Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam

Sascha Samadi, Clemens Schneider
& Stefan Lechtenböhmer
Wuppertal Institute
Döppersberg 19
D-42103 Wuppertal
Germany
sascha.samadi@wupperinst.org
clemens.schneider@wupperinst.org
stefan.lechtenboehmer@wupperinst.org

Keywords

low carbon industry, decarbonisation, chemical industry, circular economy, energy-intensive processing industries

Abstract

The Port of Rotterdam is an important industrial cluster mainly comprising of oil refining, chemical manufacturing and power and steam generation. In 2015, the area accounted for 18 % of the Netherlands' total CO_2 emissions. The Port of Rotterdam Authority is aware that the port's economy is heavily exposed to future global and EU decarbonization policies, as the bulk of its activities focuses on trading, handling, converting and using fossil fuels. Based on a study for the Port Authority, our paper explores two possible pathways of how the industrial cluster can keep its strong industrial position and still reduce its CO_2 emissions by 98 % by 2050. The "Biomass and CCS" scenario 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. 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 and feedstocks in Western Europe. The "Closed Carbon Cycle" scenario assumes that renewables-based electricity will be used at the port to supply heat and hydrogen for the synthetic generation of feedstock for the chemical industry. The carbon required for the chemicals will stem from recycled waste. Technologies particularly needed 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 paper compares both scenarios with regard to their respective technological choices and infrastructural changes. The scenarios' particular opportunities and challenges are also discussed. Using possible future pathways of a major European petrochemical cluster as an example, the paper illustrates options for deep decarbonisation of energy intensive industries in the EU and beyond.

Introduction

The Paris Agreement adopted in December 2015 by 195 countries aims to strengthen the global response to the threat of climate change by "[h]olding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC 2015). The agreement, which entered into force in November 2016, intends to do so by achieving "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". The agreement requires countries to intensify their respective strategies and policies towards this aim.

Modelling studies (Akimoto et al. 2017; Rogelj et al. 2015) suggest that in order to have a good chance to limit warming to well below 2 °C, global energy-related GHG emissions will need to be reduced quickly in the coming decades and may need to be close to zero by the middle of the century. This will require a massive transformation of all sectors of the economy. For the industrial sector the transformational challenges might be considered particularly large given its variety of different technologies and production processes, its competitive nature and its often times long reinvestment periods. We therefore believe there is a strong and urgent need to develop possible pathways for the long-term decarbonization of industrial sectors and industrial clusters. Such pathways can provide crucial support to policymakers and investors for taking appropriate near-term measures and actions that would enable a sufficient level of decarbonization in the decades to come.

Although scenario studies on the potential to deeply decarbonize entire economies (e.g. IEA 2017, Greenpeace et al. 2015) or individual industrial sectors such as the chemical sector (Dechema 2017) have become more numerous in recent years, to our knowledge, no long-term, deep-decarbonization scenarios for a specific industrial region or cluster have been developed before. We believe that such regional studies constitute an important complement to the more general studies, as they can better reflect the specific technologies, market environments and mitigation potentials at a certain location, taking into account their specific interlinkages and infrastructures, increasing the significance of such studies for regional policymakers, investors and other stakeholders. Furthermore, such regional scenario studies may also help to increase public acceptance for the transformation process, especially if they adequately involve stakeholders in the process of scenario development (Schneider et al. 2014). Ideally, these studies can help the involved companies to expand their horizons and to anticipate and pro-actively embrace potential radical future market and regulatory changes.

This article illustrates options for deep decarbonisation of energy intensive industries in the EU and beyond by describing possible future pathways of a major European petrochemical cluster, namely the industrial cluster of the Port of Rotterdam. The bulk of the port's economic activities focuses on trading, handling, converting and using fossil fuels, making the port's businesses particularly vulnerable to global and European decarbonization efforts. 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. The two deep decarbonisation scenarios focused on in this article intend to highlight that different deep decarbonization pathways can be imagined for an industrial cluster such as the one at the Port of Rotterdam, that both achieve a 98 % reduction in energy-related CO_2 emissions between 2015 and 2050.

The following section provides the background for the study prepared in 2016 that this article is based on. Subsequently, the approach of the study and particularly the modelling framework used to derive the quantitative scenarios is explained. The two developed deep decarbonization scenarios are then described in detail, before their respective challenges and opportunities are discussed. Finally, conclusions and key insights are derived.

Background

Besides being the largest seaport in Europe with an annual throughput of around 465 million tonnes in 2015, the Port of Rotterdam also comprises one of the largest European industrial clusters. Stretching 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 2017).

The port's industrial cluster is made up to a great extent of companies operating in the energy-intensive sectors of oil refining, chemical manufacturing and power and steam generation. In 2015, the area's CO_2 emissions[1] totalled approximately 30 Mt and made up 18 % of the Netherlands' total CO_2 emissions. The cluster's CO_2 emissions grew by 48 % between 1990 and 2015, mainly because 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.[2] 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 below also include industrial activity in the Moerdijk port area, as the industrial complex in Rotterdam has strong ties to the industrial complex in Moerdijk. Moerdijk's CO_2 emissions from large industrial source totalled just over 2 Mt in 2015, mainly from the chemical industry and the power and heat sector.

The Port of Rotterdam Authority is aware that future global and EU decarbonisation policies will affect the port's industrial cluster, as the bulk of its economic activities focuses on trading, handling, converting and using fossil fuels. This makes the port's businesses particularly vulnerable to global and European decarbonisation efforts.

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 (Rotterdam Climate Initiative 2009b). 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.

Against this background and in light of the targets agreed upon in the Paris Agreement, the Port Authority in early 2016 commissioned the Wuppertal Institute to conduct a study (Samadi et al. 2016) on Decarbonisation Pathways for the Industrial Cluster of the Port of Rotterdam[4]. The study intended to explore the potential challenges and opportunities of European

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[1] 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 have therefore not been taken into account in this analysis.

[2] 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 levels.

