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PORT OF ROTTERDAM BECOMES INTERNATIONAL HYDROGEN HUB

Vision Port of Rotterdam Authority

SUMMARY

Rotterdam is the energy port for Northwest Europe, where annually 8.800 petajoules (PJ) are imported and exported overseas, almost three times as much as the energy demand of the Netherlands, and 13% of the energy demand of the EU.

At the moment, this energy mostly originates from fossil resources. In a world with climate neutral energy systems in 2050, energy port Rotterdam will be a hydrogen hub for Northwest Europe, with an annual throughput of 20 million metric tons (Mt) hydrogen (2,400 PJ). This will require over 100 gigawatt (GW) electrolysis capacity, and the double amount of capacity for generation of renewable electricity due to intermittent availability of sun and wind.

Dutch offshore wind will only be able to contribute to this for a small share in 2050. The largest share will come from world regions where renewable electricity will be much cheaper, where it will be converted to hydrogen (carriers) and transported with sea-going vessels to Rotterdam.

Hydrogen will be used by renewing and new industries in the port for making transport fuels, chemical feedstock and for heating of processes. A large part will find its way to the hinterland, for use in industry and transport.

In order to realize this vision, the Port of Rotterdam Authority (PoR) will take the following actions:

1. **PoR makes it possible that 1.2 Mt climate neutral hydrogen can be produced in the port in 2030:**

PROJECTS FOR PRODUCTION CLIMATE NEUTRAL HYDROGEN UNTIL 2030	hydrogen production (kt/yr) existing	new	hydrogen use	CCUS (Mt/yr)	needed offshore wind (GW)
PORTHOS	400		feedstock industry	2-3	
H-VISION		400	process heat industry	3	
2 GW Elektrolyserpark ow. 0.5 GW projects till 2025 (BP/Nouryon; Shell) + 1.5 GW ambition 2025-2030		360	feedstock industry		4
TOTAL	1.160			5-6	4

- Blue hydrogen: With market parties PoR realizes open access infrastructure for CO_2-transport for re-use and for permanent storage underground (Porthos), and open access infrastructure for hydrogen transport through the port. The hydrogen backbone will be connected to national hydrogen pipeline infrastructure developed by Gasunie. In this way, PoR makes it possible that market actors in the port make their existing (grey) hydrogen production climate neutral (blue), and will be able to realize additional new (blue) hydrogen production with the support of subsidies from the national government on the basis of the National Climate Agreement.
- Green hydrogen: With market parties PoR realizes a 2 GW conversion park for green hydrogen, connected to high voltage cables from offshore wind farms, and to the hydrogen backbone through the port. PoR takes care of trajectories for landfall of high voltage cables. In this way, PoR makes it possible that production of

green hydrogen can be scaled up rapidly by market actors when cost parity between blue and green hydrogen will be achieved in the thirties. In the forties, Rotterdam is expected to be connected to a total of 18 to 24 GW Dutch offshore wind, and additional space for landfall of cables and pipelines and conversion to hydrogen will have to be created.

2. **Import of hydrogen:**
While development of locally produced blue and green hydrogen is important to start a market for hydrogen, starting import of hydrogen will be essential to develop a position as hydrogen hub for Northwest Europe:

- With market parties PoR develops hydrogen transport chains from world regions with large potential for development of cheap renewable electricity and hydrogen: transport chains for hydrogen transported as ammonia, in liquid organic hydrogen carriers (LOHC), as liquid hydrogen (LH2) and as synthetic methane.
- With logistics parties and industry PoR develops import terminals for hydrogen in its different transport forms, with the aim to scale up transport of hydrogen by sea-going vessels and use of existing assets in the port where possible.
- With industry in the port and hinterland (oil refining, chemicals, steel producers) as launching customers who can guarantee use, the transport chain could be developed further with logistics service providers and grid operators via inland shipping and pipelines.
- PoR promotes realization of a trading hub function of hydrogen in Rotterdam.

3. **Hydrogen as transport fuel:**

Not only transport of hydrogen, but also transport by hydrogen as a clean and climate neutral transport fuel needs to be developed. Together with other stakeholders, PoR takes the lead by supporting development of hydrogen bunker stations for inland vessels (RH2INE), tank stations for trucks (Hytruck) and hydrogen based fuels for aviation (pilot Rotterdam The Haque Airport).

