of syngas. Shell already uses hydrocarbon residues from oil refining in its gasification plant at the Pernis refinery to produce hydrogen and CO_2. In the future, the processing of oil residues to syngas (hydrogen and carbon monoxide instead of carbon dioxide, see the box on *Waste-based chemicals production*) could become an attractive business model, making value out of the industrial residues.

A more far-reaching industrial activity would be the gasification of municipal or plastic waste to produce syngas, which would be enriched with additional hydrogen from water electrolysis to get a more favourable structure that will eventually become a feedstock for chemical production. By this, the carbon content of the plastics and other waste would become part of a closed carbon cycle. To supply the petrochemical cluster with waste in such a vision, it would be necessary to collect waste in Western Europe and ship it to the port.

The port's relative advantages compared to other sites are:

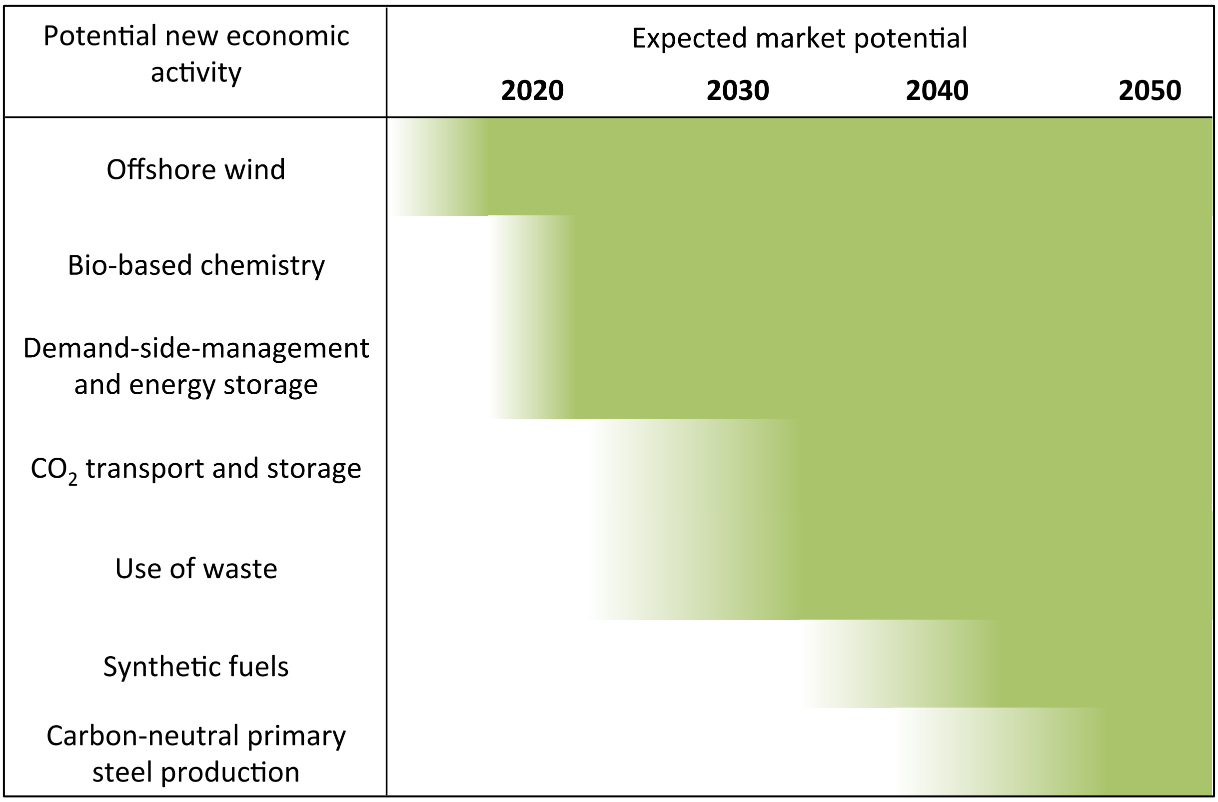
- The existing petrochemical cluster could absorb the produced syngas easily.
- Hydrogen could be imported via ships or via a hydrogen pipeline network, which already exists to some extent today.
- Waste could be shipped easily to the port.

Overview
The following Table 3 and Figure 30 provide overviews of the potential new economic activities discussed above. Table 3 offers an assessment by the authors on how likely significant market growth will be for each activity in a future decarbonizing Europe. It also lists risks associated with each activity that may prevent the activity from becoming relevant in the future. Figure 30 provides an assessment on when the respective activities may become relevant.

Table 3: Likelihood of significant market growth of new economic activities and their risks (both in case of ambitious European mitigation efforts)

Potential new economic activity	Likelihood of significant market growth	Risks (Reasons why markets could remain small or non-existent)
Offshore wind	High	• Specific offshore generation costs may remain high • Sufficient low-cost RE electricity generation from other sources (especially from onshore wind and PV) may become available
Bio-based chemistry	Medium	• Supply of sustainable biomass as feedstock may remain small, leading to severe competition on the demand side and high prices. • Bio-based chemistry production may be located at other world regions that offer better renewable energy conditions (regarding e.g. low-carbon electricity and hydrogen) and a better supply of biomass.
Demand-side-management and energy storage	High	• Supply-side flexibility may remain higher than expected, limiting the economic favourability of demand-side-management
CO_2 transport and storage	Medium	• Carbon capture on a large scale may remain technologically challenging • Cost of relatively complex technology may remain high • Breakthrough technologies in various industrial sectors may reduce emissions at lower costs in the long term • Public opposition to large-scale onshore transport of CO_2 or even to offshore CO_2 storage may arise
Use of waste	Medium to high	• Hydrogen and/or electricity prices could be too high compared to other European or world regions. • Decentralized options of waste treatment could be favoured. • Lower oil prices (as a result of lower fossil fuel demand in the transport sector) could crowd out waste as a resource.
Synthetic fuels	Medium to low	• Direct use of electricity, hydrogen and biomass combined might be able to cover all future demand for carbon-free energy in the transport sector • Synfuel production may be located at other regions of the world that offer better renewable energy conditions.
Carbon-neutral primary steel production	Medium to low	• Hydrogen and/or electricity prices could be too high compared to other European or world regions. • Conventional steel plants equipped with CCS technology may lead to a lock-in and prevent the development of other low-carbon steel technologies. • Low-carbon steel needs to be competitive, e.g. through strong global emission standards or protection within EU.

Figure 30: Expected market potential of possible new economic activities by time period in a future in which Europe pursues ambitious GHG emission reduction efforts



4 Taking steps to realize the vision

The vision of an industrial cluster in the Port of Rotterdam area that continues to prosper as part of an increasingly decarbonized Europe, will not come about without adequate action by various actors. In this chapter we outline key steps that we believe these actors will need to take in the coming years and decades in order for such a vision to be realized. In the following we will provide specific recommendations to the following three groups of actors:

- The Port of Rotterdam Authority and regional policy makers
- Companies that are part of the port's industrial cluster
- National and EU policy makers

Table 3 provides an overview of all recommendations, with each recommendation being discussed in more detail in the following sections.

Table 4: Overview of the recommendations to policy makers, the Port Authority and the port's industries

Recommendations to the Port of Rotterdam Authority and regional policy makers
• Work out a Decarbonization Roadmap for the port area in collaboration with industry • Support the ROAD project and learn from it before deciding on the future of CCS • Win support from government and EU for becoming a flagship decarbonization region • Consider adjusting the port's business model • Continue to anticipate and prepare for future developments
Recommendations to the port's industries
• Intensify strategic networking on the future role of the cluster in a decarbonising world • Identify low-risk, robust investments in line with a decarbonization pathway • Pressure policy makers to ensure sufficient investment certainty
Recommendations to national and EU policy makers
• Provide a clear vision and high certainty of decarbonization in the EU • Increase the cost of CO_2 emissions • Devise schedules for the phase-out of CO_2-intensive technologies • Subsidise RD&D and investments in new low-carbon technologies and infrastructure

Many of the recommendations, especially those addressed to national and EU policy makers, have also been raised by society and industry stakeholders during the two workshops held as part of this project in June 2016 (see Appendix C).

4.1 Recommendations to the Port of Rotterdam Authority

Work out a Decarbonization Roadmap for the port area in collaboration with industry
With the considerable regulatory changes and technological transformation ahead in the coming decades, it is highly likely that the Port Authority would do well in playing an active role in shaping the area's industrial cluster. We recommend that the Port Authority initiates a process in which it works together with the port's industry and societal stakeholders as well as with scientific advisers to develop a Decarbonization Roadmap for the development of the industrial cluster until the middle of the century. This roadmap could aim to develop trajectories against several alternative levels of ambition and action regarding Europe's climate change mitigation. The Decarbonization Roadmap should be more detailed in the short to medium term (e.g. until 2030) than in the long term (e.g. 2030 to 2050), but should describe a plausible long-term vision for the role of the port's industrial cluster in a more or less decarbonized Europe.

Comparing the alternatives with one another will help to determine which short-term technology and infrastructure investments are most "robust" in regard to future climate policy developments. Port Authority and industry could subsequently focus on these investments. The Decarbonization Roadmap should specify concrete steps to be taken by the industry and the Port Authority and it should help to ensure that short-term steps do not obstruct (via "lock-in") the long-term developments that would be required for deep decarbonization.

While such a Decarbonization Roadmap initiative would be similar to and build upon the process applied in this study, industry's involvement should be stronger (with a larger number of workshop meetings over the course of the process) and more time should be invested in discussing and modelling the cluster's future developments. The scenarios developed within the study at hand can be used for orientation or as a starting point for discussions.

We recommend that the Decarbonization Roadmap, once it has been developed, should be evaluated and adjusted continuously, for example every five years. It should furthermore be ensured that the roadmap and any future editions of the *Port Vision* are in line with one another. Alternatively, the two processes could be merged.

Scientific experts should advise the process and should especially check for consistency between the short-term steps identified and long-term vision laid out. They could also advise on the potential role of new industries in the port area.

Based on the port's Decarbonization Roadmap, the Port Authority should:

- Prioritize infrastructural investments that support low-carbon development in the area and might create an advantage for the port.

- Develop exclusion criteria for new CO_2-intensive investments in the area (in cases where it has the authority to grant or deny investments).[19]
- Develop a plan that determines which new actors/industries should be attracted to the area (and how this could be achieved).

The Port of Rotterdam Authority could also contemplate to take over a more active role regarding the required investments in new infrastructure and renewable electricity generation technologies. This includes heat grids, smart meter technologies and wind and PV generation capacities. In these fields, where significant investment in the coming decades will be needed, the port itself could become an infrastructure and service provider to its industries. Such an active role, which could also be structured as a public private partnership (PPP) would be particularly beneficial in cases where no private companies (alone) would be able or willing to make the required investments.

Support the ROAD project and learn from it before deciding on the future of CCS
It is recommended to continue to work on the realization of the ROAD CCS demonstration project in order to get a better understanding of the potentials, costs and technological challenges of this technology. With its relatively close vicinity to potential offshore storage sites and its "capture ready" design, the Maasvlakte Power Plant 3 is well suited for becoming a European CCS demonstration project.

Any further decisions on the role of CCS technology should wait until the ROAD project is operational and can be evaluated. If ROAD (and ideally other CCS demonstration projects around Europe) will be successful and if framework conditions for CCS will be promising, additional carbon capture capacity could be installed in the 2020s or early 2030s at both new coal power plants on the Maasvlakte (as is assumed in the TP and BIO scenarios). In that case, the CO_2 pipeline network would need to be extended further into the North Sea so as to gain access to additional CO_2 storage sites. An increasing share of the two power plants' fuel could come from biomass, provided enough sustainable biomass can be obtained at reasonable costs. This is assumed to be the case in the BIO scenario, where "negative" CO_2 emissions are achieved through the eventual 100%-firing of biomass at both plants.

When developing an expanded CO_2 pipeline network (i.e. expanded over the relatively limited size needed for the ROAD project), the potential of additional capture of CO_2 in the port's petrochemical industry – as well as potential CO_2 influx from other regions in the Netherlands or its neighbouring countries – should be kept in mind in regard to offshore storage and pipeline capacity as well as onshore pipeline routes. In the TP and BIO scenarios, an advanced naphtha steam cracker that is carbon capture ready is built at the petrochemical facilities in Moerdijk in 2030, so a CO_2 pipeline will eventually need to connect Moerdijk to the Maasvlakte. No assumptions on CO_2 influx from other regions have been made in the scenar-

[19] Such criteria should especially prevent CO_2-intensive investments with a high carbon lock-in risk. Such a risk could be eminent when these investments are long-term in nature (i.e. pay off only after decades) and when no options exist technologically or economically to switch to low-carbon energy sources in the future. New investments should also be assessed "too risky" if they clearly stand in contrast with the mid- and long-term requirements of a decarbonizing Europe, as such investments could turn out to be stranded assets in the future.

ios. However, CCS for industrial CO_2 plays a role in many European (as well as some German) mitigation scenarios, so the transport of CO_2 from other regions to storage sites in the North Sea via Rotterdam could be an option in the future. The Port Authority should continue to explore this option and support the exchange of ideas about a potential future Rotterdam CO_2 hub.

If costs, technological challenges and/or environmental side-effects of the ROAD demonstration project will turn out to be too high, CCS efforts should be halted and the two coal power plants on the Maasvlakte would need to be closed down sooner or later, as coal power generation needs to be phased out in Europe no later than 2050 according to mitigation scenarios. In the CYC scenario, it is assumed that both coal power plants will continue to be in operation until about 2035, albeit at decreasing full-load hours as a consequence of increasing electricity supply from wind and solar energy. In the CYC scenario it is assumed that older coal power plants in the Netherlands and in its neighbouring countries (especially in Germany) will be decommissioned earlier than the new and relatively efficient plants on the Maasvlakte. Through the methanol to olefins process, the use of plastic waste as feedstock and a strong reliance on power-to-heat technology, the CYC scenario shows that very deep emission reductions are possible even without CCS technology – although it should be noted that less power is generated in the port area in the CYC scenario compared to the TP and BIO scenarios.

Irrespective of the uncertain prospects for CCS technology, the Port Authority should continue to work with partners within and beyond the port area on the potential of expanding the utilisation of CO_2 as part of the existing OCAP pipeline. Additional greenhouses can be connected to the pipeline network to increase the use of CO_2 in the agricultural sector. In the long term, additional CO_2 sinks could be connected, for example producers of methane or methanol.

Win support from government and EU for becoming a flagship decarbonization region
The Port Authority should attempt to win financial, regulatory and other support from the Dutch government and the EU for making the port area a flagship region for industrial decarbonization. The Port Authority could emphasise that the port area's good geographic conditions (e.g. CO_2 storage sites nearby; low transport costs for internationally traded goods, including biomass) and strong international visibility make it well-suited to function as a flagship region. This promising potential should be exploited early through financial support for investments in low-carbon infrastructure. Specifically, EU support could be obtained by applying successfully for funding as part of the *NER400 Innovation Fund*, which is set to distribute billions of Euros to innovative renewable energy, CCS and industrial decarbonization projects during the period 2021-2030

Consider adjusting the port's business model
Today, almost half of the Port Authority's revenues (47% in 2015) come from seaport dues, with another half (50% in 2015) coming from the lease of land (Port of Rotterdam Authority, 2016). The seaport dues are currently calculated mainly according to the weight of the ships' cargo. In an increasingly decarbonized future, many of the goods currently traded via the port

will loose in relevance and will eventually be traded at a much smaller scale. This especially concerns fossil fuels, notably crude oil, mineral oil products and coal, as both the European mitigation scenarios in Chapter 2 as well as the port industrial cluster's scenarios in Chapter 3 suggest. Together, these fossil fuels make up almost half (48% in 2015) of the gross weight of the port's total throughput (Port of Rotterdam Authority, 2016).

This suggests that over the next 35 years, a significant share of the Port Authority's current revenue base might break away. This reduction in fossil fuel trade is unlikely to be fully compensated (in terms of weight) by growth in other type of goods. However, the economic value per tonne of throughput can be expected to increase on average in the coming decades, so the Port Authority may want to contemplate to convert the basis of how it determines seaport dues from weight to economic value.

Another potential future revenue stream is indicated by the scenarios: As new or significantly expanded energy and emission infrastructure (like smart grids and steam, hydrogen and/or CO_2 pipelines) will be required in the port area in the coming decades, the Port Authority may play a more active role in providing these infrastructures and the related services, perhaps as part of public private partnerships. The same could be true for investing in and operating renewable energy plants in the port area, especially solar PV and wind power plants.

Continue to anticipate and prepare for future developments
Many decisions that the Port Authority needs to make have long-term impacts, for example regarding its own infrastructure investments or its approach of granting private investments in large-scale facilities. As serious effort to combat climate change will lead to dramatic changes in the port's business and its industrial cluster, it may be more important than ever for the port to try to anticipate possible future developments. While it is obviously impossible to confidently predict future developments, especially decades from now, scenario building is a helpful tool to discuss several *possible* future developments. Such discussions help organizations be better prepared for future developments, whatever they may be. The port's corporate strategy division is therefore of great importance and it should be sufficiently equipped to continue to evaluate promising options for the port's future.

4.2 Recommendations to the port's industries

Intensify strategic networking on the future role of the cluster in a decarbonising world
The companies present in the port area should seek to increase their networking on strategic issues by continuously exchanging ideas on their future respective roles in a decarbonized Europe together with the Port Authority. Future challenges and opportunities could be discussed together, as well as the potential advantages in continuing to work together as a cluster. Such exchanges should help the companies to be better prepared for climate mitigation policies that are likely to play an increasingly important role in the future. A format for these exchanges could be the suggested process of developing and continuously updating a Decarbonization Roadmap for the Port of Rotterdam (see recommendations to the Port Authority above).

Identify low-risk, robust investments in line with a decarbonization pathway
Companies should evaluate what kind of low-carbon investments are worthwhile even under today's conditions, so as to identify low-risk, robust investments. They should also identify the risks associated with new investments in high-emission technologies, especially in regard to long-lived investments. The suggested process of exchanging ideas with other companies in the cluster, perhaps as part of a process that develops and continuously updates a Decarbonization Roadmap for the area, should help companies in differentiating between higher and lower risk investments in a potentially fast-changing environment.

Our decarbonization scenarios suggest that the following technologies will become much more important in the coming years and decades in any plausible mitigation scenario environment:

- Wind power (both onshore and offshore)
- Solar PV
- Smart grid technology (to help integrate wind and solar power)
- Demand-side-management (to help integrate wind and solar power)
- Power-to-heat
- Water electrolysis

The prospects for investments in these technologies or processes should be evaluated closely in the years to come. At the same time, the prospects of other potentially important mitigation technologies are as of now still associated with high uncertainty. These technologies include CCS, biomass conversion in the power generation and chemical industries and waste-to-plastics. It is unclear as of now whether investments in these technologies will to be made to a significant extent in the future and will eventually be profitable, but the industry should closely observe developments in these areas.

Pressure policy makers to ensure sufficient investment certainty
Companies should pressure policy makers to ensure sufficient investment certainty regarding low-carbon investments (see also recommendations to policy makers below). Company initiatives in this regard have been made in the past (see 3M et al. 2013) and a broad coalition of companies calling for more certainty regarding the EU's climate policy framework could help to highlight the urgency to policy makers and the broader public.

4.3 Recommendations to national and EU policy makers

Provide a clear vision and high certainty of decarbonization in the EU
National and EU policy makers should send out clear signals that ambitious decarbonization efforts – in line with the EU's long-term target and its international obligations – will be pursued in the short, medium and long-term. Broad cross-party support should be strived for and a clear communication on this issue should be backed up by respective policy measures that support the transition process.

Increase the cost of CO_2 emissions

Putting an adequate price on CO_2 emissions is widely seen as an important condition for successful decarbonization of the Port of Rotterdam area and Europe as a whole. However, the EU Emission Trading System (EU-ETS) that was intended to incentivise low-carbon investments in the industrial sector has so far not created a sufficient price level for these kinds of investments. Between the end of 2011 and the middle of 2016, allowance prices have always been below 10 Euro per ton of CO_2, with recent (July 2016) prices as low as 4 to 5 Euro. Studies show that allowance prices need to be much higher. For example, for electricity generation from coal plants equipped with carbon capture and storage technology to be competitive, the price for carbon allowances needs to reach at least 30 to 50 Euro per ton – and remain at that level.

In two of our three decarbonization scenarios (i.e. in TP and BIO), a CCS pilot project and CO_2 transport infrastructure will require considerable investments in the coming years. These investments will only come forward if there is sufficient certainty that the cost of CO_2 emissions will be much higher in the future than it is today. Alternatively, high subsidies would need to be paid to the private sector for the respective CCS investments to materialize. In all three mitigation scenarios, massive investments in new low-carbon technologies like an advanced naphtha steam cracker with carbon capture (TP and BIO scenarios), methanol to olefins (BIO and CYC scenarios), biomass gasification (BIO scenario), plastic waste gasification (CYC scenario) and power-to-heat (CYC scenario) will be required during the course of the 2020s and 2030s, and these investments will be much more likely to come forward when the costs of CO_2 emissions are high. Otherwise, alternative policies like massive subsidies or the specification of strict technological standards would be needed.

National and EU policy makers therefore need to ensure that there is sufficient incentive to invest in low-carbon technologies in the coming years and decades by taking regulatory steps to significantly increase the cost of emitting CO_2 and by credibly signalling to investors that the cost of CO_2 will remain high or increase over time. This can be achieved either by

- Adjusting the EU-ETS system at the EU level, for example by permanently retracting a large number of emission allowances.
- Introducing an EU wide carbon tax that is increasing over time and that replaces the ETS.
- Introducing a gradually increasing floor cost for CO_2 allowances. This can be done either in the EU or only in the Netherlands, following the example of the UK.

When taking steps to increase the costs of CO_2 emissions, policy makers should make sure to continue to ensure that industries that compete on a global level are not disadvantaged by national and EU climate policies. This can be done for example by pushing for similar mitigation efforts in non-EU countries with competing industries, by introducing an import duty on CO_2-intensive goods or by compensating internationally competing industries for their climate policy costs, e.g. by supporting low-carbon technologies.

Devise schedules for the phase-out of CO_2-intensive technologies

In order to create high certainty for investments in low-carbon technologies, the EU or the Dutch government can devise schedules for phasing out the use or the investment in certain technologies that are associated with high CO_2 emissions. For example, legislation could stipulate that the use of fossil fuel power plants with certain specific CO_2 emissions is to be terminated by a certain year, as currently suggested in the USA by President Obama's proposed *Clean Power Plan*. Phase-out plans could also be devised for example for new investments in oil refining technologies. No such new investments are made in our BIO and CYC scenarios (although *retrofit* investments are made in the BIO scenario).

Any such schedules should ideally be introduced based on cross-party consensus and broad societal support in order to increase the chance that these schedule will be adhered to, thus creating higher certainty for investors.

Subsidise RD&D and investments in new low-carbon technologies and infrastructure

The EU and the Dutch government should expand their financial support for RD&D efforts and investments in new low-carbon technologies that are not (yet) competitive even at an appropriate CO_2 price level but that are expected to play an important role in a decarbonized future.[20] Careful analysis is required on which technologies can be expected to be invested in anyway in case of increasing CO_2 prices and which ones need additional subsidies and RD&D support e.g. to drive down technology cost (learning curve) and overcome investor uncertainty.

Government investments and subsidies are especially justified in regard to new infrastructure that will likely be needed to realize a low-carbon future. New infrastructure investments may not be profitable in timeframes relevant to private investors and/or may be too risky for these actors to make, but may nonetheless be critical for the use of certain low-carbon technologies. Careful analysis is required to determine what type and location of infrastructure is most promising and "robust" in light of uncertain future developments.

Examples for important decarbonization technologies and infrastructure that will likely require additional RD&D support in the coming years and investment subsidies during their phase-in period are the following:

- CO_2 pipelines to storage sites
- CCS pilot plants
- Gas separation technologies for carbon capture
- Fischer-Tropsch technology
- High-temperature heat storage

[20] It should be noted that costs are not the only relevant barriers to the widespread diffusion of many low-carbon technologies (see e.g. Chappin 2016). Governments should attempt to address all relevant barriers through appropriate policies.

5 Conclusions

This study highlights the challenges that the Port of Rotterdam area will probably face in the coming decades as global and European decarbonization efforts intensify. That the EU and other nations worldwide will strengthen their efforts to combat climate change is quite probable, as this will be needed if the international community's climate change mitigation targets as laid out in the Paris Agreement are to be reached. In a decarbonizing world, however, the port's industrial cluster will most likely not be able to retain its current form in the decades to come. Instead, some elements of the current cluster, specifically refineries and unabated fossil fuel power generation, will become less relevant over time as a result of changes in regulation and market demand associated with global and European decarbonization efforts.

However, the study's three decarbonization scenarios for the Port of Rotterdam demonstrate that there are several conceivable pathways that would allow the current cluster to successfully adapt to the changing environment:

Should European decarbonization efforts until 2050 achieve only the lower end of the EU's long-term target range – an 80% GHG emission reduction vs. 1990, the transport sector's fossil fuel demand would still be of considerable size by the middle of the century. In this case, the generally favourable conditions for refineries at the Port of Rotterdam might allow them to continue to operate at only modestly reduced scale compared to today. An increasing share of their output would continue to supply a relatively stable petrochemicals production in the port's cluster. However, this would require the area's refineries to be able to increase their market share in a declining European fuel market.

In case of highly ambitious European decarbonization efforts – achieving emission reductions of 90% or more by 2050 vs. 1990, fossil fuel demand in the transport sector would be minimized by the middle of the century. Some limited refinery capacities could still be present in this scenario, as there would be a small remaining demand for hydrocarbon products. However, it is difficult to assess whether the production of these refinery products would indeed take place in Rotterdam in the future.

Even if the refineries were to eventually cease production, the study's decarbonization scenarios show that the production of chemicals in the port area could nonetheless continue beyond the middle of the century. Base chemical production at the port could switch from using mineral oil products as feedstock to natural gas liquids or it could be radically transformed so as to rely on plastic waste as feedstock in a closed carbon cycle approach. Sustainably produced biomass on the other hand is a scarce resource that will likely be needed as a feedstock for low carbon fuel. Small volume but high-value biomass-based speciality chemicals could nevertheless be an interesting field of business in the future at the port.

Unabated fossil-fuel electricity generation is likely to be completely or largely phased out by 2050 in case of ambitious decarbonization efforts in Europe. This study's decarbonization scenarios have sketched several ways on how to deal with the fossil fuel power plants currently operating at the port, especially the two new coal-fired power plants on the Maasvlakte.

These could be equipped with CCS technology, if the various challenges faced by this technology can be overcome in the next ten to twenty years.