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

[4] The study can be downloaded at https://www.portofrotterdam.com/nl/file/18544/download?token=4Ri58reM.

decarbonisation efforts for the port's industrial cluster, both in terms of the future demand for the companies' products as well as in terms of changes towards less carbon-intensive production processes. To this end the study identified possible scenarios on how the port can prepare for such a future and how it can take a pro-active stand towards deep decarbonisation.

Approach and modelling framework

The scope of the study's energy and GHG modelling is the territory of the Rotterdam port area (including the industrial site of Moerdijk south of Rotterdam) and the direct CO_2 emissions which occur within this area. Emissions caused by the extraction of resources processed at the port and by the use of the port's products also impact 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 that might emerge in the port under different socio-political and regulatory environments. For these potential future clusters, respective CO_2 emissions are quantified.

Based on the business environments foreseen by an assumed decarbonization framework, plausible economic visions for the industrial cluster were derived. Specifically, four energy and CO_2 emission scenarios for the port's industrial cluster were developed and quantitatively modelled, including one business-as-usual scenario and three CO_2 emission mitigation scenarios. In this paper, we mainly focus on the study's two most ambitious mitigation scenarios (the BIO and CYC scenarios), which both achieve a 98 % reduction in CO_2 emissions by 2050 compared to 2015 levels and can be regarded to be broadly in line with the targets of the Paris Agreement. The focus on these two scenarios was chosen to highlight that from today's perspective, different deep decarbonisation pathways can be imagined for industrial clusters in terms of technologies, infrastructures and resource-bases, and to discuss the relative advantages and disadvantages of the respective pathways. The selection of technologies in all of the study's scenarios was informed inter alia by a survey among the port's industrial stakeholders and initial scenario results were discussed with stakeholders in two workshops and refined based on the feedback received.

The sectoral system boundary of analysis was restricted to electricity generation, waste incineration and the petrochemical cluster within the analysed area. 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.

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 the literature and the results were validated with data from the European Union Transaction Log (EUTL) of 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 (distillation units, catalytic crackers, 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) was validated with the data on refineries from the Dutch energy balance.

The steam supply of the different sites along the harbour was modelled taking existing CHP capacities into account. Steam outputs and inputs of processes were balanced using a simplified approach, neglecting different steam pressure levels or discontinuities of steam supply via excess heat and steam demand.

Based on the system analysis for the base year, the study's four 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 (IEA 2015, Greenpeace et al. 2015). The European scenarios provide time series on the volume and structure of transport fuel demand, the pathway of investments in renewable electricity generation capacities (such as onshore and offshore wind, PV, geothermal energy etc.), the primary energy use and the sectoral CO_2 emissions. The EU scenario results were broken down to the relevant markets, especially the transport fuel markets.

The clusters that were envisioned were tested with Wuppertal Institute's WISEE energy and emission system model (see Figure 1 and Schneider et al. 2014) in regard to technical feasibility, energy demand and emission reduction potential (backcasting approach). Future refinery dispatch was modelled using 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. Representations of 2050 clusters were rejected if a plausible pathway could not be found.

The "Business-as-usual" and "Technical Progress" scenarios

As a background, the "Business-as-usual" and "Technical Progress" scenarios are briefly introduced in this section. The two deep decarbonisation scenarios, which are the focus of this paper, are described in detail in the subsequent sections.

The "Business-as-usual" (BAU) scenario follows a business-as-usual path for the EU (EC 2013), which envisions only little further decarbonisation in the industry, refinery, power

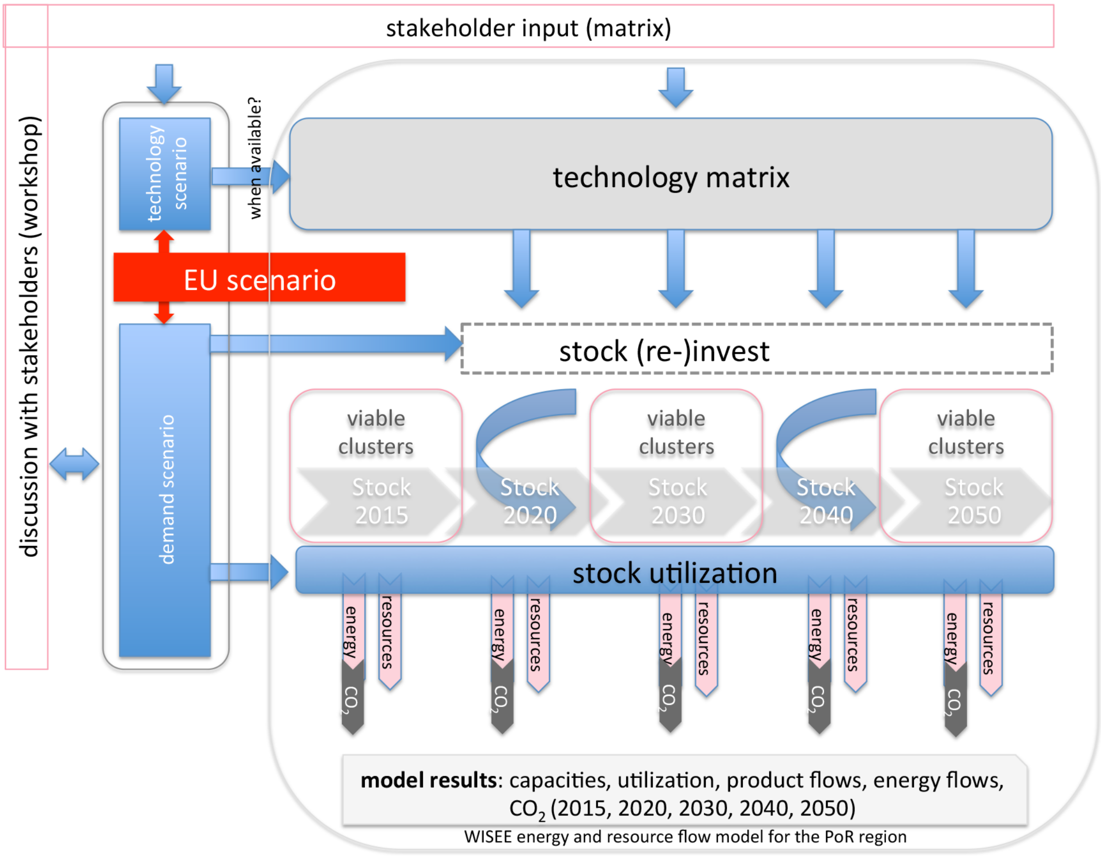

Figure 1. Schematic diagram of the model used to develop the scenarios.

plant and transport sectors. Under such circumstances, the port region can maintain its business models of producing fuels and chemicals synergistically based on crude oil and can continue operation of the fossil-fired power plants with considerable load hours. The refinery sector shrinks to some extent due to efficiency improvements in the transport sector and existing overcapacities in the North-Western European markets.