4. **Hydrogen for industry:**

Driven by the necessity to reach climate goals, it is expected that in the thirties and forties hydrogen demand will increase considerably, as feedstock for refining, chemicals and steel, replacing oil and coal. PoR focuses on needs to be developed. Together with other stakeholders, PoR takes the lead by supporting development of hydrogen bunker stations for inland vessels (RH2INE), tank stations for trucks (Hytruck) and hydrogen based fuels for aviation (pilot Rotterdam The Haque Airport).

PoR focuses on existing industries that renew themselves, as well as on new industries in the port that will use hydrogen as feedstock, for producing green methanol, Fischer-Tropsch fuels and feedstocks, and pyrolysis oil. Rotterdam is well positioned in Northwest Europe to keep and attract these industries, thanks to existing assets: plants, terminals and pipelines, as well as large scale import potential.

Cheap availability and tradability of hydrogen in Rotterdam is a pre-condition for development of these industries. Presence of these industries in the port will bind hydrogen as a cargo flow to the port. A mutually reinforcing effect, which also made Rotterdam big as an oil port.

In developing this vision on Rotterdam as hydrogen hub we made use of public research and studies. Next to that, we also we made grateful use of knowledge and insights of several companies in our port, amongst other Shell, BP, ExxonMobil and Vopak. Grateful use was also made of the knowledge and insights gained during a number of expert sessions with companies and organizations commissioned by the Port of Rotterdam Authority under the leadership of Drift, the Dutch Research Institute for Transition.

Introduction and vision

In a few years' time hydrogen has evolved from an everlasting promise as transport fuel for cars to a broadly supported key of the energy transition. In the Dutch Climate Agreement (June 2019) hydrogen is perceived as "*a robust solution in the end result of a CO_2-free energy and feedstock system*".

- The International Energy Agency states that the time is right to start developing hydrogen as an energy carrier and calls for making industrial ports the nerve centers for scaling up the use of clean hydrogen[i].
- The Hydrogen coalition, an initiative of Greenpeace supported by 27 organizations from private and public sector, calls the government to prioritize scaling up of green hydrogen as an essential building block for the energy transition[ii].
- The German government puts forward a national hydrogen strategy in which the importance of large-scale green hydrogen imports from developing countries with abundant solar and wind energy potential is emphasized[iii].
- In its vision on hydrogen, the Dutch government acknowledges the strategic importance for the port of Rotterdam to retain its position as a hub for international energy flows, whereby hydrogen could become a worldwide traded commodity with large import and export.[iv]
- Hydrogen Europe presents a very ambitious initiative for 2x40 GW green hydrogen in 2030, in the EU, Ukraine and North-Africa[v].

For the port and industrial complex of Rotterdam, this transition to a 'hydrogen economy' will have huge implications. Therefore, Port of Rotterdam Authority (PoR), the manager and developer of this complex, is closely involved in all ideation and planning processes, and translation to the port.

In the vision of PoR, in a world with climate neutral energy systems Rotterdam will be an international hub for hydrogen, where import, production, use, trade and transit come together, just like this is the case now for fossil energy. In 2050 some 20 million metric tons (Mt) hydrogen could pass through the port, 50 times as much as is now produced and consumed by port industry.

In this document this vision on Rotterdam as a hydrogen hub will be outlined.

Hydrogen is everywhere

Hydrogen is the most common, lightest and simplest element in the known universe. It forms three quarters of the mass in the universe and is the fuel and feedstock for producing stars. On Earth, hydrogen is a molecule consisting of two hydrogen atoms (H_2), which prefers to bind itself with other molecules. The most popular partners are oxygen, with which it forms water (H_2O), and carbon, with which it forms hydrocarbons.

Hydrocarbons are the main components of the fossil energy sources natural gas (CH_4), crude oil and coal, as well as biomass. Our society runs on hydrocarbons, as fuel for heating and transport and as feedstock for chemical products which find their way in everyday objects.

New sources of carbon and hydrogen needed

It is expected that in the next few decades counteracting climate change will result in drastic decrease of burning of fossil hydrocarbons, whereby CO_2 is released, the main greenhouse gas. So, we must look for new sources, which are clean and sustainable, yet reliable and cheap.

Carbon will be retrieved more and more from biomass, waste and via direct air capture. Hydrogen will be retrieved from water with the help of renewable electricity (green hydrogen), and from fossil hydrocarbons whereby CO_2 is captured and stored underground or re-used (blue hydrogen).