However, in a highly ambitious European decarbonization environment, the life-cycle GHG emissions even of coal-fired CCS plants will be too high. This study suggests that if sufficient amounts of sustainable and suitable biomass can be made available at the port at acceptable costs, the power plants could be converted to eventually run entirely on biomass and waste with the CO_2 captured and the heat utilized with the help of a heat grid. Due to the limited amount of sustainable biomass available globally and the possible need to use this potential to substitute fossil fuels in other applications, its use in the power generation sector may only be justifiable if "negative" emissions can be achieved by using CCS technology. Furthermore, renewable electricity generation from wind turbines and solar PV systems can and should play an increasing role in the port area in the years and decades ahead.

The three mitigation scenarios developed in this study combine the potential future pathways of the port's refinery, chemical and power and heat generation industries to create three plausible pathways that are consistent with the respective regulatory, market and technology developments assumed. While the actual future developments of the port's industrial cluster can and will most likely be quite different from the developments laid out in these scenarios, the scenarios are intended to help broaden today's thinking on potential future developments of the port's industry in a decarbonizing world. By thinking in an open and unrestricted way about the future, the Port Authority together with its industries and possibly other stakeholders can increase their capabilities to be prepared for potential future developments – so as to better tackle the challenges ahead and to fully exploit the opportunities awaiting. As the port's industry profits from its cluster structure, it is logical to prepare for the future jointly – even if individual companies will also have separate strategies.

The study also looked at the opportunities arising from global and European decarbonization for industrial production at the port that go beyond the existing industrial cluster. It discussed several industries and activities that may sooner or later gain importance in a decarbonizing European economy and that would also profit greatly from being located at a seaport or even specifically at the Port of Rotterdam. These are offshore wind, CO_2 transport and storage, synthetic fuel production, carbon-neutral primary steel production and use of waste. The Port Authority would be well advised to continue to observe the prospects of these new industries and activities and it may want to investigate in more detail the precise conditions that each industry and activity would need to be successful, their respective potential interactions with the existing industrial cluster and promising measures to help attract the industries and activities to the port once the time for investments has come.

The potential future industrial clusters of the Port of Rotterdam as well as the potential new industries described here heavily rely on successful research, development and demonstration of new and partly disruptive technologies in energy supply, in the chemical industry and in other sectors. The companies at the port as well as the Port Authority itself are encouraged to take a more active role in the respective research and innovation processes. Such an active and joint approach offers the potential to foster innovation and also helps to better identify promising pathways for the port. It may result in competitive advantages over other industrial clusters that are less innovative. Such a more active role in research need not be restricted to technical research but can also cover respective innovation strategies as well as the development of possible business models.

Finally, it needs to be mentioned that the current study is limited in scope to the industrial activities and to the related territorial emissions in the port area. However, it is obvious that the huge up- and downstream flows and transports of resources, energy and products that are linked to the industrial as well as logistics activities also have significant impacts on global GHG emissions and resource depletion. Via their influence on these flows and the linked value chains, the port and its industries hold an important lever for climate mitigation outside of their territorial boundaries. These options should also be systematically explored in the future and should be included in an overall strategy for the port.

This study's scenarios can only be a first step in developing decarbonization pathways for the industrial cluster of the Port of Rotterdam. One of the key recommendations to the Port Authority is to initiate a Decarbonization Roadmap process in close collaboration with the port's industry. Such a process could help to identify in more detail the conditions that would be required for the port's industry to continue to play an important role in (and for) a decarbonizing Europe. A Decarbonization Roadmap process as well as a close eye on the promising future industries and activities in a decarbonizing environment would help the Port Authority to take on an active role in shaping the port industry's future in a regulatory, market and technology environment that is likely to change much more dynamically over the years and decades to come than in the past.

6 Appendix

6.1 Appendix A – Key mitigation strategies and technologies in four sectors

6.1.1 Energy Sector

6.1.1.1 Introduction

The energy sector is the most important source for CO_2 emissions in the port area. Almost 14.5 megatons (or 48% of the area's total emissions) originated from the production of power and heat or steam in the year 2015 (see Figure 3 in Section 2). Specifically, emissions were caused by nine gas-fired plants, three coal-fired plants with biomass co-combustion and one waste incineration plant (Port of Rotterdam Authority 2016 p. 32ff.). The majority of these emissions came from the area's coal-fired power plants, which also had the highest specific (i.e. per kilowatt hour) emission. As two new coal power plants became fully operation during the first half of 2015, emissions rose by about 22 % in the energy sector compared to the previous year. Aside from thermal plants, wind turbines (around 200 MW) and some photovoltaic plants (around 1 MW in total at the end of 2014) produce renewable and emission-free electricity.

6.1.1.2 Field of Activities

The following "Fields of Activities" can be differentiated in the energy sector:

1. Energy efficiency (CHP)
2. Energy efficiency (power plants)
3. Renewable energy (fuels & heat)
4. Renewable energy (electricity)
5. Fuel shift (fossil)
6. Enabling technologies (e.g. storage and grids)
7. CCS/CCU

The general strategy in the energy sector is to increase the **energy efficiency** of existing and new plants as much as possible (fields 1 and 2) and to exploit the **renewable energy** (RE) potential as much as possible (fields 3 and 4). The most important RE technologies in the power sector are wind energy (onshore, near-shore and offshore) and the use of bioenergy in power plants. Bioenergy may also play an important role as a fuel for heat generation. The main strategies to improve the energy efficiency of power plants are to use cogeneration (or trigeneration including cold) and to upgrade processes and components of plants.

Within a transition period of perhaps one or two decades, a fuel **shift from fossil fuels** with high carbon intensity (like coal) to fossil fuels with low carbon intensity (like natural gas) might also be an option for a decarbonisation strategy (field 5).

In the long run, there will be nearly no CO_2 budget for fossil fuel emissions in a decarbonised world. This implies that in those cases where the RE potentials are not in abundance or are economically or ecologically (e.g. in regard to biomass) not viable, Carbon Capture and Storage (**CCS**) or Carbon Capture and Use (**CCU**) might supplement the options for decarbonisation in the Energy sector (field 7).

The remaining field number 6 “**Enabling technologies**” clusters those elements of a decarbonised energy system, that do not reduce carbon emissions directly, but enable e.g. the match of energy production and consumption by providing storage, grids, control (e.g. “smart meters”) and so on.

6.1.1.3 Selected Findings

In the following, the key findings are outlined for each Field of Activity:

8. Energy efficiency (CHP)

Combined Heat and Power (CHP) is an important, versatile and mature technology for reducing primary energy demand and greenhouse gas emissions. There are several technological options from conventional gas- and steam turbines over combustion and Stirling engines and fuel cells in different sizes and in central or decentralised application. Nevertheless, this might only be a sound option in the mid-term (up to 2030 or 2040), because at least in a more or less fully decarbonised energy system there is too little room for CO_2 emissions from fossil fuel power production. The limited (sustainable) biomass potential possibly may rather need to be used in the industrial sector (as a feedstock and for high-temperature processes) or in the transport sector. Furthermore, CHP plants need to increasingly compete with electricity from fluctuating RE sources (wind and PV), especially if they are operating in a heat-orientated mode. That’s why the ability to operate in a flexible manner – by providing thermal storage – is one prerequisite for CHP to play an important role over the next few decades.

9. Energy efficiency (power plants)

Retrofitting or replacing existing plants by new power stations with higher efficiency (but the same energy carrier) is a short-term option that was a common measure to save energy and reduce GHG emissions over the last decades. The two new coal-fired power plants that became fully operational in 2015 on the Maasvlakte are prominent examples for this strategy. But taking into account the long life times of these types of plants of typically at least 30 years and often times more than 40 years, they may represent an incompatible lock-in strategy with regard to climate protection, at least if CCS technology is not retrofitted. And even in the short term those plants compete with increasing electricity supply from fluctuating renewable energy sources. This increasing supply requires highly flexible operation in the rest of the electricity system. This will likely reduce the coal-fired power plant’s full load hours and compromise their profitability.

10. Renewable energy (fuels & heat)

Today bioenergy - in particular solid biomass - is the dominating renewable energy carrier in the heat or fuel sector. But as mentioned above, its (sustainable) potential is limited and bioenergy therefor should be used mainly in applications where it can’t easily be substituted by alternative low-carbon energy carriers. Especially liquid fuels from rainforests plantations (e.g. palm oil) also lack public acceptance. Today, hydrogen or synthetic methane produced from renewable electricity (*Power-to-Gas*) is economically not viable, but this seems to be a promising strategy in the long run. Cheap and abundant surplus power from renewable sources and CO_2 as a source for the methanisation process is a prerequisite for this path.

11. Renewable energy (electricity)

With regard to potentials and specific costs, wind energy in all three categories - onshore, nearshore and offshore - is the most important technology in this field. While the basic conditions in terms of wind speed are good in the port area, free undisturbed inflow and free areas are further prerequisites that may limit the use of wind energy. Photovoltaic has great development potential, but needs free, unshaded areas and a sufficient structural design (statics) for building integrated PV on roofs or facades. Both wind and PV energy are more or less emission-free but need back-up or storage technologies due to their fluctuating power production.

12. Fuel shift (fossil)

As mentioned above, fuel shift (natural gas as substitute for oil or coal) can only be an intermediate strategy. Especially the change from coal to natural gas leads to relatively high CO_2 emission reductions in the short-term and also reduces pollutants like dust, mercury or sulphur. The switch towards gas might be sustainable in the long-run, if natural gas can later be substituted by renewable synthetic gas (hydrogen, methane...).

13. Enabling technologies (e.g. storage and grids)

Examples for enabling technologies are the delivery of balancing power by clustered virtual CHP power plants (with thermal storage management), power and heat storages (in the form of batteries, tanks, aquifers and other types of storage) or smart meters. All these technologies can takes over the provision of system services and help to integrate RE into the grid. The technologies are principally available, but still have potentials for cost reduction and standardisation.

14. CCS/CCU

CCS or CCU can in principle lead to deep carbon dioxide reductions, but its actual potential very much depends on a number of issues, for example the technology's capture rate, the emissions of the upstream chain and the leakage rate of the CO_2 storage site. For CCU, the time period in which CO_2 is tied to the product determines how much or if any carbon dioxide can be separated from the atmosphere. The compatibility with the overall energy system transformation can be regarded to be low for CCS-equipped fossil fuels power plants because it is an end of pipe-technology that prolongs or even increases the use of fossil fuels and its infrastructures and might create new dependencies on scarce CO_2 storage sites. Though infrastructural conditions are favourable in the port area, today CCS is still in an early development state and very costly. A complex CO_2 infrastructure (carbon capture, compression, transport, storage and monitoring) must be built up and a legal framework needs to be established. For the reuse path (CCU), sufficient quantities of renewable fuels (e.g. H_2) must be available as a starting material.

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
1	Efficiency (CHP)	Implementation of **central** and **industrial CHP**	+ (10 - 30% depending on technology and efficiency)	↗ / ↑	↗	↘	available	Expansion of heat supply grids; Readiness for flexible operation mode (by thermal storage and grid steering)	mid-term high, but competing with fluctuating RE; Energetic retrofit of building shell reduces absolute demand for CHP heat	depending on heat grids with its high fixed costs; mayby hindering efforts for efficiency	2,3,21,22	high (but sometimes worries about support of monopolistic structures)	Heat service provided by utility; no own heating system necessary; no local emissions		
2	Efficiency (CHP)	Implementation of **decentralised CHP** (including **micro-CHP**)	+ (10 - 30% depending on technology and efficiency)	↗	↗	↘	available (micro CHP in market launch)	Readiness for flexible operation mode (by thermal storage and grid steering)	high, but competing with fluctuating RE	mayby hindering efforts for efficiency	1,3,21,22	high	self-supply possible		
3	Efficiency (CHP)	Implementation of **fuel cells** (CHP)	+ / ++ (20 - 50% depending on technology and efficiency)	↑	↗	↘	in market launch	Readiness for flexible operation mode (by thermal storage and grid steering)	high, but competing with fluctuating RE	mayby hindering efforts for efficiency	1,2,21,22	high	very low noise and pollutant emissions (SO_2, NO_x)		
4	Efficiency (CHP)	Power generation from **waste heat** (ORC, Stirling, TEG...)	+ / ++ / +++ (depending on technology and efficiency)	↑	↗	↘	available (ORC / Stirling) long term (TEG)	Readiness for flexible operation mode (by thermal storage and grid steering)	high, but competing with fluctuating RE	mayby hindering efforts for efficiency	1	high (but low awaremess)	possibly less effort for cooling		

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1]	Investment costs today [2]	Investment costs maturity [3]	Operational costs today [4]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
5	Efficiency (power plants)	**Retrofitting** of existing plants	+ (10 - 15%)	→	n.a.	→	available	-	only compatible if highly flexible operation possible (short & mid-term); long-term: fossile fuels not compatible	Possibly lock-in effects if fossil fuels are used (competing with power from fluctuating RE)	6	high to low (depending e.g. on fuel)	no additional area and infrastructur e needed	In this case the technology used for retrofit is identical with the standard technology.	
6	Efficiency (power plants)	**Replacement** of existing plants by new power stations with higher efficiency but same energy carrier	+ (20 - 30%)	→	n.a.	→	available	-	only compatible if highly flexible operation possible (short & mid-term); long-term: fossile fuels not compatible	Possibly lock-in effects if fossil fuels are used (competing with power from fluctuating RE)	5	high to low (depending e.g. on fuel)	no additional area and infrastructur e needed		
7	Efficiency (power plants)	Exploitation of (low temperature) **waste heat**	+ / ++ / +++ *) (depending on technology and efficiency)	↑	↗	↘	available (ORC / Stirling) long term (TEG)	Readiness for flexible operation mode (by thermal storage and grid steering)	high, but competing with fluctuating RE	mayby hindering efforts for efficiency	1	high (but low awaremess)	possibly less effort for cooling		
8	Renewable energy (fuels & heat)	Production and storage of renewable hydrogen/methane (**Power-to-Gas**)	+++	↑	↑	↘	mid-term (2025-2035)	sufficient surplus power from renewable sources; CO2 source for methani-sation; power and gas grid; locations for storage	very high	Con-servation / expansion of gas grid (PtG path) versus expansion of power grid (electric storage path)	12, 16, 17, 18, 19, 23	unsure (low awaremess)	-	Reference technology: extraction of natural gas	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
9	Renewable energy (fuels & heat)	**solid** fuels: Biomass **co-firing**	a) ++ / +++ b) +	→	→	→	available	sufficient capacities for supply, transport and storage of biomass feedstock	high for a period of transition	Supply of sustainable biomass (incl. sustainable transport) must be guaranteed	10	high	Pushing of the local economy, if local biomass is used	Example of 10% co-firing Mitigation potential reffered to: a) 1 kWh coal as substituted fuel b) total fuel demand	
10	Renewable energy (fuels & heat)	**solid** fuels: **Biomass** (CHP) plant (wood, straw, residuals, energy crops...)	++ / +++ (depending on feedstock and upstream chain)	↗ (depending on size)	→	→	available	sufficient capacities for supply, transport and storage of biomass feedstock	medium / high, if used in energy efficient or high temperature processes; but limited biomass potentials	Supply of sustainable biomass (incl. sustainable transport) must be guaranteed	9	high	Pushing of the local economy, if regional biomass is used	Reference technology: coal	
11	Renewable energy (fuels & heat)	Fuel switch (**liquid** fuels): Use of renewable fuels (plant oil, bio diesel = FAME, bio ethanol, bio methanol, BTL = Fischer-Tropsch)	+ / ++ (depending on feedstock and upstream chain)	→ (depending on feedstock)	→	↗ / ↑ (depending on feedstock)	available	depending on the fuel and its thermo-dynamic properties a modification of the power plant / CHP motor / boiler and / or of the transport and storage infra-structure is necessary	low, because liquid renewable fuels are limited and should preferably be used in the transport sector	Supply of sustainable biomass (incl. sustainable transport) must be guaranteed		low (see e.g. discussion about palm oil)	Pushing of the local economy, if regional biomass is used	Reference technology: oil	
12	Renewable energy (fuels & heat)	Fuel switch (**gaseous** fuels): Use of renewable fuels (biogas, biomethane, hydrogen, synthetic natural gas...)	+ / ++ / +++ (depending on feedstock and upstream chain)	→ (depending on feedstock)	→	↗ / ↑ (depending on feedstock)	available		medium / high, if used in energy efficient or high temperature processes; but limited biomass potentials	Supply of sustainable biomass (incl. sustainable transport) must be guaranteed	9	low to high (depending on feedstock)	Pushing of the local economy, if regional biomass is used	Reference technology: natural gas	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
13	Renewable energy (fuels & heat)	Exploitation of **geothermal** energy for heating and cooling (with and without heat pumps)	+ (high COP, fossil power +++ (without HP or HP with renewable power)	↑	↑	↘ (HP) ↓ (without heatpump)	available	heat source: suitable geological formation necessary; ideally high temperature level heat consumer: ideally low temperature level (high COP of the heat pump)	high, if ready for flexible operation mode (by thermal storage and grid steering); but seasonally high loads in winter, if used for space heating	Risk of rising demand for fossil power, if exploitation of RE does not keeps up with rising installations of heat pumps		generally high, but: deep geothermal: risk of seismic incident	no local pollutant emissions	Reference technology: natural gas boiler	
14	Renewable energy (fuels & heat)	Exploitation of **solar** energy for heating and cooling	+++	↑ (small) ↗ (large)	↑ (small) ↗ (large)	↓	available (but large scale systems not yet standar-dised)	collector area, backup system and / or (saisonal) storage necessary; no shading of collector	high, espacially with (saisonal) storage	-	18	high	no local pollutant emissions	Reference technology: natural gas boiler	see also good pratice (large scale) examples from Denmark
15	Renewable energy (fuels & heat)	Exploitation of **ambient** heat (heat pumps)	0 (low COP, fossil power) + (high COP, fossil power +++ (HP with renewable power)	↗	↗	→ / ↘ (depending on efficiency)	available	heat source: ideally high temperature level (ambient air, water from river, sea, rain...) heat consumer: ideally low temperature level (high COP of the heat pump)	high, if ready for flexible operation mode (by thermal storage and grid steering); but seasonally high loads in winter, if used for space heating	Risk of rising demand for fossil power, if exploitation of RE does not keeps up with rising installations of heat pumps		generally high, but: air heat pumps: noise restrictions	no local pollutant emissions	Reference technology: natural gas boiler	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
16	Renewable energy (electricity)	Exploitation of **onshore wind** energy (including repowering)	+++	→	→	↓	available	free areas with high average wind speed conditions and free undisturbed inflow opportunitiy for grid connection	high	-	8, 17	generally high, but: on-site sometimes refusial because of noise and visibility	no local pollutant emissions	Reference technology GHG: national power mix costs: fossil power mix (coal, gas, oil)	
17	Renewable energy (electricity)	Exploitation of **offshore wind** energy (including repowering)	+++	↑ (offshore) ↗ (nearshore)	↗ (offshore) → (nearshore)	↓	available, but still ponderable cost reduction potential	free areas with high average wind speed conditions and free undisturbed inflow; suitable anchorage conditions on the sea bottom; possibly conflict with shipping traffic; opportunitiy for grid connection	very high (higher full load hours than onshore wind turbines)	-	8, 16, 19 (in combination with tidal turbines?)	generally high, but: nearshore sometimes refusial because of visibility	no local pollutant emissions	Reference technology GHG: national power mix today costs: fossil power mix (coal, gas, oil)	
18	Renewable energy (electricity)	Exploitation of **solar** energy (**PV**, especially roof-top and building-integrated)	+++	↗ (small) → (large)	↘	↓	available	free unshaded areas; sufficient structural design (statics) for building integrated PV (roof / facade)	high	-	8, 14 [2 in buildings sector]	high	no local pollutant emissions	Reference technology GHG: national power mix today costs: fossil power mix (coal, gas, oil)	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1]	Investment costs today [2]	Investment costs maturity [3]	Operational costs today [4]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
19	Renewable energy (electricity)	Exploitation of **ocean** energy (tidal, wave)	+++	↑	↑	↘	Pilot	free areas for underwater turbines (possibly conflict with shipping traffic) opportunitiy for net connection	high (tidal: predictable energy production)	-	17 (possibly)	high	no local pollutant emissions	Reference technology GHG: national power mix today costs: fossil power mix (coal, gas, oil)	
20	Fuel shift (fossil)	**Fuel substitution** towards lower carbon fossil fuels (e.g. from coal or oil to natural gas)	+ (natural gas vs. oil) ++ (natural gas vs. coal)	→	→	↗	available	gas infra-structure	medium / higher in case of green gases (future)	gas infra-structure	8, 12	medium	lower pollutant emissions (SO_2, NO_x, dust)	coal / fuel oil	
21	Enabling tech-nologies (e.g. storage and grids)	Expansion of **district heating** networks	+ (10 - 30% depending on technology and efficiency; up to 100% in case of RE)	↗	↗	→	available	Expansion of heat supply grids; Readiness for flexible operation mode (by thermal storage and grid steering)	medium (high temp. high (low temp. = Low-Ex -> integration of renewable low temp. heat and waste heat); Energetic retrofit of building shell reduces economic viability	high fixed costs are mayby hindering efforts for efficiency	1, 2, 4 ,7, 13, 14, 15	high (but sometimes concern about dependency of monopol structures)	Heat service provided by utility; no own heating system necessary	Reference technology: individual heat supply	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
22	Enabling tech-nologies (e.g. storage and grids)	Delivery of balancing power by clustered **virtual CHP** power plants with thermal storage management	0 (if only provision of system service) + (if additional RE can be integrated by the provision)	→	→	→	available, but still cost reduction potential	Readiness for flexible operation mode (by thermal storage and grid steering / smart grid)	very high (takes over the provision of system services and helps to integrate RE into the grid)	-	1, 2, 3, 24	high (but low awaremess)		Reference technology: Provision of system services by conventional plants	
23	Enabling tech-nologies (e.g. storage and grids)	**Power storage** (batteries and other types of storage)	0 (if only economic optimisation) + (if additional RE can be integrated)				available, but still significant cost reduction potential	Free space	very high (enables the provision of system services and helps to integrate RE into the grid)	-	8, 24	high	higher autarkie and / or security of supply		
24	Enabling technologie s (e.g. storage and grids)	**Heat/cold storage**	0 (if only economic optimisation) + (if additional RE can be integrated)				available, but still developing and cost reduction potential (e.g. saisonal and latent heat storage)	Free space; suitable geologic formation (e.g. for aquifer storage)	very high (enables the provision of system services and helps to integrate RE into the grid)	-	8, 23	high	higher autarkie and / or security of supply		
25	Enabling technologie s (e.g. storage and grids)	**Smart meter** rollout and smart grid infrastructure	0 (if only economic optimisation) + (if additional RE can be integrated and / or energy efficiency potentials be realised)				available, but still developing and cost reduction potential (e.g. standardi-sation)	Incentives or obligation for the imple-mentation	high	-	8, 23	high	higher autarkie and / or security of supply		

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Technological maturity	Infra-structure and framework require-ments	Com-patibility with overall energy system transfor-mation	Reversibility / path de-pendency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
26	CCS/CCU	Carbon Capture and Storage (**CCS**)	+ / ++ / +++ (depending on technology, capture rate, upstream chain and leakage rate of storage)	↑	↑	↗ / → (depending on develop-ment of technology and energy / CO2 prices)	Pilot	Build-up of a complete CO2 infra-structure (carbon capture, com-pression, transport, storage and monitoring) Develop-ment of a legal framework; Existance of suitable storages	low end of pipe-technology; prolongs and increases use of fossil fuel and its infra-structures; creates new dependen-cies on CO2 storages	high risk of lock-in effects (see com-patability)	27	low	-	Reference technology: coal power plant without CCS	
27	CCS/CCU	Carbon Capture and Usage (**CCU**)	0 / + / ++ / +++ (depending on technology / process / product, capture rate, upstream chain and storage period)	↑	↑	↑ / ↗ / → (depending on process / product and developmen t of technology)	Pilot	Build-up of a CO2 infra-structure (carbon capture, com-pression, transport) Sufficient renewable fuels (H2) as starting material; gas / H2 infra-structure	medium end of pipe-technology; possibly prolongs and increases use of fossil fuel and its infra-structures; GHG mitigation potential unsure and higly depending on particular process / product	risk of lock-in effects (see com-patability)	26	unsure (low awaremess)	-		

1) Mitigation potential relative to average technology in the stock
   0 = net/zero savings vs. standard technology
   + = small (up to 33% savings vs. standard technology)
   ++ = medium (33 to 66% savings)
   +++ = high (66 up to 100% savings)

2) Investment costs today relative to standard technology
3) Investment costs at status of maturity of the technology vs. standard and expected date of maturity
4) Operational costs of current technology vs. standard technology at moderate real energy price increase

↗ / ↑ ... higher than standard technology by more than 33% / 66%
→ ... equivalent standard (+- 33%)
↘ / ↓ ... lower than standard technology by more than 33% / 66%

6.1.2 Crude oil refining and transport fuel supply

6.1.2.1 Introduction

This sector is the second largest emitter of CO_2 in the port area (see Figure A1). However, if downstream emissions from burning of fuels are regarded, it is by far the most important sector: 58 million tons of crude oil can be processed in one year at the port – annual potential downstream CO_2 emissions equal about 180 million tons.

So on the one hand the refinery sector has to mitigate GHG emissions in processing itself. On the other hand decarbonisation of the transport sector requires a shift in the supply of fuels from today's oil based fuels to low or zero carbon fuels.

The role of refineries has another dimension: the supply of material stock for the petrochemical industry. Therefore, the cluster at the Port of Rotterdam can be described as an optimized system providing fuels and stock.

There are at least two other trends and developments which are a challenge to the sector and require adaption:

First, there are increasingly strict legal standards for fuels in regard to sulphur content. Second, the ratio between gasoline and middle distillate demand will probably shift further to middle distillate – as it has done since the 1980s. Both developments require adaption of the production stock (and of crude oil supply) in the mid-term but can lead to stranded investments if long-term decarbonisation of the whole transport sector is not regarded at the same time.

6.1.2.2 Fields of Activities

Five key strategies have been identified for the sector, at least the first four of them also have a downstream dimension, which needs to be regarded when thinking about decarbonisation of the sector and its role within a decarbonized energy system.

1. Energy efficiency
2. Fuel shift (fossil)
3. Electrification
4. Renewable energy
5. CCS/CCU

Energy efficiency plays a role in the operation of vehicles, planes etc. and thus has consequences for the (physical) size of the oil products market. At the same time, energy losses accrue in the refinery sector as it transforms crude oil to products. Most of these energy losses are equivalent to the burning of fuels and thus lead to direct CO_2 emissions in the sector (and emissions are included in the data shown in Figure A1) and energy efficiency within the refining sector helps to save resources and bring down the sector's CO_2 emissions.

Fossil fuel shift is a further option. Oil's specific emissions are higher than those of natural gas because of the higher relative carbon content compared to hydrogen. Again, the shift can be addressed ***within*** the sector and ***downstream*** (in the transport market).

