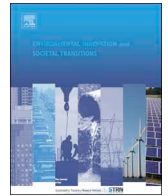


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## Risks and opportunities associated with decarbonising Rotterdam's industrial cluster

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### ABSTRACT

The Port of Rotterdam is an important industrial cluster, comprising mainly oil refining, chemical production and power generation. In 2016, the port's industry accounted for 19% of the Netherlands' total CO<sub>2</sub> emissions. The Port of Rotterdam Authority is aware that the cluster is heavily exposed to future decarbonisation policies, as most of its activities focus on trading, handling, converting and using fossil fuels. Based on a study for the Port Authority using a mixture of qualitative and quantitative methods, our article explores three pathways whereby the port's industry can maintain its strong position while significantly reducing its CO<sub>2</sub> emissions and related risks by 2050. The pathways differ in terms of the EU's assumed climate change mitigation ambitions and the key technological choices made by the cluster's companies. The focus of the paper is on identifying key risks associated with each scenario and ways in which these could be mitigated.

### 1. 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 achieve this through “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 limiting warming to well below 2 °C will require a rapid reduction in global energy-related GHG emissions over the coming decades, with levels 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 could be extensive given the variety of different technologies and production processes used and its generally long reinvestment periods. The sector's competitive nature makes it particularly difficult for early adopters to accept – even temporarily – higher costs

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associated with new technologies.<sup>1</sup> Consequently, we believe there is an urgent and significant need to develop scenarios or pathways<sup>2</sup> for the long-term decarbonisation of industrial sectors and industrial clusters. Such pathways can provide crucial support to policymakers and investors, helping them to make informed decisions about immediate and appropriate measures and actions to take to result in a sufficient level of decarbonisation in the decades to come.

In recent years, there have been an increasing number of scenario studies on the potential to deeply decarbonise entire economies (e.g. IEA, 2017; Greenpeace et al., 2015), or individual industrial sectors such as the chemical sector (Dechema, 2017). However, to our knowledge, no long-term, deep-decarbonisation scenarios for a specific industrial region or cluster have previously been developed. We believe that such regional scenarios are important for complementing 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. In this way, the regional approach can increase the relevance of a decarbonisation study for regional policymakers, investors and other stakeholders. Furthermore, regional scenario studies may also help to identify and address region-specific risks associated with decarbonisation pathways, especially if they adequately involve stakeholders in the process of scenario development (Schneider et al., 2014; Lechtenböhmer, 2017; Espert et al., 2016). Ideally, such studies involving stakeholders can improve decision-making processes and foster acceptance for transformational pathways among the public, as well as helping companies to anticipate and pro-actively embrace potential radical future market and regulatory changes if participation is "underpinned by a philosophy that emphasises empowerment, equity, trust and learning" (Reed, 2008).<sup>3</sup>

This article identifies options for the deep decarbonisation of energy-intensive industries in the EU and beyond by describing possible future pathways for a major European petrochemical cluster, namely the industrial cluster of the Port of Rotterdam. The port's industrial cluster comprises, to a great extent, companies operating in the energy-intensive sectors of oil refining, chemical manufacture and power and steam generation. The five refineries in the port constitute 87% of the Dutch and 8% of the total EU capacity. Steam cracking, as the most relevant initial process in the value chain of petrochemicals manufacturing, is represented in the port's cluster with one third of the Dutch and 4% of the total EU steam cracking capacity, while the two newly built coal-fired power stations amount to half of the Dutch capacity of coal-fired electricity generation.<sup>4</sup>

In 2016, the cluster's CO<sub>2</sub> emissions<sup>5</sup> totalled approximately 31 Mt (Port of Rotterdam Authority, 2017a) and accounted for 19% of the Netherlands' total CO<sub>2</sub> emissions (Statistics Netherlands, 2018). The cluster's CO<sub>2</sub> emissions grew by 48% between 1990 and 2016, mainly because the energy sector's CO<sub>2</sub> emissions in the port area more than doubled between 1990 and 2016 (Port of Rotterdam Authority, 2017a; DCMR, 2008, personal communication with DCMR in September 2016). Emissions from the chemical sector and from crude oil refining also increased slightly as economic output grew over the years, offsetting the emission-reducing effects of higher energy efficiency.<sup>6</sup> Looking only at the more recent years, there is evidence of a significant increase in the cluster's CO<sub>2</sub> emissions (by 24%) between 2013 and 2016. This growth can mostly be accounted for by the two new coal-fired power stations owned by Engie (previously GDF Suez) and E.ON becoming operational during this period.

The Port of Rotterdam Authority is aware that future global and EU decarbonisation policies will affect the port's industrial cluster, as most of its economic activities focus on trading, handling, converting and using fossil fuels. This makes the port's businesses particularly vulnerable to global and European decarbonisation efforts. Against this background, and in light of the Paris Agreement targets, the Port Authority decided to take a proactive role towards transforming the port area (Bosman et al., 2018) and 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.<sup>7</sup> The aim of the study was to explore the potential challenges and opportunities arising for the port's industrial cluster from European decarbonisation efforts, both in terms of future demand for the companies' products and changes towards less carbon-intensive production processes. To this end, the study identified scenarios up to 2050 illustrating how the port could prepare for such a future and how it could take pro-active action towards deep decarbonisation. The study involved stakeholders who took part in a technology review as well as in a discussion of key mitigations strategies and scenario narratives. Due to the nature of a scoping study, only preliminary scenario results were discussed with stakeholders. However, the scenarios were

<sup>1</sup> Due to their high CO<sub>2</sub> emissions, a transformation of the energy-intensive processing industries is particularly important for global climate change mitigation efforts. For a characterisation of energy-intensive processing industries and a discussion of their decarbonisation potential, see Wesseling et al. (2017) and Bataille et al. (2018).

<sup>2</sup> The terms "scenarios" and "pathways" both describe concrete trajectories from today's situation of a nation, a region or a sector to a possible or desired future. In this sense, both terms are used partly synonymously in this paper. However, when we talk about *scenarios*, we typically perceive a coherent set of future developments on all relevant levels from global via European or Dutch to local and industry level at the Port of Rotterdam. When we use the term *pathways*, we refer to the concrete investment and business trajectories of our focus area, the industrial cluster at the Port of Rotterdam, within the respective broader scenario.

<sup>3</sup> At the same time, potential pitfalls of involving stakeholders need to be considered (Mielke et al., 2016). Specifically, scientists need to be aware that each stakeholder has a unique interest, making it important to check the legitimacy of stakeholders' claims and to ensure that the scientific approach is not captured by stakeholders.

<sup>4</sup> All shares mentioned were derived by a data analysis of the Wuppertal Institute's database on industry production stock in Europe and represent the status as of May 2019. See more information on the database and the associated WISEE model below.

<sup>5</sup> Non-CO<sub>2</sub> 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.

<sup>6</sup> One reason for increased emissions from the refinery sector was the introduction of stricter regulations on transport fuel emissions, requiring higher energy use and thus CO<sub>2</sub> emissions in refining to reduce the fuels' SO<sub>2</sub> levels.

<sup>7</sup> The study can be downloaded at <https://www.portofrotterdam.com/nl/file/18544/download?token=4Ri58reM>.

used by the Port Authority as an input into discussions at Dutch national level about measures and strategies for achieving GHG mitigation. As part of this process, stakeholders were given further opportunities to put forward and discuss their own visions for the future of the port's industrial cluster (*Werkgroep Industriecluster Rotterdam-Moerdijk, 2018*).