Demand for hydrogen could increase significantly

Current demand for hydrogen mainly comes from industry for usage as feedstock. In the port of Rotterdam hydrogen is mainly used in oil refining: to desulfurize oil products (hydrotreating) and to produce more light oil products (hydrocracking). A relatively small, closed market, when compared to the market potential.

TABLE 1

CURRENT DEMAND FOR HYDROGEN	Mt
Rotterdam	0.4
Netherlands (total)	0.8
Germany	1.6

The *Roadmap Hydrogen* of the Topsector Energy[vi] indicates a possible demand of 14 Mt hydrogen in the Netherlands by 2050.

Further research by ISPT[vii] confirms this (see table 2), whereby it is assumed that by 2050 half of the feedstock demand of chemical industry will come from recycled waste material.

If there would be enough sustainable biomass available (and accepted by society) as input for biofuels in ships and airplanes and as bio-feedstock for chemicals, then, according the research, national demand for hydrogen would be much less: 522 PJ (4,4 Mt) in 2050.

TABLE 2 DUTCH HYDROGEN DEMAND 2050

NETHERLANDS climate neutral in 2050 Hychain-1, max scenario, limited availability biomass	hydrogen demand PJ	Mt
Feedstock industry	388	3.2
Process heat industry	255	2.1
Build environment, greenhouses	54	0.5
Mobility over land	205	1.7
Aviation (H2 in synthetic fuels)	230	1.9
Maritime shipping (H2 in liquid fuels)	500	4.2
Total demand in the Netherlands	**1,632**	**13.6**

TABLE 3 GERMAN IMPORT NEED

GERMANY climate neutral in 2050	hydrogen import Mt
Energy and fuels	10.2
Feedstock chemicals	12.0
Feedstock steel	1.8
Total hydrogen import	**24.0**

The German demand for hydrogen is potentially also huge. In *Klimapfade für Deutschland*[viii] it is stated that, in order to be 95% climate neutral in 2050, Germany will have to import *hydrogen and synthetic fuels* (see annex 1). The German *Roadmap Chemie 2050*[ix] pictures a huge need for electricity and hydrogen for production of *synthetic feedstock* (see annex 2).

The German steel industry also indicates a large need of hydrogen in order to green its production. In total, it would concern an import need of 24 Mt hydrogen (see table 3), for which more than two times as much electricity would be needed as is produced in Germany now.

Concawe[x], the research institute of the European oil refining sector, speaks of a need for electricity in 2050 of half the present electricity consumption in the EU in order to produce 32 Mt green hydrogen with which EU refineries would be able to make their processes and products mostly climate neutral, by producing biobased and synthetic fuels (see annex 3).

How much hydrogen comes to Rotterdam in 2050?

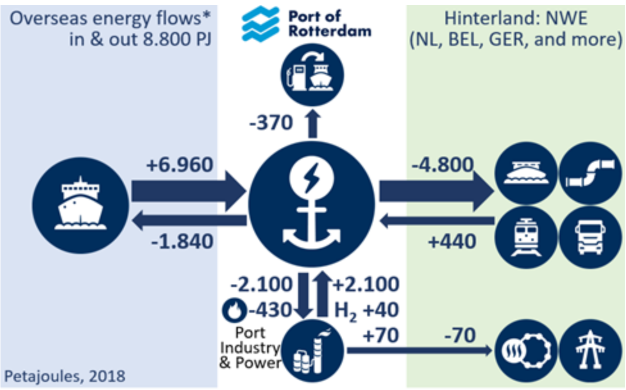
When we make some assumptions on possible hydrogen flows via Rotterdam for the different market sectors that contribute to the national demand in table 2, then this would add up to a potential of 7 Mt, over half of national demand (see table 4).

However, the potential for the port of Rotterdam is much larger than national demand. Today, Rotterdam is the energy hub for Northwest Europe. Overseas in and outbound energy flows amount to 8,800 PJ, almost three times total Dutch energy demand, see the graph below.

