**ACT ALIGN CCUS Project No 271501**

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# Accelerating Low carboN Industrial Growth through CCUS

# Deliverable Nr. D5.2.2

## Modifications Required to Existing Infrastructure in the Port of Rotterdam Area to Transition to Clean 'Blue' Hydrogen

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# Executive summary

The Port of Rotterdam contributes considerably to the economy of the Netherlands but also generates over 15% of the total $CO_2$ emissions of the country. The port authorities are currently evaluating decarbonization pathways. The deployment of CCUS and the greater use of 'blue' hydrogen have considerable technical potential for reducing emissions.

The Port of Rotterdam have studied the feasibility of using low-carbon hydrogen instead of fossil fuels for use in the chemical industry, refineries and power plants through a project named H-Vision (hydrogen vision). The H-Vision concept that has been developed involves the large scale production of clean hydrogen using both refinery fuel gas and natural gas as feedstock, called blue hydrogen. The overall goal of the H-Vision concept is to enable significant $CO_2$ emissions reductions in the power and industrial sector in Rotterdam, while developing the infrastructure for 'green hydrogen'. The aim is to utilize green hydrogen once electrolysis installations can be scaled-up and sufficient renewable power is available on the grid. The additional hydrogen produced can be used for high-temperature heating processes in the large refinery sector of the port, but also for power generation either through the use of gas turbines (able to run on hydrogen rich fuels), or through the conversion of existing coal-fired power plants. It is understood that the H-Vision concept could reduce $CO_2$ emissions from the processes in the port area by between 2 to 6 megatons per annum (Mtpa).

ALIGN-CCUS deliverable D5.2.1 evaluated different production routes for hydrogen in combination with CCUS. To develop this knowledge further this report will assess the technical feasibility of utilizing hydrogen in existing and new processes in the Port of Rotterdam area. The modifications required to existing infrastructure to convert to blue hydrogen are reviewed. Infrastructure developments would also be required for the use of green hydrogen which is not covered in this report.

Power generation in the Rotterdam region is predominantly through the use of natural-gas and coal. To support the phase-out of coal in the Netherlands hydrogen-fired steam generation (HFSG) is an available technology, and the conversion of coal-fired steam generation to HFSG is understood to be feasible and economical. Hydrogen can also be fed into existing natural gas turbines with limited modifications required for low percentages of hydrogen blending. New turbines are necessary for use with hydrogen blends over approximately 40%.

Existing refineries already utilize hydrogen for processes such as hydrocracking and hydrotreating, and so could switch to clean hydrogen with no modifications required. Alongside this, the produced refinery fuel gas could also be converted to hydrogen and then the hydrogen burned to generate high-temperature heat in the refineries. This would require modifying or replacing furnace fuel-burners to make them compatible with the resulting $H_2$-rich fuel. Low-NOx technology is required. If a centralized concept is deployed, additional infrastructure is also needed to transport refinery fuel gas to a centralized hydrogen facility, as well as to transport blue $H_2$ back to the refineries.

Many chemical industrial processes already utilize hydrogen in the Port of Rotterdam, although on a much smaller-scale than power generation and the petrochemical sector. These could transition to clean hydrogen use although may require very high purities of hydrogen compared to power and heat generation. This is therefore not envisaged as a primary use in the H-Vision project but may have potential for longer-term deployment.

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# 1 Introduction

The Port of Rotterdam is the largest seaport in Europe with an area of approximately 105 square kilometres. The area comprises 5 oil refineries, production plants for hydrogen, industrial gas producers, a variety of chemical plants (45 chemical locations) and power generation sites (9 plants) which include both coal-based and gas-based fuel sources. The total port region generated an added value of €45.6 billion to the Dutch economy in 2018 and created direct and indirect employment for over 385,000 people. The estimated $CO_2$ emission levels in the Port of Rotterdam region (from the port plus industries in the area) during 2018 were are around 27 mega-tons (Mt) ("Port of Rotterdam," 2020).

A majority of $CO_2$ emissions in the Port of Rotterdam area are from the energy sector and crude oil refining. The chemical sector is also a large contributor towards the port's $CO_2$ emissions (Samadi et al., 2016). Large quantities of heat are also currently released as waste products which may be utilised in order to reduce the climate impact of the port's operations. Heat is in high demand from chemical companies, industrial greenhouses and households in the region. These energy sources are currently being utilized and exchanged via pipelines in the port which contributes to a sustainable port and ensures a profitable and sustainable business climate. A breakdown of $CO_2$ emissions by industry in the port is given in Figure 1.