Electrification is probably the most important option in long-term decarbonisation as it has the greatest potentials in the supply of low/zero carbon energy. Electric energy can provide directly almost all energy needs within a refinery (incl. heat and steam supply). The (downstream) electrification of the transport sector is more complex. There are different ways of direct and indirect electrification, including batteries, fuel cells and synthetic fuels.

Another **renewable energy** form is biomass, which already plays a role in fuel supply today. Second generation biofuels (enriched with renewable hydrogen) are a possible way of using biomass more efficiently. Other forms of renewable energy like geothermal energy can provide heat or even steam within the refinery sector and are described in the section above.

Other emissions are due to process requirements (so called process-related emissions). The most prominent example is the operation of FCC units. The catalyst in this process is polluted by the formation of petcoke. To regenerate the expensive catalyst, the coke has to be burned, leading to direct GHG emissions. **Carbon capture** and storage or usage of CO_2 (**CCS/CCU**) is an end-of-the pipe technology that can be applied to the CO_2 rich flue gas of FCC units.

6.1.2.3 Selected Findings

1. Energy efficiency

There are a number of energy efficiency strategies that can be applied to the existing refinery stock. However, the ones which have not been applied yet are mostly only profitable if they can be implemented within a general retrofit, requiring mid-term pay-back. In a shrinking market, this is a challenge.

2. Fuel shift (fossil)

Fossil fuel shift is often regarded as a bridge towards a low-carbon energy system. The role of natural gas in the refinery sector itself is probably limited. Natural gas use has gained importance due to rising hydrogen need but the fuel demand of the refinery sector can be supplied more economically with oil-based LPG and refinery gas, which occur as a by-product in the processing of crude oil anyway. Most refineries have already shifted fuel supply for process heat and steam from carbon rich heavy fuel oil (emission factor of 78g CO_2/MJ) to refinery gas with a lower emission factor of 65 g CO_2/MJ.

In the transport sector, natural gas – also in liquefied form (LNG) – could gain a role in the decarbonisation development if efficiency of gas motors and the tank system can be further improved. In the long-term, synthetic methane could replace natural gas, relying on an established LNG drivetrain and supply infrastructure.

3. Electrification

Battery electric vehicles (BEV) as well as fuel cell vehicles (FCV) are the most promising energy efficient ways to electrify and decarbonise passenger road transport. However, the supply of this fuel can be organized in a more decentralized way than today's fuel supply. So the port area has only limited opportunities to profit from this trend. Indirect electrification via synthetic hydrocarbon fuel production could play a prominent complementary role in the long term to supply road freight and vessels as well as aviation. The respective Fischer-Tropsch processes are very capital intensive and can only partly profit from existing assets at the port (e.g. hydrocracker). On the other hand, they can be integrated into the existing petro-chemical cluster (see below).

Another way of electrification is power-to-heat (PtH), which can be applied to meet the refinery's heat and steam demand. If used as a measure of demand-side-management in the electricity market, PtH alone cannot ensure full decarbonisation but has to be complemented with temporally flexible production systems, heat storage systems and/or a fuel-based backup system.

If integration of crude oil refining in a carbon cycle is successful in the long term, PtH could play a decisive role in fully decarbonising the sector.

4. Renewable energy

Biomass could be the sustainable source of carbon in the future fuel market. All decarbonisation scenarios are based on the assumption that hydrocarbons will still be needed in a decarbonised future energy system to some extent, at least to fuel aviation or vessels.

The only alternative is capturing CO_2 from the air, a very inefficient option in regard to electricity demand.

5. CCS/CCU

CCS/CCU could gain a role in FCC operation, steam reforming and fossil fuel use within the refinery – as well as cogeneration of electricity and heat in (refinery) power plants (see above). Carbon capture *and storage* will probably only be implemented in the context of the operation of coal-fired power plants with a high CO_2 load, justifying the high initial investment to build pipelines and develop the storage site(s). In most of the potential cases for CO_2 usage, great amounts of hydrogen are needed to bond the carbon in a hydrocarbon product. Fuels based on CCU are fossil fuels with respective emissions (unless biomass is used). Carbon neutral CCU is only achieved if the carbon can be kept within a cycle of product use and carbon recycling.

The most efficient way of applying carbon capture technology in the refining sector are FCC units and steam reforming. In the first case there is a quite high proportion of CO_2 already in the flue gas (of catalyst regeneration) – higher than in other refinery flue gases. Finally, steam reforming provides a relatively pure CO_2 stream which can be fed into a CO_2 pipeline quite easily. Another option to cope with the carbon content in natural gas is to run steam reformers in a CO mode, i.e. to produce less hydrogen per unit of natural gas feedstock but to produce CO instead of CO_2, which can be used as a synthesis gas in the petrochemical industry.

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today[2)]	Investment costs maturity[3)]	Operational costs today[4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
1	Energy efficiency	Crude distillation unit upgrades (BAT)	+	not applicable		↘	available		medium to high			very high		standard CDU unit	the investment is a standard retrofit; additional investment costs appear if technical lifetime of the existing production stock has not expired yet
2	Energy efficiency	Vacuum distillation unit design improvements (BAT)	+	not applicable		↘	available		medium to high			very high		standard VDU unit	
3	Energy efficiency	Fluidized-bed catalytic cracker (FCC) design improvements (BAT)	+	not applicable		↘	available		medium to high		17	very high		standard FCC unit	
4	Energy efficiency	Hydrocracker design improvements (BAT)	+	not applicable		↘	available		medium to high			very high		standard HC unit	
5	Energy efficiency	Optimisation of fouling control (refineries)	+	→		↘	available					very high		total refinery	
6	Energy efficiency	Optimisation of drivers (motors, pumps, compressors, fans (BAT))	+	→		↘	available		high			very high		all drivers in the refinery	
7	Energy efficiency	Optimisation of process heaters and furnaces (BAT)	+	→		↘	available		high			very high		all process heaters and furnaces in the refinery	
8	Energy efficiency	Optimisation of waste heat recovery	+	depends on process		0	available	heat grid	high		13	very high		total refinery	Excess heat from flue gases can be used to preheat fuel in furnaces.
9	Energy efficiency	H2 recovery and optimisation	+				available	hydrogen grid	high			very high		total refinery	
10	Fuel shift (fossil)	Use of LNG as fuel	depending on system boundary			depending on existing supply networks, fuel taxation and drivetrain costs	available	Expand LNG petrol station network, natural gas network can be used, if natural gas is liquified at petrol stations.	mid	LNG introduction can hinder elctrification of HDV transport	15, 16	mid	Less air pollutants in the use phase		

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
11	Fuel shift (fossil)	Fuel switch from oil to natural gas (in refineries)	depending on oil reference (heayy fuel oil (+) or LPG (0))	→	→	↗	available	-	mid		7	high	Less air pollutants	total refinery	
12	Electri-fication	Use of hydrogen from water electrolysis as fuel feedstock instead of steam methane reforming (SMR)	+	depending on di-mensioning (expected full load hours)	depending on di-mensioning (expected full load hours)	↗	available, but still significant cost reduction potential	hydrogen grid	high, but competing with direct use of hydrogen as a fuel in fuel cells			high	electricity grid stabilization	hydrogen production	competing with PtH (times with low electricity prices)
13	Electri-fication	Use of electrical boilers and furnaces (power to heat)	+++	→/↘/↓	→/↘/↓	↗	available, but still significant cost reduction potential	market evolvement	high to very high, especially if used as DSM (with higher shares inducing higher need to expand RE)			very high	Less air pollutants, electricity grid stabilization	all process heaters and furnaces in the refinery	low additional investment costs (but redundant), partly even lower invest if not redundant, but then very high (base load) operational costs.
14	Electri-fication	Providing new fuels: hydrogen and methanol	depending on system boundary	depending on system boundary	depending on system boundary	↗	drivetrains not mature	petrol station network, new fleets	very high (renewable H2 can be produced in DSM mode)			mid to high	electricity grid stabilization		
15	Electri-fication	Providing conventional fuels based on new processes (methane, methanol-to-gasoline, Fischer-Tropsch fuels)	depending on system boundary	↑	↑	↑	Pilot	CO2 pipelines, hydrogen grid	high	possible lock-in (hindering direct electri-fication of drivetrains)	16, 18	mid to high			

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
16	Renewable energy	Use of biomass as feedstock for synfuels	depending on system boundary	↑	↗	↗	Pilot	biomass logistics (partly existing)	medium to high, biomass use competing with other biomass use	acceptance for biomass usage required	15, 18	low			
17	CCS/CCU	Carbon capture on FCC stacks	++	↗	↗	↗	Pilot	CO2 storage or usage infrastructure	mid	possible lock-in	3	depending on CO2 use (high) or storage (mid)		FCC unit	In an FCC, pet coke is produced, which coates the catalyst. To regenerate the catalyst, the coke is burned. As this is process-related, fuel shift is not viable. CC of flue gas is remaining option for deep decarb. Instead of FCC, hydro-cracking could be applied, but product yields are different.
18	CCS/CCU	Use of "waste" CO2 from carbon capture as feedstock for synfuels	depending on system boundary				available	CO2 pipeline	high	possible lock-in	15, 16	high			

1) Mitigation potential relative to average technology in the stock
0 = net/zero savings vs. standard technology
+ = small (up to 33% savings vs. standard technology)
++ = medium (33 to 66% savings)
+++ = high (66 up to 100% savings)

2) Investment costs today relative to standard technology

3) Investment costs at status of maturity of the technology vs. standard and expected date of maturity

4) Operational costs of current technology vs. standard technology at moderate real energy price increase

↗ / ↑ ... higher than standard technology by more than 33% / 66%
→ ... equivalent standard (+/- 33%)
↘ / ↓ ... lower than standard technology by more than 33% / 66%

6.1.3 Petrochemical sector

6.1.3.1 Introduction

The petrochemical sector is the third largest emitter within the port area. Equivalent to the refinery sector, its products are hydrocarbons. So the petrochemical sector is a direct emitter – needing energy to process feedstock to (intermediate) products – and delivers products which are carriers of carbon and are therefore potential downstream CO_2 emitters. Products like solvents based on hydrocarbons diffuse during the use phase and degrade to CO_2 in the atmosphere, whereas plastics are fired in waste treatment plants after the use phase, emitting CO_2. The mitigation of diffuse CO_2 emissions requires a change of material (towards materials not based on carbon) or a sustainable carbon feedstock (CO_2 from biomass or the atmosphere) whereas carbon in waste can be provided as a feedstock again and thus be kept in a cycle.

The bulk of direct CO_2 emissions of the petrochemical sector can be attributed to steam cracking. In the process of steam cracking, a share of the original mineral oil-based feedstock is burned to feed process heat into the chemical process of cracking long C_nH_{2n+2} molecules to shorter C_nH_{2n} molecules like C_2H_4 (ethylene), C_3H_6 (propylene), C_{4+} molecules or aromatic rings.

Most other petrochemical processes use heat or steam provided by an external source, i.e. boilers, furnaces, a steam grid (supplied by CHP plants) or surplus heat of other processes. So most of the other GHG emissions in the petrochemical sector are indirect emissions, which can be avoided or reduced by alternative sources of heat.

6.1.3.2 Fields of Activities

1. Energy efficiency
2. Fuel shift (fossil)
3. Renewable energy
4. Feed shift (fossil)
5. Feed shift (renewable)
6. Electrification
7. CCS/CCU

Energy efficiency includes a number of strategies which are process-specific (steam cracking) as well as some other strategies which are cross-sectional (e.g. heat integration).

Fossil fuel shift is not a promising decarbonisation option for the sector (and will thus not be discussed below). The use of waste as a fuel is already standard today. Instead of firing material utilisation, it is favourable to keep the fossil carbon within the product cycle.

Renewable energy as a fuel or heat source could be biomass – or geothermal heat (see above)

Fossil feedstock shift (from mineral oil to natural gas) is no (direct) CO_2 mitigation option but rather an alternative way of producing dedicated hydrocarbons via methanol once transport fuel supply by crude oil processing fades out.

Feed shift to non-fossil (**renewable**) carbon feedstock relies on biomass – or on CO_2 captured technically from the air by electricity-intensive air separation processes.

Electrification of the petrochemical industry includes different options: Direct electrification of heat supply, indirect electrification via syngas fuel use, the shift to electro-chemistry and hydrogen feed supply by water electrolysis.

The **CCS/CCU** option also has two dimensions in the sector: First, post-combustion carbon capture from flue gas of the steam cracker can greatly reduce the sector's direct CO_2 emissions. Second, the sector can be a sink for CO_2 emissions of other sectors by integrating fossil carbon into hydrocarbon products.

6.1.3.3 Selected Findings

Many **energy efficiency** strategies displayed in the table below are required by the regulatory body as "best available technology" when approving new investments or retrofit of the production stock. Investments in an advanced steam cracker technology is not standard today, but if the steam cracker should be reinvested in the mid-term, a more energy efficient technology could save a considerable amount of CO_2 emissions and resources.

Waste heat or steam can be most simply integrated in a nearby process with similar conditions (temperature level/pressure). Recuperators are used to keep the flows of the different processes physically apart and heat or steam grids are used to exchange heat between sites. They have to be operated at one (optimized) temperature and pressure level, so the waste heat streams are aggregated. Processes can be optimized in regard to the available waste heat. If operated at lower temperatures, potential heat sinks can be connected to a heat grid more easily because waste heat is often available only at a level of about 100°C.

Feed shift to non-fossil (**renewable**) carbon feedstock is a very important long-term option to reduce the extraction of fossil carbon feedstock. Extraction of fossil feedstock bears the risk that the fossil carbon cannot be kept in a product cycle. In cases where the hydrocarbon product degrades to CO_2 (solvents), biomass or carbon from air separation are the only options to carbon-neutral production and use of the product. Biomass being a scarce resource and air separation being a very energy-intensive alternative, solvents should be developed which are either derived directly from biomass (bio-chemicals) or which require no hydrocarbons.

Electrification is a very low investment regarding steam supply but if a fuel-based backup is needed, it is a redundant (additional) investment. Today, running electrical boilers as a base load is too expensive. The challenge of the mid-term future is to balance out renewable electricity production and electricity demand using DSM options like PtH, but in the long term, base load operation of electrical boilers (and the respective capacities of electricity generation) could turn out as the more economic solution compared to the use of storable synfuels – with the implication that not the whole amount of disposable renewable electricity can be integrated into the market. The production of base chemicals requires a great (net) amount of hydrogen, which can be supplied by water electrolysis.

Water electrolysis competes with steam reforming, especially in cases where carbon feedstock is needed anyway (**CCU**) or if there is a CO_2 storage system available (**CCS**). In the latter case, carbon capture at the steam cracker is also an obvious option. However, the existing cracker at Moerdijk is around 50 km away from the coal power plants at Maasvlakte, requiring a grid extension. So CCS offers a broad range for CO_2 mitigation in several sectors, but mitigation relies consequently on only one main strategy, which is associated with several risks and uncertainties. The risks and uncertainties of relying on CCS are described in more detail in the box "Coal use in power plants and Carbon Capture and Storage" in Section 3.4.

Another way of **CCU** is the use of waste plastic or – more generally – waste hydrocarbon products as a carbon resource. Gasification and pyrolysis of plastic waste are technical solutions which have already been tested under pilot conditions. In some cases waste polymer plastics can be recycled to the respective monomers (building blocks), which could be a more efficient solution in the future than destroying the molecular structure of the hydrocarbons and building it up again based on the atomic structure.

As soon as the hydrocarbon stock can be kept stable (needing no additional carbon), no additional fossil carbon would need to be added into the system and the industrial metabolism could rely on the existing "waste" feedstock. A circular system like this is sketched in the CYC scenario, specifically in the box "Waste-based chemicals production" in Section 3.6.

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today[2)]	Investment costs maturity[3)]	Operational costs today[4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
1	Energy efficiency	Combined heat and power (CHP)	0 - +	depending on electricity/heat ratio and grid length	depending on electricity/heat ratio and grid length	↗	available	heat grid	mid-term high, but competing with fluctuating RE; energy efficiency reduces absolute demand for CHP heat	possible lock-in	6, 20	high	electricity grid stabilization	all process heaters and furnaces in the sector	
2	Energy efficiency	Integration of gas turbines with cracking furnace (steam cracking)	+	→	→	↘	available, but still significant cost reduction potential	-	high	possible lock-in crowding out other options to produce olefins)		high		steam cracker	
3	Energy efficiency	Use of advanced steam crackers (high temperature cracking or catalytic cracking)	+	↗	→	↘	available, but still significant cost reduction potential	-	high	possible lock-in crowding out other options to produce olefins)		high		steam cracker	
4	Energy efficiency	Use of catalytic crackers in steam cracking (new invest)	+	↗	→	↘	available, but still significant cost reduction potential	-	high	possible lock-in crowding out other options to produce olefins)		high		steam cracker	
5	Energy efficiency	Optimisation of insulation				↘ / ↓	available	-	very high			very high		total sector	
6	Energy efficiency	Waste heat recovery				↘ / →	available	heat grid to connect sources and sinks	very high		1	high		total sector	
7	Energy efficiency	Optimisation of process control		→	→	→	available	-	very high			very high		total sector	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1]	Investment costs today [2]	Investment costs maturity [3]	Operational costs today [4]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
8	Energy efficiency	Use of membrane technology instead of distillation	up to +++	n.a.	n.a.	↘	Pilot / R&D	-	very high			very high	(Less air pollutants)	single process	
9	Energy efficiency	Use of improved (still-to-be developed) catalysts	+ - ++	n.a.	n.a.	n.a.	R&D	-	neutral					single process	
10	Fuel shift (fossil)	Use of waste as fuel	0				available	waste logistics	high in the midterm			mid		total sector	
11	Feed shift (fossil)	Methan-to-olefins	0	↗		↗	available, but still cost reduction potential	-	medium	possible lock-in in the very long run		mid		olefin production	
12	Feed shift (renewable)	Bioprocessing (e.g. use of bioreactors or fermentors)		n.a	n.a	n.a	Pilot / R&D	biomass logistics (partly existing)	very high	acceptance for biomass usage required		mid to high(depending on product)			
13	Feed shift (renewable)	Methanol-to-olefins	depending on methanol chain and system boundary	↗		n.a	available	-	high	relies on great renewable electricity extension		mid		olefin production	
14	Feed shift (renewable)	Methanol-to-aromatics	depending on methanol chain and system boundary	↗		n.a	available	-	high	relies on great renewable electricity extension		mid		aromatics production	
15	Feed shift (renewable)	Lignin based aromatics production	depending on system boundary	↑	n.a.	↗	Pilot / R&D	biomass logistics (partly existing)	high, but biomass use competion	acceptance for biomass usage required		mid		aromatics production	
16	Feed shift (renewable)	Bioethanol based aromatic production	depending on system boundary	↑	n.a.	↗	Pilot / R&D	biomass logistics (partly existing)	high, but biomass use competion	acceptance for biomass usage required		mid		aromatics production	
17	Feed shift (renewable)	Bioethanol-to-olefins	depending on system boundary	↑	n.a.	↑	Pilot / R&D	biomass logistics (partly existing)	high, but biomass use competion	acceptance for biomass usage required		mid		olefin production	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
18	Feed shift (renewable)	Use of biomass as feedstock (oxo-alcohols)	depending on system boundary	→	→	0/↗	available	biomass logistics (partly existing)	high, but biomass use competion	acceptance for biomass usage required		mid		oxo-alcohols production	
19	Electri-fication	Use renewable energy hydrogen as feedstock instead of steam reforming	up to +++	depending on di-mensioning (expected full load hours)	depending on di-mensioning (expected full load hours)	↗	available, but still significant cost reduction potential	(hydrogen grid)	high, but hydrogen use competing with hydrogen fuel supply (fuel cells)			high	electricity grid stabilization	hydrogen supply	
20	Electri-fication	Use of power to heat for steam production	up to +++	↘	↘	depending on full load hours and flexibility of heat sink	available	back-up needed based on a storagable energy carrier	very high			high		steam supply	
21	Electri-fication	Use of synthetical methane as fuel	up to +++	→	→	↑	Pilot	-	very high			mid		fuel use in the sector	
22	Renewable energy	Use of biomass as fuel	depending on feedstock	→	→	↗	available	biomass logistics (partly existing)	mid, competing with other biomass use			low		fuel use in the sector, incl. upstream	
23	CCS/CCU	Use of recycled plastic as feedstock (pyrolysis etc.)	depending on system boundary	↗	↗	↘	Pilot / R&D	waste logistics	very high			high			
24	CCS/CCU	Use of carbon capture in steam cracking (post combustion)	+++	↗	↗	↗	Pilot	CO_2 pipeline	mid-high	possible lock-in if depending on storage	2-4	depending on CO2 use (high) or storage (mid)		steam cracker	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
25	CCS/CCU	Use of carbon capture and use (CO2 of steam reforming)	+ (compared to CCS because of leakage rates)	depends on CO2 use	depends on CO2 use	depends on CO2 use	available	CO_2 pipeline	mid, steam reforming competing with H2O hydrogen supply			high			steam reformers can be operated in an CO mode producing CO instead of CO2 but with lower hydrogen yields
26	CCS/CCU	Use of CO2 from carbon capture as feedstock to produce synthesis gas (CO/CO2)	depending on source (kind of flue gas) and on the reference process	n.a.	n.a.	n.a.	Pilot	CO_2 pipeline	high		11,13,14	high			

1) Mitigation potential relative to average technology in the stock
   0 = net/zero savings vs. standard technology
   + = small (up to 33% savings vs. standard technology)
   ++ = medium (33 to 66% savings)
   +++ = high (66 up to 100% savings)
2) Investment costs today relative to standard technology
3) Investment costs at status of maturity of the technology vs. standard and expected date of maturity
4) Operational costs of current technology vs. standard technology at moderate real energy price increase

↗ / ↑ ... higher than standard technology by more than 33% / 66%
→ ... equivalent standard (+/- 33%)
↘ / ↓ ... lower than standard technology by more than 33% / 66%

6.1.4 Building Sector

6.1.4.1 Introduction

As Figure A1 shows, the building sector with its CO_2 emissions of about one megaton in the year 2015 (3 % of total port area emissions) is of relatively little relevance. Nevertheless, the energetic refurbishment of building shells and building services offer potential to reduce GHG emissions in a range of 30 to 80% - depending on the energy performance standard of the existing buildings.

Energy demand and (direct as well as indirect) CO_2 emissions in the building sector mainly stem from the functions heating, cooling, ventilation and lighting of buildings. Further relevant sources for emissions are the power consumption for office equipment as well as for information and communications technology (ITC). Heat is mostly provided by fossil fuels or by waste heat (industrial or CHP provided by district heating). Electricity can be assumed to come to a large extent from local production in the port area with its generation mix of coal, biomass, natural gas and - to a small extent - wind energy.

6.1.4.2 Fields of Activities

The following "Fields of Activities" can be identified in the Building sector:

1. Energy efficiency (buildings)
6. Energy efficiency (technical systems)
7. Renewable energy (fuels & heat)
8. Renewable energy (electricity)
9. Integrated concepts

The typical emission reduction strategy in the building sector is to **reduce** the **energy demand** of existing and new buildings as far as possible (fields 1 and 2) and to cover the residual demand by **renewable energy** (RE) to the greatest possible extent (fields 3 and 4).

Thermal insulation of building envelopes (walls, roofs and floors), the retrofit of windows (triple-glazing) and the reduction of thermal bridges are the key elements in the field of building (shell) efficiency (field 1). The efficiency of technical systems (field 2) can be improved by optimising or replacing heating, hot water, cooling and ventilation systems or by installing heat recovery units. Further optimisation potentials are in lighting, drives (pumps, motors and fans), building automation (e.g. time and presence control, adaptive ventilation with CO_2 sensor) and office equipment / ICT (PC, server, printer, photocopier, router, beamer...).

The most important RE source in the building sector, that can be used on-site, is solar energy and geothermal and ambient heat. Solar energy can be used on roofs or building integrated (e.g. in facades or shading systems) to produce heat (using solar collectors) or electricity (using photovoltaic cells / PV). Near-surface geothermal heat and ambient heat is usually lifted to a higher temperature level by electric pumps or gas heat pumps, whereas deep geothermal heat can be used directly for heating or hot water production. Furthermore, fossil energy carrier can basically be substituted by solid, liquid or gaseous biomass.

Some technologies like heat pumps or free cooling only work efficiently and economically in buildings with low specific heating or cooling demand and with low supply temperatures. That's why *integrated concepts* (field 5) play an important role to use synergy effects and to optimally exploit the available renewable energy potentials.

6.1.4.3 Selected Findings

In the following, the key findings are outlined for each Field of Activity:

2. Energy efficiency (buildings)

The energy efficiency technologies in the field of building shells are mature, well-demonstrated and - if refurbishment is necessary anyway - economically viable. The combination of thermal insulation, reduction of thermal bridges and ventilation losses can cut both energy demand and CO_2 emissions by 50 to 80%. Those measures should be realised together with concepts for mechanical ventilation with heat (or cold) recovery to avoid the risk of mildew and to obtain higher comfort and better working conditions for inhabitants and employees. If the refurbishment of roofs is joined with the installation of PV cells or solar thermal collectors (or - for shaded areas - with rooftop greening), synergies can be exploited.

10. Energy efficiency (technical systems)

Usually there is great potential for optimisation and retrofitting of heating / cooling and hot water systems. This includes not only the generation, distribution and storage of heat and cold, but also the installation of heat recovery systems for showers or the reduction of hot water demand by water-saving armatures. Heat exchangers in mechanical ventilation systems can reduce the ventilation losses of buildings by 80 to 90 %. Decentralised Combined Heat and Power (CHP) - in the form of combustion and Stirling engines or fuel cells - is a further efficiency technology for reducing primary energy demand and GHG emissions. Fuels cells are still costly and in an early phase of market introduction, but promise high electric efficiency and cost reduction potential.

11. Renewable energy (fuels & heat)

Today bioenergy - in particular solid biomass - is the dominating renewable energy carrier in the heat or fuel sector. But as mentioned above, its (sustainable) potential is limited and bioenergy therefor should be used mainly in applications where it can't easily be substituted by alternative low-carbon energy carriers. Especially liquid fuels from rainforests plantations (e.g. palm oil) also lack public acceptance. Today, hydrogen or synthetic methane produced from renewable electricity (*Power-to-Gas*) is economically not viable, but this seems to be a promising strategy in the long run. Cheap and abundant surplus power from renewable sources and CO_2 as a source for the methanisation process is a prerequisite for this path. In contrast to bioenergy, the renewable sources solar, geothermal and ambient heat can be harvested directly on or nearby the building. For the use of solar heat, sufficient and unshaded collector areas, a backup system and an (ideally seasonal) storage is necessary. Heat pumps can utilise low-temperature (LowEx) heat from the ground, from ambient air or from water of rivers, the sea, rain and so on. They are compatible to a future energy system if they work on a low temperature level (high COP[21] of the heat pump) and are able to operate in a flexible mode (by using thermal storage). Free cooling (natural cooling) is an example for a renewable cooling option with high energy saving potential compared to conventional cooling devices. A low cooling load of the building and a natural heat sink are prerequisites for this technology.