Especially, German industry is an important port customer, one third of the oil and coal demand of German industry is supplied via Rotterdam.[xi]

TABLE 4 HYDROGEN VIA ROTTERDAM IN 2050

domestic demand (max scenario with limited use of biomass)	share %	R'dam Mt
Feedstock chemicals	25%	0.8
Process heat indusry	50%	1.1
Build environment, greenhouses	25%	0.1
Mobility over land	50%	0.8
Aviation (H2 in synthetic fuels)	50%	1.0
Maritime shipping (H2 in liquid fuels)	75%	3.2
Total domestic demand via Rotterdam		**7.0**
demand in Germany via Rotterdam	33%	8.0
other demand in NWE via Rotterdam		5.0
Total potential demand		**20.0**



*Energy flows: crude oil & oil products (86%), coal (8%), LNG (3%), bio (3%)

If Rotterdam would be able to maintain its position as energy port for Germany, this would imply that one third of the German import need for hydrogen (table 3) would be supplied via Rotterdam: around 8 Mt.

Additionally, Rotterdam could play a role in importing hydrogen for other Northwest European countries.

So, an ambitious scenario would be 20 Mt (2,400 PJ) hydrogen through the port of Rotterdam in 2050.

Green hydrogen still in its infancy

A growing need for hydrogen will more and more be met by winning hydrogen from water with electrolysis. However, this production of green hydrogen still has to be developed to a commercial scale.

This year, Shell will start up an electrolyser of 10 megawatt (MW) at its oil refinery near Cologne, the largest in the world so far. Announced plans in Rotterdam aim for scaling up to around 450 MW by 2025. For 20 Mt hydrogen an electrolysis capacity of around 110.000 MW would be needed in 2050! Considering the intermittent availability of wind, almost twice as much offshore wind capacity would be necessary for this, around 200 gigawatt (GW)[xii].

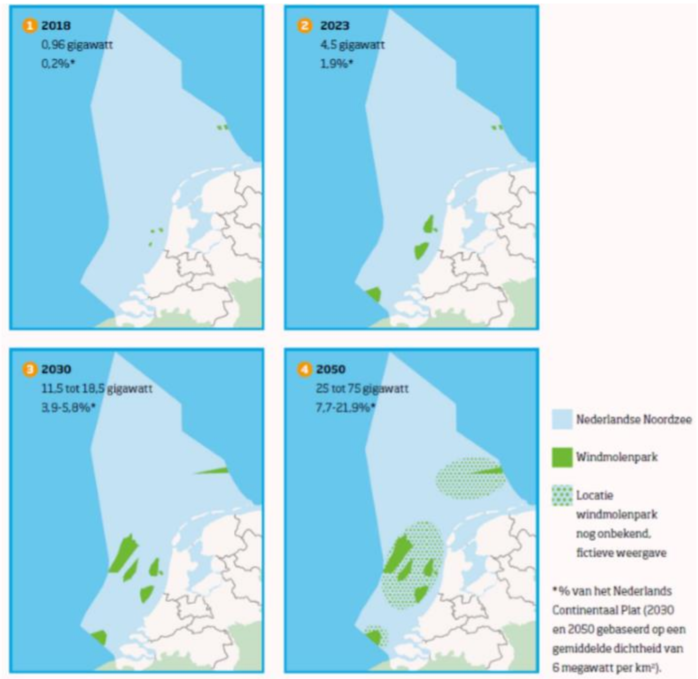
TABLE 5 GREEN HYDROGEN PRODUCTION	needed offshore wind	capacity elektrolysers	output hydrogen
RefHyne: Shell Rheinland Raffinerie, Cologne, 2020		10 MW	1.3 kton
Conversion park Maasvlakte 2: - Shell, 2023	0,2 GW	200 MW	20 kton *
- BP/Nouryon, 2025	0,5 GW	250 MW	45 kton **
Climate Agreement, elektrolysers in NL in 2030	5-7 GW	**3- 4 GW**	540-720 kton **
Rotterdam NW European energy hub in 2050	200 GW	110 GW	**20 Mton** **

* elektrolyser runs on basis of offshore wind supply (4.500 full load hours)
** elektrolyser runs full capacity (8.000 full load hours)

Big plans for wind farms at sea

At the moment, 1 GW wind energy is installed at the Dutch part of the North Sea (map upper left).
The Dutch Energy Agreement of 2013 initiated a scale up to 4½ GW in 2023 (map upper right). Meanwhile, the plots for this are issued.