The "Technical Progress" (TP) scenario follows a scenario developed by the IEA (2015) as a global (pre-Paris) 2-degrees scenario, where the EU reaches a GHG reduction of roughly 80 % compared to 1990. A reduction of 80 % leaves relevant amounts of remaining emissions, which in IEA's energy scenario is "used" to allow for fossil fuel use in transport (especially heavy road freight, aviation and navigation), in heat production and for some non-captured CO_2 in the carbon capture process at coal and gas-fired power plants. In this scenario, the port has to adapt its "oil business model" and its "coal business model". Refinery outputs shrink to a large extent, but the refineries are still suppliers of transport fuel and petrochemical feedstock. The big coal and gas power stations as well as carbon intensive refinery processes like FCC and hydrogen production from steam reforming are equipped with carbon capture and connected to an offshore CO_2 pipeline. Although the TP scenario displays a higher emission level in 2050 than the BIO scenario, larger amounts of CO_2 need to be geologically stored than in the BIO scenario. Consequently, the development of even more distant gas fields will eventually become necessary in this scenario.

The two deep decarbonisation scenarios

In the following, an overview of the two high ambition decarbonisation scenarios is provided. Both decarbonisation scenarios assume that the EU aims for a more ambitious 90 % to 95 % GHG emission reduction until 2050 (relative to 1990) and that respective policies are enacted.

As mentioned above, the general assumption about the future clusters is that they still participate in the markets they supply today, i.e. the supply of fuels and petrochemicals. Whereas fuel supply is assumed to be substantially lower in line with projections for the EU (see above), the production of chemical products is assumed be stable – which is a simplifying assumption taking great differences in the projections of future demand in and trade of chemical products into account (IEA 2013, Cefic 2013, Dechema 2017).

Generating and selling electricity is also an important business within today's industrial cluster. In this respect, we analysed how generation capacities within the port might evolve under certain market conditions for different types of power plants. In the European framework scenarios used, the electricity generation mix in 2050 differs substantially from today's mix. Consequently, electricity generation at the port will also change: In the BIO case the application of CCS is an option to continue the operation of thermal power plants, but coal will eventually be substituted by biomass and waste. Without this option, and as in the CYC scenario, electricity generation in the port will eventually be restricted to wind turbines and PV modules. Due to space limitations within the port area, the potential to apply these technologies is relatively low in terms of