This article introduces the four scenarios from the study (*Samadi et al., 2016*) and then focuses on identifying and discussing the risks associated with each of the scenarios.

Section 2 explains the mixed-methods approach of the study and the modelling framework used to derive the quantitative scenarios. Section 3 then describes and compares the four scenarios. Subsequently, Section 4 identifies key risks as well as opportunities associated with each scenario and discusses how the main risks associated with the deep decarbonisation scenarios could potentially be mitigated. Finally, Section 5 concludes and derives key insights from the study.

## 2. Approach and modelling framework

The scope of the study's energy and GHG modelling covers the direct CO<sub>2</sub> emissions occurring within the territory of the Rotterdam port area, including the industrial site of Moerdijk, south of Rotterdam. Emissions caused either by the extraction of resources processed at the port, or by the use of the port's products, are also part of the GHG emissions from the port's value chain – but are not quantified here. This approach is justified as the main aim of the study is not to derive a quantitative GHG target for the port, but to sketch viable future industry clusters that might emerge at the port under different socio-political and regulatory environments in the overall context of deep decarbonisation.

The port area forms a complex cluster with many interlinkages and value chains. For this analysis, however, the sectoral system boundary of the analysis was restricted to electricity generation, waste incineration and the petrochemical cluster within the analysed area, as the bulk of the GHG emissions can be attributed to these GHG and energy-intensive resource and product flows.

### 2.1. System analysis

Before developing the scenarios, the port's energy system was analysed in detail. As there are no energy statistics available specifically for the port area, the energy system was modelled for the base year (2015). Relevant combustion plants and their capacities were identified based on the port's "Facts & Figures" brochure (*Port of Rotterdam Authority, 2016*) and crosschecked with databases on electricity generation units and heavy industry stocks from the WISEE model (see below).

The following capacities were taken into account:

- Electricity generation units (in MW<sub>el</sub>; 70 units)
- Refinery processes (in t/a; 32 units)
- Several important petrochemical processes (in t/a; 53 units)

The specific energy and resource demand of the processes analysed was derived from the literature and the results were validated with data from the European Union Transaction Log (EUTL) of the European Union Emissions Trading System (EU ETS), which provides site or plant-specific data on annual CO<sub>2</sub> emissions in the form of time series.

Refinery use was modelled using an optimisation procedure. The different kinds of processes were modelled for all five Rotterdam refineries, as well as for the only other refinery in the Netherlands, the Vlissingen refinery. The results for all six Dutch refineries were validated with the available aggregated data for all 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, ignoring different steam pressure levels or discontinuities of steam supply via excess heat and steam demand.

### 2.2. Scenario analysis

A number of different methods – both qualitative and quantitative – were used to develop the scenarios. The steps are outlined in Fig. 1 and can be summarised as follows:

- Meta analysis of European energy scenarios
- Technology review based on literature and interviews
- Development of plausible qualitative scenario narratives of "viable clusters"
- Translation of scenario narratives into reinvestment/new investment pathways regarding power and heat generation and industrial plants, resulting in future production capacities (stock)
- Quantitative energy system simulation including scenario validation, modelling stock utilisation, energy demand, CO<sub>2</sub> emissions and product flows
- Discussion of initial scenario versions with stakeholders and subsequent refinement of scenarios and their narratives

The scenarios are designed to analyse the range of opportunities for the port's industrial cluster under different environments. Although the Port of Rotterdam Authority is an important national stakeholder and is involved in the Dutch debate on decarbonisation targets and strategies, from the perspective of the port's stakeholders European climate and energy policy can be

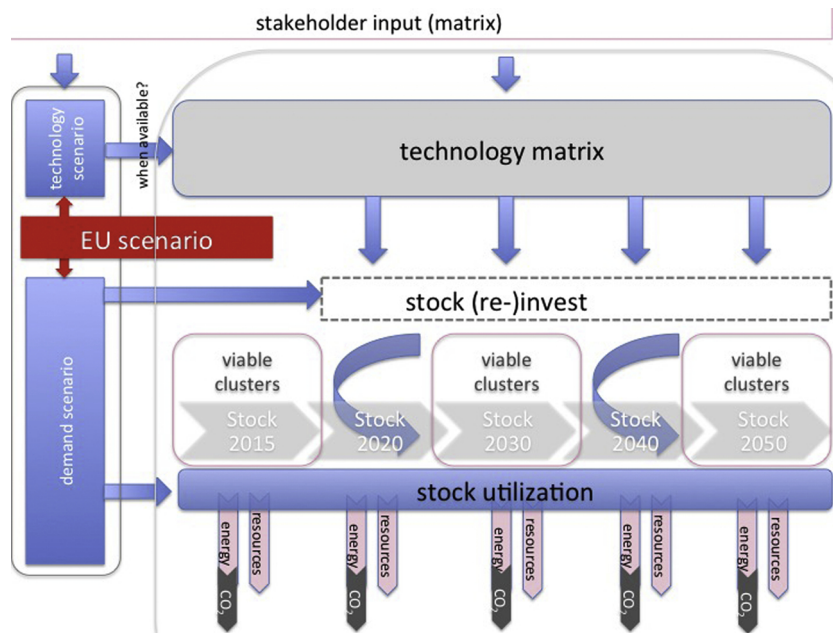


Fig. 1. Schematic diagram of the model used to develop the scenarios.

regarded as a largely exogenous variable. Therefore, it is reasonable to rely on EU scenarios as an overarching framework and to explore the different opportunities for the port under three different climate mitigation regimes:

- no additional mitigation measures;
- mitigation measures in line with the EU's 80% reduction target for 2050; and
- mitigation measures in line with the EU's 95% reduction target for 2050.

This is a methodology commonly used in strategic corporate planning (Burmeister et al., 2004).

Based on the system analysis for the base year (see above), the study's scenarios were built by combining a backcasting and a forecasting approach. The starting point for defining industrial clusters in the port area for the year 2050 (see Fig. 1) were European energy and emissions scenarios (EC, 2011; IEA, 2015a; Greenpeace et al., 2015). The European scenarios provide time series on the volume and structure of transport fuel demand, the pathway of investment in renewable electricity generation capacities (such as onshore and offshore wind, PV, geothermal energy etc.), the primary energy use and the sectoral CO<sub>2</sub> emissions. The EU scenario results were broken down into the markets that are relevant for the cluster's businesses, especially the North-Western European transport fuel market.

Based on three different climate regimes and thus three different business environments derived from the available European energy scenarios, four plausible economic visions for the industrial cluster were developed as scenario narratives. These four energy and CO<sub>2</sub> emission scenarios for the port's industrial cluster are referred to as "technology scenarios" in Fig. 1. They were developed and quantitatively modelled and include one business-as-usual scenario as well as three CO<sub>2</sub> emission mitigation scenarios – one for the 80% reduction environment and two for the 95% reduction environment

A technology review showing GHG mitigation potentials and market-readiness of various industrial technologies was carried out on the basis of the available literature, particularly using industry branch roadmap studies carried out at national (UK) and EU levels.<sup>8</sup> The resulting technology matrix summarises information on technology-readiness, acceptance, economics, use potential, synergies with certain GHG mitigation strategies, energy efficiency and GHG emissions. It draws upon proven technologies in order to foster stakeholder buy-in, as scenarios built on such technologies could be considered easier to achieve (Giurco et al., 2011) and more realistic. However, it became apparent the technology portfolios identified in the roadmap studies were insufficient for achieving far-reaching reductions in GHG emissions. Consequently, they were tailored to the existing production stock at the port and an additional strong electrification strategy was assumed for achieving greater reductions in GHG emissions (see e.g. Lechtenböhmer et al., 2016). The existing roadmap studies did not incorporate such a strong electrification strategy. The technology assessment was commented on and amended by several stakeholders through a survey sent by email in May 2016.<sup>9</sup> Consequently, the selection of technologies in

<sup>8</sup> See WSP et al. (2015) for a summary on the UK roadmaps. At European level, branch roadmaps have been developed by industry itself, e.g. by Cefic (2013) for the chemical sector.