At the beginning of 2018 the government announced plans in its *Roadmap Wind Energy at Sea 2030* to add another 7 GW, making a total of 11½ GW in 2030, representing over 40% of current Dutch electricity consumption, nowadays still generated for almost 80% from coal and natural gas[xiii].



Figuur 2: De verwachte groei van windenergie op de Nederlandse Noordzee tussen nu en 2050.
Bron: Stichting De Noordzee en Natuur & Milieu.

The Climate Agreement of June 2019 offers space for even more windfarms before 2030, "*unless connected to specific locations at the coast, where there is enough demand for electricity or other energy carriers after conversion, so that extensions of the national high voltage grid can be prevented as much as possible*"[xiv].

The ambition of the hydrogen programme in the Climate Agreement is 3 to 4 GW installed electrolyser capacity in 2030. So, this has to be developed in the industrial clusters at the coast. This will result in 7 GW additional demand for wind energy at sea in 2030 (totaling to 18½ GW, map lower left).

The European Commission expects a need for 450 GW offshore wind in Europe in 2050[xv]. According to WindEurope, 212 GW of this can be realized at the North Sea, of which 60 GW at the Dutch part[xvi].

This is in line with the scenarios of the Dutch Planning Bureau for the Environment[xvii]. In a scenario study for the *Integral Infrastructure Exploration 2030-2050* by grid operators Gasunie and Tennet, even a theoretical maximum of 72 GW offshore wind in 2050 is assumed[xviii]. The occupation of the North Sea for this kind of wind capacities is shown on the map lower right.

Dutch wind at sea will not be enough

Table 6 makes clear that by 2050 Dutch offshore wind will only contribute for a small share to the total need of electricity for conversion into hydrogen which potentially will flow through the port of Rotterdam.

In conclusion: by 2050 the largest part of hydrogen in Rotterdam will be imported from overseas.

TABLE 6 DUTCH WIND AT SEA IN 2050, MAX SCENARIO	GW
Maximum feasible installed capacity	60-72
Assume half is for final electricity demand end consumers	25*
Maximum available for conversion into hydrogen	35-47
Assume half goes to Rotterdam	18-24
Needed for production of 20 MMT hydrogen	200

* assumption electricity demand in 2050 will be twice as high as now
as a result of electrification in all sectors: 225 TWh.
Assume half covered with wind at sea: 112.5 TWh/4,500h = 25 GW

CLIMATE AGREEMENT MAKES RAPID DEVELOPMENT OF HYDROGEN POSSIBLE

As we have seen, the market potential for hydrogen could be huge for Rotterdam: from 0.4 Mt now (table 1) to 20 Mt in 2050 (table 4): 50 times as much. PoR has to take steps now in order to realize this market potential. Already, Germany is in contact with North-African countries as well as with Australia with the aim to supply them with technology and capital for large scale deployment of renewable electricity and conversion into hydrogen, and then import it to Germany. Development of import flows may already be a game changer in this decade.

At the same time, in Rotterdam demand for hydrogen will have to be developed. Thanks to the Climate Agreement demand could accelerate, since hydrogen can be produced climate neutral, which helps a lot in reaching Dutch climate goals.

In the context of the climate agreement process in 2018 potential demand for hydrogen in the industrial clusters was identified: 253 PJ (2.1 Mt) in 2030, of which 85 PJ (0.7 Mt) in Rotterdam (see map on the right).

This concerns existing and potential demand for hydrogen from the industry, that could be produced climate neutral in Rotterdam in 2030.
Meanwhile, two years after this survey, there are concrete projects in Rotterdam for 0.9 Mt climate neutral hydrogen till 2030, and the ambition is still higher.