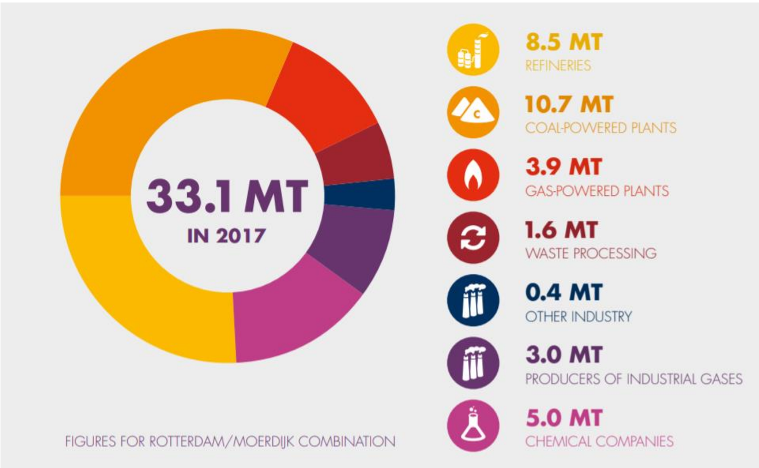


**Figure 1** *$CO_2$ emissions by industry based in the Port of Rotterdam (Source: Port of Rotterdam, 2017).*

Creating a centralized facility for the decarbonisation of natural gas to produce hydrogen in the Rotterdam Port area could help mitigate emissions in the high $CO_2$ emitting facilities. Hydrogen is used as a feedstock in numerous chemical industries and could produce a range of new clean chemical building blocks for chemical processes in the region. A centralized facility could also send part of the produced hydrogen to the nearby coal fired power plants where the coal can be replaced by the burning of hydrogen. However, some processes (such as use in the food industry) would require high purity hydrogen which would require further purification processes to hydrogen produced for fuel-grade use. The hydrogen can also be transported to the Rotterdam refineries for desulfurization of fuels. The clean hydrogen combined with clean power and substantial volumes of $CO_2$ could create opportunities for the re-utilization of the $CO_2$ and co-produced low level heat, which can be used for heating nearby existing greenhouses at the north side of the port area.

Power is currently generated in the Port of Rotterdam by 3 gas-fired and 3 coal-fired power stations. There is the potential to blend hydrogen into the gas-fired power station with limited modifications but cofiring solid-fuel in combination with hydrogen requires more infrastructure modifications.

The ALIGN-CCUS project is dedicated to advancing this idea to a working concept, conducting pre-feasibility activities and producing a roadmap for deployment. ALIGN-CCUS deliverable D5.2.1 provides a review of the potential blue hydrogen production technologies that could be developed in the Port of Rotterdam. The report outlines the technical feasibility and requirements to develop large-scale hydrogen production facilities. This report (D5.2.2) follows on from this work and aims to review what modifications that would be required for current technologies and infrastructure (e.g. for power generation, refineries and chemical production) to utilise clean blue hydrogen as a heat and power source. This is the first step to assessing the technical feasibility of converting coal-fired power plants in Rotterdam to hydrogen-fired power generation and further utilization of hydrogen in existing and new processes for the Rotterdam region.

# 2 Decarbonisation Options using Hydrogen

The Netherlands is currently a large producer and consumer of hydrogen with a current annual supply of approximately 175 petajoules (PJ) (DNV GL, 2019). It is estimated that The Port of Rotterdam currently uses 300-400 kilotons (kt) of hydrogen as feedstock in industry (H-Vision, 2019). Currently, the main method for producing hydrogen is through the steam methane reforming (SMR) of natural gas which has associated $CO_2$ emissions. Hydrogen is also produced as a by-product in industrial chemical processes such as chlorine production and crude oil refining.

The Netherlands plans to incorporate hydrogen into its decarbonization scenarios for 2050 (Gigler & Weeda, 2018) with 'clean' hydrogen produced through renewable energy (green hydrogen) and through natural gas reforming in combination with CCUS technologies (hereafter referred to as 'blue' hydrogen). This report does not focus on the source of $CO_2$ or production scenarios required to meet the 2050 targets. For more information regarding hydrogen production please refer to ALIGN-CCUS Deliverable D5.2.1. This report reviews the modifications required to currently existing infrastructure in the Port of Rotterdam area to allow for a transition to blue hydrogen specifically. This includes for use in power generation, high-temperature heat production and for use in chemical processes.

This section of the report outlines the potential ways hydrogen could be utilized in the Port of Rotterdam. It includes the use of hydrogen both as a fuel to generate power or heat and as a raw material for industrial processes.

## 2.1 Power Supply

Hydrogen can be utilized as a fuel and combusted in conventional power plants for electricity production. This use of hydrogen in power generation is discussed in detail in Section 3 of this report. The amount of hydrogen required is highly site specific and dependent on the type of fuel utilized. For newer gas turbines, hydrogen can typically be blended in with limited modifications required for low percentages of hydrogen. For solid fuels, where hydrogen has to be cofired, less hydrogen is utilized and more infrastructure modifications are required. Pure hydrogen turbines are not currently commercially available but are in development and may be available in the near-term for power generation.

In the Port of Rotterdam current power supply demands are being met using predominantly natural gas and coal. These hydrocarbon fuels could be replaced and the demand fulfilled by utilizing hydrogen production (from various sources in combination with CCUS). This could be conducted within the already existing power plants, with modifications to specific elements such as the gas turbines. Industrial companies in the port mainly use energy to generate heat for their production processes. To decarbonize the power supply produced in the Port of Rotterdam, a giga-watt (GW) scale of power generation would need to be guaranteed which can meet the needs of a large variety of industrial clusters. The H-Vision concept concluded that these power supply demands could be met through the deployment of blue hydrogen.

## 2.2 High-Temperature Heat Supply

High-temperature heat generally refers to heat over 100°C (Kreijkes, 2017) and industry processes are often designed for heat supply temperatures of around 100°C to

200°C. Natural gas and refinery fuel gases (RFGs) are currently being burnt as high-temperature process fuels in the Port of Rotterdam. At the nearby Shell Moerdijk site, cracked gas from the naphtha crackers is used as fuel gas. High-temperature furnaces are used in a variety of processes within the Port of Rotterdam to heat up process streams. One of the largest consumers of high-temperature heat in the port is for use within petrochemical industries, mainly oil refineries. Industrial installations, such as atmospheric and vacuum distillation units, hydrotreating and hydrocraking units, catalytic reformers and solvent de-asphalting units all require high-temperature furnaces to operate (H-Vision, 2019).