<sup>9</sup> Key stakeholders were identified and provided by the Port Authority. 34% of the stakeholders contacted (corresponding to 11 companies or associations) filled out and returned the questionnaire. The response rate was much higher for industrial stakeholders (10 out of 19 companies or associations responded) than for societal stakeholders (only 1 out of 13 organisations responded).

the study's scenarios was informed *inter alia* by the port's stakeholders.

The clusters identified were tested in relation to technical feasibility, energy demand and emissions reduction using a backcasting approach and the Wuppertal Institute's WISEE energy and emissions system model.<sup>10</sup>

Following the energy system model classification of Herbst et al. (2012), the WISEE model can be classified as a bottom-up simulation model with a very detailed representation of energy system technologies and a low degree of endogenisation. Consequently, many parameters can be changed by incorporating stakeholders' knowledge, e.g. via assessments of future market shares of certain technologies. The focus of such models is on unveiling existing energy efficiency and GHG mitigation potentials, rather than on finding the cost-optimal pathway for achieving a given target (see Hourcade et al., 2006). Lund et al. (2017) argue that simulation models leave more room for "political decisions" than optimisation models. In the case of our scenarios for the Port of Rotterdam industrial cluster, the target function is multi-dimensional and various non-quantifiable perspectives from the different stakeholders were taken into account. The simulation approach is well-suited in this type of case as it allows for consideration of such issues (Lund et al., 2017). The risks and uncertainties related to a selection of key issues such as public acceptance or infrastructure development are discussed below.

The WISEE model was used to test the viability of the clusters by calculating their respective net energy demand and their respective CO<sub>2</sub> emissions. Based on the model results it was assessed whether energy demand and CO<sub>2</sub> emissions of the port's cluster appear to be compatible with the overall energy supply and CO<sub>2</sub> reduction pathways as described by the corresponding European energy and emissions scenarios.

As a next step, concrete investment pathways for creating the future clusters were defined, taking into account the lifetime of existing stock, future demand for transport fuels as well as other products and investment cycles. The analysis focused on the question of how to bring necessary reinvestment in line with the pathways to future viable clusters.

For the intermediate scenario years 2020, 2030 and 2040, energy demand, resource demand and CO<sub>2</sub> emissions were calculated in the model, testing compatibility with the overall system as described in the European energy scenarios with regard to energy use and CO<sub>2</sub> emissions. The pathways were subsequently analysed to detect challenges in regard to the availability of technologies and the investments needed and to define decision windows. Representations of 2050 clusters were rejected if a plausible pathway could not be found.

The four preliminary scenarios and their narratives were discussed in two workshops in June 2016, one with industry stakeholders and another with representatives of civil society. The workshop with industry stakeholders included representatives of key industrial players at the port, such as ENGIE, Huntsman, Shell, Air Liquide, while the workshop with societal stakeholders consisted of representatives from environmental groups such as NMZH and relevant authorities, for example from the City of Rotterdam.<sup>11</sup> The general role of crucial strategies like biomass, CCS, energy efficiency and electrification were critically reviewed during these workshops and the insights gained from the workshops resulted in modified scenario narratives, refined investment pathways and the consideration of an additional scenario variant, as discussed in the next section.<sup>12</sup> The final scenarios were completed in September 2016.

### 3. Description and comparison of scenarios

This section briefly describes and compares the "Business-as-usual" (BAU) scenario and the three decarbonisation scenarios in terms of their reinvestment/new investment in production stock and their energy use and GHG emissions.

#### 3.1. Brief description of the four developed scenarios

The general assumption made about the future clusters in all scenarios is that they will still participate significantly in the markets they supply today, i.e. the markets for fuels and petrochemicals. Whereas fuel supply is assumed to be substantially lower in line with projections for the EU, the production of chemicals is assumed to be stable – which is a simplified assumption reflecting significant differences in current projections of future demand in and trade of chemical products (IEA, 2013; Cefic, 2013; Dechema, 2017).

Generating and selling electricity is also an important business in today's industrial cluster. We analysed how generation capacities within the port might evolve under different climate regimes for various types of power plants. In all three European framework scenarios used, the electricity generation mix in 2050 differs substantially from today's mix.

The "Business-as-usual" (BAU) scenario follows a business-as-usual path for the EU (EC, 2011), which envisages little further decarbonisation in the industry, refinery, power plant and transport sectors. Under such circumstances, the port region might be able

<sup>10</sup> See Fig. 1 and Schneider et al. (2014) for more information on the model.

<sup>11</sup> The discussions held at the two workshops are summarized in the annex of Samadi et al. (2016).

<sup>12</sup> Specifically, the strongly deviating views among stakeholders regarding the future viability of a strong reliance on biomass and CCS – with industry stakeholders mostly optimistic and societal stakeholders mostly pessimistic – led to the decision to differentiate the two deep decarbonisation scenarios more strongly compared to their original form. One of the two scenarios now relies heavily on biomass and CCS, while the other one now focuses on closing carbon cycles, enabling the scenario to use much less biomass and to refrain from the use of CCS. In addition, several stakeholders pointed towards the ongoing discussions in the Netherlands of phasing out coal electricity generation early in order for the country to meet its existing 2020 and proposed 2030 GHG reduction targets. To reflect the possibility of an early exit of coal power generation, a scenario variant was added to one of the deep decarbonisation scenarios in which the two relatively new coal power plants in Rotterdam are assumed to be closed by 2019 and 2025 respectively.

to maintain its current business model of producing fuels and chemicals synergistically based on crude oil and could continue operating the fossil-fired power plants. The refinery sector, however, would already shrink in the BAU scenario, mainly 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 (2015a) as a global 2 °C Scenario, in which by 2050 the EU achieves a reduction in energy and process-related CO<sub>2</sub> emissions of roughly 80% compared to 1990. A reduction of 80% still permits a certain level of emissions, which in the IEA’s energy scenario is assumed to allow for fossil fuel use especially in some difficult-to-decarbonise modes of transport, in heat production and for some non-captured CO<sub>2</sub> in the carbon capture process at coal and gas-fired power plants. In the TP scenario, the port must adapt its “oil and coal-based business model”. Refinery output shrinks considerably, but the refineries are still suppliers of transport fuels and petrochemical feedstock. The big coal and gas-fired 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<sub>2</sub> pipeline.

The “**Biomass and CCS**”(BIO) scenario assumes – as does the CYC scenario (below) – that the EU aims for a more ambitious 90% to 95% reduction in GHG emissions by 2050 relative to 1990 and that respective policies will be enacted.

The BIO scenario assumes that large amounts of biomass can be supplied sustainably. In total, 140 PJ or 9 million tons of dry biomass are needed annually by 2050 as feedstock and would have 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 base year 2015.