12. Renewable energy (electricity)

Electricity from photovoltaic systems is more or less emission-free and the only relevant renewable power technology in the context of buildings. There is still great development potential, but free unshaded areas and a sufficient structural design (statics) for building-integrated PV on roofs or facades are needed. To increase the share of self-consumption of the fluctuating PV electricity generation, batteries become increasingly more relevant. Customer generation from PV is already often cheaper than the final consumer's tariff for grid electricity and both PV and battery systems still have further potential for cost reductions.

13. Integrated concepts

Integrated building concepts and holistic planning processes are essential to use synergy effects, to exploit the renewable energy potentials and to ultimately achieve strong reductions in primary energy demand and CO_2 emissions of between 80 and 95%.With this approach it will be possible to implement zero-energy and plus-energy building standards at low life-cycle costs. Integrated concepts are initially applied in new buildings and later – and as far as possible – also for the refurbishment of existing buildings. Beyond that, an energy-sensitive urban and quarter development allows for optimised infrastructures e.g. for common use of local district heating or cooling, storage for power, heat and cold, cascade use of waste heat or Low-Ex-Systems. Solar architecture can help to tap the full potential of solar heat and power.

[21] COP: Coefficient of Performance

	FIELD of ACTIVITY	**STRATEGY**	Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infrastructure and framework requirements	Compatib. with overall energy system transfor-mation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
1	Dissemination (advice & support)	Networking, performing of road shows, supply with information materials (brochures etc.), support for receiving	Strategy is too general in nature to assess these categories												
2	Efficiency (buildings)	**Thermal insulation** of building envelope (walls, roof and floor) and reduction of thermal bridges	++ / +++ (depending on standard of existing buildings)	→ / ↗	→	↘	available	enough space for insulation of outer facades; concepts for (mechani-cal) ventilation	high, especially for Low-Ex and renewable energy heat supply systems	ressource aspects of insulation material have to be considered	3, 4, 5, 6 [18 in buildings sector]	medium to high	higher comfort (less draught, higher surface temperatures of walls); less risk of mildew	Reference: Refurbish-ment without energy measures	use of synergy effects possible if refurbishment of roofs is joined with installation of PV cells or solar thermal collectors (or - if shaded - with rooftop greening)
3	Efficiency (buildings)	Retrofit of **windows** (triple-glazing)	++ (vs. low-end double glazing) +++ (vs. single glazing)	→	→	↘	available	to avoid condensing on walls, sufficient insulation capability of walls must be assured	high	-	2, 5 [18 in buildings sector]	high	higher comfort (less draught, higher surface tempera-tures of windows)	Reference technology: low-end double glazing / single glazing	new windows can be combined with integrated ventilation system
4	Efficiency (technical systems)	Optimisation of **heating** and **hot water** systems (incl. e.g. Installation of heat recovery systems for showers, reduction of hot water demand by water-saving armatures)	++ / +++ (depending on standard of existing technology)	→ / ↗	→ / ↗	→ / ↘	available	Interplay with refurbishment of building shell (No.2)!	high	-	2, 10 and nearly all heating technologies (see above)	medium to high	-	Reference technology: standard systems	
5	Efficiency (technical systems)	Optimisation of **cooling** and **ventilation** systems	+ / ++ (depending on standard of existing technology)	→	→	→ / ↘	available	Interplay with refurbishment of building shell (No.2)!	high	-	2, 8, 10, 11, 19	medium to high	possibly higher comfort (user adapted)	Reference technology: standard systems	
6	Efficiency (technical systems)	Installation of ventilation systems with **heat recovery**	+ (related to total heat demand of building) +++ (related to ventilation losses of building)	↗	→	→ / ↘	available	Interplay with refurbishment of building shell (No.2)!	high	-	2, 10	medium to high	possibly higher comfort (less draught)	Reference technology: window ventilation	

	FIELD of ACTIVITY	STRATEGY	Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infrastructure and framework requirements	Compatib. with overall energy system transfor-mation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
7	Efficiency (technical systems)	Use of **waste heat** from waste water (by heat pumps)	++	↗	↗	↘	available / pilot projects	Central heating with central waste water heat exchanger and collaboration with local community / supplier required	high	depends on waste water infrastructure	4	high	-	Reference technology: gas condensing boiler	
8	Efficiency (technical systems)	Optimisation of **lighting** (LED, presence or daylight control, use of daylight)	++ / +++ (depending on existing technology)	→ / ↗	→	↘ / ↓	available	-	high	-	2, 3, 5, 10, 22	high	possibly higher comfort (user adapted); less waste heat from lighting	Reference technology: incan-descent lamp / flourescent lamp without presence or daylight control	
9	Efficiency (technical systems)	Optimisation of **drives** (pumps, motors and fans)	+ / ++ (depending on standard of existing technology)	→	→	→ / ↘	available	-	high	-	4, 5	high	-	Reference technology: standard systems	
10	Efficiency (technical systems)	**Building automation** (e.g. time and presence control, adaptive ventilation with CO2 sensor)	+ / ++ (depending on existing technology)	→ / ↗	→	→ / ↘	available	Briefing or training for accurate user behaviour	high	-	4, 5, 6, 8, 9, 11	low to high (depending on implemen-tation and user behaviour)	-	Reference technology: manual operation	
11	Efficiency (technical systems)	Highly energy efficient **office equipment / ICT** (PC, server, printer, photocopier, router, beamer...)	+ / ++ (depending on existing technology)	→	→	↘	available	-	high	-	5, 10	high	less waste heat from equipment	Reference technology: standard systems	
12	Efficiency (technical systems)	Highly energy efficient **other equipment** (e.g. elevators, coffee maker, kitchen/canteen equipment)	+ (depending on existing technology)	→	→	→	available	-	high	-	10	high	less waste heat from equipment	Reference technology: standard systems	

	FIELD of ACTIVITY	STRATEGY	Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infrastructure and framework requirements	Compatib. with overall energy system transfor-mation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
13	Renewable energy (fuels & heat)	Fuel switch (**solid** fuels): Use of biomass (wood pellets or chips)	++ / +++ (depending on feedstock and upstream chain)	↗ (vs. oil with oil tank) ↑ (vs. gas without tank)	↗ / ↑	↘	available	sufficient capacities for supply, transport and storage of biomass feedstock	medium / high, if used in energy efficient buildings (e.g. passive house standard) or in high temperature processes; but limited biomass potentials	Supply of sustainable biomass (incl. sustainable transport) must be guaranteed	2	medium to high	Pushing of the local economy, if regional biomass is used	Reference technology: gas condensing boiler or oil boiler	
14	Renewable energy (fuels & heat)	Fuel switch (**liquid** fuels): Use of renewable fuels (plant oil, bio diesel = FAME, bio ethanol, bio methanol, BTL = Fischer-Tropsch)	+ / ++ (depending on feedstock and upstream chain)	→ (depending on feedstock)	→	↗ / ↑ (depending on feedstock)	available (1 st Generation)	depending on the fuel and its thermo-dynamic properties a modification of the power plant / CHP motor / boiler and / or of the transport and storage infra-structure is necessary	low, because liquid renewable fuels are limited and should preferably be used in the transport sector	Supply of sustainable biomass (incl. sustainable transport) must be guaranteed	2	low (see e.g. discussion about palm oil)	Pushing of the local economy, if regional biomass is used	Reference technology: oil boiler	
15	Renewable energy (fuels & heat)	Fuel switch (**gaseous** fuels): Use of renewable fuels (biogas, biomethane, hydrogen, synthetic natural gas...)	+ / ++ / +++ (depending on feedstock and upstream chain)	→ (depending on feedstock)	→	↗ / ↑ (depending on feedstock)	available		medium / high, if used in energy efficient or high temperature processes; but limited biomass potentials	Supply of sustainable biomass (incl. sustainable transport) must be guaranteed	2	low to high (depending on feedstock)	Pushing of the local economy, if regional biomass is used	Reference technology: natural gas condensing boiler	
16	Renewable energy (fuels & heat)	Exploitation of **geothermal** energy for heating and cooling (with and without heat pumps)	+ (high COP, fossil power +++ (without HP or HP with renewable power)	↑	↑	↘ (HP) ↓ (without heatpump)	available	heat source: suitable geological formation necessary; ideally high temperature level; heat consumer: ideally low temperature level (high COP of the heat pump)	high, if ready for flexible operation mode (with the help of thermal storage); but seasonally high loads in winter, if used for space heating	Risk of rising demand for fossil power, if exploitation of RE does not keeps up with rising installations of heat pumps	2	generally high, but: deep geothermal: potentially risk of seismic incident	no local pollutant emissions; synergy effects with use of free cooling systems	Reference technology: natural gas condensing boiler	

	FIELD of ACTIVITY	STRATEGY	Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infrastructure and framework requirements	Compatib. with overall energy system transfor-mation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
17	Renewable energy (fuels & heat)	Exploitation of **solar** energy for heating and cooling	+++	↑ (small) ↗ (large)	↑ (small) ↗ (large)	↓	available (but large scale systems not yet standar-dised)	collector area, backup system and / or (saisonal) storage necessary; no shading of collector	high, espacially with (saisonal) storage	-	2, 20, 21, 22, 23	high	no local pollutant emissions	Reference technology: natural gas condensing boiler	see also good pratice (large scale) examples from Denmark
18	Renewable Energy (fuels & heat)	Exploitation of **ambient heat** (heat pumps)	0 (low COP, fossil power) + (high COP, fossil power +++ (HP with renewable power)	↗	↗	→ / ↘ (depending on efficiency)	available	heat source: ideally high temperature level (ambient air, water from river, sea, rain...) heat consumer: ideally low temperature level (high COP of the heat pump)	high, if ready for flexible operation mode (by thermal storage and grid steering); but seasonally high loads in winter, if used for space heating	Risk of rising demand for fossil power, if exploitation of RE does not keeps up with rising installations of heat pumps	2	generally high, but: air heat pumps: noise restrictions	no local pollutant emissions	Reference technology: natural gas condensing boiler	
19	Renewable energy (fuels & heat)	**Free cooling** (natural cooling)	++ / +++	→	→	↘	available (but systems not yet standardised)	Holistic planning (building design) and natural heat sink needed	high	-	2, 5, 16, 21, 22, 23	high	synergy effects with use of geothermal heating systems	Reference technology: refrigerating machine	
20	Renewable energy (electricity)	Exploitation of solar energy (**PV**, especially roof-top and building-integrated)	+++	↗ (small) → (large)	↘	↓	available	free unshaded areas; sufficient structural design (statics) for building integrated PV (roof / facade)	high	-	2, 17, 21, 22, 23	high	no local pollutant emissions	Reference technology GHG: national power mix today costs: fossil power mix (coal, gas, oil)	

	FIELD of ACTIVITY	STRATEGY	Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infrastructure and framework requirements	Compatib. with overall energy system transfor-mation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG / cost balancing (in relation to reference technology)	Remarks
21	Integrated concepts	Implementation of **zero-energy** and **plus-energy buildings**	+++	→ / ↗	→	↘	available (especially for new buildings)	Holistic planning; often need for (seasonal) storage	high; can (partially) provide other buildings with surplusses of heat and power	-	2, 17, 20, 22, 23	high	higher comfort and resilience / autarky	Reference: statutory Energy Per-formance Standard	
22	Integrated concepts	**Solar architecture**	+	→	→	→	available	Holistic planning	high	-	2, 8, 17, 20, 21, 23	high	higher comfort	Reference: Standard Building	
23	Integrated concepts	Optimisation of **infrastructure** / energetic **urban** and **quarter** development / **system** integration (e.g. local heating or cooling networks, LowEx concept, heat & cold & power storage, (cascade) use of waste heat)	+ / ++	→ / ↗	→ / ↗	→ / ↘	Pilot projects	Holistic planning; space for (seasonal) storage	high; supports to exploit the potentials of (LowEx) renewable energy, waste heat and storage options	-	2, 4, 7, 16, 17, 18, 19, 20, 21, 22	medium to high	use of synergy effects	Reference: No con-sideration of integrated infra-structure planning	

1) Mitigation potential relative to average technology in the stock
   0 = net/zero savings vs. standard technology
   + = small (up to 33% savings vs. standard technology)
   ++ = medium (33 to 66% savings)
   +++ = high (66 up to 100% savings)
2) Investment costs today relative to standard technology
3) Investment costs at status of maturity of the technology vs. standard and expected date of maturity
4) Operational costs of current technology vs. standard technology at moderate real energy price increase

↗ / ↑ ... higher than standard technology by more than 33% / 66%
→ ... equivalent standard (+/- 33%)
↘ / ↓ ... lower than standard technology by more than 33% / 66%

6.1.5 Transport and Logistics Sector

6.1.5.1 Introduction

The provision of logistics services usually deploys staff, vehicles, transport infrastructure, transshipment facilities, intralogistics and logistics buildings. For the latter, it is sufficient to refer to the strategies for buildings, as has been described extensively in the previous section.

Given the limited scope of logistics operations within the Port of Rotterdam area itself and the enormous volumes of CO_2 emissions caused by energy conversion and other energy intensive industrial processes located there, it comes as no surprise, that logistics makes up only a minor share in the area's total CO_2 emissions.

CO_2 emissions of transport and logistics operations in the port area were around 2 Mt in 2015, and saw little change since 1990 (see Figure A1). As logistics operations increased since 1990 and is expected to continue to increase in the future, substantial efficiency gains have occurred and will be required in the future to keep the sector's CO_2 emissions from rising.

Based on earlier efforts to quantify the global potentials of decarbonisation strategies in freight transport and logistics and to estimate the feasibility of their implementation (see Table A1), the question arises which strategies may to what extent be implemented at the Port of Rotterdam.

Decarbonisation strategies	Potential Abatement (Mt of CO_2eq)	Perceived feasibility	(Partial) Implementation at Ports?
Low Carbon Sourcing: Agriculture	178	Medium	No
Vehicle Technologies	175	High	Yes
Despeeding the Supply Chain	171	High	Yes
Low Carbon Sourcing: Manufacturing	152	Medium	Yes *
Smart Packaging	132	High	Yes
Efficient Networks	124	High	Yes
Training/Communication	117	Medium	Yes
Switch to Low Carbon Modes	115	Medium	Yes
Energy Efficiency of Buildings	93	High	Yes
Reverse Logistics / Recycling	84	Medium	Yes
Reducing Congestion	26	Low	Yes
Home Delivery	17	Medium	No
Nearshoring	5	Medium	No

Table A1: Estimates of global decarbonisation potentials and assessment of feasibilty of strategies in transport and logistics (* as far as manufacturing is located at ports)

Source: *Compilation based on WEF (2009)*

Some strategies are solely relevant for activities at a port or its vicinity. However, maritime and inland shipping as well as rail and road freight related to a port clearly stretch beyond the area of a port. Notwithstanding this, a port – while depending on the larger networks of mode-related transport infrastructure – is at the same time an important entrance into or destination within those networks that can have a substantial impact on the modal split of hinterland transport.

Furthermore, efforts to reduce air pollution from the burning of heavy fuel oil on seagoing vessels have started in port regions with surrounding conurbations, where such emissions were considered untenable in the context of the attainment of ambient air quality objectives.

With logistics buildings, transshipment facilities and intralogistics located at a port, implementation entirely rests with port authorities, companies and logistics service providers operating at that port. Opposed to this, only a limited fraction of transport operations which touch upon a port can directly be influenced by local actors. Therefore, what follows is focused on transhipment and freight transport as well as passenger transport of staff within the port region. Other transport and logistics activities will be mentioned briefly but are mostly beyond the scope of this study.

6.1.5.2 Fields of Activities

Given that buildings used for the provision of logistics services are extensively referred to in in the previous section, the following specific fields of activities can be identified in the transport and logistics sector:

- Modal shift (internal freight and passenger transport)
- Energy efficiency (vehicles, transshipment, intralogistics)
- Renewable energy (fuels, electricity)
- Integrated concepts

6.1.5.3 Selected Findings

In the following, the key findings are outlined for each Field of Activity:

- Modal Shift (internal freight and passenger transport)

Shifting transport demand towards more climate-friendly transport modes will remain to be one of the most important levers for decarbonisation in transport and logistics as long as there are substantial distinctions with regard to mode-specific carbon intensities. However, only a fraction of freight transport activity performed by vessels that call at a port takes place within a port's region. In that context, the provision of well-equipped multi-modal transport infrastructure is a prerequisite for modal shift of freight transport operations. There also needs to be sufficient infrastructure capacity of relevant modes beyond the port's area.

Shifting passenger transport to less carbon intensive transport modes at the Port of Rotterdam is primarily about commute trips of staff from companies located in the port's area and internal trips within the port area. Reducing car trips of staff in the port area can primarily be achieved via the implementation of bus services. Another measure may be the provision of human powered or electric bicycles. Provided that the successful implementation meets social acceptance criteria, significant co-benefits may arise in the form of land area available for other use than car parking and less congestion of main internal traffic arteries during peak hours.

- Energy Efficiency (vehicles, transshipment, intralogistics)

Energy efficiency is usually primarily envisaged from a technical perspective and its implementation is thus for the most part based on investment in new technical equipment. However, in particular for logistics, energy efficiency may strongly be influenced by organisational practices which is often overlooked (Pastowski et al. 2014). The implementation of technical or organisational energy efficiency can directly be influenced at a port.

Technical energy efficiency of vehicles as well as transshipment and logistics infrastructure is to a large extent dependent on the age of the equipment in use and technical progress that has occurred since its implementation. Creating overcapacities in order to cater for future growth is an important factor with regard to energy efficiency of sophisticated intralogistics. Modularity may be a strategy to achieve a better match between capacity and current demand. In order to successfully implement operational changes for increased energy efficiency, it is very important to take stock of energy use at a sufficiently disaggregated level to better understand which operational practices may be applied to promote efficient energy use.

- Renewable energy (fuels & heat, electricity)

With regard to renewable energies and electricity, there is a core area of vehicle and equipment use where ports and logistics service providers can independently implement related technical equipment as well as energy supply. Moreover, renewable electricity may be supplied to ships at berth in order to reduce emissions from main engines or auxiliary power units. All tethered stationary equipment and modes of transport with electric drives will directly benefit from either a growing share of renewable electricity supplied via the grid or locally produced at the port's premises. This holds particularly true for railways with electric traction but also for forklifts, reach stackers, container gantry cranes and stationary intralogistics.

Renewable energy will be a decisive factor in decarbonising energy use of operations at ports and beyond. However, international shipping will require some time for the implementation of low-carbon fuels. Shipping will not have to struggle as much as other modes of transport with relatively low energy densities of low carbon fuels like hydrogen that may compromise economic efficiency beyond energy cost through reduced payload. At the same time the provision of renewable hydrogen from particularly sunny regions along the equator to Europe via the Port of Rotterdam may create new economic opportunities while imports of crude oil are expected to decline over the coming decades.

At ports, implementation of low-carbon fuels with maritime shipping may start via obligations to operate vessels with zero emissions in the ports' areas. For example, the early implementation of renewable hydrogen in international shipping may start on selected routes with high traffic densities in order to limit investments in bunkering infrastructure.

- Integrated concepts

With regard to integrated concepts, it is obvious that there may be a good match between volatility of supply of renewable electricity and operational practices at big cold warehouses, owing to the buffering capacity of such installations. On the one hand, this may help to achieve a good system integration of renewable energy, while on the other hand it may create new business opportunities for companies that are operating cold warehouses.

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
1	Renewable Energy (fuels & heat)	Fuel switch (solid fuels): Use of biomass (wood pellets or chips)	see buildings												
2	Renewable energy (fuels & heat)	Fuel switch (liquid fuels): Use of renewable fuels (plant oil, bio diesel = FAME, bio ethanol, bio methanol, BTL = Fischer-Tropsch)	see buildings												
3	Renewable energy (fuels & heat)	Fuel switch (gaseous fuels): Use of renewable fuels (biogas, biomethane, hydrogen, synthetic natural gas...)	see buildings												
4	Renewable energy (fuels & heat)	Exploitation of geothermal energy for heating and cooling (with and without heat pumps)	see buildings												
5	Renewable energy (fuels & heat)	Exploitation of solar energy for heating and cooling	see buildings												
6	Renewable energy (fuels & heat)	Exploitation of ambient heat (heat pumps)	see buildings												
7	Renewable energy (electricity)	Exploitation of wind energy (on-site, small-scale)	see buildings												
8	Renewable energy (electricity)	Exploitation of solar energy (PV, especially roof-top and building-integrated)	see buildings												
9	Energy efficiency	Optimisation of heating and hot water systems	see buildings												
10	Energy efficiency	Optimisation of lighting	see buildings												
11	Energy efficiency	Optimisation of cooling and ventilation systems	see buildings												
12	Efficiency (technical systems)	Optimisation of drives (e.g. pumps, motors, compressors)	see buildings												
13	Enabling technologies (e.g. storage and grids)	Optimisation of cold storage houses	++	Solely operational	Solely operational	Can be profitable	Available	Short-term supply-based electricity prices	High systemic value in matching supply and demand	Fully reversible	Fosters renewable electricity use	Likely high/ working conditions issue?	Security of supply	Overall system beyond case of application	

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1]	Investment costs today [2]	Investment costs maturity [3]	Operational costs today [4]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
14	Modal shift freight	Road to rail	++	Depends on volume and existing facilities	Not applicable	Not applicable	Available	Potential expansion of rail tracks and trans-shipmemt	Increasing use of (renewable) electricity	As with comparable transport infra-structure - relatively high	Combines well with fuel switch	High	Reduced noise and air pollutants, less traffic jams on road arteries, reallocation of road space for other use		
15	Modal shift freight	Road to barge	++	Depends on volume and existing facilities	Not applicable	Not applicable	Available	Potential expansion of berth and trans-shipmemt capacity		As with comparable transport infra-structure - relatively high	Combines well with fuel switch	High			
16	Modal shift passengers	Road to rail / car to bus for employees (commute)	++	Not applicable for outsourced services	Not applicable for outsourced services	Not applicable	Available	Bus stops instead of car parks	Increasing use of (renewable) electricity if combined with electric vehicles	As with comparable transport infra-structure - relatively low	Combines well with fuel switch	Depends on cost, convenience and multimodal integration for employees	Reduced noise and air pollutants, less traffic jams on road arteries at commute times, reallocation of road space for other use		Renewably produced hydrogen also an option
17	Modal shift passengers	Car to bicycle / pedelec for employees (internal trips)	++	Not applicable for outsourced services	Not applicable for outsourced services	Not applicable	Available	Bike/ pedelec instead of car parks	Increasing use of (renewable) electricity	As with comparable transport infra-structure - relatively low	Combines well with renewable electricity	Depends on cost, and convenience for employees	Reduced noise and air pollutants, less traffic jams on road arteries, reallocation of road space for other use		Renewably produced hydrogen also an option

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today[2)]	Investment costs maturity[3)]	Operational costs today[4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
18	Renewable energy (fuels)	Fuel switch (renewable liquid fuels): bio diesel = FAME (blend)	(-)/(+) (depending on feedstock and upstream chain)	→	→	→	Vehicle technology available for blended fuels	No re-quirements for blended fuels	Limited biomass potential, high share of fossil-based inputs	Prolongation of the era of the internal combustion engine		Working conditions with imports, food vs. fuel dilemma	Less air pollutants		Less useful as pure fuel
19	Renewable energy (fuels)	Fuel switch (renewable liquid fuels): BTL = Fischer-Tropsch (blend)	+	→	→	→	Vehicle technology available for blended fuels	No re-quirements for blended fuels	Limited biomass potential, high share of fossil-based inputs	Prolongation of the era of the internal combustion engine		Working conditions with imports, food vs. fuel dilemma	Less air pollutants		Less useful as pure fuel
20	Renewable energy (fuels)	Fuel switch (renewable liquid fuels): bio ethanol (blend)	(-)/(+) (depending on feedstock and upstream chain)	→	→	→	Vehicle technology available for blended fuels	No re-quirements for blended fuels	Limited biomass potential, high share of fossil-based inputs	Prolongation of the era of the internal combustion engine		Working conditions with imports, food vs. fuel dilemma	Less air pollutants		Less useful as pure fuel
21	Renewable energy (fuels)	Fuel switch (renewable gaseous fuels): biomethane	(-)/(+) (depending on feedstock and upstream chain)	↗	↗	↗	Vehicle technology available	Can rely on existing infra-structure for natural gas	Limited biomass potential, high share of fossil-based inputs	Prolongation of the era of the internal combustion engine		Working conditions with imports, food vs. fuel dilemma	Less air pollutants		
22	Renewable energy (fuels)	Fuel switch (renewable gaseous fuels): synthetic natural gas	+++	↗	↗	→	Vehicle technology available	Can rely on existing infra-structure for natural gas	High as Power-to-Gas	Prolongation of the era of the internal combustion engine	Combines well with renewable electricity		Less air pollutants		
23	Renewable energy (fuels)	Fuel switch (renewable gaseous fuels): hydrogen	+++	↑	↑	↑	Vehicle technology available	Can partly rely on existing infra-structure for natural gas	Combines well with renewable electricity		Combines well with renewable electricity		Less air pollutants		
24	Fuel shift (fossil)	Fuel switch towards lower carbon fossil fuels (e.g. from diesel to natural gas)	+	↗	↗	→	Vehicle technology available			Prolongation of the era of the internal combustion engine			Less air pollutants		

	FIELD of ACTIVITY	STRATEGY	GHG Mitigation potential[1)]	Investment costs today [2)]	Investment costs maturity [3)]	Operational costs today [4)]	Tech-nological maturity	Infra-structure and framework re-quirements	Com-patibility with overall energy system trans-formation	Reversibility / path dependency / Potential lock-in effects	Interplay with other strategies	Social acceptance	Co-Benefits	System boundary in GHG/cost balancing (in relation to reference technology)	Remarks
25	Energy efficiency	Increasing efficiency of vehicles	+	→/↗	→/↗	↘	Available						Less air pollutants		
26	Energy efficiency	Increasing efficiency of transshipment (container gantry cranes, reach stackers etc.)	+	→/↗	→/↗	↘	Available						Less air pollutants		
27	Renewable energy (fuels)	Fuel switch (liquid fuels): Use of renewable fuels for forklifts, reach stackers etc.: (plant oil, bio diesel = FAME, bio ethanol, bio methanol, BTL = Fischer-Tropsch)	(-)/(+) (depending on feedstock and upstream chain)	↗ / ↑	↗ / ↑	→	Vehicle technology available	Depends on fuel, can rely on existing infra-structure for blends		Prolongation of the era of the internal combustion engine		Working conditions with imports, food vs. fuel dilemma	Less air pollutants		
28	Renewable energy (fuels)	Fuel switch (gaseous fuels): Use of renewable fuels for forklifts, reach stackers etc: (biogas, biomethane, hydrogen, synthetic natural gas...)	(-)/(+) (depending on feedstock and upstream chain)	↗ / ↑	↗ / ↑	→	Vehicle technology available	Depends on fuel, can partly rely on existing infra-structure for natural gas		Prolongation of the era of the internal combustion engine		Working conditions with imports, food vs. fuel dilemma	Less air pollutants		
29	Energy efficiency	Increasing efficiency of forklifts, belt conveyors, floor conveyors, cranes etc.	+	→/↗	→/↗	↘	Available						Less air pollutants		
30	Enabling technologies (e.g. storage and grids)	Provision of shore-side (low-carbon) electricity to ships at berth	+	↗	↗	↘	Available	Local grid extensions					Less air pollutants		

1) Mitigation potential
relative to average technology in the stock
0 = net/zero savings vs. standard technology
+ = small (up to 33% savings vs. standard technology)
++ = medium (33 to 66% savings)
+++ = high (66 up to 100% savings)

2) Investment costs today relative to standard technology

3) Investment costs at status of maturity of the technology vs. standard and expected date of maturity

4) Operational costs of current technology vs. standard technology at moderate real energy price increase

↗ / ↑ ... higher than standard technology by more than 33% / 66%

→ ... equivalent standard (+- 33%)

↘ / ↓ ... lower than standard technology by more than 33% / 66%

6.2 Appendix B – Stakeholder questionnaires

6.2.1 Stakeholders involved

The list of stakeholders is divided in the two categories of "industry" and "society" stakeholders, NGOs and municipalities being within the second group. All together, 19 stakeholder from industry companies and 13 from society were addressed. The companies and organisations are as follows:

Name of company or organisation	Organisation's website
Air Liquide	http://www.airliquide.de
Air Products	http://ariproducts.com
Akzo	https://www.akzonobel.com
AVR	http://www.avr.nl
Clean Tech Delta	http://www.cleantechdelta.nl
DeltaLinqs	http://www.deltalinqs.nl/en
EMO	http://www.emo.nl/en/
Eneco	http://www.eneco.com
Engie	http://www.engie.com/en/
Evides Industriewater	https://www.evidesindustriewater.nl
Exxon / Esso	http://corporate.exxonmobil.com
Havenschap Moerdijk	http://www.havenschapmoerdijk.nl
Huntsman	http://www.huntsman.com
Lyondell	https://www.lyondellbasell.com
Neste	https://www.neste.com
Uniper	https://www.uniper.energy/de/index.html
Shell	http://www.shell.com
Stedin	https://www.stedin.net
Clustercommissaris	http://www.offshorehavens.nl
Christelijk Natiionaal Vakverbond (CNV)	https://www.cnv.nl
DCMR	http://www.dcmr.nl
Drift	https://www.drift.eur.nl
Federatie Nederlandse Vakbeweging (FNV)	https://www.fnv.nl
Gemeente Rotterdam	http://www.rotterdam.nl
Greenpeace	http://www.greenpeace.nl
Milieudefensie	https://milieudefensie.nl
MinEZ	http://www.minez.nl
Natuur en Milieu (NMZ)	https://www.natuurenmilieu.nl
Natuur en Milieufederatie Zuid-Holland (NMZH)	http://milieufederatie.nl
Rotterdam Climate Initiative (RCI)	http://www.rotterdamclimateinitiative.nl
VON-NCW	https://www.vno-ncw.nl

6.2.2 Methodology

The stakeholders were selected and identified by the Port Authority, who made available the names and contact details to the Wuppertal Institute.