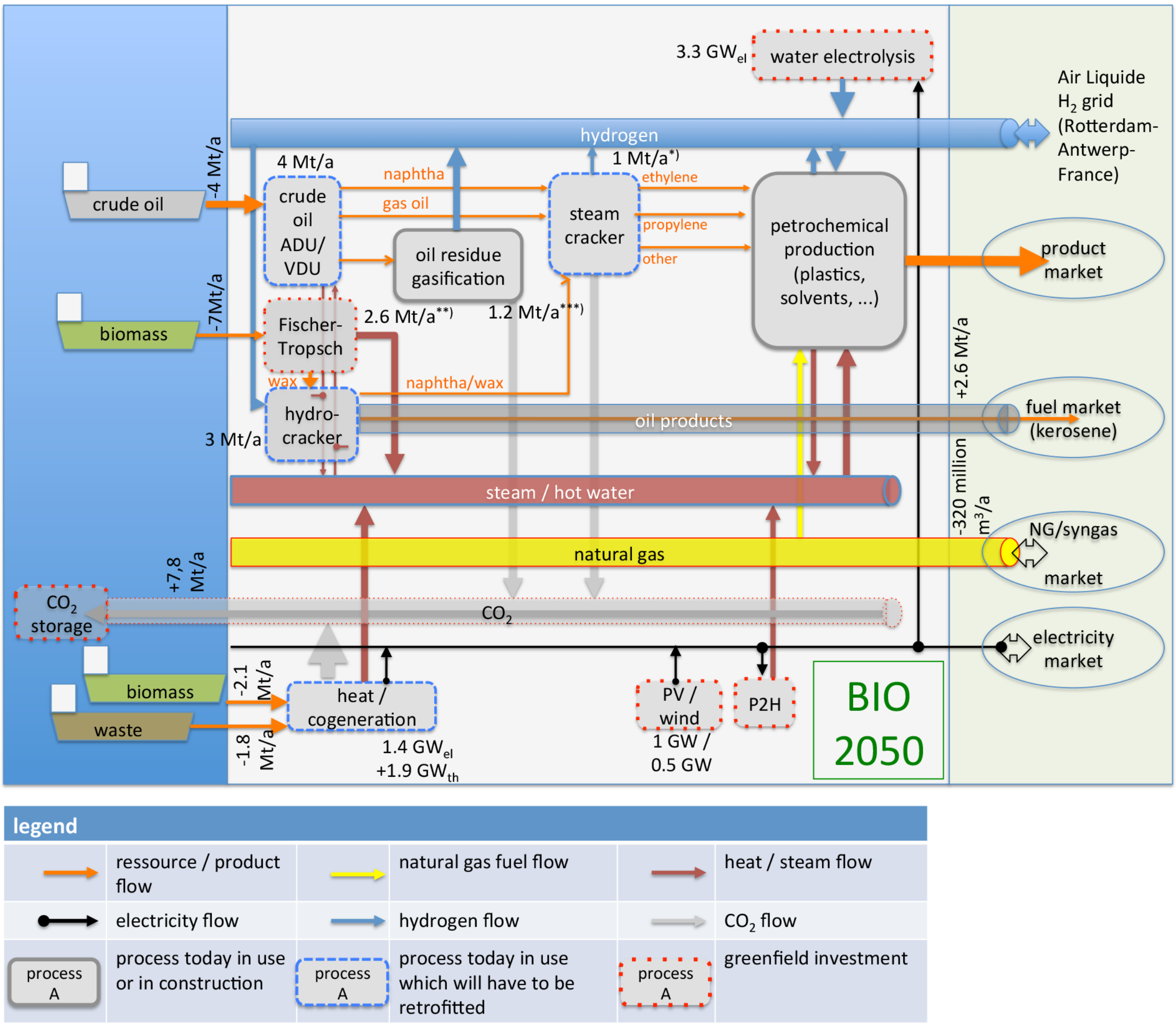

Figure 2. The port's industrial cluster in the BIO scenario (2050). Source: Own graph. Remarks: Figures in rotated text indicate annual flows, figures in text with horizontal orientation indicate capacities of stock.

**) capacity based on ethylene output*

***) capacity based on gasoil output*

****) capacity based on oil conversion*

electricity generation compared to centralised thermal power stations (see Figure 4).

THE "BIOMASS AND CCS" SCENARIO

In regard to key decarbonisation technologies, the "Biomass and CCS" scenario (BIO) assumes that large amounts of biomass can be supplied sustainably. In sum, 140 PJ or 9 million tons of (dry) biomass are needed annually by 2050 as a feedstock and would need to be imported from abroad via vessels. This compares to 4 million tons of coal and 50 million tons of oil, which were calculated to be the cluster's annual demand in the scenario's base year 2015.

Figure 2 shows that the conversion of the industrial cluster along the lines of the BIO scenario requires significant additional investment (indicated with a red-dotted line around the process boxes): CO_2 pipelines connect different sources within the port area, among them processes with relatively pure CO_2 streams ("low-hanging fruits") such as steam reformers producing hydrogen from natural gas or oil residue gasification plants. In addition, storage sites and infrastructure need to be developed: The CO_2 captured 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. In close proximity to this field there are other possible deposits with a combined storage capacity of 100 Mt (TNO 2011). However, the total amount of CO_2 that is to be captured and stored in the BIO scenario over the full period of CCS application between 2022 and 2050 equals 158 Mt. 80 Mt can be attributed to refineries and the steam cracker and 78 Mt to the coal and (later on) biomass/waste-fired power plants. As a consequence, the CO_2 storage infrastructure would need to be extended in the future. The total technical potential to store CO_2 in the Netherlands has been estimated to be 3,000 Mt (Koornneef et al. 2008). An extension of the CO_2 grid to the North of the Netherlands could make further large storage sites accessible and would also allow the inclusion of additional CO_2 sources from beyond Rotterdam, especially from the steel industry.

Another crucial greenfield investment in the BIO case is Fischer-Tropsch technology to produce synthetic fuels from syngas, which plays an important role in this scenario, allowing the port to become a key cluster for the production of synthetic fuels in Western Europe.

Further investments are needed on the commodity supply side: hydrogen is produced by water electrolysis and steam is supplied by local geothermal sources and Power-to-Heat technology. Other infrastructure either needs to be *reinvested* (blue-dotted lines around the process boxes), such as heat and cogeneration plants due to end of lifetime of existing technology or needs to be extended, such as the hydrogen and probably the electricity grid. Reinvestment of the Moerdijk steam cracker (commissioned in the 1970s) is crucial in this scenario. It enables the cluster to continue the processing of oil products to chemical feedstocks.[5] The steam cracker reinvestment itself does not necessarily lead to a lock-in of the cluster, as imported or domestically produced and biomass-derived Fischer-Tropsch products could also be processed instead of oil if the design of the cracker allows for flexibility – which today is the standard when reinvesting. However, the reinvestment of one of the oil refineries, which coincides with steam cracking reinvestment in this scenario (in combination with CCS), eventually leads to an oil lock-in of the cluster in this scenario – so a later change of the pathway towards an alternative feedstock (as in the CYC case) would become difficult.

THE “CLOSED CARBON CYCLE” SCENARIO

The “Closed Carbon Cycle” scenario (CYC) on the other hand assumes that plenty of renewables-based electricity will be used at the port to supply heat as well as hydrogen for the synthetic generation of feedstock for the chemical industry. The carbon required for the chemicals will stem from recycled waste (see Figure 3). Technologies and investments particularly needed 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. In the CYC scenario we choose a methanol route to supply olefins to the chemical cluster. This allows for a dedicated production of olefins from syngas. Other possible routes could have been an ethanol-based olefin production or steam cracking of Fischer-Tropsch intermediates – the latter being a possible further evolution out of the path described in the BIO case.

The bulk of electricity needed in this scenario goes into water electrolysis supplying the hydrogen needed for methanol synthesis. During the gasification of polymer plastic waste for example, 30 % to 40 % of hydrogen is lost as heat (Brems et al. 2013). Furthermore, the share of hydrogen contained in olefins related to hydrogen contained in the MTO educt methanol is lower than 50 %[6]. So in sum only around 30 % of hydrogen bound in the waste polyethylene will end up in the newly produced raw (poly-)ethylene – the remaining amount needs to be re-supplied by water electrolysis.

A complementing heat network is installed, connecting geothermal sources as well as the industrial heat sources and sinks. Due to the great extension of the entire industrial area, heat transmission could be based on hot water instead of steam. The required energy delta to supply steam in different conditions could then be delivered by decentralised power-to-heat stations and compressors.

In the CYC scenario, only the most downstream parts of the fuel supply value chains remain at the port. Hydrocrackers process imported bio-based intermediates to deliver the relatively small part of hydrocarbon liquid fuels (especially kerosene for aviation or diesel for navigation) still used in the transport sector.