The conversion of the industrial cluster along the lines of the BIO scenario requires significant additional investment: CO<sub>2</sub> pipelines connect different sources within the port area, among them processes with relatively pure CO<sub>2</sub> streams such as steam reformers producing hydrogen from natural gas or oil residue gasification plants. These sources can be regarded as “low hanging fruits” for carbon capture.

Other infrastructure either requires *reinvestment*, such as heat and cogeneration plants due to end of lifetime of existing technology, or *new investment*, such as the hydrogen and probably the electricity grid. The petrochemical cluster remains unchanged but needs reinvestment in the core basic process of steam cracking.

The “**Closed Carbon Cycle**” (CYC) scenario, on the other hand, assumes that the port’s petrochemical cluster will use waste as a feedstock in the future instead of fossil resources. This means that carbon required for the olefins and aromatics will stem from waste. The port could make use of its recent role as a hub for plastic waste and strengthen it by creating an additional value chain, as opposed to only shipping the plastic waste.

Chemical recycling of the waste at the port via gasification to carbon monoxide and hydrogen, as well as the subsequent step of methanol production, implies energy losses resulting in the need for considerable amounts of renewables-based electricity by the middle of the century. In the CYC scenario this electricity cannot be sourced from within the port area. Electricity will be used at the port to supply heat as well as hydrogen for the synthetic generation of feedstock for the chemical industry (see Figure 4). Technologies and investments particularly required in this scenario are in the area of water electrolysis and gasification or pyrolysis to capture carbon from waste, as well as technologies for the production of base chemicals from syngas. In this scenario there is no technological need to adapt the downstream value chains with their existing assets of processing olefins to polymers. The petrochemical cluster thus remains integrated.

For the fuel supply chain, however, it is assumed in the CYC scenario that only the most downstream parts of the value chains will remain at the port by the middle of the century. Hydrocrackers will process imported bio-based intermediates to deliver the relatively small volume of hydrocarbon liquid fuels still used in the transport sector, particularly bio-based kerosene for aviation.

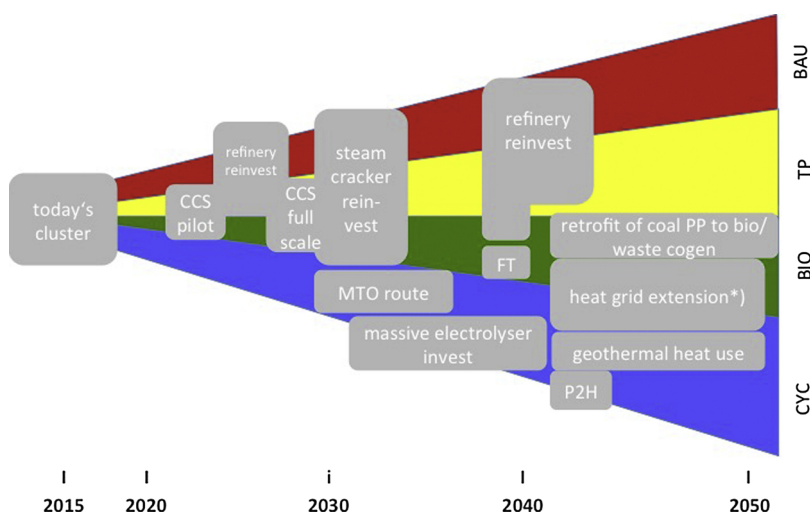
A variant of this scenario, the Early-Coal-Exit scenario (CYC-ECE) describes the development if the coal-fired power stations at the port are closed earlier, i.e. in 2019 and 2025 respectively. This possibility reflects current political discussions in the Netherlands on how to achieve national GHG emission reductions targets for the years 2020 and 2030.

### 3.2. Comparison of the scenarios

Fig. 2 briefly describes the results of the model-based backcasting and forecasting scenario development, showing the timescales for making key investments in the respective scenarios.

The figure indicates that the TP and BIO scenarios require fast adoption of a first CCS pilot plant to keep the two new coal-fired units in operation in accordance with short to medium-term GHG mitigation targets. If the fuel markets change only marginally, as assumed in the BAU and TP scenarios, where electric mobility is assumed to require more time to be widely adopted, refinery reinvestment would be due during the 2020s in order to maintain the port’s market share in the European fuel market. Reinvestment into the Moerdijk steam cracker commissioned in the 1970s is crucial in the BAU, TP and BIO scenarios. This would enable the cluster to continue processing oil products to platform chemicals.<sup>13</sup> According to the authors’ estimates, which are based on the date of commission and on typical lifetimes given in the literature, reinvestment into the steam cracker would need to be made around the year 2030. The steam cracker reinvestment itself would not necessarily lead to the cluster being locked into a fossil oil-based route: imported or domestically-produced and biomass-derived Fischer-Tropsch products could also be processed in the future instead of fossil oil, if the design of the cracker allows for this kind of flexibility – which is standard in current cracker technology. Even the use

<sup>13</sup> Materials derived from crude oil will typically end up as fossil CO<sub>2</sub> 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<sub>2</sub> is not geologically stored when incinerating the waste. Incinerating the amounts of ethylene and propylene produced annually in Rotterdam would result in CO<sub>2</sub> emissions of around 7 Mt/a.



**Fig. 2.** Key reinvestment/new investment to be made in the four scenarios over time.  
Source: Own figure

of plastic waste as a feedstock for petrochemicals as foreseen in the CYC scenario could be combined with a flexible steam cracker if the plastic waste was liquefied priorly in a pyrolysis process. However, reinvestment into one of the oil refineries, which coincides with steam cracking reinvestment (including CCS) in the TP and BIO scenarios would eventually lead to an oil lock-in of the cluster in these scenarios – so a later change of the pathway towards an alternative feedstock, as is assumed in the CYC case, would become difficult.

Radical decarbonisation of the transport sector, as assumed in the BIO and CYC scenarios, assumes a shift to battery or hydrogen-driven fuel cell vehicles and electric long-haul trucks using overhead lines on main motorways. Shipping, aviation and other heavy road transport fuel is provided by synthetic fuels based on renewable hydrogen and non-fossil carbon (Greenpeace et al., 2015). We assume that these will be imported methanol for shipping and Fischer-Tropsch kerosene and diesel. European and specifically Rotterdam's refinery capacities would need to be adjusted respectively.

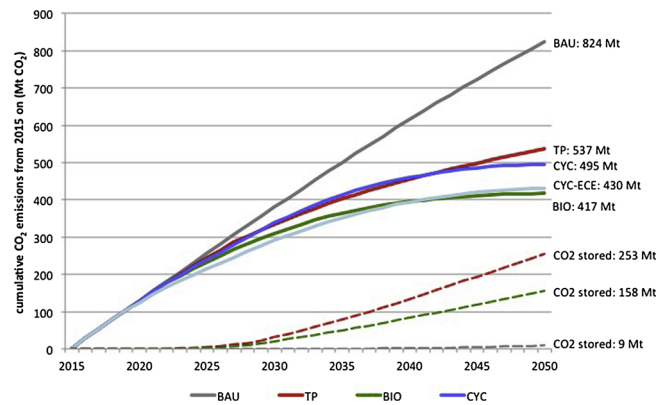
For GHG mitigation in thermal power plants and for some other processes in refineries and petrochemicals production, a scale-up of CCS will be necessary in the 2030s in the BIO and TP scenarios – based upon learning from the CCS pilot plant assumed to be implemented in the 2020s in these scenarios. The assumption is made that the CO<sub>2</sub> captured will 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. There are other possible deposits in close proximity to this field with a combined storage capacity of around 100 Mt (TNO, 2011). However, the total amount of CO<sub>2</sub> to be captured and stored in the BIO scenario over the full period of CCS application between 2022 and 2050 would be 158 Mt. In the TP scenario, as much as 250 Mt would be required. Consequently, the CO<sub>2</sub> storage infrastructure would need to be extended. An extension of the CO<sub>2</sub> grid to the northern part of the Netherlands could make further large storage sites accessible and would also allow for the inclusion of more CO<sub>2</sub> sources beyond the Rotterdam industrial cluster, e.g. from the Dutch or western German steel industry.