The response rate was 40 % (corresponding to 13 actors) for both groups, but only 34 % (corresponding to 11 persons) actually filled out the questionnaire. The rate was higher for the industry group, where 10 out of 19 actors responded and filled out the given questionnaires. From the society group, only one stakeholder gave response, so it is not possible to evaluate the answers for the group, respectively an analysis of answers with regards to the two different groups is not possible.

The complete questionnaire consisted of four sections representing the following sectors:

- Energy & Utilities
- Petrochemicals & Refining
- Transport & Infrastructure
- Buildings

The Energy & Utilities sector was the one where most actors assessed the respective technologies (compare Figure A1), followed by the sector of Petrochemicals & Refining. Within this sector, the sub-sector of Refining was filled in by more stakeholders, while in the sub-sector of petrochemicals the number of answers was considerably lower (compare number of answers given in Figure A2).

Out of 13 stakeholders, only two were working with the questionnaire regarding the sector of Buildings and only one filled out the assessment for Transport & Infrastructure. The number of answers in Figure A1 does not sum up to 13 but to 16 because some stakeholders received and filled the questionnaire for more than one sector.

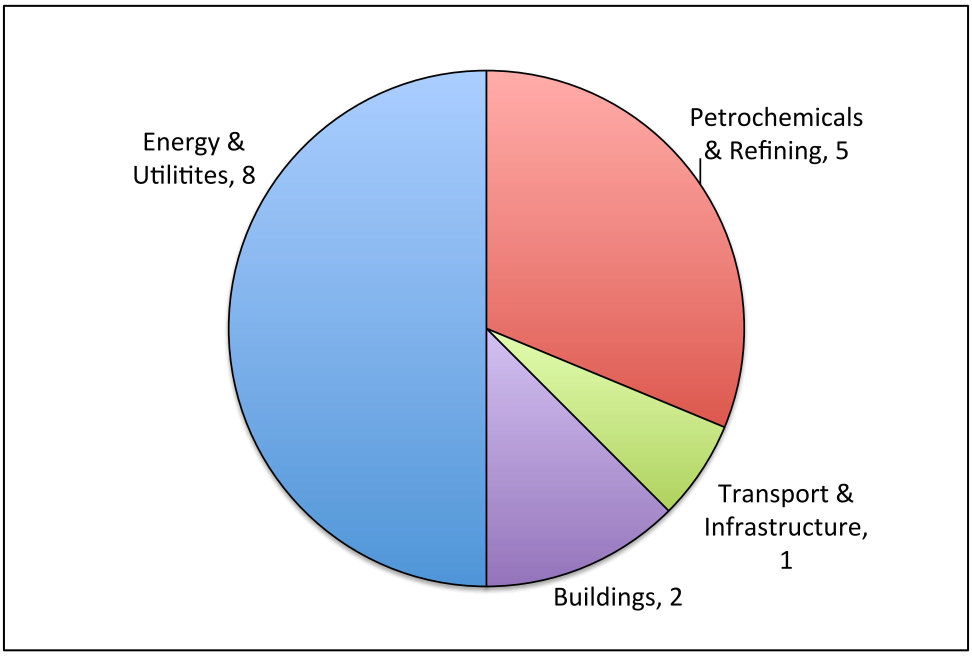


Figure A1: Number of stakeholders assessing the technologies according to the sectors [own compilation of results]

In each sector, fields of activities were defined as described in Appendix A above. All together, 121 technologies were addressed and 474 answers given. As mentioned, the technologies in the sector Energy & Utilities were assessed the most, while the number of answers in the sectors of Transport & Infrastructure as well as Buildings is not enough to run a scientific evaluation on this fields. The results are nevertheless shown in the following sections.

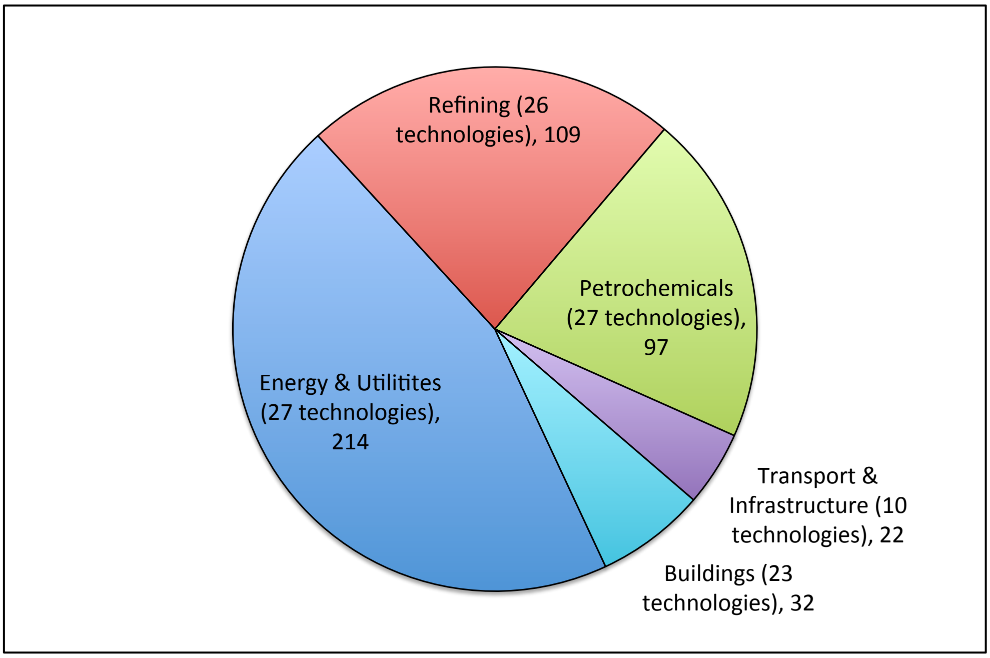


Figure A2: Number of answers given by stakeholders in the respective sectors and sub-sectors [own compilation of results]

The questionnaire contained two questions under the headline "Please imagine that the Port of Rotterdam region will have to reduce its CO_2 emissions by at least 80 % by 2050 compared to 2010." The questions were

- When do you expect this technology/strategy to be commercially available? The options were "already available"; "short-term (until 2025)"; "mid-term (2025 - 2035)"; "long-term (2035 - 2050)"; or "never".
- In the above mentioned environment of ambitious climate protection efforts: Should this technology/strategy be implemented in your opinion in the Port of Rotterdam region between now and 2050?

The questions in this combination aim at the assessment of the stakeholder with regard to the technical and commercial availability. It turned out, however, that most actors focussed on the rather technical assessment and left the first question blank. For the second question, the same time frames as for the first were set, so the possibilities to answer were "yes, in the short-term (until 2025)"; "yes, in the mid-term (2025 - 2035)"; "yes, in the long-term (2035 - 2050)"; "no (= never)". The stakeholders were asked to mark the respective cell in the questionnaire table. More than one cell could be marked, if the stakeholder – for example – expected the technology to be implemented in the short- to mid-term. Additional technologies could be added by the stakeholders to the questionnaire and there was space for any further comments. Figure A3 shows an exemplary excerpt from the sector Energy & Utilities. The pink cells had to be filled.

Please imagine that the Port of Rotterdam region will have to reduce its CO_2 emissions by at least 80 % by 2050 compared to 2010.
Sector: Petrochemical and refining

Name(s):
Organisation:

			When do you expect the technology/strategy to be commercially available?	**In the above mentioned environment of ambitious climate protection efforts: Should this technology/strategy be implemented in your opinion in the Port of Rotterdam region between now and 2050?**				**Comments *(OPTIONAL)***
			Already available Short-term (until 2025) Mid-term (2025-2035) Long-term (2035-2050) Never or only after 2050	Yes, short-term (until 2025)	Yes, mid-term (2025-2035)	Yes, long-term (2035-2050)	No	
			Please make a selection in each coloured cell. Feel free to also modify our assessments in the white cells in case you disagree with them.	*Please mark the time horizon when the technology should be used with an "x". You can mark more than one cell (see examples).* Example 1 Example 2				*You can specify for example, why a technology/strategy should or should not be implemented in your opinion.*
SECTOR	**FIELD OF ACTIVITY**	**TECHNOLOGY/STRATEGY**						
Refining	Energy efficiency	Crude distillation unit upgrades (BAT)	Already available					
Refining	Energy efficiency	Vacuum distillation unit design improvements (BAT)	Already available					
Refining	Energy efficiency	Fluidized-bed catalytic cracker (FCC) design improvements (BAT)	Already available					
Refining	Energy efficiency	Hydrocracker design improvements (BAT)	(please select)					
Refining	Energy efficiency	Optimisation of fouling control (refineries)	Already available					
Refining	Energy efficiency	Optimisation of drivers (motors, pumps, compressors, fans (BAT))	Already available					
Refining	Energy efficiency	Optimisation of process heaters and furnaces (BAT)	Already available					
Refining	Energy efficiency	Optimisation of waste heat recovery	(please select)					

Figure A3: Exemplary excerpt from the questionnaire for the sector Energy & Utilities

6.2.3 Aggregated results of stakeholder feedback

The overall result of the evaluation of the stakeholder questionnaire is shown in Figure A4. As can be seen, the selection of technologies included was mostly approved by the stakeholders. Only 9 % of answers were "no [the technology should not be implemented in environment of ambitious climate protection efforts in the Port of Rotterdam region]", evaluated over all sectors and technologies. Most of the technologies should be implemented according to the stakeholders in the short-term until 2015 (49 % of answers), followed by the mid-term between 2025 and 2035 (27 % of answers) and the long-term after 2035 until 2050 (14 % of answers).

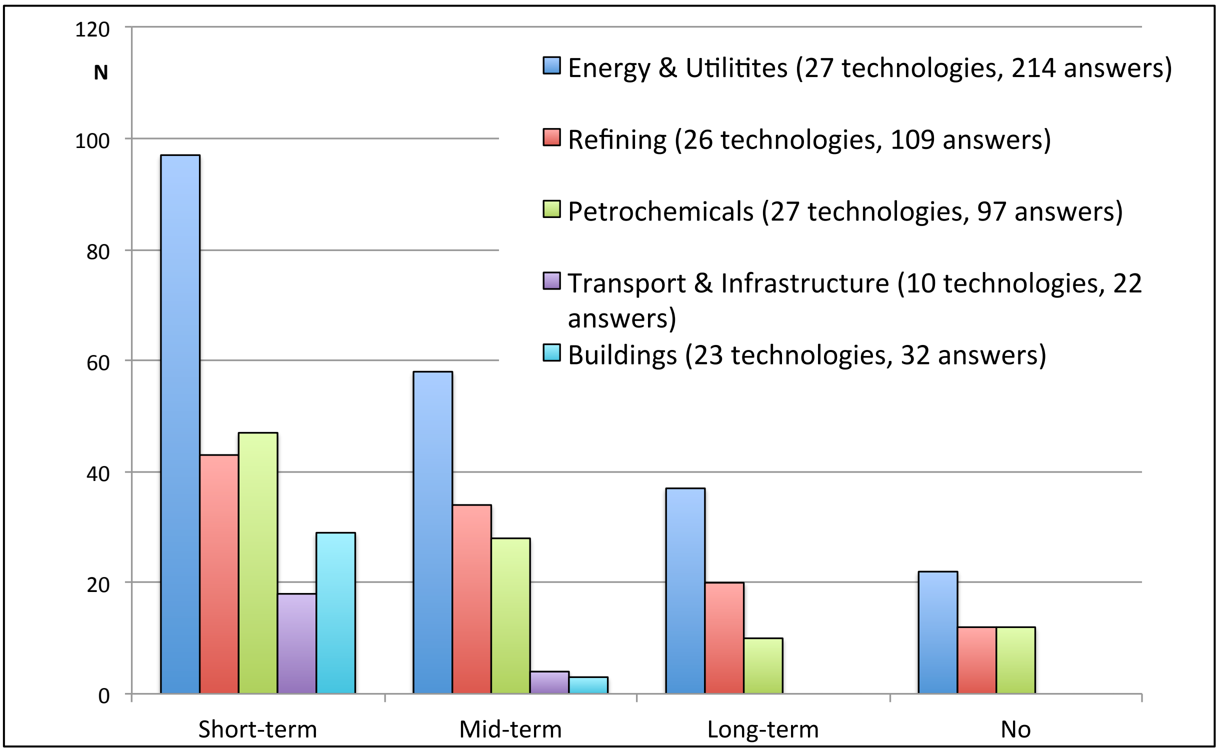


Figure A4: Overall results of stakeholder evaluation fort he sectors and sub-sectors [own compilation of results]

The results are shown according to the sectors or sub-sectors, respectively. In particular for the sectors of Energy & Utilities and Petrochemicals & Refining, the number of technologies was rather large, making the resulting diagrams very complex. Therefore, the evaluation focuses on so-called *key technologies* that are of special importance and relevance to the process of scenario building. They were selected by the project team due to their high CO_2 mitigation potential and the long-term perspective. The key technologies are shown at first in Figure A5, Figure A7 and Figure A9, followed by the overall evaluation graphs in Figure A6, Figure A8 and Figure A10.

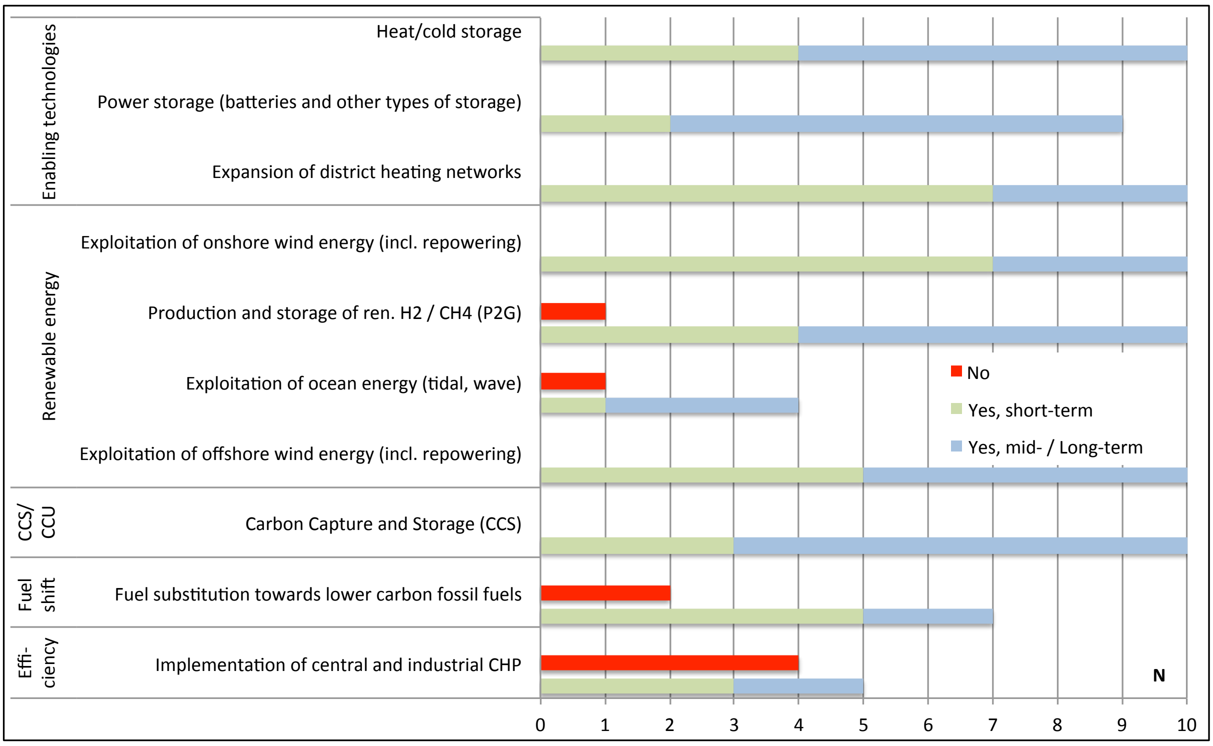


Figure A5: Evaluation of stakeholder questionnaire for the sector of Energy & Utilities; key technologies [own compilation of results]

The stakeholder assessed the key technology with a tendency to a mid- to long-term implementation, as can be seen in the graph in Figure A5. From the ten key technologies selected here, only three are rated more often for the short-term as for the mid- to long-term. These are *expansion of district heating networks*, the *exploitation of onshore wind* and the *fuel substitution towards lower carbon fuels (fossil fuel shift)*. All three are meant here as transition technologies; the understanding of the stakeholders and Wuppertal Institute is the same. The exploitation of offshore wind energy is assessed equally to be implemented in the short- as in the mid- to long-term.

From the ten technologies, four were voted with a "no [should not be implemented in the Port of Rotterdam region until 2050]". The *exploitation of ocean energy* as a relatively new and innovative technology is one of them, as is the *production and storage of renewable hydrogen or methane* in the context of power-to-gas. The earlier mentioned fossil fuel shift was assessed negative by two stakeholders.

Noticeable is the dissent on the "implementation of central and industrial CHP". While there are five voices for the implementation (of which three are for short-term and another two for mid- to long-term, as well four stakeholders voted against this strategy. This issue was raised in the stakeholder workshop (see excerpt of minutes in Section 6.3.2), where the actors gave the explanation, that the topic of CHP (combined heat and power) is generally seen as critical by many actors, because it is hard to manage CHP projects under the given framework conditions in a economically feasible manner.

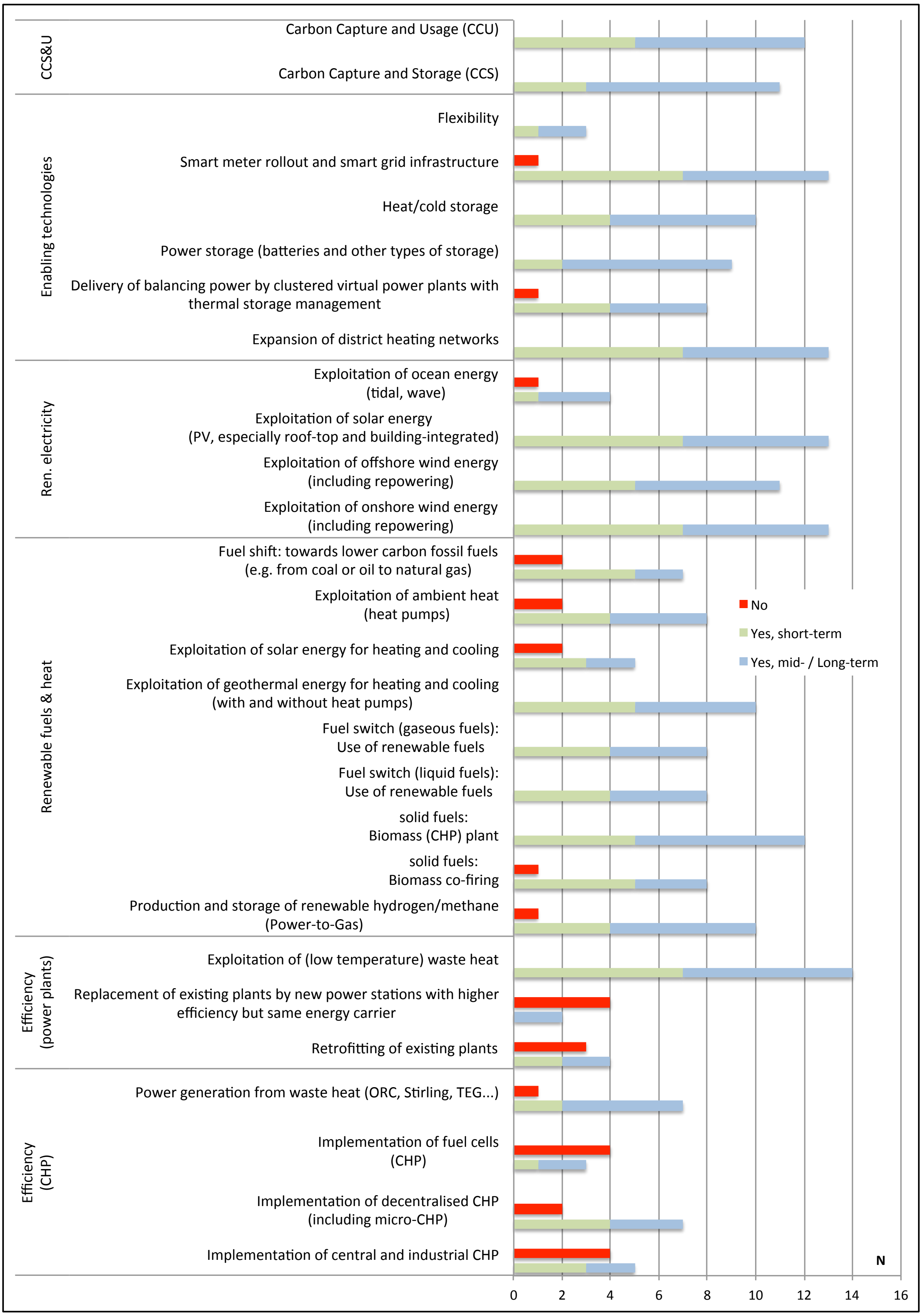


Figure A6: Evaluation of stakeholder questionnaire for the sector of Energy & Utilities; all technologies [own compilation of results]

When looking at the list of all technologies from the sector Energy & Utilities, more red bars for "no" are visible (Figure A6). About half of the 27 technologies were assessed as "not to be implemented" by the stakeholders, but with a maximum of four times "no" per technology, the positive voices predominate the picture.

The picture is similar for the sub-sector of refining (compare Figure A7): the selection of technologies is mostly accepted by the stakeholders, as the red bars are in total less and smaller than the rest. Three technologies – the carbon capture on FCC stacks, the use of biomass for synfuels and the providing of conventional fuels based on new processes such as methane, methanol-to-gasoline and Fischer-Tropsch - were without any exception rated positive. Again, there is a tendency to implement the technologies rather in the mid- to long-term and not in the short-term, with the exemptions of use of biomass for synfuels and the use of electrical boilers and furnaces in the Power-to-heat context. Here, similar to the previous sector, a dissent is visible: three stakeholders voted Power-to-heat to be implemented in the short-term, while two would not implement it at all. As was discussed further in the workshop, the reasons for the refusal is a general scepticism against the use of power in order to provide (low temperature) heat, as the exergy of the energy carrier is wasted to a big extend. The other side argues that this does not matter equally if the energy carrier is abundant in a de-carbonised world. That would, however, be more valid in the long-term rather than in the short-term.