By 2050, the BIO as well as the CYC scenario achieve CO_2 emission reductions of 98 % compared to 2015. The BIO scenario has the lowest cumulated CO_2 emissions over the scenario period, with 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 for the 35 years from 2015 to 2050 will only be achieved due to the assumed 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. The BIO scenario is built on two pillars, CCS and massive energetic use of biomass and the realisation of both pillars might encounter difficulties resulting from potential negative sustainability effects. When applying CCS, CO_2 needs to be stored for at least several hundred years to fulfil the requirements of the Dutch legal framework for CCS. On the other hand, global sustainable biomass potentials are limited and in the BIO scenario by 2050, the port’s industrial cluster alone exceeds the estimated per capita amount of sustainable biomass that could be assigned to the Netherlands as a whole.[7]

The development of cumulative emissions in the CYC scenario demonstrates that limiting long-term cumulative emissions of CO_2 is also possible without the use of CCS. In this case, however, the fact that the two new coal-fired power stations are assumed to operate until 2035 without CCS added[8] results in higher cumulated emissions compared to the BIO scenario (500 Mt vs. 420 Mt), where emission cuts are realized earlier. This is not inevitable, of course, as a scenario variant (CYC-ECE) shows. With an earlier exit from coal-fired power generation, total cumulative emissions similar to the BIO case may be achieved. Both scenarios show that it would be possible

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[5] Materials derived from crude oil will typically end up as fossil CO_2 emissions from waste incineration after the end of the use phase of the materials if carbon is not recycled in a gasification or pyrolysis process or the remaining CO_2 is not geologically stored when incinerating the waste. Incinerating the amounts of ethylene and propylene produced annually would result in an emission level of around 7 Mt/a.

[6] This calculation is based on a total olefin yield of 37 % (mass-%) according to Tian et al. (2015), who give a specific methanol demand of 2.67 t of methanol per ton of olefin, resulting in a 43 % share of hydrogen bound in olefins.

[7] In the BIO scenario, 136 PJ of woody biomass is required annually by the port’s industry by 2050 for biofuels production and BECCS. Based on several available studies (Zeddies et al. 2014, Schweinle et al. 2010, Thrän et al. 2010), we assume that the world’s sustainable forestry biomass potential is around 20 to 30 PJ. The population of the Netherlands or the EU (17 million or 507 million people) currently represents about 0.2 % or 6.9 % of the global population. The 136 PJ represent between 0.45 % to 0.68 % of the 20 EJ to 30 EJ mentioned above. This suggests that the need for sustainable biomass in the in the BIO scenario in the port’s industrial cluster alone exceeds the per capita amount that could be assigned to the Netherlands as a whole and represents about 7 % to 10 % of the EU’s total share in global sustainable biomass potential. For a more detailed discussion, please refer to Section 3.5 of the full report (Samadi et al. 2016).

[8] It should be noted that the new Dutch government’s coalition pact of October 2017 states that all coal-fired power plants in the Netherlands should be shut down already by 2030 (Reuters 2017).

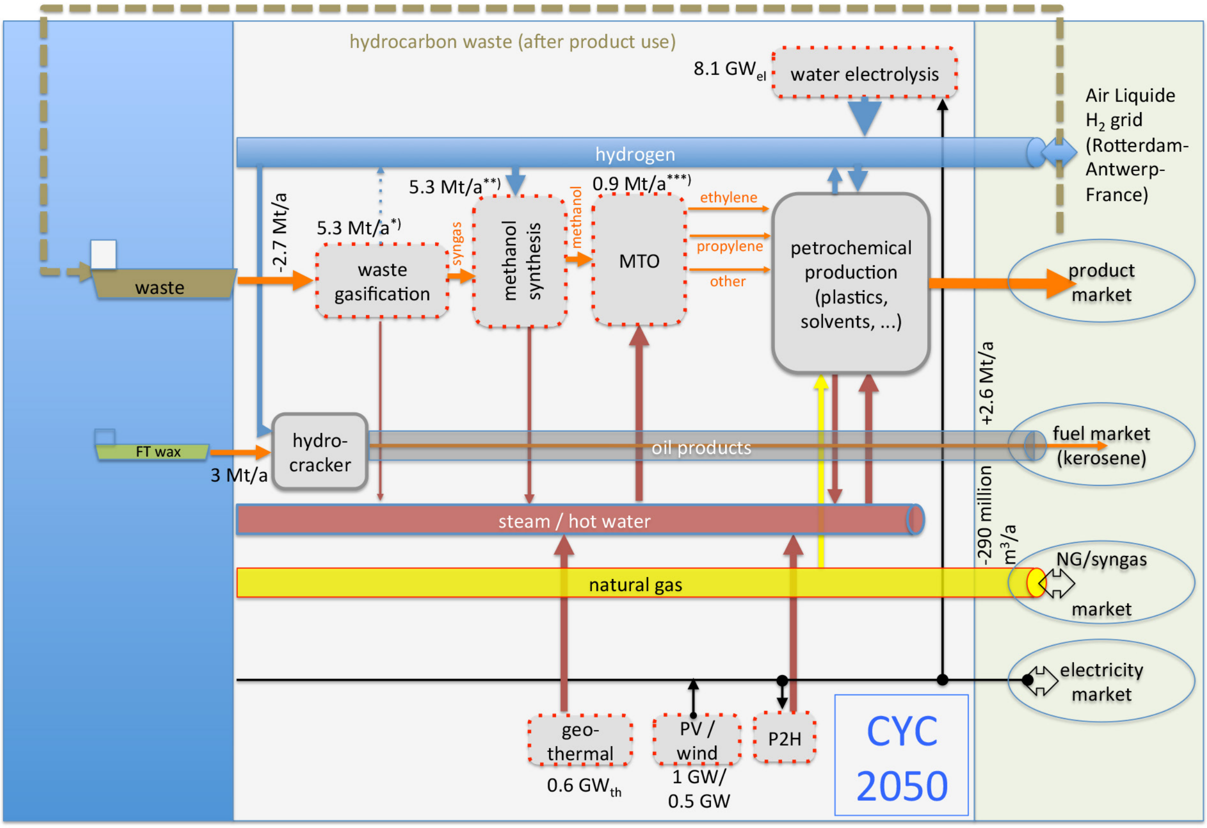

Figure 3. The port's industrial cluster in the CYC scenario (2050) – See legend in Figure 2. Source: Own graph. Remarks: Figures in rotated text indicate annual flows, figures in text with horizontal orientation indicate capacities of stock.