Refinery fuel gas (RFG) is produced during the refining process and then recycled, predominantly to be used as fuel for high-temperature heat in boilers and process heaters throughout a refinery or petrochemical plant. This is discussed in detail in Section 4 of this report. Without carbon capture, this process results in large $CO_2$ emissions produced in the refinery's boilers and process heaters. Consequently, there is the potential to combine CCUS with the utilization of the refinery fuel gas to produce hydrogen. Blue hydrogen can be produced at a centralized facility using RFG and then this hydrogen can be used as the high-temperature heat source at the refinery. Blue hydrogen production has significant potential to decarbonize the use of RFG, which is not the case for the other decarbonization alternatives. Infrastructure modifications would be required to transport RFG to a centralized hydrogen production facility and also to deploy fuel-flexible burners in the refinery.

## 2.3 Material Feedstock

Hydrogen is already being utilized as an important material feedstock in chemical processes such as ammonia production and crude oil refining. Hydrogen has a long history with material based use as a feedstock in chemical and metallurgic industries (Hydrogen Europe, 2017b). The industrial uses for hydrogen are discussed in detail in Section 5 and the use of hydrogen as a raw material in oil refinery processes is discussed in Section 4.

The conventional method to produce ammonia fertilizer is to combine hydrogen (usually produced by reforming natural gas) and nitrogen, through a method called the Haber-Bosch process. Ammonia production is the most energy-intensive process in the fertilizer industry. Alternatively, hydrogen sources with a lower $CO_2$ footprint (e.g. green hydrogen) can be produced on-site or supplied from external sources. Conventional ammonia plants produce large flows of almost pure $CO_2$ gas, captured after the natural gas reforming step. These are potentially well suited for carbon storage (CCS) (Batool & Wetzels, 2019).

Hydrogen is also used in the production of synthetic gas (syngas). Syngas is a gas mixture consisting primarily of hydrogen and carbon monoxide, with some residual carbon dioxide. Syngas is an intermediate in the production of synthetic natural gas (SNG), methanol or synthetic hydrocarbons through the Fischer-Tropsch process. However, the main application for syngas is currently in electricity generation in coal-based power plants that include a gasification step and at refineries where residue oil is gasified to produce syngas. Syngas is combustible and in principle could also be used as a fuel of internal combustion engines.

The Port of Rotterdam have recently joined a research consortium to investigate the use of a new technology by Enerkem (a Canadian clean technology company) to manufacture synthesis gas from domestic waste which could be used as a feedstock for making products such as methanol and ammonia (Port of Rotterdam, 2015). Ammonia production in the Port of Rotterdam is discussed in Section 5.1.

## 2.4 Low-Temperature Heat Supply

Low-temperature heat generally refers to heat under 100°C (Kreijkes, 2017). During many industrial processes heat is generated as a by-product but can be recycled for purposes such as domestic heating and in commercial greenhouses. Hydrogen is already utilized in some low-temperature heat applications such as for heating and drying. In the future hydrogen may be used further to decarbonize some sources of low-temperature heat supply such as through the use hydrogen burners or fuel cells (Hydrogen Europe, 2017a).

There are many potential options for decarbonizing low-grade heat, including the use of heat pumps and electrical resistance heating. Low-temperature heat decarbonization through the use of hydrogen is not currently a prominent decarbonization pathway in the Port of Rotterdam. The focus for district heating in the Rotterdam area is mainly focused on renewable and geothermal energy utilization. The modifications requirements for hydrogen to be used to generate low-temperature heat is therefore not included in this report but should be noted as a potential long-term option.

# 3 Power Generation

A majority of power generation occurring in the Port of Rotterdam is through three coal and three gas fired power stations currently in operation. For some of the gas-fired turbine technology being used it is possible to use the same infrastructure to utilize hydrogen by blending it into the existing gas fuel system. Hydrogen has different properties to natural gas which will limit the re-purposing potential of current power generation assets:

- Hydrogen has a third of the volumetric-energy density of natural gas and therefore a larger flow of hydrogen gas is required to produce the same amount of energy in comparison to natural gas.
- Hydrogen has a higher flame temperature and burning velocity, which means modifications are required to either allow the turbines to operate at these temperatures or to mitigate the combustion temperature through dilution. Also, the higher flame speed increases the flame temperature locally, generating nitrogen oxides (NOx) which must be minimized.
- Hydrogen is more hazardous (more reactive, more prone to leakages, more difficult to detect, wider explosion range) and will therefore require different risk management strategies.

Some power generation infrastructure will therefore require modifications before hydrogen can be utilized. The current status of hydrogen turbine technology for power generation is outlined below, highlighting the modifications that would be required for the gas and coal fired power stations in the Port of Rotterdam.

## 3.1 Current hydrogen turbine technology

There are currently no commercial-scale turbines that are able to run on pure hydrogen. Two major areas of research currently underway regarding hydrogen turbines are:

- Hydrogen turbines are currently experiencing NOx emission issues and a key research activity is to reduce these emissions.
- Flame positioning shifting is also causing overheating issues of some components which is also a key area of research.

Many gas turbines currently in use are already fuel flexible. This means many can already operate on a blend of hydrogen and natural gas with limited or no modifications required for blends of hydrogen under 20-25%. Some turbines can run on larger volumes, for example, General Electric's (GE) DLN 2.6e combustion system can run on a 50% hydrogen blend (which has been applied to 7HA and 9Ha gas turbines). Mitsubishi Hitachi Power Systems (MHP) have also developed a large-scale 30% hydrogen combustor. A summary of ongoing work in this area is given below for the major commercial turbine providers.

***Mitsubishi Hitachi Power Systems***

Mitsubishi Hitachi Power Systems (MHPS) are currently refining their Dry Low NOx (DLN) combustor which traditionally mixed the fuel with air in advance of the combustor to maintain a relatively cool flame and keep the NOx emissions down. This approach doesn't work well with hydrogen and therefore the combustor is currently being modified at MHPS in Japan. The solution is to cool the flame through the use of diluents (such as demineralized water, steam or nitrogen). As well as reducing NOx emissions, this also reduces the efficiency in comparison to a DLN combustor.