During the 2030s, the respective investment pathways for 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 the stations need to be converted to allow for waste and biomass-firing and to connect them to the heat grid to supply high-temperature heat for the cluster. In this context, it is assumed that an extensive heat grid with heat storage will be developed to optimise the supply of heat for the industrial cluster.

The CYC scenario differs significantly from the other scenarios. It does not assume reinvestment in the refineries or steam crackers, nor the retrofitting 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 and secondary materials such as plastic and other waste, requiring investment into methanol to olefins technology (MTO). Almost in parallel, massive investment in electrolyzers will be needed to supply renewables-based hydrogen to methanol synthesis, feeding the MTO process. A complementing heat network would need to be installed, connecting geothermal sources as well as the industrial heat sources and sinks.<sup>14</sup>

The BIO and CYC scenarios show two possible ways for the port to adapt to potential future external pressure demanding quick and deep decarbonisation. Both scenarios describe rather prototypical pathways. A more likely deep decarbonisation pathway will consist of a combination of these two scenarios. Some of the strategies could be used in both scenarios, reducing the risk of relying on

<sup>14</sup> Due to the huge spatial 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.



**Fig. 3.** Cumulative CO<sub>2</sub> emissions of the industrial and energy cluster at the port in the four scenarios (and one scenario variant) and geological CO<sub>2</sub> storage in the scenarios.

Source: Own graph

only one feedstock or technology. However, pursuing certain strategies will limit the potential to use alternative strategies. One example is plastic waste, which in the BIO scenario is used to fire power plants connected to CCS, whereas in the CYC scenario it is used as a feedstock. On the other hand, the biomass-to-fuel route of the BIO scenario could be combined with the CYC circular strategy for petrochemicals, although this would further increase the technological complexity and lead to higher hydrogen demand at the cluster.

**Fig. 3** shows cumulative CO<sub>2</sub> emissions in the different scenarios over the period 2016–2050. Cumulative emissions are a better indicator of the actual climate burden of a scenario than the emissions of a certain year. As modelling covers only the base year 2015 and the four scenario years 2020, 2030, 2040 and 2050, CO<sub>2</sub> emissions for the intermediate years were generally derived by linear interpolation. However, the introduction of CCS was taken into account in a more precise way, by considering the actual years of connection of the CCS plants to the existing power plants. These are 2022 and 2029 in both the TP and BIO scenarios

The **BAU** scenario – which results in only slight reductions in annual CO<sub>2</sub> emissions – shows an almost linear development of cumulative emissions. In this scenario, the mark of 400 Mt, which roughly represents the total CO<sub>2</sub> budget of the two most ambitious scenarios (BIO and CYC-ECE), is fully used as early as 2030. The **TP** scenario shows considerable reductions in the medium term, as indicated by a flattening of its emissions curve in **Fig. 3**. However, it fails to approach zero additional emissions even in the long term. The **BIO** scenario leads to the lowest total amount of CO<sub>2</sub> emissions over the scenario period, with emissions almost levelling off after 2040, meaning that very little CO<sub>2</sub> will be emitted after 2050. However, the net CO<sub>2</sub> emissions of 420 Mt can only be reached through 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.<sup>15</sup> The development of cumulative emissions in the **CYC** scenario demonstrates that a long-term saturation of CO<sub>2</sub> emissions is also possible without the use of CCS. In this case, however, the assumed continued unabated operation of the two new coal-fired power stations until 2035 results in higher cumulative emissions compared to the BIO scenario, in which deeper emission reductions are achieved early on. 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 in this scenario variant are similar to the BIO case. Both scenarios show that it would be possible to limit the total future CO<sub>2</sub> emissions of the Port of Rotterdam industrial cluster to around 420 Mt to 430 Mt.

Finally, **Fig. 4** shows the effects of decarbonisation on the electricity balance of the port. Whereas a considerable net surplus is delivered to the electricity grid today, the strategy of electrification reverses the situation in the future in the two deep decarbonisation scenarios BIO and CYC, making the port a net consumer of electricity in the long term. The external electricity demand in the two deep decarbonisation scenarios is very high, especially in the CYC scenario. The bulk of electricity needed in this scenario is used for water electrolysis, supplying the hydrogen needed for methanol synthesis.

Even in the CYC scenario, the electricity demand is still well below the estimated potential for renewable electricity generation in the Netherlands as a whole by 2050 (Greenpeace/EREC 2013). In the CYC scenario, the port area is the most important provider of hydrocarbon products in 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, such as electrolysis and electric steam generation, could be managed in a way to maximise its temporal flexibility. In this way, the port's industrial cluster could contribute to optimising the use of fluctuating electricity generation from wind and solar PV, stabilising the Dutch and European electricity grid.

<sup>15</sup> It should also be stressed that biomass is assumed here to be CO<sub>2</sub>-neutral – a common approach in scenario studies. This is, however, typically not the case for most types of biomass (Welfle et al., 2017), meaning that the GHG emissions in this scenario would actually be higher if biomass life-cycle emissions were taken into account.

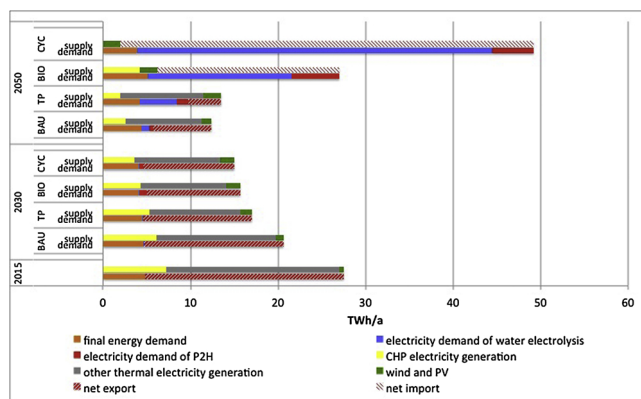


Fig. 4. Electricity balance of the port area.

Source: Own graph

#### 4. Discussion of key risks and opportunities associated with each scenario

In this section we identify and discuss key risks and opportunities associated with each of the four alternative technology and investment pathways for the Port of Rotterdam’s industrial cluster presented above. As suggested by *Lieu et al. (2019, this issue)*, two categories of risks can be differentiated. Implementation risks are potential barriers to realising the developments described in each scenario, while consequential risks are unintended negative outcomes of the scenarios. Subsection 4.1 identifies the implementation risks and consequential risks and discusses which ones could be relevant to what extent for each of the four scenarios. Subsection 4.2 then identifies and discusses relevant opportunities associated with each scenario. Finally, subsection 4.3 focuses on the deep decarbonisation scenario CYC and briefly discusses how the most relevant risks could be mitigated and which kinds of stakeholders could play a role in their mitigation.