**) capacity based on carbon monoxide output*

***) capacity based on methanol output*

****) capacity based on ethylene output*

to limit total future CO_2 emissions of the Port of Rotterdam industrial cluster to slightly more than 400 Mt.

Finally, Figure 4 displays the electricity balance of the port in 2015, as well as in 2030 and 2050 in the BIO and CYC scenarios.

According to our bottom-up estimates (Samadi et al. 2016), the port area produced around 28 TWh of electricity in 2015, but consumed only 5 TWh[9]. By 2030, the port will still be a net exporter of electricity in the two scenarios, as both, the cluster's production as well as its consumption will decline. Consumption will decline due to significant energy efficiency improvements and the closing of parts of the refinery capacity. By 2050, however, the port will have become a significant net importer of electricity in both scenarios. In the BIO scenario, 21 TWh will need to be net imported (e.g. from the North Sea region) and 47 TWh in the CYC case.

The study therefore emphasises the need for an ambitious expansion of electricity generation from renewable energy sources in a sustainable manner in the Netherlands and Europe.

Discussion of the port's future challenges and opportunities

In this section we focus on a discussion of the challenges and opportunities for the port's industrial cluster that would be associated with its pursuit of deep decarbonisation until the middle of the century. That said, the cluster may of course also follow a business-as-usual development or a less ambitious CO_2 emission reduction strategy in the coming decades. The main advantage of pursuing such a less radical development is the ability for companies to continue to rely on the business model that has made them successful in past decades. No significant – and potentially risky – new technology and infrastructure investments would need to be made, and incremental energy efficiency improvements could instead continue to be pursued. However, the mid to long-term risks of not pursuing strong emission reductions – and instead realizing investments that sustain the cluster's carbon lock-in for decades to come – are large: If the world (or just parts of the world including Europe) will indeed undertake ambitious climate change mitigation efforts in the coming years and decades, as foreseen by the Paris Agreement and the EU's emission reduction targets, strong mitigation policies will be forthcoming in the near to mid-term future. These policies would almost certainly lead to or take the form of high CO_2 prices – which could render much of the cluster's current in-

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[9] The electricity consumption calculated for the base year 2015 neglects a significant number of smaller electricity consumers such as buildings, oil pumping and dock cranes. This demand could not be assessed due to a lack of available data.

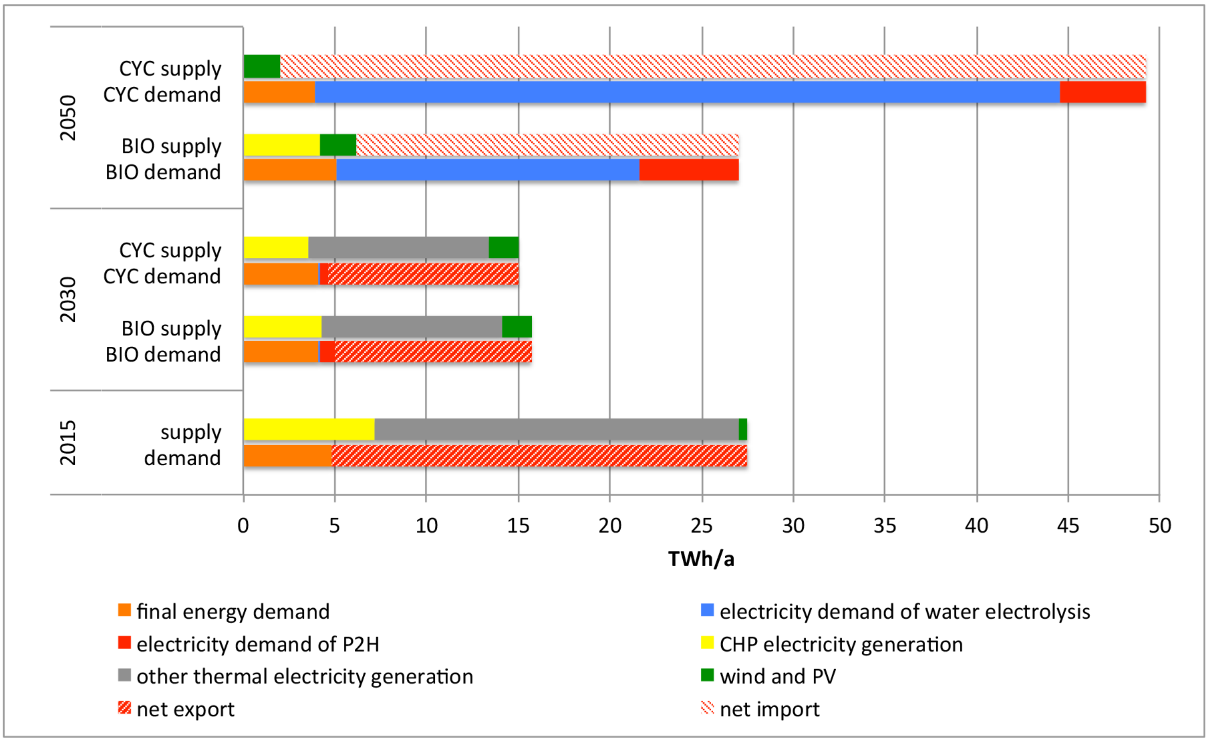

Figure 4. Electricity balance of the port area. Source: Own graph.

dustrial activity uncompetitive – and would lead to a considerable reduction in market demand for some of the cluster's currently produced goods (especially transport fuels).