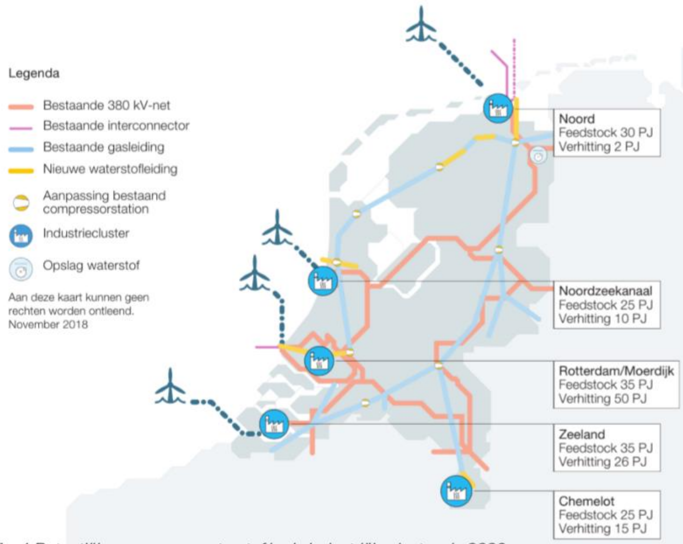


fig. 1 Potentiële vraag naar waterstof in de industriële clusters in 2030

More than 1 mt production of climate neutral hydrogen by 2030

Currently, a consortium of PoR, EBN and Gasunie, under the name of Porthos, is developing infrastructure for Carbon Capture, Utilization & Storage (CCUS). Potential launching customers are Shell, Esso, Air Liquide and Air Products[xix]. From their current hydrogen production these companies could capture 2 to 3 Mt CO_2 per year and offer this for storage underground. For an investment of around € 0.5 billion and a project duration of 15 years Porthos could store 37 Mt CO_2 in an empty gas field under the North Sea, some 20 km from the coastline.

Furthermore, a consortium of companies in the port of Rotterdam, under the name of H-vision, is working out a plan for a new hydrogen plant. This plant would use mostly high caloric waste gasses from oil refining to produce hydrogen, thereby separating the CO_2 and offering this to Porthos for storage underground, while the hydrogen is used for process heating in the industry. For this, the CCUS infrastructure would have to be extended to other empty gas fields against additional investments of over € 0.3 billion[xx].

Nouryon and BP are doing a feasibility study together with PoR, under the project name H2-Fifty, for an electrolysis plant of 250 MW, that would produce a maximum of 45 kton hydrogen per year. Shell announces plans to produce green hydrogen from offshore wind, which will be used at their Pernis refinery in order to make production of fuels more sustainable. The green hydrogen plant will have an electrolyser capacity of 200 MW and will be on stream in 2023.

PoR works with grid operators Tennet and Stedin on the spatial embedding and electrical connection of a 2 GW Electrolyser park in the western port area, where above mentioned projects will be located as launching customers. If everything goes as planned, almost 1.2 Mt climate neutral hydrogen could be produced in Rotterdam in 2030[xxi]:

TABLE 7

PROJECTS FOR PRODUCTION CLIMATE NEUTRAL HYDROGEN UNTIL 2030	hydrogen production (kt/yr) existing	new	hydrogen use	CCUS (Mt/yr)	needed offshore wind (GW)
PORTHOS	400		feedstock industry	2-3	
H-VISION		400	process heat industry	3	
2 GW Elektrolyserpark ow. 0.5 GW projects till 2025 (BP/Nouryon; Shell) + 1.5 GW ambition 2025-2030		360	feedstock industry		4
TOTAL	1.160			5-6	4

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Blue paves the way for green

Current production costs without CCS (grey hydrogen) amount to € 1,30 per kg in Europe (see annex 4). When CCS is applied (blue hydrogen) this would be around € 2 per kg (annex 4). This cost rise could be covered from SDE++ subsidy, which will become available in September this year.

Subsidy applicants compete on the basis of necessary amount of subsidy per abated ton CO_2. The CO_2-abatement costs of the launching customer volumes of Porthos (€ 75-95/ton CO_2) and H-vision (86-146/ton CO_2) are relatively low compared to many other CO_2-reduction measures, which makes these projects promising for subsidy.

However, for H-vision, the estimated abatement cost is based on al low level of return, up to € 200/t CO_2 may be needed to create an affordable project. In general, for CO_2-reduction measures with blue hydrogen in refineries you are talking about € 60-250/t abatement costs[xxii].