##### 4.1. Identification and discussion of risks associated with pursuing the scenarios

The key risks identified in relation to the scenarios are listed in *Table 1*. The table provides an assessment of how relevant each risk is for the four main scenarios developed. A double X (XX) means that a particular risk is of high relevance for a scenario, a single X means there is a medium risk and a blank space means that a particular risk is deemed to be low or irrelevant.

As the table shows, we assess implementation risks to be more numerous than consequential risks for all the developed scenarios. This is because (as explained above) each pathway for the industrial cluster of the Port of Rotterdam relies heavily on specific global and European framework conditions. During the implementation phase of the pathways, there will inevitably be uncertainties regarding the future development of these conditions. For example, if a BAU development is pursued by the cluster, an unforeseen tightening of European climate policies would pose a major threat to the economic viability of such a pathway. Similarly, pursuing either the BIO or the CYC pathway, perhaps in response to early signs of highly ambitious EU climate mitigation targets, carries considerable economic risk should these targets decrease. The implementation risks, therefore, mirror the uncertainty regarding future EU and global climate mitigation ambition and policy. On the other hand, consequential risks, by definition, only occur if scenarios are realised. This will only happen if there is a sufficient match between global and EU framework developments and

**Table 1**  
Implementation and consequential risks identified for the four scenarios developed.

Risks	BAU	TP	BIO	CYC
<b>Implementation risks</b>				
Anticipated technological developments fail to be realised		X	XX	XX
Insufficient incentives for investment in new technologies		X	XX	XX
Delay in, or lack of, infrastructure investment		XX	XX	X
Opposition from status-quo interests		X	X	XX
Lack of public acceptance for the use of new technologies	X	XX	XX	X
Lack of public acceptance for the use of existing technologies	XX	X	X	X
Lack of sufficient access to, or excessive future prices of:				
biomass		X	XX	X
electricity			X	XX
hydrogen and/or synthetic fuels				X
CO <sub>2</sub> emissions allowances	XX	X		
<b>Consequential risks</b>				
Economic structure might not remain sustainable post-2050	XX	X	X	
Industrial activities could be affected by climate change impacts	XX	XX	X	X

corresponding investment decisions by the cluster. Therefore, in terms of consequential risks, any risks associated with a mismatch between framework conditions and the cluster's actions are not relevant – with the result that we only envisage a few consequential risks. However, it should be stressed that it cannot be ruled out that we simply lack the imaginative power to foresee additional potential consequential risks.

In the following, each identified risk and its scenario-specific assessments (as shown in Table 1) will be briefly explained.

#### 4.1.1. Discussion of implementation risks

##### *Anticipated technological developments fail to be realised*

Deep decarbonisation in the more ambitious scenarios depends to some extent on technologies yet to be scaled up, with typically low technological readiness levels at demonstration plant or even at pilot plant status. Although assumptions regarding future technological progress appear to be quite conservative in the scenarios as no highly speculative new technologies were assumed to be deployed, there is nonetheless some risk that technological developments will be slower than assumed in the scenarios or even not successful at all. Development of nuclear fusion technology is an example of a very long and as yet unsuccessful development period (Cohn, 1997).

The main technological development risk in the scenarios consists of the combination of technologies, such as water electrolysis, carbon capture at different plant types, MtO and waste gasification and geological CO<sub>2</sub> storage, which have been proven in individual R&D project contexts but not on the scale and in the combination required for the industrial production of base chemicals and fuels. The thermodynamic integration of the processes, their control and optimised operation under market conditions remains a technological challenge to be accepted and tackled by engineers and decision makers.

We assess the BIO scenario and the CYC scenario as having similar degrees of risk in terms of technological development. The BIO scenario relies on the construction and successful operation of large-scale CCS plants and infrastructure, whereas the CYC scenario depends to a great extent on cost reductions in electrolyser technologies through R&D and technological learning.<sup>16</sup>

##### *Insufficient incentives for investment in new technologies*

Putting aside whether or not technological developments will progress quickly enough, the scale of the necessary investment in the scenarios poses an additional implementation risk. Companies might lack sufficient incentives to invest in cleaner technologies. Given that markets such as those for basic chemicals tend to be highly competitive, any clean investment frontrunners will have difficulties recovering their investment if they are unable to pass the higher costs of low-carbon production onto consumers. This is a particular concern as under current framework conditions the specific production costs of most of the low-carbon technologies available or emerging for the use in energy-intensive industries are expected to remain higher compared to conventional technologies (Wesseling et al., 2017; Dechema, 2017). As in the case of the previous risk, this risk is most relevant for the two deep decarbonisation scenarios, given their generally higher need for investment into new and typically more expensive technologies.

##### *Delay in, or lack of, infrastructure investment*

The three mitigation scenarios require the development of new infrastructure. Especially the BIO and CYC scenarios need high investment into infrastructure for the distribution of heat in the port area. The BIO and TP scenarios assume pipelines for the transport and sequestration of CO<sub>2</sub>. Especially the CYC scenario uses large quantities of renewables-based electricity, whereas the BIO and the CYC scenarios rely on significant amounts of hydrogen.

We assess the infrastructure-related risks to be higher in the BIO scenario than in the CYC scenario, as the CCS infrastructure required in the BIO scenario is likely to be more expensive and more complicated to implement than the additional<sup>17</sup> electricity or hydrogen infrastructure required in the CYC scenario. The heat grid is mainly limited to the port area and the associated risks, such as a lack of willingness by local companies to participate in the exchange of heat, are, therefore, internal to the cluster. Conversely, CO<sub>2</sub> transport and sequestration infrastructure, as well as an expansion of the electricity or hydrogen grid, require at least in part external cooperation or certain external developments, making public involvement in terms of planning, acceptance and funding crucial.

##### *Opposition from status-quo interests*

Existing industrial businesses in the port are long-established and are mainly owned by large international companies such as Shell, Engie and E.ON. In the decarbonisation scenarios, many of these businesses' assets will either not be renewed over time or will even be devalued, potentially affecting their owners' balance sheets as well as the interests of the work force. Consequently, there might be strong incentives for status-quo interests to oppose any scenarios other than BAU. This holds particularly true for refineries

<sup>16</sup> IEA's "Technology Roadmap Hydrogen and Fuel Cells" (IEA, 2015b) foresees massive potential capital cost reductions, e.g. from 2,600 US-\$/kW in 2015 to 800 US-\$/kW in 2030 and even 640 US-\$/kW in 2050 for polymer electrolyte membrane (PEM) electrolyzers. With regard to the calculated capacity need of 5.7 GW in the CYC scenario, this would still imply an investment of 3.6 billion US-\$ by 2050. Schmidt et al. (2017) derive similar results on potential investment cost reductions from an expert panel and also analyse technical lifetime and energy efficiency potentials as two important factors contributing to operational costs. They identify capacity scale-up as the major driver for future total cost reduction, more relevant than R&D funding.

<sup>17</sup> The word "additional" refers to the fact that in the BIO scenario the electricity transmission and distribution infrastructure will already need to be expanded and/or amended compared to today, although probably to a lesser degree than in the CYC scenario, as the scenarios' electricity balances (see Fig. 4) indicate.

and conventional electricity generation companies, as these industries quickly lose relevance especially in the non-CCS scenario CYC.<sup>18</sup> The chemical industry might also oppose decarbonisation efforts, not because decarbonisation would cause their business to cease, but because of the inherent technological, economic and organisational challenges of converting their production assets.