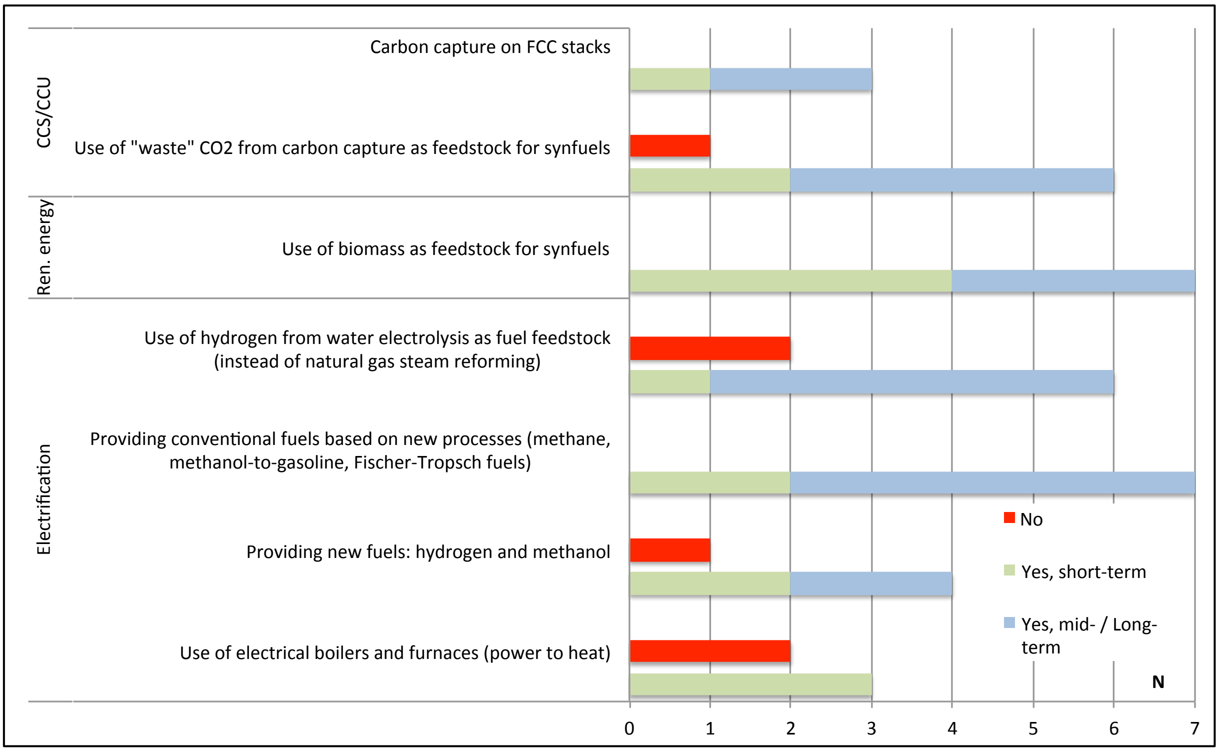


Figure A7: Evaluation of stakeholder questionnaire for the sub-sector of Refining; key technologies [own compilation of results]

The complete list of technologies for the sub-sector of reefing contains 27 technologies compared to seven key technologies. Among the 27, five have not been assessed by the stakeholders or did not get any voting. These are three in the field of activity "CCS / CCU", the use of waste as fuel and the additionally mentioned "role of process intensification", that was inserted by an actor, but apparently more as a question or comment that as a concrete technology.

In the rather wide field of energy efficiency, which contains 12 technologies as some of best available technologies (BAT) and some optimisation activities, all together only three voices voted "no [should not be implemented]", but there are some more "nos" in the other fields of activity as electrification and fuel shift. All in all, the short-term and mid- to long-term ratings are more or less equally distributed.

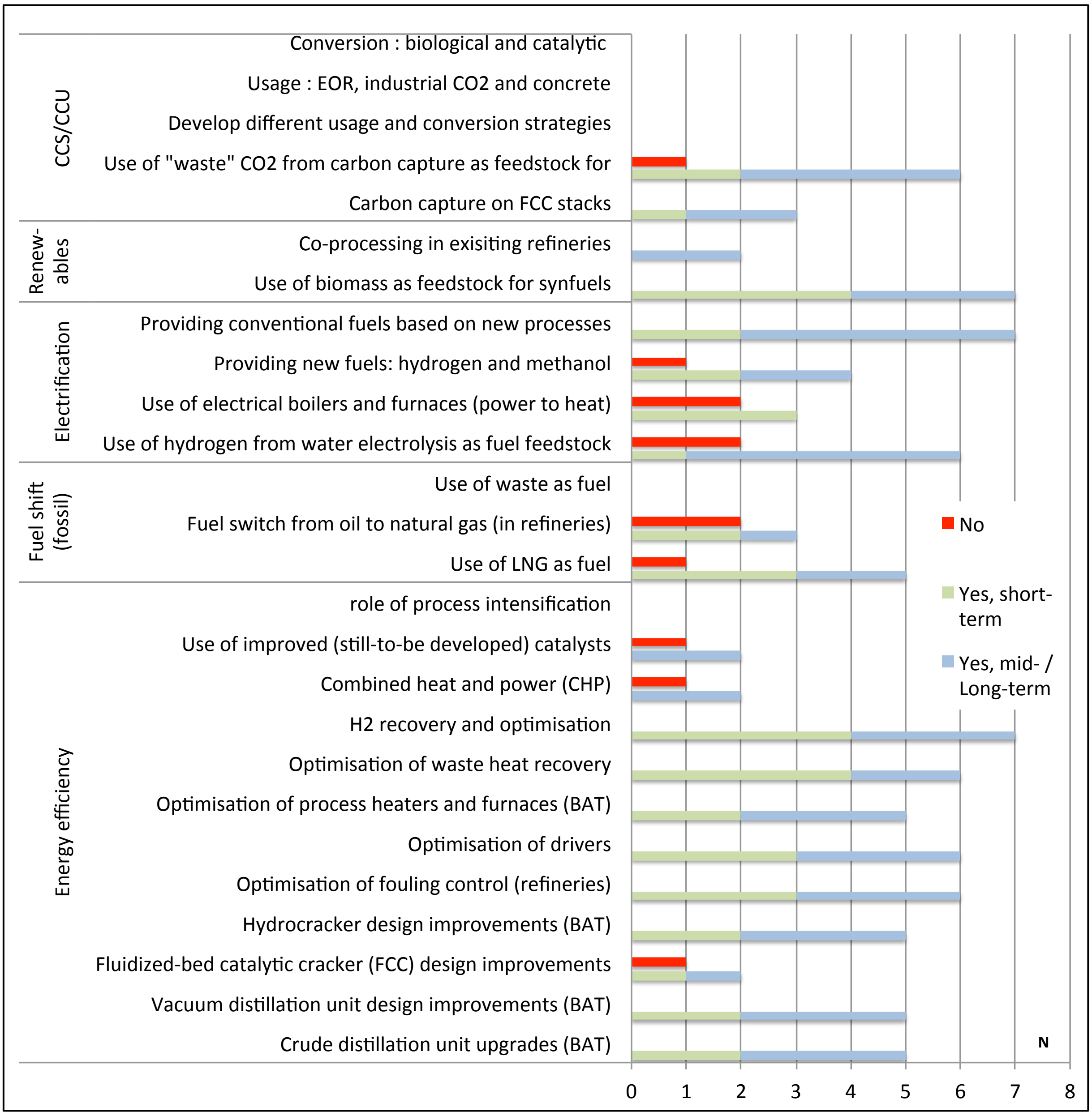


Figure A8: Evaluation of stakeholder questionnaire for the sub-sector of Refining; all technologies [own compilation of results]

The sub-sector of petrochemicals was assessed by fewer stakeholders than the other one of refining, as is especially visible for the key technologies. This is partly due to the higher complexity of the petrochemical production routes.

The feedback from stakeholders with regard to the selected key technologies is close to the limit where an evaluation is not possible from a scientific point of view; statements and finding have to be regarded in this context. The picture given in Figure A9 is diverse; from the twelve key technologies, only three did not receive a “no [should not be implemented]”. The other nine (with one exemption) were all assessed by one “no”. While taking the anonymity of the questionnaire serious, it is nevertheless important to state that there was not a single actor assessing every technology negative, but contrarily, the stakeholders were assessing the petrochemicals technologies all very different. Even at the workshops, this diverse picture could not be clarified.

The number of answers is a bit higher when looking at the complete list of technologies from the petrochemicals sector in Figure A10. The stakeholders assess especially the field of activity of energy efficiency positively and measures are expected rather in the short-term.

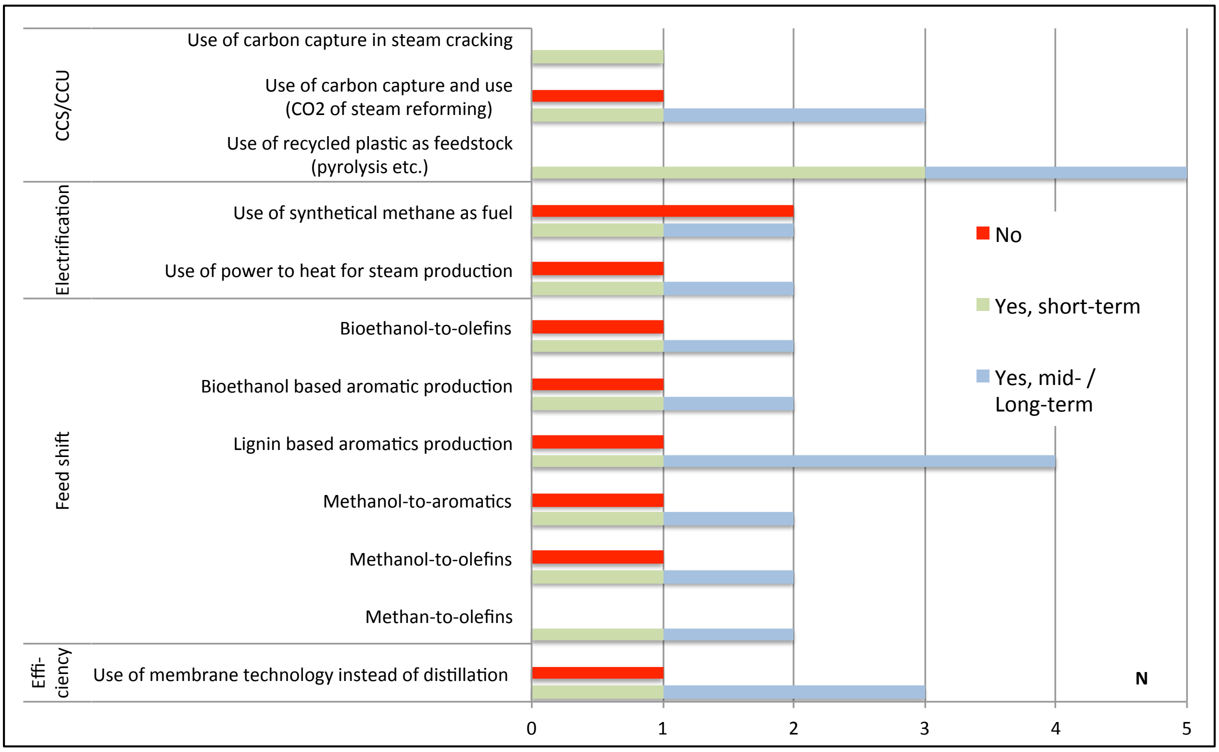


Figure A9: Evaluation of stakeholder questionnaire for the sub-sector of Petrochemicals; key technologies [own compilation of results]

Figure A10: Evaluation of stakeholder questionnaire for the sub-sector of Petrochemicals; all technologies [own compilation of results]

The results for the two sectors of Transport & Infrastructure (in the sub-sectors of Transport and Logistic &Infrastructure separately) and Buildings are shown in the following figures for the sake of completeness and transparency, but are left without comment. The number of answers is too small to run a scientific evaluation of the results.

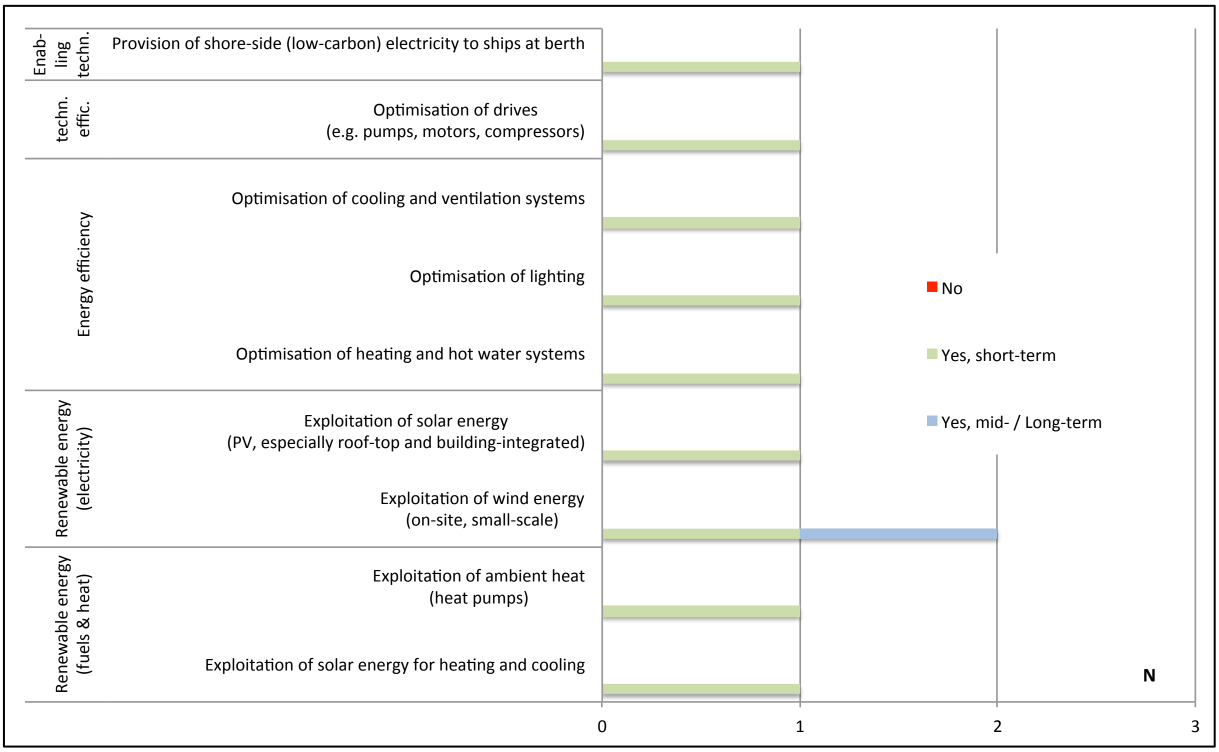


Figure A11: Evaluation of stakeholder questionnaire for the sub-sector of Logistic & Infrastructure; all technologies [own compilation of results]

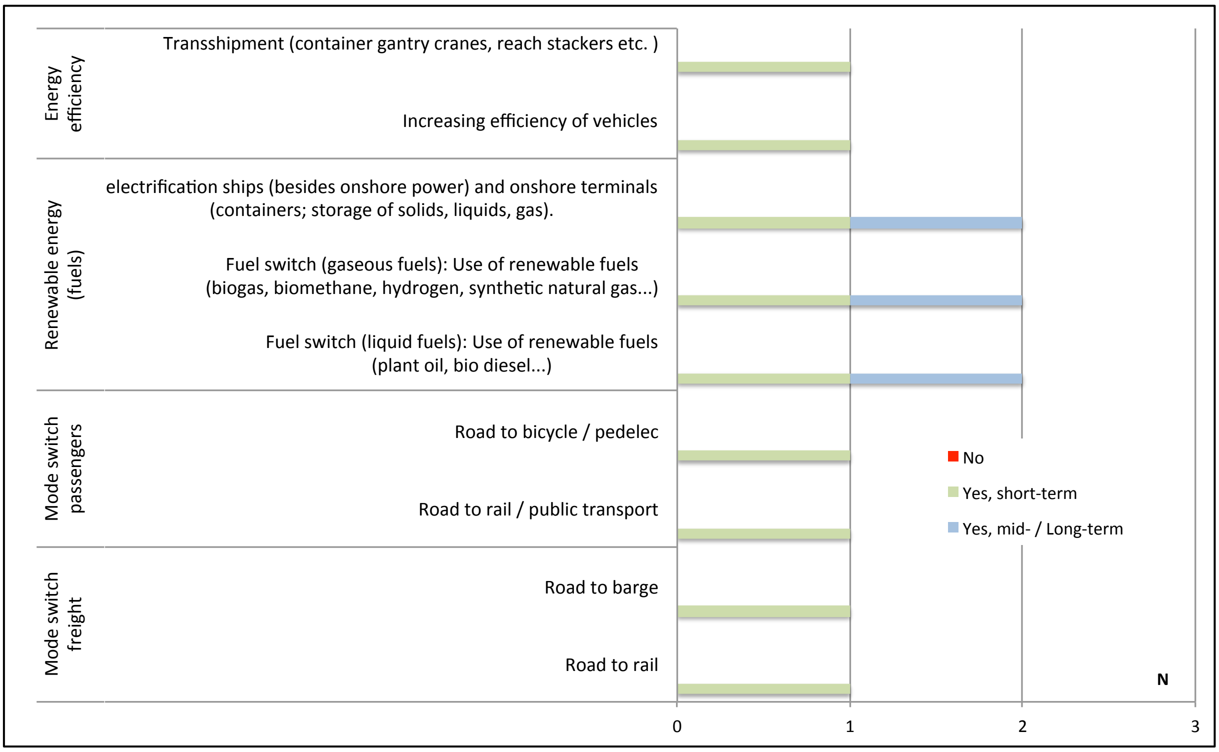


Figure A12: Evaluation of stakeholder questionnaire for the sub-sector of Transport; all technologies [own compilation of results]

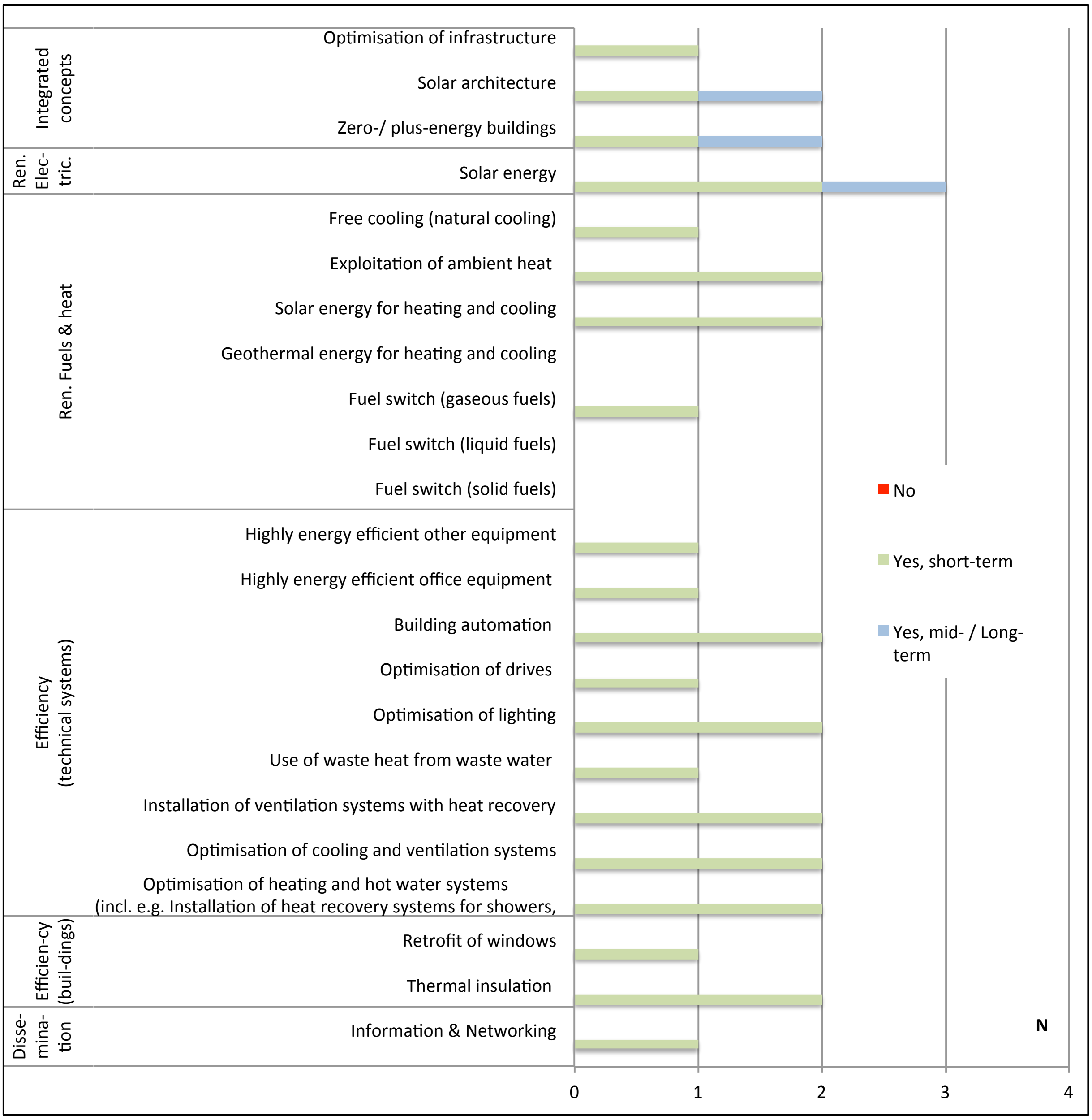


Figure A13: Evaluation of stakeholder questionnaire for the sector of Buildings; all technologies [own compilation of results]

6.3 Appendix C – Workshops

In the second half of the project duration, two workshops were conducted with the double aim of (1) further involving the stakeholders in the process, report and validate the results of the questionnaire and (2) explain the state of work on the scenarios and get stakeholders approval for the story lines and their specific form.

6.3.1 Description (planning, agenda, participants etc.)

The participants of the workshops were recruited from the list of stakeholders that received the questionnaire. So, names and contact details were provided by the Port Authority, who sent out the invitations, as well. The two groups of industry and society stakeholders were divided and invited on two consecutive days, in order to allow the discussion to focus on the specific issues and questions that each group may have. The structure and agenda of the workshop was nevertheless nearly identical. It is show below in Figure A14.

Deep Decarbonisation Pathways: Port of Rotterdam **Workshop with industry stakeholders** ***June 22, 2016, 12:00-17:00*** *Location: World Port Center, Wilhelminakade 909, Rotterdam*	
12:00 – 13:00	**Arrival of participants, get-together and welcoming lunch**
13:00 – 13:15	Welcome and introduction to the project *Caroline Kroes, PoR Authority*
13:15 – 14:00	Introduction of the decarbonization scenarios for the Port region: • Methodology and key assumptions • Preliminary results • Level of agreement between mitigation strategies selected in scenarios and stakeholders' views according to questionnaires *Clemens Schneider, Wuppertal Institute*
14:00 – 14:45	Feedback from stakeholders • Questions • Comments / Opinions *Facilitator: Karin Arnold, Wuppertal Institute*
14:45 - 15:15	**Coffee break**
15:15 – 16:45	In-depth discussion of key issues, including • Future use of biomass • Role of Rotterdam refineries in a shrinking market environment • What kind of new industries in the Port region by 2050? • Key conditions for industry to realize deep decarbonization • [Any further key issues raised by stakeholders during workshop] *Facilitator: Stefan Lechtenböhmer, Wuppertal Institute*
16:45 – 17:00	Wrap-up *Stefan Lechtenböhmer, Wuppertal Institute / Nico van Dooren, PoR Authority*
17:00	**End of Workshop** **Coffee and opportunity for socialising**

Figure A14: Agenda of workshop for industry stakeholders

In the focal point were the sectors of Energy & Utilities and Petrochemicals & Refining, as these are the biggest levers for transformation of the port's industry.

6.3.2 Main results from each workshop (excerpt from summary minutes)

Following the agenda, after the introduction and the brief summary of stakeholder feedback from questionnaire, the presentation of preliminary scenario assumptions and results was the most important topic, before the discussion turned to several topics as selected (energy) technologies.

During and after the presentation the **general objectives of the study and its basic approach** were discussed and clarified by the industry stakeholders, following several questions from participants. It was pointed out by the Port Authority that there is no formal commitment by the Authority to reduce the area's CO_2 emissions by 80 to 95% by 2050. The Port Authority and the Wuppertal Institute explained that instead the study's scenarios are an attempt to explore possible mid- to long-term prospects of the port's industrial cluster by 2050 if the world and/or Europe significantly reduce their GHG emissions in line with their long-term climate policy targets (EU: 80 to 95% GHG emission reduction by 2050 compared to 1990; international community/Paris Agreement: Limiting global warming to significantly below 2 °C). In this case significant changes to the market environment of the port's industries are to be ex The study aims to open up the discussion on two linked topics:

- A) how the Port Authority, the port's industry and other stakeholders can best prepare themselves for this possible future and the changes it brings.
- B) which visions can be developed to take an active role in decarbonising the port's industries, using the advantages of the industrial cluster and if possible using the opportunities provided by the overall climate policy.

It was emphasised by the Port Authority and the Wuppertal Institute that the study does not assume that the port area should reduce its emissions in any case by 80 to 95% by 2050. Instead, the study attempts to identify plausible scenarios of how the port's industry can adapt to a future in which such reductions are achieved in Europe and in which also the rest of the world achieves emission reductions in line with the 2 °C target. It was further noted that one purpose of the study is to help the port community prepare for discussions likely coming up in the future on how the port area can contribute to decarbonization in the Netherlands and Europe.

It was acknowledged that the temporal characteristics of the scenarios i.e. the transition pathways are important for understanding the scenarios and how they can be implemented. The Wuppertal Institute and the Port Authority will discuss what can be done to make the various steps during the transition as clear as possible in the report (given the limitations of time and budget).

Stakeholders stated that a close look at the **boundaries of the greenhouse gas balance** is essential, as emissions in the PoR area can reduce emissions elsewhere, for example by providing chemicals for insulating materials. Also the question was raised on how the study deals with "imported" or "exported" emissions. The Wuppertal Institute responded by pointing out that the study's modelling is restricted to the territorial emissions of the port area but that the expected market environment as well as overall GHG reductions in Europe and the world are taken into account in the scenarios by making consistent scenario-specific assumptions on demand and supply in the rest of Europe and the world (e.g. concerning the likely future demand for fuels in the transport sector).

It was also pointed out that regarding emission reductions, the PoR area does not necessarily need to achieve the same relative change as the rest of Europe. For example in one scenario (scenario "Technological Progress" or "TP") it is assumed that the refineries in the port area are able to increase their market shares compared to today. This increase in market shares makes lower-than-average emission reductions in the PoR territory consistent.

The strong interlinkages of the port's industries are a main reason for today's success and efficiency of the industrial cluster, as some stakeholders stated, so any future changes to one element of this cluster may have negative repercussions for the rest of the cluster.