MHPS's work on this project is still in the early stages. The new combustor has been tested on a small gas turbine using Liquefied Petroleum Gas (LPG). It requires the replacement of the fuel nozzle, combustor basket, transition piece, ignitors and flame detectors. Fuel lines must also be augmented to cope with the larger fuel flow required when using hydrogen. MHPS wants to retrofit this technology into existing gas turbines and turbines running on 100% hydrogen are planned for the Nuon Magum power plant project for deployment in 2023 (NS Energy, 2019).

In the meantime, the MHPS has successfully completed a firing test with 30% hydrogen using existing dry low NOx (DLN) turbine technology at 1600°C. This resulted in $CO_2$ emissions 10% lower than those running only on natural gas (Turbomachinery Magazine, 2018).

***Siemens***

Siemens are currently working with non-mainstream fuels (often referred to as 'opportunity fuels'), some of which have high hydrogen contents. Typically these comprise process off-gases, such as refinery gas or coke over gas. Siemens is researching getting the fuel into the combustors safely, burning it stably and reliably, and controlling the combustion emissions. Their research on high-hydrogen fuels is moving away from diffusion flame combustion systems to DLN combustion. It seeks to mitigate flashback risk and combustion instabilities. Siemens has hydrogen capability at various levels across its gas turbine portfolio from 4 megawatt (MW) to 567 MW.

Most recently, progress has been made on enhancing the hydrogen capabilities of its dry low emission (DLE) combustion systems. Its SGT-600, -700 and -800 gas turbines (24 MW to 57 MW) offer up to 60% hydrogen in natural gas on a volume basis with NOx emission levels as low as 25 part per million (ppm). Siemens are currently working on a capability-expansion project to enable the burners to be able to operate on up to 100% hydrogen (Turbomachinery Magazine, 2018).

***General Electric (GE)***

GE's hydrogen-containing fuel turbines have been operated in steel mill plants, integrated gasification combined cycle (IGCC) power plants, refineries, and petrochemical plants with waste or process gases containing hydrogen. GE has developed a premixed combustor capable of operating on high-hydrogen fuels. This combustor (capable of operating on a natural gas blend with about 50% hydrogen) is named the DLN 2.6e and is now integrated on GE's 9HA gas turbines announced in October 2019 (GE Power, 2018).

GE offers upgrade packages, so that its operational gas turbines can run on fuels beyond their initial configuration. This may provide financial security for the plant owner or operator; and may also aid in providing energy security for the electrical utilities, since gas turbines can be re-configured to consume other fuels as situations require (GE Reports, 2019).

***Ansaldo***

Ansaldo and Equinor are currently collaborating to run Ansaldo's GT36 H-class gas turbine combustor on pure hydrogen, as announced in an agreement in Oct 2019 (Ansaldo Energia, 2019). Ansaldo Energia's service team (AT) is working on combustion technology for fuel mixing and greater hydrogen content. AT's low emission combustor (LEC III™) is available for up to 25% hydrogen. Its FlameSheet™ combustor can tackle up to 40% hydrogen. Tests are ongoing to demonstrate 80% hydrogen capability for FlameSheet™ and development work is ongoing for a 100% hydrogen demonstration.

## 3.2 Implications for the Port of Rotterdam

A list of power plants in the Port of Rotterdam and their feasibility to switch to hydrogen are presented in Figure 2.

| Unit | Power output (installed capacity) [MWe] | Fuel type | Hydrogen (partial) switch option |
|---|---|---|---|
| Uniper Maasvlakte 3 | 1070 | Coal / biomass | Yes |
| Eneco Enecogen | 870 | NG | No |
| Rijnmond Energie CV | 820 | NG | No |
| Engie MaasStroom | 800 | Coal / biomass | Yes |
| Air Liquide Pergen | 300 | NG | Yes |
| Shell Refinery Per+ | 142 | Syngas | Yes |
| Eurogen | 88 | NG | No |

**Figure 2** *List of coal and gas-fired power generation plants in the Rotterdam area (Source:* H-Vision, 2019)

Four of these (two goal and two gas) have been identified as part of the H-Vision Project as having the potential for partial switching to hydrogen. The two gas-fired power plants are operated by Air Liquide Pergen and Shell Refinery Per+ which have proven turbine technology compatible with partial hydrogen use. The other two gas-fired power plants (Enecogen and Rijnmond Energie) have gas turbine technology not yet proven for use with hydrogen as a fuel and hence may require extensive modifications or replacement. The other power plants are hence are not viable for short-term use with hydrogen.

The two coal-fired power plants are due to be phased out by 2030 following the Dutch government's decarbonization targets. A proposed bill prohibiting the production of electricity from coal will prevent the use of hydrogen alongside coal as a decarbonization option. It is therefore proposed to replace the coal with biomass fuel and fire hydrogen either inside the existing boilers or in new gas turbines.

## 3.3 Modifications Required

Although the blending of hydrogen is technically feasible, the combustor component of a turbine requires major redesign to utilize 100% hydrogen as the fuel. 100% hydrogen turbines are still under development with a TRL 4 to 7 and possible application in 3 to 10 years (Hers, Scholten, van der Veen, van de Water, & Leguijt, 2018). No commercial 100% hydrogen turbines are currently in operation.

The modifications currently required are therefore based on short-term goals of partially mixing hydrogen in fuel-flexible turbines. The H-Vision project reviewed the costs associated with modifying current power plants in the Rotterdam area for use with hydrogen. For solid fuel (e.g. coal) fired power plants the modification costs fall under three main items (H-Vision, 2019):

- Investment in and installation of new gas turbines;

- Modifications to enable hydrogen firing in the preheat sections; and
- Cost of full steam integration between the hydrogen production plant and the power plants, plus steam transfer and condensate return lines.