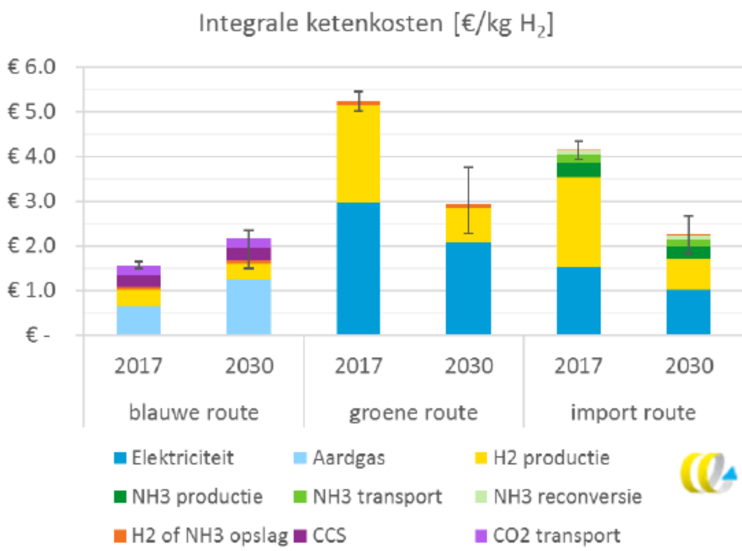
Not only do blue hydrogen projects need significant subsidies, also infrastructure should be in place, as well as a policy regulation structure, including storage of CO_2. There is a considerable exposure, which should not turn into a first mover disadvantage. Governments, as well as companies with government stake, should de-risk the business case for launching companies.

Today, green hydrogen still costs roughly € 6 per kg.[xxiii] So, blue hydrogen is 3 times as cheap as green hydrogen. However, when prices of fossil energy and CO_2 would rise the next decade also blue hydrogen would become more expensive. Moreover, continuous re-investment in accessing new storage fields for CO_2 would be necessary, which also would make blue hydrogen more expensive over time.

On the other hand, green hydrogen is expected to become cheaper. Producers of electrolysers expect substantial decrease of capital costs as a result of upscaling and standardization of production. In the Climate Agreement a 65% capex reduction of electrolysers (from € 1 billion to € 350 million per GW) till 2030 is mentioned. With this capex, almost three quarters of the price of green hydrogen will be determined by electricity costs in 2030. In the Climate Agreement an aim for 3-4 ct/kWh production costs (excluding transmission costs) for wind at sea in 2030 is mentioned, half of the current price level.

According to a study of CE Delft, Gasunie and Nuon[xxiv] blue and green hydrogen will converge to the same cost range of € 2 to 3 per kg by 2030.

In this study also import of hydrogen from North-Africa was considered and found to be in the same cost range by 2030, because the savings on electricity costs would cover additional costs of transport of hydrogen in the form of ammonia, including costs of conversion and reconversion (see graph on the right for a comparison of blue, green and import).



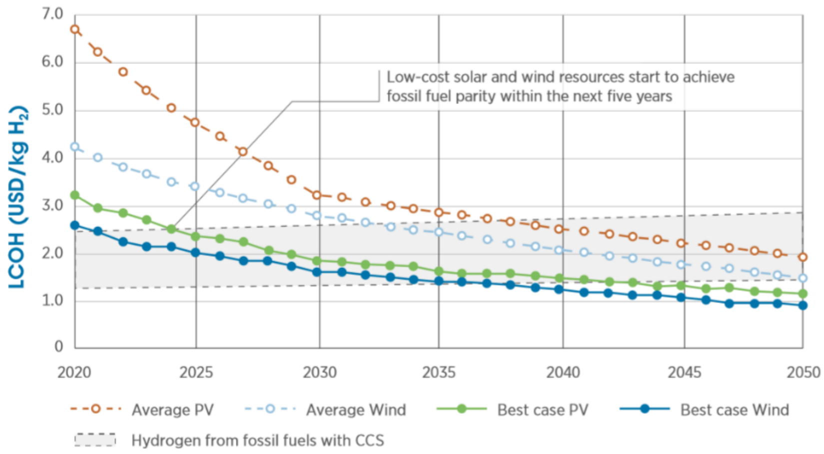
Wood Mackenzie expects cost parity of green hydrogen with grey hydrogen by 2030, under the assumption of a renewable electricity price of USD 30/MWh and 50% full load hours[xxv].
IEA finds that, depending on local gas prices, electricity at USD 10- 40/MWh and at around 50% full load hours is needed for green hydrogen to become cost-competitive with blue hydrogen.[xxvi]

IRENA expects that in the best locations, green hydrogen will be competitive in the next 3 to 5 years compared to blue hydrogen.

By 2035, average-cost renewables also start to become competitive (see graph of IRENA report on the right and note for electricity prices).[xxvii]

BloombergNEF also concludes the cost of producing green hydrogen is likely to plummet in the coming decades, to as low as $ 1.40/kg in 2030, and $ 0.80/kg in 2050[xxviii], in line with best cases in the IRENA graph.