A considerable part of the industry workshop was dedicated to the **discussion on the framework conditions** that will be required to realize deep decarbonization. Regarding future framework conditions that the industry needs in order to invest in low-carbon technologies, participants *from the industry group* mentioned the following aspects:

- Long-term certainty on carbon prices (spanning at least two decades) is essential to trigger low-carbon investments, this can be realised by a CO_2 price (ETS or carbon tax) that is sufficiently high or that increase over time in a predictable manner.
- The government needs to create certainty by formulating a clear vision (e.g. a "Roadmap to 2050") and then sticking to it. However, regarding this suggestion there appeared to be some level of disagreement among participants, as some participants were highly critical of the government "picking winners" and preferred to rely on the market (in combination with sufficiently high CO_2 prices) to decide future technology developments ("technology neutrality"). Other participants noted that at least in regard to the required infrastructure investments (e.g. electricity grid, CO_2 pipelines), some assumptions on the success of future technologies need to be made by the government/the PoR Authority. One participant also argued that the government cannot support all kinds of technologies through R&D funding but rather needs to make smart choices in allocation R&D resources.
- Consistent policies were called for, including subsidy schemes. The German support for RE technologies in electricity generation was referred to as a positive example.
- As long as low-carbon technologies are considerably more expensive, either environmentally aware consumers (with a higher willingness to pay for environmentally friendly products) and/or investors ("divestment") or an import tax ("level playing-field") are needed to justify/enable their use. However, one participant noted that an import tax on CO_2 intensive products is unlikely to be realised as trade partners can be expected to retaliate with their own import taxes.
- One participant called on the port's industry to coordinate more strongly to secure EU research funds. However, other participants were sceptical that strong R&D coordination among the area's companies is possible, given their different interests and the fact that most companies are large international players that often decide elsewhere about their R&D strategy.

- The need for a positive and appealing vision for the future development of the port's industrial cluster in a decarbonized world was pointed out.

Each of the following frameworks conditions were suggested by at least one participant *of the society group*:

- CCS/CCU could be made obligatory at some point in time for power plants, refineries and petrochemical plants
- The number of EU ETS allowances until 2050 should be determined soon, so that investors have more certainty regarding the reduction in emissions that will be required in the medium and long term. An additional floor price on allowances could provide additional certainty.
- Financial incentives could be introduced (e.g. a "transition fund") for investments in low carbon technologies or RD&D in this area.
- The PoR Authority could use its own regulation to influence economic activity in the port area in the future, e.g. it could prohibit emission intensive plants that do not use CCS/CCU technology. It could also offer reduced taxes in case low-emission technologies are used. The PoR Authority could also provide more incentives for "green" ships, including less CO_2-intensive ships. It could also introduce caps on emissions when granting investment permits or it could provide permits preferably to innovative industries.
- The PoR Authority notes that in general the aforementioned ideas are very good, but the necessity to have a "level playing field" with other ports and areas needs to be taken into account by the PoR Authority when thinking about such measures.
- The PoR Authority was encouraged to use its opportunities as a provider of infrastructure.
- Port could provide electricity to ships
- PoR policy on products produces: companies producing solvents
- It was noted that besides CO_2 emissions, already today other environmental concerns (e.g. NO_x emissions, noise) are being taken into account when deciding on investment permits.
- Waste regulation should be reviewed in order to improve the prospects of circular economy approaches.

The topic of **Carbon Capture and Storage and Carbon Capture and Usage, respectively (CCS/CCU)** was more broadly discussed in the societal group than in the industry group. It was stated, that especially CCU could be promising in the area as the CO_2 could be used by the chemical industry in the future. A starting option could be to upgrade the coal power plants with capture units including the needed infrastructure and then use this infrastructure for biomass or waste CCS or for CCU (e.g. chemicals). One participant noted that the equipment of the port's coal power plants with CCS technology should be assumed to take place between 2020 and 2030, not between 2030 and 2040 as is currently assumed in the preliminary TP scenario. The question was also raised whether coal CCS power plants could possibly also be used in the long-term, even in an environment with very strong GHG emission reductions ("-95% world"). The Wuppertal Institute noted that it doubted that CCS retrofits could achieve the capture rates probably required in such an environment (about 99%) and even then, methane emissions during coal mining mean that such a world will most likely not be able to rely on coal CCS power plants.

Another participant raised concerns about CCS and said that only CCU is seen as an acceptable strategy, noting that allowing coal plants to be equipped with CCS technology would likely mean that these coal plant units would keep running for many more decades ("coal lock-in"). This participant also noted that CO_2 is already used in the region (in greenhouses) and there is more potential that can be exploited in the short to medium term, thus strengthening the vote for CCU. Several participants pointed out that there appears to be little acceptance for onshore storage of CO_2 in the Netherlands (while CO_2 pipelines are accepted by the public), but that there does not seem to be relevant opposition in case of offshore CO_2 storage sites. Finally it was noted that deep geothermal energy could be used to provide the heat required in the carbon capture process, thus enhancing the climate protection contribution.

Another topic of discussion in both workshops with industry and society was the **possible future use of biomass** in the port area. One participant from industry noted that for what purpose (energetic use or material use) to use biomass is a political question that will be decided by political framework conditions. The participant noted that the discussions surrounding the use of biomass and its sustainability will continue in the future, no matter for what purposes biomass will be used. It was noted in both groups, industry as well as society, that biomass could be used in the port area in the future in combination with CCS technology (bioenergy & CCS, "BECCS"), as the port is in a very good position in regard to both biomass and CCS infrastructure. This technology could make the port a future provider of "negative" emissions and might require additional biomass imports. However, it was also pointed out that the life-cycle emissions of biomass need to be taken into account when assessing the CO_2 reduction potential of biomass. The Wuppertal Institute noted that it will consider whether the use of BECCS could be in line with the ATP scenario's storyline, while the use of bio-based solvents could be in line with the SDO scenario's storyline.

While one participant of the societal group was highly sceptical about the use of biomass and did not see any potential for the sustainable use of biomass (other than the very limited use of residues), another participant pointed towards the results of the "Corbey Commission"[22].This commission has released several studies over the past few years and concluded that there is potential for the sustainable use of biomass in the Netherlands.

One participant noted that a cascading use of biomass would be most preferable to make the best use of the limited biomass potential, another participant suggested that biomass should be used as a feedstock to produce solvents and similar products that eventually degrade and emit CO_2. As solvents are produced today in the port area, this was seen as an especially promising future activity. At least in the mid-term (until synthetic fuels are available in sufficient quantities), biofuels could and should be used to substitute for fossil fuels in aviation and possibly

[22] Commissie Duurzaamheidsvraagstukken Biomassa, http://www.corbey.nl

also in shipping, according to one participant. There was a brief discussion about the potential for growing algae in the port area (to be used as biomass), but it was concluded that the space demand for growing algae in relevant volume is too high, especially for the port area with its high land cost.

One participant from industry argued that the future potential of biomass should not be underestimated and that globally the potential for sustainable biomass (including the production of algae) is significant. The Wuppertal Institute and the Port Authority will discuss which biomass technologies can be taken into account in greater detail in a selected scenario.

Regarding **other renewable energy sources in the port area**, it was noted that for the City of Rotterdam (not including the port area) a study exists on the technical potential for the use of PV modules. The potential is estimated to be around 1,000 GWh per year (corresponding to about 1 GW of capacity). Based on this information, the Wuppertal Institute will make an estimate for the long-term PV potential in the port area.

In the port area there is some potential for high temperature (250 °C) deep geothermal energy, which has so far not been considered in the scenarios. With a view to the exploitation of wind energy, participants noted that often times there is local opposition in the Netherlands to any plans to build new onshore wind turbines.

With regard to the **discussion on the possible future use of power-to-heat** in the port's industries, different views were raised about the future competitiveness of power-to-heat applications, as has been briefly mentioned in the earlier Section 6.2.3 with regard to the dissent on power-to-heat. Some participants noted that in the foreseeable future (or during the transition phase) the costs of power-to-heat should be expected to remain high and that the use of steam generated from fuels would make more sense economically. The concern was raised that investments in more efficient steam-using technologies may not be attractive for many years to come if there is a need to switch to power-to-heat applications in the mid-term (e.g. by 2030). As a result, the prospects of power-to-heat could lead to higher emissions in the short to mid term. Another participant pointed out that currently the use of heat is critical for the port's industry and a key reason for the existence of the industrial cluster at the port. One participant argued that even in the long-term there may not be enough sustainable electricity generation for the widespread use of power-to-heat and that any kind of waste heat that is available should always be used before thinking about power-to-heat applications.

In the discussion on the **future of the refinery sector in the PoR area**, one participant noted that Shell and Exxon are currently investing heavily in conversion capacities at their PoR refineries to process heavier fractions and to react to the need for higher middle distillate shares as demanded by the market. Another participant argued that even in the long term demand for kerosene can be expected to remain relevant, due to the high growth rate of the aviation industry. Similarly, another participant suggested that even in a deeply decarbonized world, niche refineries (for asphalt, lube oil, kerosene) may still play a role in the port area.

When asked, what **potential new or transformed industries could operate in the port area** by 2050. the following industries were named by participants as possibly attractive for the port area in a future decarbonized world. Each of the following "future industries" were suggested by at least one participant of either group:

- Aluminium plants
- Ship-building (especially if aluminium and steel producers will be located in the area)
- LNG and/or methanol imports, as energy storage might become a successful business model in the area (e.g. power-to-gas / methanol)
- Pharmaceutical industry
- One participant noted that a promising future technology for using CCS in natural gas power generation could be advanced carbonate fuel cells[23].
- The chemical industry could still play a large role in the future, possibly using alternative processes, energy sources and feedstock
- Similarly, flexible production (e.g. using chlorine storage) could be a business model in a future NL/Europe with high shares of intermittent electricity generation
- Heat storage could also play a growing role in the future
- Process intensification in the chemical sector might be a promising route to reduce emissions, save energy, costs and space
- Establishing an offshore wind industry
- New generation steel manufacturing (not using blast furnaces)
- Making use of CO_2 as a commodity by installing a CO_2 pipeline in which the Port of Rotterdam area may play a central role. One participant pointed out that currently a network of companies and NGOs is exploring the potential for such a CO_2 pipeline, delivering CO_2 not only to greenhouses (as is currently the case in Western Netherlands, see http://www.ocap.nl) but to various other potential users like a TATA steal site: https://www.bloc.nl/bloc-works/co2-smart-grid/
- In the future, there might be potential to use CO_2 in the production of methanol, olefins etc.
- The recycling industry could potentially flourish in Rotterdam, extracting valuable metals from waste, for example.
- The port could become home to data centres.
- Waste incineration (with CCS) could be an option in the future (with waste imported from several region), although one participant was sceptical of this idea, pointing out that the reduction and recycling of waste should always be prioritized when aiming for a sustainable future, with incineration only as the last option.
- Waste pyrolysis could be an alternative use of waste in the future.
- The production of cars could be an option in the future, especially if indeed the steel and possibly also the aluminium industry were to locate in the port area.

[23] http://corporate.exxonmobil.com/en/technology/energy-efficiency/carbon-capture-and-storage/advanced-carbonate-fuel-cell-technology

Closing remarks by the PoR Authority and the Wuppertal Institute

The project team experienced lively discussions at the workshops and were provided by many ideas and suggestions that was taken into consideration in the course of finalisation of the project. It was stressed by the participants as by the Port Authority, that an appealing, positive visions of the future in general and the future of the port are important for the further development of industry clusters. Within that, the definition design of pathways are important, not just the end points. Feedback loops between the port area and the rest of the world need to be taken into account and need to be made explicit in order to work with them for the long-term vision.

6.4 Appendix D – Documentation of the numeric scenario assumptions and results

Capacities in the power sector (incl. Moerdijk power plants), BAU scenario

electricity generation capacities (MW_{el})	2015	2020	2030	2040	2050
coal, w/o carbon capture	2'910	1'870	1'870	1'870	1'870
coal with carbon capture	0	0	0	0	0
natural gas w/o cogen	1'773	1'773	2'037	2'237	600
natural gas with carbon capture in cogen	0	0	0	0	0
natural gas in cogen	2'214	2'214	1'648	817	944
refinery gas w/o cogen	55	55	0	0	0
refinery gas in cogen	55	55	55	0	0
waste with carbon capture	0	0	0	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass	36	36	36	0	0
biomass with CCS w/o cogen	0	0	0	0	0
biomass in cogen	22	22	22	0	0
biomass with CCS in cogen	0	0	0	0	0
photovoltaics	0	0	0	0	0
wind energy	254	336	476	524	597

steam generation capacities (MW_{th}) in CHP	2015	2020	2030	2040	2050
natural gas with carbon capture	0	0	0	0	0
natural gas w/o carbon capture	1'824	1'824	1'169	1'164	1'530
refinery gas in cogen	200	200	200	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass in cogen	36	36	36	0	0
biomass with carbon capture in cogen	0	0	0	0	0

Capacities in the power sector (incl. Moerdijk power plants), TP scenario

electricity generation capacities (MW_{el})	2015	2020	2030	2040	2050
coal, w/o carbon capture	2'910	1'870	0	0	0
coal with carbon capture	0	0	1'391	1'391	1'391
natural gas w/o cogen	1'773	1'773	1'637	2'637	2'000
natural gas with carbon capture in cogen	0	0	1'000	1'500	1'500
natural gas in cogen	2'214	2'214	1'254	53	0
refinery gas w/o cogen	55	55	0	0	0
refinery gas in cogen	55	55	55	0	0
waste with carbon capture	0	0	0	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass	36	36	36	0	0
biomass with CCS w/o cogen	0	0	0	0	0
biomass in cogen	22	22	22	0	0
biomass with CCS in cogen	0	0	0	0	0
photovoltaics	0	50	350	650	950
wind energy	254	304	533	605	605

steam generation capacities (MW_{th}) in CHP	2015	2020	2030	2040	2050
natural gas with carbon capture	0	0	1'000	1'500	1'500
natural gas w/o carbon capture	1'824	1'824	672	34	0
refinery gas in cogen	200	200	200	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass in cogen	36	36	36	0	0
biomass with carbon capture in cogen	0	0	0	0	0

Capacities in the power sector (incl. Moerdijk power plants), BIO scenario

electricity generation capacities (MW_{el})	2015	2020	2030	2040	2050
coal, w/o carbon capture	2'910	1'870	0	0	0
coal with carbon capture	0	0	696	696	0
natural gas w/o cogen	1'773	1'773	1'987	1'987	0
natural gas with carbon capture in cogen	0	0	0	0	0
natural gas in cogen	2'214	2'214	1'254	53	0
refinery gas w/o cogen	55	55	0	0	0
refinery gas in cogen	55	55	55	0	0
waste with carbon capture	0	0	348	348	0
waste with carbon capture in cogen	0	0	0	0	696
biomass	36	36	36	0	0
biomass with CCS w/o cogen	0	0	348	348	0
biomass in cogen	22	22	22	0	0
biomass with CCS in cogen	0	0	0	0	696
photovoltaics	0	50	525	1'020	1'040
wind energy	254	304	573	602	602

steam generation capacities (MW_{th}) in CHP	2015	2020	2030	2040	2050
natural gas with carbon capture	0	0	0	0	0
natural gas w/o carbon capture	1'824	1'824	672	34	0
refinery gas in cogen	200	200	200	0	0
waste with carbon capture in cogen	0	0	0	0	935
biomass in cogen	36	36	36	0	0
biomass with carbon capture in cogen	0	0	0	0	935

Capacities in the power sector (incl. Moerdijk power plants), CYC scenario

electricity generation capacities (MW_{el})	2015	2020	2030	2040	2050
coal, w/o carbon capture	2'910	1'870	1'870	0	0
coal with carbon capture	0	0	0	0	0
natural gas w/o cogen	1'773	1'773	1'987	1'987	0
natural gas with carbon capture in cogen	0	0	0	0	0
natural gas in cogen	2'214	2'214	1'254	53	0
refinery gas w/o cogen	55	55	0	0	0
refinery gas in cogen	55	55	55	0	0
waste with carbon capture	0	0	0	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass	36	36	36	0	0
biomass with CCS w/o cogen	0	0	0	0	0
biomass in cogen	0	0	0	0	0
biomass with CCS in cogen	0	0	0	0	0
photovoltaics	0	50	525	1'020	1'040
wind energy	254	304	573	602	602

steam generation capacities (MW_{th}) in CHP	2015	2020	2030	2040	2050
natural gas with carbon capture	0	0	0	0	0
natural gas w/o carbon capture	1'824	1'824	672	34	0
refinery gas in cogen	200	200	200	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass in cogen	0	0	0	0	0
biomass with carbon capture in cogen	0	0	0	0	0

Capacities in the power sector (incl. Moerdijk power plants), scenario variant CYC-ECE

electricity generation capacities (MW_{el})	2015	2020	2030	2040	2050
coal, w/o carbon capture	2'910	800	0	0	0
coal with carbon capture	0	0	0	0	0
natural gas w/o cogen	1'773	1'773	1'987	1'987	0
natural gas with carbon capture in cogen	0	0	0	0	0
natural gas in cogen	2'214	2'214	1'254	53	0
refinery gas w/o cogen	55	55	0	0	0
refinery gas in cogen	55	55	55	0	0
waste with carbon capture	0	0	0	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass	36	36	36	0	0
biomass with CCS w/o cogen	0	0	0	0	0
biomass in cogen	0	0	0	0	0
biomass with CCS in cogen	0	0	0	0	0
photovoltaics	0	50	525	1'020	1'040
wind energy	254	304	573	602	602

steam generation capacities (MW_{th}) in CHP	2015	2020	2030	2040	2050
natural gas with carbon capture	0	0	0	0	0
natural gas w/o carbon capture	1'824	1'824	672	34	0
refinery gas in cogen	200	200	200	0	0
waste with carbon capture in cogen	0	0	0	0	0
biomass in cogen	0	0	0	0	0
biomass with carbon capture in cogen	0	0	0	0	0

Electricity balance, BAU scenario

electricity balance (TWh)	2015	2020	2030	2040	2050
electricity consumption					
final energy consumption	4.8	4.9	4.6	4.4	4.4
electricity use in water electrolysis	0.0	0.0	0.1	0.4	0.9
electricity use in steam boilers	0.0	0.0	0.0	0.0	0.4
electricity production					
coal, w/o carbon capture	14.6	8.9	8.4	7.9	7.5
coal with carbon capture	0.0	0.0	0.0	0.0	0.0
natural gas w/o cogen	5.1	4.3	5.1	5.6	1.2
natural gas with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
natural gas in cogen	6.7	5.9	5.7	2.6	2.6
refinery gas w/o cogen	0.2	0.1	0.0	0.0	0.0
refinery gas in cogen	0.2	0.2	0.3	0.0	0.0
waste with carbon capture	0.0	0.0	0.0	0.0	0.0
waste with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
biomass	0.1	0.1	0.1	0.0	0.0
biomass in cogen	0.1	0.1	0.1	0.0	0.0
biomass with carbon capture	0.0	0.0	0.0	0.0	0.0
biomass with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
PV	0.0	0.0	0.0	0.0	0.0
wind energy	0.5	0.6	0.9	1.0	1.1
sum generation	27.5	20.2	20.6	17.1	12.4
sum consumption	4.8	4.9	4.7	4.8	5.7
balance (net exports)	*22.7*	*15.3*	*15.9*	*12.3*	*6.7*

Electricity balance, TP scenario

electricity balance (TWh)	2015	2020	2030	2040	2050
electricity consumption					
final energy consumption	4.8	4.9	4.5	4.2	4.2
electricity use in water electrolysis	0.0	0.0	0.1	1.4	4.2
electricity use in steam boilers	0.0	0.0	0.0	0.7	1.3
electricity production					
coal, w/o carbon capture	14.6	8.9	0.0	0.0	0.0
coal with carbon capture	0.0	0.0	6.6	7.0	7.0
natural gas w/o cogen	5.1	4.3	3.7	4.5	2.5
natural gas with carbon capture in cogen	0.0	0.0	1.4	1.9	2.0
natural gas in cogen	6.7	5.9	3.8	0.1	0.0
refinery gas w/o cogen	0.2	0.1	0.0	0.0	0.0
refinery gas in cogen	0.2	0.2	0.1	0.0	0.0
waste with carbon capture	0.0	0.0	0.0	0.0	0.0
waste with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
biomass	0.1	0.1	0.1	0.0	0.0
biomass in cogen	0.1	0.1	0.0	0.0	0.0
biomass with carbon capture	0.0	0.0	0.0	0.0	0.0
biomass with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
PV	0.0	0.0	0.3	0.6	0.8
wind energy	0.5	0.6	1.0	1.2	1.2
sum generation	27.5	20.2	17.0	15.3	13.5
sum consumption	4.8	4.9	4.6	6.3	9.7
balance (net exports)	*22.7*	*15.3*	*12.4*	*9.0*	*3.8*

Electricity balance, BIO scenario

electricity balance (TWh)	2015	2020	2030	2040	2050
electricity consumption					
final energy consumption	4.8	4.8	4.1	5.1	5.1
electricity use in water electrolysis	0.0	0.0	0.1	4.6	16.5
electricity use in steam boilers	0.0	0.0	0.8	2.7	5.4
electricity production					
coal, w/o carbon capture	14.6	8.9	0.0	0.0	0.0
coal with carbon capture	0.0	0.0	2.8	2.4	0.0
natural gas w/o cogen	5.1	4.3	4.1	3.7	0.0
natural gas with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
natural gas in cogen	6.7	5.9	3.9	0.1	0.0
refinery gas w/o cogen	0.2	0.1	0.0	0.0	0.0
refinery gas in cogen	0.2	0.2	0.3	0.0	0.0
waste with carbon capture	0.0	0.0	1.4	1.2	0.0
waste with carbon capture in cogen	0.0	0.0	0.0	0.0	2.1
biomass	0.1	0.1	0.1	0.0	0.0
biomass in cogen	0.1	0.1	0.1	0.0	0.0
biomass with carbon capture	0.0	0.0	1.4	1.2	0.0
biomass with carbon capture in cogen	0.0	0.0	0.0	0.0	2.1
PV	0.0	0.0	0.5	0.9	0.9
wind energy	0.5	0.6	1.1	1.1	1.1
sum generation	27.5	20.2	15.7	10.6	6.2
sum consumption	4.8	4.8	5.0	12.4	27.0
balance (net exports)	*22.7*	*15.4*	*10.7*	*-1.8*	*-20.8*

Electricity balance, CYC scenario

electricity balance (TWh)	2015	2020	2030	2040	2050
electricity consumption					
final energy consumption	4.8	4.8	4.1	3.9	3.9
electricity use in water electrolysis	0.0	0.0	0.1	19.5	40.6
electricity use in steam boilers	0.0	0.0	0.4	1.9	4.7
electricity production					
coal, w/o carbon capture	14.6	8.9	5.6	0.0	0.0
coal with carbon capture	0.0	0.0	0.0	0.0	0.0
natural gas w/o cogen	5.1	4.3	4.1	3.7	0.0
natural gas with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
natural gas in cogen	6.7	5.9	3.3	0.1	0.0
refinery gas w/o cogen	0.2	0.1	0.0	0.0	0.0
refinery gas in cogen	0.2	0.2	0.2	0.0	0.0
waste with carbon capture	0.0	0.0	0.0	0.0	0.0
waste with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
biomass	0.1	0.1	0.1	0.0	0.0
biomass in cogen	0.1	0.1	0.1	0.0	0.0
biomass with carbon capture	0.0	0.0	0.0	0.0	0.0
biomass with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
PV	0.0	0.0	0.5	0.9	0.9
wind energy	0.5	0.6	1.1	1.1	1.1
sum generation	27.5	20.2	15.0	5.8	2.0
sum consumption	4.8	4.8	4.6	25.3	49.2
balance (net exports)	*22.7*	*15.4*	*10.4*	*-19.5*	*-47.2*

Electricity balance scenario variant CYC-ECE

electricity balance (TWh)	2015	2020	2030	2040	2050
electricity consumption					
final energy consumption	4.8	4.8	4.1	3.9	3.9
electricity use in water electrolysis	0.0	0.0	0.1	19.5	40.6
electricity use in steam boilers	0.0	0.0	0.4	1.9	4.7
electricity production					
coal, w/o carbon capture	14.6	3.8	0.0	0.0	0.0
coal with carbon capture	0.0	0.0	0.0	0.0	0.0
natural gas w/o cogen	5.1	4.3	4.1	3.7	0.0
natural gas with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
natural gas in cogen	6.7	5.9	3.3	0.1	0.0
refinery gas w/o cogen	0.2	0.1	0.0	0.0	0.0
refinery gas in cogen	0.2	0.2	0.2	0.0	0.0
waste with carbon capture	0.0	0.0	0.0	0.0	0.0
waste with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
biomass	0.1	0.1	0.1	0.0	0.0
biomass in cogen	0.1	0.1	0.1	0.0	0.0
biomass with carbon capture	0.0	0.0	0.0	0.0	0.0
biomass with carbon capture in cogen	0.0	0.0	0.0	0.0	0.0
PV	0.0	0.0	0.5	0.9	0.9
wind energy	0.5	0.6	1.1	1.1	1.1
sum generation	27.5	15.1	9.4	5.8	2.0
sum consumption	4.8	4.8	4.6	25.3	49.2
balance (net exports)	*22.7*	*10.3*	*4.8*	*-19.5*	*-47.2*

Transport fossil fuel demand (PoR pipeline market), BAU scenario (Mt fuel/a)

	2014	2020	2030	2040	2050
LPG	0.4	0.6	0.6	0.6	0.6
Gasoline	10.0	7.1	5.2	4.8	4.7
Kerosene	9.2	10.2	10.3	10.3	10.6
Diesel 10 ppm	18.5	17.6	17.3	17.3	17.5

Transport fossil fuel demand (PoR pipeline market), TP scenario (Mt fuel/a)

	2014	2020	2030	2040	2050
LPG	0.4	0.5	0.5	0.6	0.5
Gasoline	10.0	7.5	5.7	3.9	2.4
Kerosene	9.2	8.8	6.9	5.5	5.2
Diesel 10 ppm	18.5	17.6	13.1	10	7.2

Transport fossil fuel demand (PoR pipeline market), BIO and CYC scenarios (Mt fuel/a)

	2014	2020	2030	2040	2050
LPG	0.4	0.3	0	0	0
Gasoline	10.0	7.3	4.1	0.6	0
Kerosene	9.2	13.2	11.8	7.8	0
Diesel 10 ppm	18.5	17.4	9.3	1.6	0

Refinery balance, BAU scenario*)

Refinery balance PoR (million metric t/y)

	2015	2020	2030	2040	2050
feed	48	49	34	30	30
ethylene	0.2	0.2	0.2	0.2	0.2
propylene	0.6	0.5	0.6	0.6	0.6
butylene	0.4	0.4	0.3	0.3	0.3
light ends	2	2	2	2	2
naphtha	15	15	11	9	9
middle distillates	19	21	16	13	13
fuel oils	5	1	1	2	2
solids	1	1	2	3	3
residues	6	9	1	0	0

*) Chemicals production from FCC only.

Refinery balance, TP scenario*)

Refinery balance PoR (million metric t/y)

	2015	2020	2030	2040	2050
feed	48	49	34	24	24
ethylene	0.2	0.2	0.2	0.2	0.2
propylene	0.6	0.5	0.6	0.6	0.6
butylene	0.4	0.4	0.3	0.3	0.3
light ends	2	2	2	1	1
naphtha	15	15	11	8	8
middle distillates	19	21	16	10	10
fuel oils	5	1	1	1	1
solids	1	1	2	2	2
residues	6	9	1	0	0

*) Chemicals production from FCC only.