The cost of full steam integration is specific to the concept developed for the H-Vision feasibility study, which entails a high degree of steam/utilities integration between the existing coal-fired power plants at Maasvlakte and the new blue $H_2$ production plant.

H-Vision have estimated the cost for hydrogen turbines to be in the order of €60 million per 147 megawatts electric unit (MWe) (which includes installation costs). This means the total costs for each coal-fired power plant (2 turbines) would be €120 million.

For the two gas-fired power plants the H-Vision concept assumed that the existing turbines would be able to fire a fuel mix containing 25% hydrogen without modifications (H-Vision, 2019). For the Air Liquide PerGen site placeholder cost estimates were used of €5 million for a 50% hydrogen blend scenario and €15 million for a 100% hydrogen blend scenario to reflect the modifications to the burners and fuel supply systems required.

# 4 Oil Refineries

Oil refineries are one of the largest $CO_2$ emitters in the Port of Rotterdam with 8.5 Mt of $CO_2$ released in 2017 (see Figure 1). A large source of these emissions is from the use of refinery fuel gas (RFG) to produce high-temperature heat although roughly 3.5 Mtpa $CO_2$ are process emissions that do not directly result from burning either natural gas or RFG for energy.

Refinery fuel gas (RFG) is produced as a byproduct of various chemical processes undertaken during oil refining, such as thermal cracking, fluid catalytic cracking, or hydro-processing. It is a complex combination of light gases consisting of nitrogen, hydrogen, hydrocarbons (methane, ethylene, etc.), carbon monoxide and carbon dioxide (Chevron Phillips, 2012). Refinery fuel gases are primarily used as a fuel for fired heaters. The high-temperature heat produced is required for running units such as atmospheric and vacuum distillation columns, hydrotreating and hydrocracking units, catalytic reformers and solvent de-asphalting units, which all require high temperature furnaces to operate.

The $CO_2$ emissions from different petrochemical processes in the Rotterdam area are shown in Figure 3.

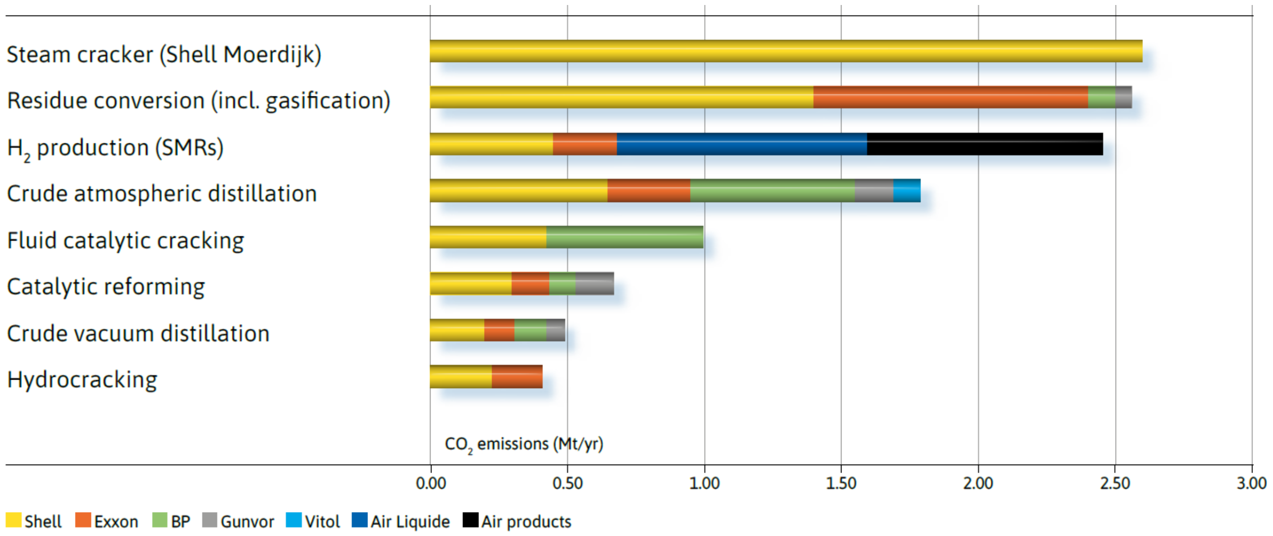


**Figure 3** *$CO_2$ emissions from petrochemical processes in the Rotterdam area (+ Shell Moerdijk). TNO estimates based on CBS statistics, typical emissions profiles & feedback from industrial partners. (Source:* H-Vision, 2019*).*

The H-Vision concept proposes to use blue hydrogen at oil refineries to replace the refinery fuel gases used. One possible implementation of the concept is to transport refinery fuel gas from multiple sites to a centralized blue hydrogen production plant where the $CO_2$ resulting from $H_2$ production can be captured and routed to a CCS facility. The produced blue hydrogen is then returned to the sites and used in the oil refinery furnaces to replace the refinery fuel gas, as depicted schematically in Figure 4.