Embarking on a pathway that leads towards deep decarbonisation by the middle of the century would enable the cluster to avoid the risks associated with no or insufficient CO_2 emission reductions. However, such a pathway would of course also be associated with both challenges and opportunities for the Port of Rotterdam, its industrial cluster and the region as a whole. This section attempts to identify these key challenges and opportunities in relation to the two deep decarbonisation scenarios developed and described above. It should be noted that while the challenges are discussed at quite some length, this is not meant to discourage efforts to achieve deep decarbonisation, but to help decision makers and stakeholders anticipate potential or probable challenges early on, making it more likely that these can be avoided or mitigated and overcome through smart planning.

CHALLENGES

We identify the following five key challenges, which are interrelated to some extent with one another:

- Considerable changes in the structure of the port's industry
- Need for new product portfolios and new industrial activity
- High investment needs
- Risks of (early) investments becoming stranded
- Coping with RES variability

It should be noted that the port will need to face some of these challenges (especially the first one) irrespective of the mitigation efforts that the port and its industry will strive for.

Considerable changes in the structure of the port's industry

The structure of the port's industry will likely change dramatically in a decarbonised future over the coming decades as demand for products of the refinery sector – currently the dominating sector in the port's industry – is widely expected to decrease significantly as a consequence of decarbonisation efforts in the transport sector. Likewise, the currently significant electricity generation from fossil fuels, particularly from coal but also from natural gas, will very likely decrease strongly during the course of the next two decades as a consequence of the expected transformation towards a renewables-dominated electricity system.

NEED FOR NEW PRODUCT PORTFOLIOS AND NEW INDUSTRIAL ACTIVITY

The structural changes can be mitigated if companies from existing industries are successful in renewing their respective product portfolios so as to adapt to market changes brought about by ambitious decarbonisation efforts. For example, the refinery sector could attempt to focus on products such as kerosene (which will likely be needed for air transport until at least the middle of the century) or they can attempt to produce biomass or synthetic fuels or process the respective (imported) platform products. In the BIO scenario, the synthetic fuel value chain is almost completely concentrated at the port, whereas in the CYC scenario only processing remains. Similarly, operators of coal-fired power plants may want to try to switch the fuels they use towards (higher shares of) biomass. However, in a world in which the overall capacity of these industries (refineries and thermal power generation) is widely expected to decline, the success of such a strategy is uncertain. That is, if the port area wishes to continue to hold the industrial relevance it has today, new industrial activity will likely need to be attracted to the port region. (See below at "Opportunities" for a discussion of the possibilities for new types of products and new industries gaining relevance at the port in the future.)

High investment needs

As the two decarbonisation scenarios discussed above suggest, the need for radical technological changes in production processes, new product portfolios and also for new industrial activities will require massive future investments in both existing and new industries. Currently, the costs of key mitigation technologies, the price of CO_2 emission allowances and the nature of energy and climate regulation do not allow the investments envisioned in either of the two decarbonisation scenarios to be recouped by private investors, as the market environment still favours carbon-intensive production processes. While the port itself can undertake efforts to make it an investment-friendly port for low-carbon and sustainable investments (e.g. by improving low-carbon compatible infrastructure such as heat grids or by providing incentives for investments into low-carbon activities), it will ultimately require support in the form of an adequately ambitious, stable and predictable national and European climate change mitigation policy environment.

In the BIO scenario, considerable investments will be needed especially for the Fischer-Tropsch plant and electrolysers. In the CYC scenario, considerable investments will be needed especially for electrolysers and MTO plants as well as for heat grid extensions and geothermal heat plants.

Risks of (early) investments becoming stranded

Related to the high investment needs and the considerable technological, regulatory and market changes described in deep decarbonisation scenarios, there will be a marked risk of making investments into technologies, infrastructures and production capacities that may eventually prove not to be economically sustainable. This is generally the case if low-carbon technologies are invested in that are more expensive than more carbon-intensive incumbent alternatives, relying on sufficiently high future CO_2 prices (or low electricity prices) that may not be realised. This kind of risk can be mitigated by adequate and predictable long-term climate policy regulation. However, there are many other risks that are independent of government regulation.

For example, the BIO scenario requires significant amounts of sustainable biomass for electricity generation and fuel production. Investing into these biomass-based processes (including negative emissions through biomass CCS) to reduce CO_2 emissions may be a risky strategy as it is extremely difficult to foresee future supply and demand and the related market prices for sustainably sourced biomass. It is therefore possible that unexpected and uncontrollable production and consumption decisions all over the world (e.g. the enactment of very strict sustainability standards in production and/or exploding global demand) will ultimately lead to very high biomass prices, which could render initial investments into biomass-based production processes uncompetitive.

Similarly, and particularly in the CYC scenario, there is a need – especially in the longer term – for large quantities of affordable renewable (or more generally low-carbon) electricity to be available to the port's industry. This massive growth in electricity demand is in line with other decarbonisation studies for the industrial sector (Dechema 2017, Lechtenböhmer et al. 2016) and underlines the need for a massive scale-up in renewable electricity generation capacity in Europe in the coming decades. If sufficient amounts of low-carbon electricity will not be available for the port's industry or if electricity prices will be particularly high, the production processes envisioned in this scenario may prove to remain uncompetitive, and production may shift to other regions of the world with either less stringent climate policies or availability of cheaper renewable energy. However, as there is in general a large potential for renewable electricity in Europe and the MENA region (which can principally contribute to European power supply) and demand for this electricity will not be global as in the case of sustainably sources biomass, we believe this is less of an uncontrollable risk compared to the risk of insufficient amounts of affordable biomass in the BIO scenario. Additionally, a new energy carrier such as methanol from renewable electricity could also be imported, while processing could remain at the port. In that case the value chain integration at the port would be similar to today's.