#### *Lack of public acceptance for the use of new technologies*

CCS technology has been intensively debated and is facing public opposition in the Netherlands (van Egmond and Hekkert, 2015; Brunsting et al., 2011). Potential difficulties in implementing CCS technology pose a threat to all scenarios except the CYC scenario. Certain industrial technologies may also face a lack of public acceptance in the future. Particularly waste pyrolysis, which would require waste shipments to Rotterdam, as well as new pipelines for hydrogen or other chemicals might be affected. Also, the sustainability of large-scale biomass imports from overseas for energy or feedstock is a matter of public debate in the Netherlands and other countries (van Hilst et al., 2017) and could eventually lead to a lack of public acceptance for such a strategy, which would be particularly problematic for the BIO scenario.<sup>19</sup>

#### *Lack of public acceptance for the use of existing technologies*

The debate about coal-fired electricity generation has been gaining momentum in recent years, particularly in the Netherlands where NGOs and some political parties have long been calling for a phase-out of coal-fired power plants. Consequently, the BAU and to a lesser extent the TP scenarios could be affected by reduced public acceptance for the unsustainable business models locking the cluster into high carbon pathways. With a likely future increase in the visibility of climate change-related environmental damage, this could become a significant risk making the BAU pathway unsustainable by 2050. Recent stringent political decisions in the Netherlands about coal-fired power plants – affecting also recently-built plants – are a clear indication that this business risk is relevant (Meijer, 2018). The risk could also become relevant in the future for the refineries and chemical plants, at least if a BAU pathway is followed.

#### *Lack of sufficient access to, or excessive future prices of, green energy or CO<sub>2</sub> emission allowances*

All scenarios need significant external resources to mainly replace the fossil intake of oil and coal in the metabolism of the industrial cluster.

- Biomass is currently the most competitive clean energy carrier but increasing demand could push prices up. Furthermore, there are strong doubts about whether substantial biomass resources are really available with low life-cycle GHG emissions. This creates the significant risk that sustainable biomass supply will be severely restricted in the future, leading to higher biomass prices and potentially compromising the viability of the BIO scenario.
- Large amounts of renewables-based electricity will be needed in the CYC scenario in particular. Its availability depends on a strong future expansion of renewables-based electricity generation in the Netherlands and the rest of Europe, as well as on related changes in the electricity transport and storage infrastructure. While the costs for electricity from renewable sources such as wind and solar PV have significantly reduced in recent years (Samadi, 2018; IRENA, 2018), the expansion and system integration of renewables – particularly for the CYC scenario – would have to happen quickly and it is unclear whether this is achievable.<sup>20</sup>
- The main risk regarding the use of hydrogen and/or synthetic fuels, which are mainly used in the BIO and CYC scenarios, is that the global development of renewables-based hydrogen or synthetic fuels will not occur at sufficient speed or scale. Consequently, the cost of these energy carriers would remain too high. Infrastructure issues, in contrast, do not seem to pose a relevant risk here. Synthetic fuels in particular could make use of the obsolete capacities of mineral oil-based energy infrastructures.
- Particularly in the BAU scenario the availability of CO<sub>2</sub> emission allowances at reasonable cost for the operation in the industrial cluster could become an issue, given the already-determined reduction factors in the EU-ETS and the European GHG emission reduction targets for 2050.

#### *4.1.2. Discussion of consequential risks*

##### *Economic structure might not remain sustainable post-2050*

The economic structure of the port's industrial cluster might not remain economically viable after 2050. This is especially true for the BAU scenario. Even if such a scenario is viable until 2050 as a result of weak European climate mitigation efforts, it is possible that mitigation efforts will intensify in the second half of the century, finally endangering the business case of the cluster. In some sense the risk of a cluster becoming economically unsustainable is a standard risk for any industrial cluster, but in times of climate

<sup>18</sup> Unlike in the CYC scenario, the existing coal power plants continue to be utilised beyond 2050 in the BIO scenario, although with a change in fuel. Long-term refinery capacity in the BIO scenario is also slightly higher than in the CYC scenario.

<sup>19</sup> It should be noted that strategies exist to increase public acceptance for the use of new technologies (Frewer, 1999; Terwel et al., 2011). The appropriate use of such strategies can considerably reduce the risk of technologies failing to be deployed due to public opposition.

<sup>20</sup> Hydrogen and/or synthetic fuels could, to some extent, provide an alternative to the direct use of electricity. These energy sources could be produced elsewhere in the world and then shipped to Rotterdam as energy input. The potentially global supply significantly reduces risks. The production of both energy carriers, however, incurs significant conversion costs on top of the costs of the renewables-based electricity required. (See also the following discussion of the risks associated with hydrogen and synthetic fuels.)

**Table 2**  
Opportunities identified for the four scenarios developed.

Opportunities	BAU	TP	BIO	CYC
Contributing substantially to global climate change mitigation efforts		X	XX	XX
Benefitting from being a frontrunner in industrial decarbonisation		X	XX	XX
Gaining a competitive edge in an increasingly decarbonised future world			X	XX
Improving air quality			X	XX

change it is certainly higher for emission-intensive clusters and for production sites with large, inherently inflexible production assets. This is the case in both the BAU scenario and – to a lesser extent – in the TP scenario, with the key role of big refineries, crackers and coal-fired power plants. In the BIO scenario, uncertainty regarding the availability of sustainably-sourced biomass at acceptable cost in the post-2050 period poses a risk because global production might increasingly seek to shift to biomass, asserting pressure on costs and availability.

#### *Industrial activities could be affected by climate change impacts*

Rotterdam is a coastal region and is, therefore, particularly vulnerable to climate change impacts such as rising sea levels, flooding due to periods of heavy rainfall, storms etc. It seems plausible that under the BAU scenario, increased global warming and associated climate impacts would occur more readily compared to the mitigation scenarios.

#### *4.2. Discussion of opportunities*

Scenarios are not only associated with risks, but also with opportunities. As for risks, opportunities differ from one scenario to another and this is shown in Table 2. The greatest opportunities are associated with the most ambitious decarbonisation scenarios, particularly for the CYC scenario.

#### *Contributing substantially to global climate change mitigation efforts*

The decarbonisation scenarios make a significant contribution to national and European climate mitigation targets. Particularly the BIO and CYC scenarios reduce the emissions of one of the major GHG-emitting regions of the Netherlands to practically zero by 2050. By helping to develop key mitigation technologies for the industrial sector and by successfully showcasing their implementation, the chance of similar technologies and strategies being used in other industrial clusters around the world increases. By becoming a frontrunner in industrial decarbonisation, the port may serve as an important example for other petrochemical clusters in Europe, such as Antwerp in Belgium, the Rhine-Ruhr area and Ludwigshafen in Germany, Stenungsund in Sweden or Tarragona in Spain, or even beyond Europe. The port could demonstrate that it is possible for such regions to embark on a pathway that ultimately aims to completely avoid net CO<sub>2</sub> emissions. In the TP scenario, these benefits only partly apply, as it is less ambitious regarding climate protection and implies less use of key new deep decarbonisation technologies. No such benefits exist in the BAU scenario.