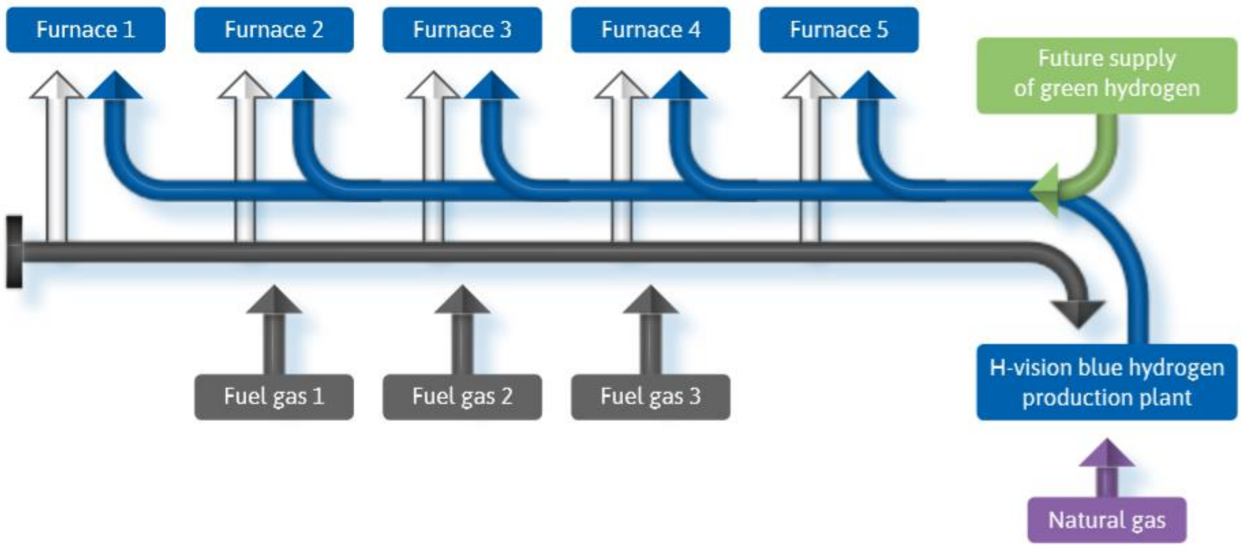


**Figure 4** *The proposed way to integrate the H-vision concept within existing fuel gas grids. Natural gas and refinery fuel gas feed the blue hydrogen production plant. The blue hydrogen is then used in the furnaces. In case there is imbalance on the hydrogen grid, refinery fuel gas can still be used in the furnaces* (H-Vision, 2019)*.*

The amount of hydrogen that will be required is highly site specific. All refineries are different given that the naturally occurring hydrocarbon distribution in crude oil varies between sites and does not always match customer demand and specifications. Various additional processing steps are required to re-adjust the molecules, reshape them and remove contaminants to ensure the refinery products meet the requirements for end-use and the product demand profile, as well as environmental performance (Marquez & Tian, 2016). Existing refinery infrastructure will dictate the amount of hydrogen that can be utilized and therefore the extent of modification and investments required will be site specific.

Producing hydrogen by converting refinery fuel gas is a newer, more complex process which will require different infrastructure modifications in comparison to utilizing natural gas. Steam reforming based hydrogen plants may be able to utilize refinery fuel gas as a potential feedstock. Although the incorporation of RFG into the hydrogen plant feed slate is not straightforward in terms of plant design and operation. The technical challenges to be overcome may comprise (Broadhurst & Hinton, 2011):

- high olefin levels;
- significant sulfur levels (as $H_2S$);
- substantial levels of higher hydrocarbons which may include naphthenes and/or aromatics;
- less usual trace and minor components; and
- variability in the RFG composition as the blend of off gases changes with fluctuating operation of the contributing unit operations.

Alongside hydrogen replacing RFG, there is also the potential to use hydrogen as a raw material within petrochemical processes. Hydrogen is already utilized in oil refineries as part of the refining process for two main purposes:

- Hydrotreating: to remove impurities (e.g. sulfur), and hydrogenate aromatics and olefins.

- Hydrocracking: to break larger molecules into smaller (higher value) molecules.

The hydrotreating and hydrocracking processes and the role of hydrogen are explained below:

> *"Hydrotreating … is introduced to remove sulfur, a downstream pollutant, and other undesirable compounds, such as unsaturated hydrocarbons and nitrogen from the process stream. Hydrogen is added to the hydrocarbon stream over a bed of catalyst that contains molybdenum with nickel or cobalt at intermediate temperature, pressure and other operating conditions. This process causes sulfur compounds to react with hydrogen to form hydrogen sulfide, while nitrogen compounds form ammonia. Aromatics and olefins are saturated by the hydrogen and lighter products are created. The final product of the hydrotreating process is typically the original feedstock free of sulfur and other contaminants.*
>
> *The hydrocracking process is a much more severe operation to produce lighter molecules with higher value for diesel, aviation and petrol fuel. Heavy gas oils, heavy residues or similar boiling-range heavy distillates react with hydrogen in the presence of a catalyst at high temperature and pressure. The heavy feedstocks are converted (cracked) into light distillates (for example, naphtha, kerosene and diesel) or base stocks for lubricants. The hydrocracker unit is the top hydrogen consumer in the refinery. Hydrogen is the key enabler of the hydrocracking to reduce the product boiling range appreciably by converting the majority of the feed to lower-boiling products. Hydrogen also enables hydrotreating reactions in the hydrocracking process; the final fractionated products are free of sulfur and other contaminants."*
> (Source: Marquez & Tian, 2016)

Due to the more severe nature of the process, hydrocracking requires three to four times more hydrogen per ton of feedstock compared to hydrotreating. Both processes currently provide a demand for hydrogen in the Port of Rotterdam. Infrastructure modifications are likely to be required in the future to meet the increasing demand for hydrogen. It is predicted that the demand for hydrogen is going to increase for refining purposes as the demand for lighter hydrocarbons increases and the demand for heavier (less refined) hydrocarbons decreases. Alongside this increase in demand the extraction of heavier hydrocarbons is predicted to increase in the future with more unconventional hydrocarbon sources being used. With the demand for hydrogen therefore likely to increase, where the hydrogen will be sourced from is also likely to change. Hydrogen for petroleum refining in the Port of Rotterdam is currently produced through the SMR process both within the refineries at two large reformers outside of the refineries (operated by Air Liquide and Air products). There may be the need for more clean hydrogen to be utilized in the oil refining process in the future. This is not part of the H-Vision concept but is worth noting as a potential long-term use for blue hydrogen in the port.