Coping with RES variability

Both of the deep decarbonisation scenarios discussed in this article (as well as other studies such as Lechtenböhmer et al. (2016) and DECHEMA (2017)) emphasize that deep decarbonization of industrial activity will require considerable amounts of low carbon electricity. By the middle of the century, all or most of this low carbon electricity generation is widely expected to come from renewable energy sources, mostly in the form of wind and solar PV (at least in Europe). These renewable energy sources lead to the challenge of successfully integrating large shares of intermittent renewable energy sources into Europe's electricity system. There are several elements that may be combined to enable the integration of high shares of wind and PV. These include electricity grid expansions, more flexible demand as well as short-term (e.g. batteries, pumped hydro storage) and long-term storage (e.g. hydrogen electrolysis) (see e.g. IEA 2014). Finding a technologically sound and economically appropriate set of solutions will certainly be an important challenge for Europe in the coming decades. However, this challenge shall not be discussed here at length, as it is generally a system-wide challenge, not one that is specific to the port's industrial cluster. However, the respective solutions to make demand more flexible and to store hydrogen or heat will have to be applied at the port at a large scale.

OPPORTUNITIES

Benefiting from being a front-runner in industrial decarbonization

Early and meaningful decarbonisation efforts offer the possibility to become a front-runner in industrial decarbonization. This in turn will presumably make it more likely that the region will receive grants for early demonstration projects and will become particularly attractive for new, low-carbon industrial activities. As part of the study conducted for the Port of Rotterdam, we identified the following new products and new industrial activities – each with high potential relevance in a decarbonised future world – as possibly being well suited to be realised in or attracted to the port area:

- Offshore wind
- Bio-based chemistry

- Demand-side-management and energy storage
- CO_2 transport and storage
- Use of waste
- Synthetic fuels
- Carbon-neutral primary steel production

By becoming a front runner in industrial decarbonisation, the port may also serve as an important example for other petrochemical clusters in Europe (e.g. Antwerp, Rhine and Ruhr in Western Germany, Ludwigshafen Stenungsund, Tarragona or Płock) and beyond, demonstrating that it is possible for such regions to embark on a pathway that ultimately aims to completely avoid net CO_2 emissions. The Port of Rotterdam may in the future be able to offer insights on how to shape a decarbonisation process and best-practice examples would ideally be adopted by other regions, making the port internationally known as the world's leading "Port of Decarbonisation". We are not aware of similarly far-reaching deep decarbonisation discussions and plans for other industrial regions in the world, although studies exist or are currently being conducted that discuss the potential for achieving significant emission reductions at other industrial regions in Europe (e.g. TNO 2018) and other countries (e.g. Liu et al. 2018). Obviously, efforts to decarbonize the port's inbound, outbound and internal transport also need to be part of a holistic decarbonization strategy and could possibly support decarbonization efforts at the industrial cluster. The Port Authority has recently commissioned a study that further investigates options to achieve deep decarbonization until the middle of the century in the transport sector as well.

Gaining a competitive edge in a future world that becomes increasingly decarbonised

Early steps towards decarbonisation may offer potential for the region to obtain a competitive edge over other regions and similar industrial locations, thus ensuring continued economic relevance and prosperity for the Rotterdam area. The potential for gaining a competitive edge is further aided by opportunities the port's industrial cluster appears to have in taking advantage of its unique geographical location. The cluster, for example, is in close proximity to potential CO_2 storage sites in the North Sea as well as to North Sea areas that are well suited for offshore wind power generation. The port also provides the possibility to import low-carbon energy carriers in the form of biomass and/or renewables-based synthetic fuels at relatively low transport costs.

Improving air quality

The strong reductions in the use of fossil fuel energy sources in power generation and industry will provide a considerable co-benefit to the region in the form of air quality improvements. Progressively switching from fossil fuels to electricity and hydrogen in industrial end-use will eventually virtually eliminate industries' local air pollution in the CYC scenario. The improvements are less pronounced in the BIO scenario with its heavy use of biomass for electricity generation and fuel production, each being associated with local pollution of its own.

Conclusion

Achieving deep decarbonisation globally will only be feasible if industrial clusters reduce their GHG emissions significantly. As CO_2 emission reduction regulation in Europe and other countries becomes increasingly stringent, industrial clusters face growing pressure to change their production technology as well as their product portfolio. This will be particularly relevant for the Port of Rotterdam, as its business model is centred around the transport, handling and conversion of carbon.

Following "conservative" strategies as depicted in the underlying study's BAU and TP scenarios would lead to continuing carbon lock-in, limiting the emission reductions that can ultimately be achieved and making significant investments into CCS necessary. It is questionable whether these scenarios would be compatible at all with ambitious long-term climate mitigations efforts.

The two ambitious scenarios that we developed for the industrial cluster, however, suggest that a transformation from a highly CO_2 intensive business model towards a decarbonised supply of basic chemicals as well as fuels would be possible for the Port of Rotterdam and would promise significant economic opportunities for its industries.

However, the scenarios also make it clear that such a transformation would be very ambitious, as it requires new integrated technological concepts, which are associated with significant investments into renovation and upgrading as well as into new production assets and infrastructures in the Rotterdam chemical cluster. For such investments to come forward from private investor, stable and ambitious long-term climate policy frameworks will be indispensible. Furthermore, the envisioned transformation towards deep decarbonisation also depends on the future supply of large amounts of sustainable biomass and/or renewable-based electricity, both of which need international efforts in the establishment of the necessary value chains and infrastructures.

Public participation in and acceptance of decarbonisation strategies is crucial, as radical transformations entail risks for companies, investors, and employees and as new investments (e.g. into large scale off-shore wind, geothermal energy use or CCS) crucially require support within affected communities. New visions for a more sustainable industry at the Port or Rotterdam therefore need to be developed among stakeholders with a clear vision and leadership, and optimally guided by scenarios which demonstrate the necessities as well as the opportunities of such changes. Such participatory processes, which were also used in the creation of the study for the Port of Rotterdam that this paper is based on, may play an important role to engage stakeholders and help them to understand the needs for change, to accept potential disadvantages and to identify related opportunities for themselves and their communities.

The fact that the Rotterdam Port Authority has adopted such a strategy to position itself as a leading European region for decarbonisation can be an important signal to other industrial regions and stakeholders to follow suit on the development and stepwise implementation of transformation strategies for their industrial businesses to transform them from being a contributor to climate change to becoming a key part of the solution.

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