Refinery balance, BIO scenario*)

Refinery balance PoR (million metric t/y)

	2015	2020	2030	2040	2050
feed	48	49	25	4	4
ethylene	0.2	0.2	0.0	0.0	0.0
propylene	0.6	0.5	0.1	0.0	0.0
butylene	0.4	0.4	0.1	0.0	0.0
light ends	2	1	1	0	0
naphtha	15	15	8	1	1
middle distillates	19	21	12	0	0
fuel oils	5	1	1	2	2
solids	1	1	1	0	0
residues	6	9	2	1	1

*) Chemicals production from FCC only. Untreated gas oils are regarded as fuel oil in the standard model reporting. The bulk of the 2040 and 2050 is gas oil, which is a feed to the steam cracker. Fischer-Tropsch fuels are not regarded in the table.

Refinery balance, CYC scenario*)

Refinery balance PoR (million metric t/y)

	2015	2020	2030	2040	2050
feed	48	49	25	0	0
ethylene	0.2	0.2	0.0	0.0	0.0
propylene	0.6	0.5	0.1	0.0	0.0
butylene	0.4	0.4	0.1	0.0	0.0
light ends	2	1	1	0	0
naphtha	15	15	8	0	0
middle distillates	19	21	12	0	0
fuel oils	5	1	1	0	0
solids	1	1	1	0	0
residues	6	9	2	0	0

*) Chemicals production from FCC only.

6.5 Appendix E – Documentation of the WISEE model

Wuppertal Institute System Model for Energy and Emissions (WISEE)

Following Herbst et al. (2012) WISEE can be classified as a bottom-up simulation model, with a very detailed representation of energy system technologies and a low degree of endogenization, *i.e.*, many parameters can be changed by bringing in stakeholders' knowledge. Its focus is on unveiling existing energy efficiency and GHG mitigation potentials rather than finding the optimal pathway to achieve a given target (Hourcade et al. 2006).

Four energy demand sectors are represented in WISEE (industry, households, service and transport). The figure (above) gives an overview on the model architecture with a ***focus on the industry sector***. In the WISEE "Industry" module, more than 20 energy-intensive industrial production processes are described, with all relevant input and output flows, together with various future technology options. The time series of energy intensities for production processes are determined for every sector-specific technology (e.g., electric arc furnace, blast oxygen furnace, steam cracking) and for cross-cutting technologies (e.g., motors, lighting, space heating) in the respective modules. To do this, there are vintage stock models for all major plants in energy intensive industries. The vintage stock models account for all major production stocks individually with their specific age, capacity and efficiency using data from industry reporting to the European Trading Scheme (ETS) and further information from emission reporting by the companies under the pollution prevention directive.

A technology matrix provides base assumptions for the specifications of new investments or replacements (lifetime, efficiency, energy carriers) and their availability dates. Assumptions about lifetimes have been derived from Fraunhofer-ISI (2011) and stakeholder inputs during the process of building stakeholder-based scenarios for energy-intensive industries in the German state of North Rhine Westphalia (NRW) within the NRW Climate Protection Plan. Stakeholders actively helped to construct the assumptions on best available technologies (BAT), *i.e.*, technologically proven and economically viable options. Low Carbon (LC) technologies have been assessed by the Wuppertal Institute based on literature, and were validated by the stakeholders.

Adaption of the WISEE model and scenario calculation
In the context of the *Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam* project the WISEE model (see box above) was adapted and partly extended to get a fit to project-specific questions.

But first of all, an extensive system analysis was carried out to identify the relevant energy and emission intensive processes in the port area. To get the system boundaries right different sources on industry capacity data were analysed, most prominently different editions of the Port Authority's *Facts & Figures* brochure. Platts' database on electricity generation units was the base for the respective database in WISEE. The following industrial production processes were considered in the model with their capacity (in t/y) and (if available) information on commissioning and retrofit.

acetone	FCC gasoline dedicated	PET
atmospheric crude oil distillation	FCC propylene dedicated	Phthalic anhydride
	flexicoking	Polybutadiene rubber
benzene	formaline	polypropylene
butadiene	gas oil hydrotreater	polyvinyl chloride (PVC)
carbon anodes	hycon	propylene
carbon black	Hydrocracker	propylene oxide
catalytic reformer	isobutylene	PTA
chlorine	isopropanol	steam cracker
cyclohexane	MDI	styrene monomers
distillate hydrotreater	MTBE	thermal cracker
epoxy resins	naphtha hydrotreater	titanium dioxide
ethylbenzene	oil gasification	vacuum distillation
ethylene dichlorid	ortho-xylene	vinyl chloride monomer
ethylene glycols	oxo-alcohols	visbreaker
ethylene oxide	para-xylene	

The resource flows connected with the identified processes within the Rotterdam cluster were simulated, taking specific resource demand and yield structures into account.

Specific energy and resource demand of these processes were estimated using literature data on Western European Standard performance (e.g. IEA 2009, Ren 2009, Cefic 2013, JRC 2015 and JRC 2014).

To simulate refinery dispatch and refineries' hydrogen demand a dispatch model was used. This tool calculates the dispatch of refinery stock for any defined year (also the base year 2015) taking specific yields of different crude oils, their sulphur content and the yield structure of the different production facilities into account. The dispatch is determined by optimizing the revenues from processing. The dispatch of the different kinds of processes (ADU, VDU, FCC, cokers, visbreakers, hydrocrackers, reformers and three types of hydrotreating units) was modelled for all five Rotterdam refineries (as one synthetic "Rotterdam refinery") and the Vlissingen refinery. The total results (for all capacities of the six Dutch refineries) could be validated with the Dutch energy balance on refineries.

The data on petrochemical plants and refineries were validated then with statistical data of the European Emission Trading System (ETS) on annual emissions. The ETS provides validated data on the level of single plants.

Power plant use was modelled on an annual basis on the base of assumptions about typical full-load hours (see tables below). Information on existing heat grids within the port area were not available. However, CHP plants within the port area were assigned to nine different virtual heat grids (Botlek and Botlek Refinery, Europoort and Europoort Refinery, Maasvlakte, Moerdijk, Pernis and Pernis Refinery, Indorama). Every petrochemical and refinery site was assigned to one of the heat grids as well. CHP plant utilization was then derived from heat demand and heat generation capacity within the relative grid.

Efficiency of power plant units was derived from operators' websites or assessed according to typical performance of the units according to type and age. Calculated power plant emission data were validated with ETS data again.

The projection of the cluster's production stock and the relevant framework data are described in Chapter 3.

Utilization rates of power plants in the BAU scenario

FLH (h/a)	2015	2020	2030	2040	2050
heat driven base load	6000	6000	5500	5000	4000
heat driven peak load	2000	2000	1500	1250	1000
electricity base load	5000	4750	4500	4250	4000
electricity load following	3000	2500	2500	2500	2000
electricity peak load	1000	1000	1250	1250	1250
Wind onshore	1850	1900	1900	1900	1900
Wind offshore	4000	4000	4000	4000	4000
PV	874	874	874	874	874

Utilization rates of power plants in the TP scenario

FLH (h/a)	2015	2020	2030	2040	2050
heat driven base load	6000	6000	5500	5000	4000
heat driven peak load	2000	2000	1500	1250	1000
electricity base load	5000	4750	4750	5000	5000
electricity load following	3000	2500	2250	2000	1700
electricity peak load	1000	1000	1250	1250	1250
Wind onshore	1850	1900	1900	1900	1900
Wind offshore	4000	4000	4000	4000	4000
PV	874	874	874	874	874

Utilization rates of power plants in the BIO scenario

FLH (h/a)	2015	2020	2030	2040	2050
heat driven base load	6000	6000	5000	4500	4000
heat driven peak load	2000	2000	1500	1250	1000
electricity base load	5000	4750	4000	3500	3000
electricity load following	3000	2500	2250	2000	1700
electricity peak load	1000	1000	1250	1250	1250
Wind onshore	1850	1900	1900	1900	1900
Wind offshore	4000	4000	4000	4000	4000
PV	874	874	874	874	874

Utilization rates of power plants in the CYC scenario

FLH (h/a)	2015	2020	2030	2040	2050
heat driven base load	6000	6000	5500	5000	4000
heat driven peak load	2000	2000	1500	1250	1000
electricity base load	5000	4750	3000	2500	1700
electricity load following	3000	2500	2250	2000	1700
electricity peak load	1000	1000	1250	1250	1250
Wind onshore	1850	1900	1900	1900	1900
Wind offshore	4000	4000	4000	4000	4000
PV	874	874	874	874	874

Scenario Analysis

Beneath energy use and GHG emissions on the level of single facilities, production sites and port area, the model allows to analyse the cluster's product balance (is enough of x produced to provide process y?) and also the regional aspects of heat/steam use. Therefore a GIS interface was used to make regional aspects visible. However, regional analysis depends on the assumptions made. Assumption about the location of a future facility adds an additional level of uncertainty to the existing level about *if* the facility will be built. Assumptions about the retrofit of an existing facility are more robust than assumptions about green field investments. So regional analysis was only carried out in the case of robust assumptions, e.g. in the case of the BIO scenario. In this scenario waste heat and CHP play a very prominent role and the clusters with existing plants or plants to be retrofitted could be clearly identified.

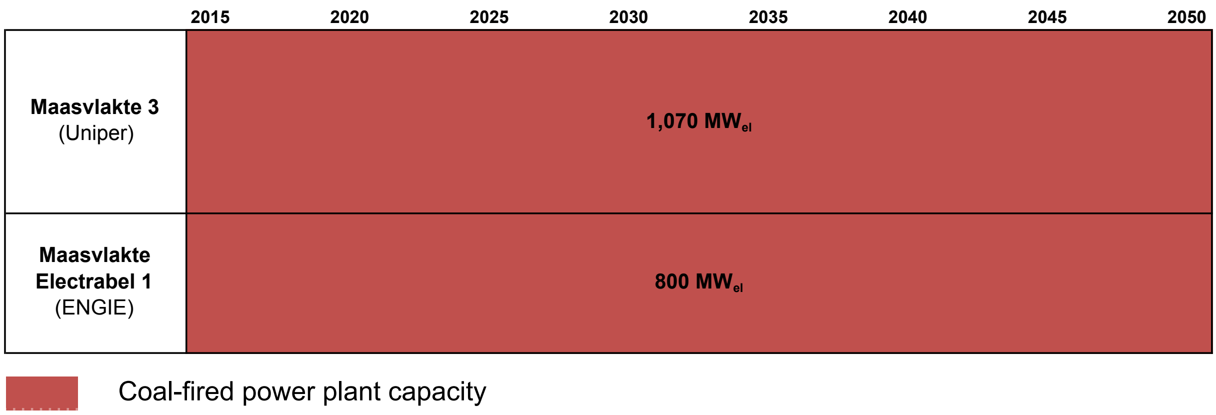
6.6 Appendix F – The future role of coal-fired power plants in the scenarios

Currently, four large coal-fired power plants are operating in the Port of Rotterdam area. Two of them (Maasvlakte 1 and 2, with a combined capacity of 1,040 MW_{el}) are scheduled to be closed by the end of the year 2016. This is taken into account in all of the study's scenarios.

Regarding the two new coal power plants (Maasvlakte 3 with a capacity of 1,070 MW_{el} and Maasvlakte Electrabel 1 with a capacity of 800 MW_{el}), which both started full operation in the year 2015, policymakers and society currently debate on how long and in what form these power plants should operate in the future. In this study's scenarios, very different assumptions have been made regarding the future operation of these two power plants, reflecting differences in the level of climate protection ambition and differences in the mitigation strategies pursued in the respective scenarios. This Appendix provides an overview of how the two new large coal power plants are assumed to be operated in the coming decades in each of the study's scenarios.

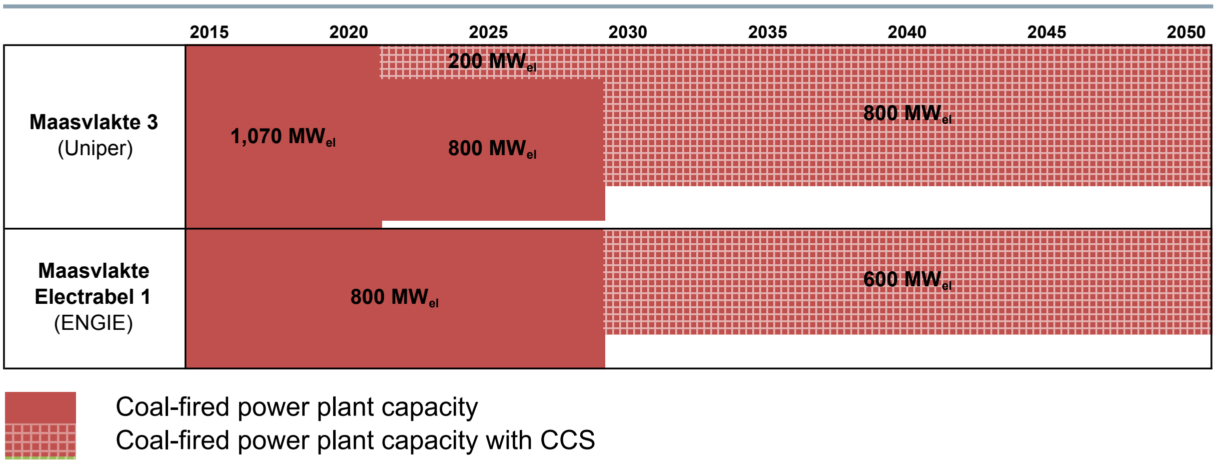
In the BAU scenario, which assumes that no new climate policy measures are enacted, both coal-fired power plants continue to be operated unchanged until the end of their operational lifetime, which is expected to be beyond 2050. As no additional government support for CCS is forthcoming and as CO_2 allowance prices remain low, any efforts to equip one or both of these plants with CCS technology are abandoned.

Scenario BAU:



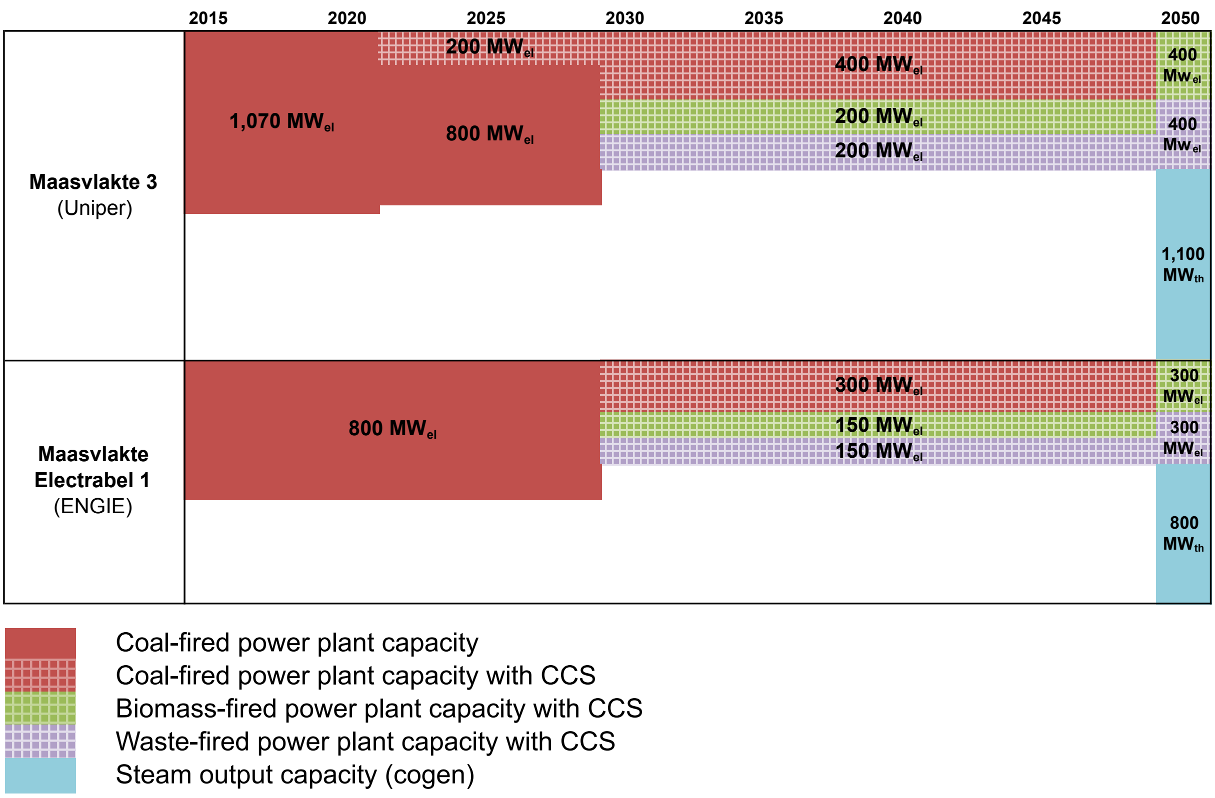
In the TP scenario, climate mitigation efforts in the Netherlands are assumed to be in line with the EU's (lower-end) target of reducing its domestic GHG emissions by 80% until 2050 (relative to 1990). In this scenario, the CCS pilot project ROAD is expected to be pursued further in the coming years and it is assumed that the pilot project is up and running from 2022 on at the Maasvlakte 3 power plant. It is further assumed in this scenario, that the successful operation of this pilot plant will lead to further investments in CCS capacity, with both coal power plants being fully equipped with CCS from 2029 on. Due to the "energy penalty" of capturing CO_2, the electric output of both plants is reduced from its original (combined) 1,870 MW_{el} to 1,400 MW_{el}.

Scenario TP:



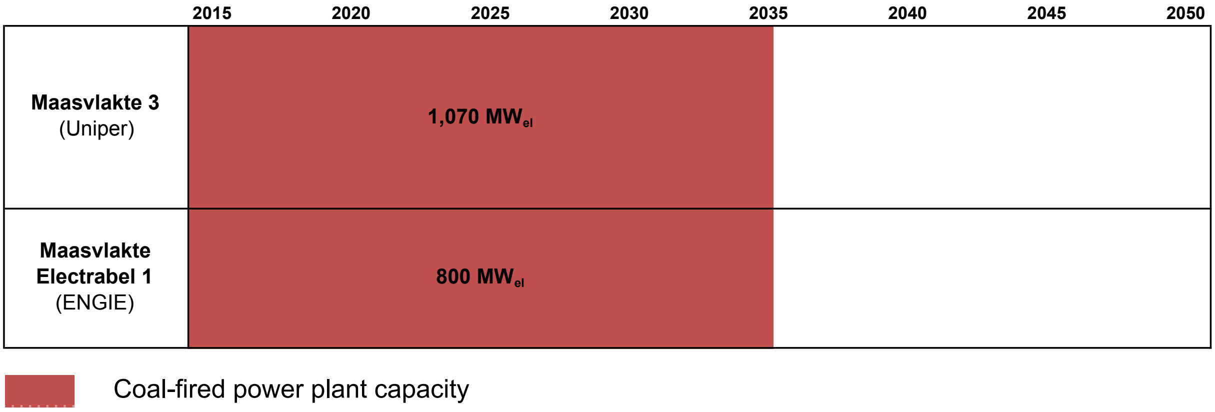
As in the TP scenario, in the BIO scenario the ROAD CCS pilot project will be realised and fully operational from 2022 on and both plants also become fully equipped with CCS by 2029. In addition (and to fulfil the stricter climate protection requirements assumed to be in place in this scenario compared to the TP scenario), in this scenario both plants are assumed to be co-fired to a significant extent with biomass and waste from 2029 on, requiring significant additional investments. Towards the end of the observed scenario period (from 2049 on), it is assumed that both plants run entirely on biomass and waste and it is furthermore assumed that both plants are further modified and expanded to allow for a considerable amount of steam to be generated and fed into a high-temperature heat grid.

Scenario BIO:



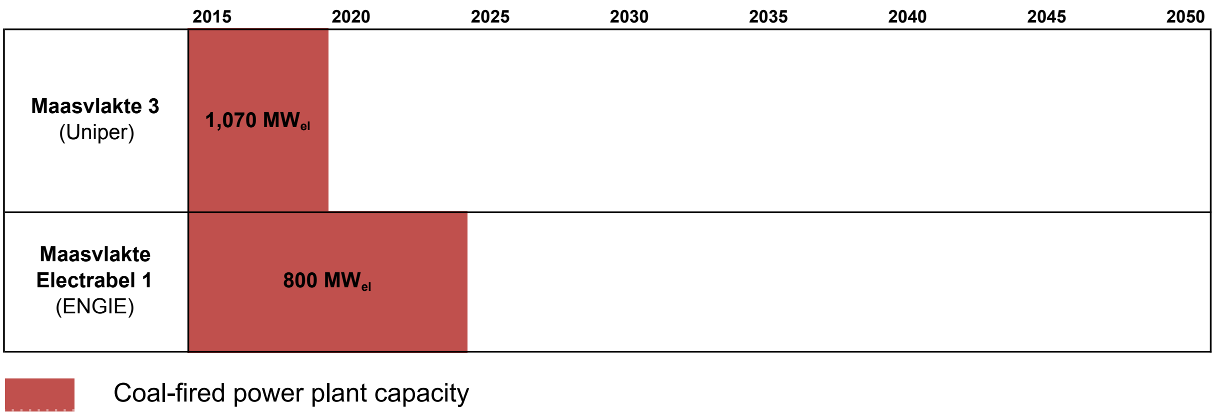
In the CYC scenario, which does not rely on CCS technology, but which assumes that climate protection measures will be as strict as in the BIO scenario, both plants are assumed to stop operating by 2035. While in the regulatory environment assumed in this scenario many other coal power plants in Europe are closed much earlier, it is assumed in this scenario that the two plants in Rotterdam will be among the last coal power plants to be closed in Europe due to their relatively high respective conversion efficiencies.

Scenario CYC:



The CYC-early-coal-exit (CYC-ECE) scenario variant takes into account the current debate in the Netherlands on the future of its coal power plants amid the country’s 2020 and proposed 2030 GHG reduction targets. In line with a recent report by CE Delft (2016), it is assumed that in order to reach the 2020 target of reducing GHG emissions by 25% below 1990 levels (which is actively pursued by the Dutch government in this scenario), one or two of the new coal power plants built in recent years in the Netherlands will need to be closed by 2019. It is assumed in the CYC-ECE scenario variant that the Maasvlakte 3 power plant will be ordered to close down by the end of 2019. With a complete phase-out of the country’s coal power plants assumed by 2029 the latest (reflecting the strict 2030 target recently tabled by the Dutch parliament), we further assume in this scenario variant that the other new coal power plant (Maasvlakte Electrabel 1) will be ordered to stop operating by 2025.

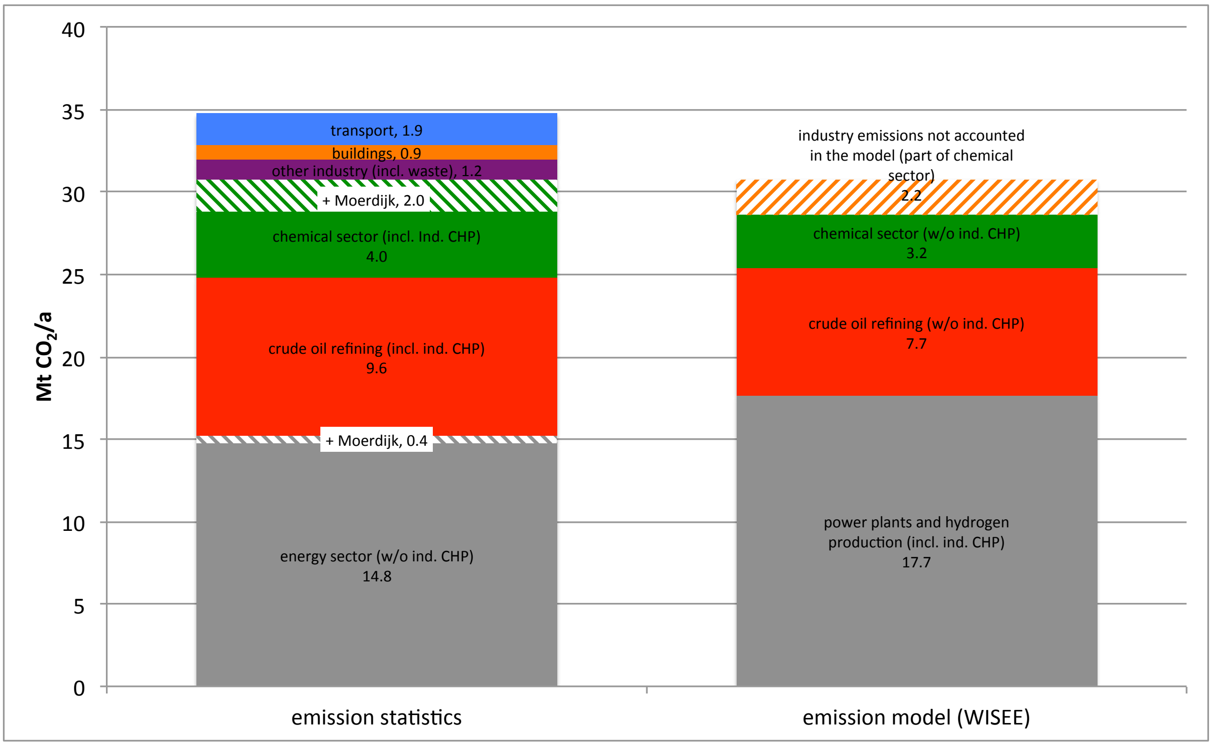
Scenario CYC-ECE



6.7 Appendix G – Comparison of emission statistics and model results for the base year 2015

The following Figure G1 compares the emission statistics of DCMR (for the Port of Rotterdam area) and emissieregistratie.nl (for Moerdijk) with the model results for the study's base year 2015. In the statistics, industrial CHP plants are accounted for under refineries or the petrochemical industry respectively, if the operating company is not an energy company. Process-related emissions of hydrogen production are accounted for under "refineries" (if the refineries produce it themselves) or under "energy companies" (if refineries or the petrochemical industry buy it from a gas provider).

Figure G1: Comparison of emission statistics and WISEE model results (base year 2015)



Source: DCMR (PoR data); emissieregistratie.nl (Moerdijk); WISEE model

Statistical data are contrasted with the model results. The model results are aggregated in another way, summing up all power plants and all hydrogen production, crude oil refining and the chemical sector, respectively. The model results show that the model covers 82% of the port area's emissions reported by statistics. Taking into account that the buildings and transport sectors as well as "other industries" have not been part of the modelling, the model covers 93% of the relevant emissions. An amount of 2.2 Mt/a CO_2 of the chemical sector cannot be explained by the model. The total delta between model results and emission statistics amounts to 6.2 Mt/a. In the projections shown in Chapter 3, this delta is not accounted for. However, in general the emissions not covered by the model can potentially be reduced to a similar extent as those covered by the model.

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