## 4.1 Implications for the Port of Rotterdam

There are five refineries in the Port of Rotterdam which produce products such as gasoline, kerosene and heating oil. These are operated by:

- Shell Nederland;
- ExxonMobil;
- Vitol (formerly owned by Koch);
- BP; and

- Gunvor Petroleum Rotterdam.

These oil refineries have a combined distillation capacity of 58 Mtpa. The crude oil is delivered to the port by tanker, mainly from the North Sea region, Russia and the Middle East. The crude oil is then transported to the five refineries via pipeline. The locations of the refineries are shown in Figure 5.


**Figure 5** *Map of the Port of Rotterdam with the locations of the five oil refineries ('raffinaderijen' in Dutch) ("Port of Rotterdam," 2020)*

## 4.2 Modifications Required

To enable the existing refineries in the Port of Rotterdam to use hydrogen to produce high-temperature heat instead of firing RFG, several modifications would be required. Fuel-flexible burners would be required in the refineries but also a new transport network would be required to allow for the RFG to be utilized for hydrogen production. New safety modifications would also be required alongside upgraded de-NOx units.

As illustrated in Figure 4, one cost efficient option to utilize the RFG from all five refineries for hydrogen production is through one centralized hydrogen plant. This would require infrastructure modifications to allow for suitable transfer pipelines and grids. The hydrogen plant would also be required to meet the following requirements:

- *"Fired heater burners would have to be replaced by fuel-flexible burners which can fire fuel with a very high hydrogen content.*
    - *Instrumentation, safeguarding and controls around the furnaces also have to be upgraded to enable seamlessly switching between fuels while in operation.*

- *In addition to replacing burners, new fuel distribution systems would have to be installed to supply hydrogen fuel.*

- *Firing a hydrogen-rich fuel increases burner flame temperatures, resulting in higher NOx emissions.*
  - *This is generally not regarded as a show-stopper and ultra-low-NOx burner technology is under development. A high margin was applied to cost estimates for furnace modifications to account for this.*
- *As a consequence of various process upsets, the $H_2S$ concentration in RFG frequently spikes up to levels of 10,000 ppm and above. The current frequency is several times per year, so it's important to address this.*
  - *The design of the pre-treatment section of the H-vision hydrogen production plant should take the concentration spikes into account.*
  - *Alternatively, perhaps also due to HSE restrictions, the refinery in question could temporarily stop exporting fuel gas to the hydrogen plant, and switch back to RFG firing in the furnaces (fall back to the existing situation) until the cause is remedied. This will lead to a temporary increase in $CO_2$ emissions.*
  - *The hydrogen production plant needs to cope with a broad range of feedstock compositions, which reflect different refinery operating modes, turnaround cases and upset scenarios."*

(Source: H-Vision, 2019)

The H-Vision concept factored these technical considerations into their cost estimates and concluded that the combined cost of all these modifications in the refinery sector would be in the range of 0.1 - 0.15 million euros per mega-watt of thermal capacity (M€/MWth). Conservatively, the high value of 0.15 M€/MWth was used for the economic model of H-vision.

# 5 Chemical and Industrial Processes

The H-Vision concept developed by the Port of Rotterdam focused on the use of hydrogen as an energy carrier. There is also the potential to use blue hydrogen to replace the hydrogen currently used in industrial processes as a raw material. Hydrogen as a raw material feedstock may require higher purities than those required for heat supply or energy production, and hence was not included in the H-Vision concept as it may require longer-term infrastructure developments.

The use of blue hydrogen as a raw-material feedstock in industry can be realized relatively quickly, apart from the potential cost barriers associated with CCS (Hers et al., 2018). Several modifications would be required to allow for new fuel distribution networks to be added and several modifications would also be expected for transport instrumentation, safeguarding and control systems.

Alongside the use of hydrogen in oil refinery processes (described in Section 4) there are other industrial processes that require hydrogen as part of their chemical processes. These include: (list taken from Brown, 2019)

- Ammonia Production
- Methanol Production
- Hydrochloric Acid Production
- Metallic Ore Reduction
- Hydrogenating Agent
- Atomic Hydrogen Welding
- Hydrogen as a coolant
- Hydrogen as a searching gas
- Hydrogen Peroxide Production
- As a reducing agent

There is a large potential for $CO_2$ reduction in the Netherlands through the use of blue hydrogen as a raw material for ammonia production. The largest ammonia sites are not located in the Rotterdam area, and hence were not included in the H-Vision concept, but hydrogen produced in Rotterdam could be utilized for ammonia production nationally.

## 5.1 Ammonia Production

The largest demand for hydrogen in the Netherlands is from the production of ammonia. There are two ammonia production plants in The Netherlands, OCI Nitrogen in Geleen and the Yara site in Sluiskil. Together these two sites account for 2.5 Mtpa of ammonia production. Some ammonia is also imported, 250 kilotons per annum (ktpa). Together, this accounts for 500 ktpa of hydrogen use for ammonia production in the Netherlands (H-Vision, 2019).

The Haber-Bosch process reacts atmospheric nitrogen with hydrogen to produce ammonia ($NH_3$). Ammonia is the precursor to most modern nitrogen-based fertilizers. Hydrogen is produced through the SMR process onsite which produces hydrogen and nitrogen in the 3:1 molar ratio required for ammonia. The hydrogen/nitrogen mixture from the SMR is pressurized to about 200 bars where it reacts to ammonia at 400-500°C. These conditions make it difficult to start and stop the production process (H-Vision, 2019).