#### *Benefitting from being a frontrunner in industrial decarbonisation*

Early and meaningful decarbonisation efforts offer the possibility of becoming a frontrunner in industrial decarbonisation. This, in turn, should make it more likely for the region to receive grants for early demonstration projects and to attract new, low-carbon industrial activities and related innovations. As part of the study conducted for the Port of Rotterdam (Samadi et al., 2016), we identified the following new products and new industrial activities – each with high potential relevance in a future decarbonised world – for possible development in the port area:

- Offshore wind
- Bio-based chemistry
- Demand-side management<sup>21</sup>
- CO<sub>2</sub> transport and storage
- Use of waste
- Synthetic fuels
- Carbon-neutral primary steel production

If the deep decarbonisation pathways are successfully pursued, the Port of Rotterdam may internationally become known as the

<sup>21</sup> 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), such as electrolysis and electric steam generation, are generally suitable for flexible operation, with higher demand at times of low electricity prices and lower demand at times of high prices. Steam generation in particular is generally well-suited to flexible operation due to (typically) relatively low investment costs and the possibility of taking advantage of the storage capacities of existing heat and steam grids.

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 projects and initiatives exist or are currently being conducted that discuss the potential for achieving significant emission reductions in other industrial regions in Europe (e.g. TNO, 2018; MWIDE, 2018) and in other countries (e.g. Liu et al., 2018). Obviously, efforts to decarbonise the port's inbound, outbound and internal transport also need to be part of a holistic decarbonisation strategy and could possibly support global transport sector decarbonisation efforts.<sup>22</sup>

#### *Gaining a competitive edge in an increasingly decarbonised future world*

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 for the port's industrial cluster to take advantage of its unique geographical location. The cluster, for example, is in close proximity to potential CO<sub>2</sub> storage sites in the North Sea as well as to North Sea areas that are well suited to offshore wind power generation. The port also provides the possibility of importing low-carbon energy carriers in the form of biomass and/or renewables-based synthetic fuels at relatively low transport costs.

#### *Improving air quality*

Significant 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 for gasification and Fischer-Tropsch, each being associated with local pollution of its own.<sup>23</sup>

#### *4.3. Taking steps to mitigate the scenario-related risks*

Table 3 shows the four risks identified in Section 4.1 that are likely to be the most relevant for the ambitious CYC scenario. The table also indicates how each of these risks might be mitigated and who the relevant stakeholders are. Our analysis indicates that most of the risks could be significantly mitigated by appropriate policies pursued by the EU and the Dutch national government. Appropriate policies include stringent CO<sub>2</sub> pricing through emission trading and/or a carbon tax, offering long-term certainty to investors, active RD&D support, investment support for key new low-carbon technologies and infrastructure, and trade and market policies to enable bulk products like decarbonised and/or renewables-based basic chemicals to be competitive in their respective markets.

Mitigating the risks associated with deep decarbonisation pathways does not seem to face general conceptual problems, as a broad suite of policy instruments already exist as known enablers of GHG emissions mitigation (Åhman et al., 2017; Bataille et al., 2018). However, the risk management of ambitious decarbonisation strategies for an industrial cluster requires a strong package of such climate policy instruments, together with appropriate industrial policy strategies (Nilsson et al., 2017). In this regard, the EU and national governments appear to be the key actors with the tools to motivate and enable industrial stakeholders to take action towards ambitious strategies.

It can be argued, of course, that it is too simple to merely call on national governments and the EU to enact appropriately strong policy packages, as such sweeping policy changes are only likely to happen when there is sufficient pressure from within society to embark on such pathways. It follows, therefore, that the public needs to be informed about the possibilities and advantages associated with deep decarbonisation pathways for industrial clusters. Participatory analyses, such as the one presented in this article, serve to provide insights to help inform both policymakers and the general public. In order to ensure long-term acceptance and buy-in from the public, it is critically important to use such approaches to secure early public engagement when devising and implementing transformation processes.

## **5. Conclusion**

This paper explains how a combination of qualitative and quantitative research methods can be used to develop a range of plausible pathways for industrial clusters to achieve CO<sub>2</sub> emission reductions by the middle of the century in line with the still uncertain future global or regional climate mitigation ambitions – and thereby significantly reduce the risks associated with the current CO<sub>2</sub>-intensive business model. The insights gained from this analysis can inform individual companies and regional authorities such as the [Port of Rotterdam Authority](#) on the range of conceivable future developments of the cluster, including the respective technological and infrastructural changes. The insights can also inform policymakers, especially by highlighting how an appropriate policy framework can address the key implementation risks related to decarbonisation scenarios.

The analysis of risks associated with each scenario found that a key risk of any pathway aiming for deep decarbonisation by 2050 is if the mitigation ambition as expressed in the Paris Agreement fails to be underpinned by appropriate and continuous energy, climate and industrial policy measures. This could render early investment into clean technology uncompetitive, even in the long

<sup>22</sup> Long-term options to decarbonise the port's inbound and outbound transport activities have also recently been proposed by a report commissioned by the Port Authority (see [Lechtenböhmer et al., 2018](#)).

<sup>23</sup> The exact air pollution outcomes of the scenarios depend heavily on specific future technological configurations. Our modelling approach is not sufficiently detailed to provide a quantitative assessment of scenario differences in air pollution.

**Table 3**  
Potential measures and relevant actors involved in mitigating the key risks identified for the deep decarbonisation scenario CYC.

Key risk	Potential mitigation measure(s)	Relevant actor(s) involved
Anticipated technological developments fail to be realised	Intensify RD&D for key deep decarbonisation technologies	National government, European Union
Insufficient incentives for investment in new technologies	Framework conditions need to provide sufficient long-term signals, such as a sufficiently high carbon price, support for market introduction, green investment support, roadmaps and infrastructure planning	European Union, National government
Opposition from status-quo interests	Intensify efforts to support current market players to re-orient themselves, strengthen new market actors	National government, European Union
Lack of sufficient access to, or excessive future prices of, electricity	Intensify investments in renewable electricity generation capacities in Europe and investigate potential to support such investments in the Middle East & North Africa (MENA) region	National government, European Union

term. On the other hand, the key risk of BAU or insufficient mitigation is that carbon-intensive production continues to be locked in. This would lead to high production costs and diminishing demand for transport fuels and other products if the “rest of the world” sooner or later decides to follow through with ambitious climate protection.<sup>24</sup>

Our analysis of scenario risks also suggests that the two highly ambitious deep decarbonisation scenarios differ considerably in terms of some of the identified implementation risks. The biomass and CCS-focused BIO scenario is associated with higher implementation risks linked to infrastructure expansion, public acceptance and biomass availability, although the circular economy scenario CYC might be opposed more strongly by status-quo interests and depends to a greater extent on the sufficient availability of carbon-free electricity from outside the cluster. In the BIO scenario, the liquid fuel supply chain is strengthened by establishing a chain at the port ranging from the conversion of crude biomass to final products (i.e. fuels), whereas in the CYC scenario the petrochemical sector is converted to a system, which could be more robust to post-2050 developments. In order to hedge some of the risks, strategies from both scenarios may be, to some extent, combined. This would mean to strengthen the bio-fuel chain while at the same time adapting the petrochemical sector to a circular economy. Such a combination could open up synergies but would also increase strategy-related risks.

It is an urgent task for policymakers and for underlying advocacy from within society to ensure the policy framework takes a form that makes the risks associated with deep decarbonisation scenarios lower than the risks associated with insufficient mitigation action. It is likely that such a policy framework would need to include more active public roles in enabling forward-looking investment in clean technologies, in providing the required infrastructure and in enabling green production to compete with dirtier production at lower market cost. In other words, a strong, coherent and targeted industrial and climate policy framework will be required.

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<sup>24</sup> The lock-in dangers of BAU are exaggerated by climate change effects and likely subsequent acceptance problems.

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