Hydrogen from a H-vision plant could be used in ammonia production for various uses:

1. Fuel (Energy) for the existing SMRs

The current SMR of natural gas used to produce ammonia only captures approximately 60-70% of the $CO_2$ produced. Therefore, to decarbonize this process blue hydrogen from the Port of Rotterdam could be utilized instead of natural gas. Consumption of hydrogen for fuel would be around 400MW in Geleen and around 600MW in Sluiskil. Although significant, these consumptions will most likely not be sufficient to justify the investment in a hydrogen pipeline from Rotterdam to existing plants (H-Vision, 2019). The H-Vision concept therefore does not include the use of blue hydrogen production as a fuel for SMR ammonia production.

2. Feedstock for the ammonia synthesis

In an ammonia plant a mixture of hydrogen and nitrogen is used to produce ammonia. The hydrogen has very high purity requirements and will have a strict composition specification. The hydrogen produced in the H-Vision concept would not meet these requirements and hence an extra purification step would be required. This purification step would produce byproducts (methane and $CO_2$) that would ideally be recycled into the hydrogen production plant. The hydrogen could be purified at the H-Vision plant allowing the methane to be recycled on site and the pure hydrogen could be sent to the ammonia plants. The large volumes of hydrogen required in the ammonia plants could validate the installation of new pipelines to Geleen or Sluiskil from Rotterdam.

For hydrogen from Rotterdam to be utilized for hydrogen production H-Vision concluded that:

> *"…it would make more sense to build a new ammonia synthesis plant in Rotterdam close to the H-Vision plant. This would require significant investments (several 100's of million Euros) depending on the size. Building a new ammonia plant in Rotterdam would create some logistical issues as the governmental policy is to minimize the transportation of ammonia due to its toxicity. When only replacing the current import at OCI's terminal in Rotterdam, the hydrogen consumption of the ammonia plant would be relatively small"*
>
> (H-Vision, 2019)

The development of an ammonia production plant in the Port of Rotterdam which could utilize the blue hydrogen produced, would add flexibility to the system. The ammonia plant could maximize production when surplus hydrogen is produced and use storage tanks as a buffer before shipment to consumers. This could be utilized as an alternative to the storage of hydrogen in salt caverns. Either of these options would require significant investment, either in new ammonia production facilities in Rotterdam or in pipelines to the existing sites in Geleen or Sluiskil.

## 5.2 Methanol Production

Another potential future use for blue hydrogen in the Rotterdam area is for the production of methanol. The Port of Rotterdam have recently joined a research consortium to investigate the use of a new technology by Enerkem (a Canadian clean technology company) to manufacture syngas from domestic waste and use it as a feedstock for making products such as methanol (Port of Rotterdam, 2015). The consortium, led by AkzoNobel, are going to build a factory in Rotterdam that converts plastic and organic waste into methanol. The plant must produce 220 kt of methanol annually from an estimated 360 kt of waste. The methanol will produced using the Enerkem technology using hydrogen provided by AkzoNobel and Air Liquide (AkzoNobel, 2018). Should this project be successful, and eventually reach commercial scale, blue hydrogen could be utilized.

# 6 Conclusions and Next Steps

The H-Vision concept has been developed as part of the Port of Rotterdam's review of pathways to meet decarbonization targets. The H-vision concept aims to establish the short-term development of blue hydrogen infrastructure to pave the way towards the large-scale use of green hydrogen in the port. The amount of hydrogen planned to be integrated into the Port of Rotterdam's energy system will greatly determine the modifications required to existing infrastructure. The main two areas where hydrogen integration is envisaged is in power-generation and high-temperature heat production.

The H-Vision reference case concept is based on the development of a centralized hydrogen plant which will deliver blue hydrogen to both refineries and power plants. This will then require the development of a transport network to feed hydrogen into various industries around the port.

To replace the currently existing coal and gas power generators to use hydrogen as a fuel, modifications will be required to the existing turbines. Up to 25% hydrogen can already be co-fired in existing natural gas turbines with limited modifications. For higher percentages of hydrogen modifications, or new turbines, would be required. For the H-Vision concept the estimated cost for hydrogen turbines to replace coal-fired power generation is in the order of €60 million per 147 megawatts electric unit (MWe). This means the total costs for each coal-fired power plant (2 turbines) would be €120 million. For the two gas-fired power plants the H-Vision concept cost estimates were used of €5 million for a 50% hydrogen blend scenario and €15 million for a 100% hydrogen blend scenario to reflect the modifications to the burners and fuel supply systems required.

The second main use of hydrogen in the port is planned for utilization in oil refineries and petrochemical plants. Modifications would be required to develop a refinery fuel gas network to allow for its use in the production of hydrogen at a centralized facility. Modifications would also then be required in the refineries for the replacement for refinery fuel gas for firing with hydrogen to produce high temperature heat. The H-Vision concept estimated the combined cost of all modifications in the refinery sector would be in the range of 0.1 - 0.15 million euros per mega-watt of thermal capacity (M€/MWth).

There is also the potential for blue hydrogen to replace the carbon intensive hydrogen also being used as a raw material feedstock in other areas. This is not envisaged as part of the H-Vision project at the Port of Rotterdam given the high purity hydrogen required but could potentially be utilized in the long-term.

The H-vision concept is technically feasible and the modifications required could be implemented for blue hydrogen to start production in 2025. This is due to the technologies required already being at high technology readiness levels. For high-temperature heat the reuse of existing infrastructure can be maximized, meaning limited modifications are required. Power generation will require more significant modifications to existing infrastructure.

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