Figure 14: Hydrogen production costs from solar and wind vs. fossil fuels



Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

The Hydrogen Council states that within five to ten years — driven by strong reductions in electrolyser capex of about 70-80% and falling renewables' levelized costs of energy (LCOE) — renewable hydrogen costs could drop to about $1-1.50/kg in optimal locations, and roughly $2-3/kg under average conditions[xxix], also in line with above graph. The report adds that achieving this cost-competitive green hydrogen by 2030 will require economies of scale equivalent to the deployment of 70 GW of electrolyser capacity worldwide, requiring $20bn of investment.

The report points out Chile, Australia and Saudi Arabia as favorable sweet spots for producing green hydrogen from combined wind and solar at high load factors, at costs perhaps as low as $ 1.20/kg by 2030, well below the average for grey hydrogen, and even close to parity with optimal grey hydrogen costs in 2030 if CO_2 costs are factored in.

Furthermore, potential large hydrogen consumers may be willing to pay a little more for climate neutral hydrogen, because they may be able to sell their products with a premium for being produced climate neutral. More security of supply may be another reason for paying a little more, since there will be a larger spread of sweet spots in the world for producing green hydrogen than for natural gas.

On the other hand, countries with dominant fossil energy export positions and favorable climate conditions for renewable energy production, as well as the resources for such investments (for example Saudi Arabia), will try to maintain this position through hydrogen export. In general, apart from the ability to produce cheap hydrogen, also ease of doing business, political ambitions with respect to climate goals, and own energy consumption needs will be key factors for sweet spots to develop.

To conclude, blue hydrogen is still much cheaper, but green hydrogen will become cost competitive in the thirties. So, a sound strategy for the port would be to pave the way for green hydrogen now with blue hydrogen. With large and relatively secured volumes blue hydrogen could boost the development of a market for hydrogen in the twenties. Blue hydrogen offers the industry security of continuous availability of climate neutral hydrogen for heating their processes. This will enable industry to make their installations for process heating on their sites suitable for hydrogen during the next turnarounds in the twenties, so that they become large hydrogen consumers.

This would justify a port infrastructure for hydrogen, to supply companies with hydrogen at the fence. This market and infrastructure for hydrogen will then be a stepping stone for green hydrogen in the port, which will come to the market in larger volumes after 2030 in order to satisfy the rapidly growing demand in the thirties and forties.

Import of hydrogen

Whereas development of locally produced blue and green hydrogen will be essential to boost a market for hydrogen, development of import of hydrogen will be crucial in order to position Rotterdam as hydrogen hub for the Northwest European hinterland. For now, importing LNG and decarbonizing it to blue hydrogen in the port will be a cost-effective alternative to importing green hydrogen. However, as import of hydrogen will become competitive to local production of blue and green hydrogen in the thirties, already now the focus must be on development of international transport chains, from supply to demand.

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Large scale overseas transport chains will mostly have to focus on North Africa and Middle East, and possibly Chile and Australia. In these regions the potential for production of cheap renewable electricity is huge, and local markets to absorb this renewable energy are relatively modest.

As a large energy import hub today, Rotterdam is widely expected to be first mover as a hydrogen import hub. In its vision on hydrogen, the Dutch government looks to PoR for mapping potential overseas supply of hydrogen for import. However, other European ports will also take steps to import hydrogen, driven by national strategies to mix climate neutral hydrogen in gas grids. So, Rotterdam should grasp the opportunities which arise now, like the development of a 1 GW solar park in Portugal for production and export of hydrogen, which could give a kick start to the development of import.

In order to initiate these transport chains, PoR aims to work closely with logistic parties and industrial consumers, to develop import terminals for different hydrogen energy supply chains. Between Australia and Japan, the first demonstration pilot project for technologies for long distance marine transportation and loading and unloading of liquefied hydrogen is under development by a consortium under the name of HySTRA[xxx], in which Shell participates. Consortium lead Kawasaki Heavy Industries announced that construction of the world's first liquified hydrogen carrier, named Suiso Frontier, will be completed by late 2020[xxxi].

Apart from liquified hydrogen, which is transported with a temperature of minus 253 degrees Celsius, liquid organic hydrogen carrier (LOHC) technology is under development. LOHC technology is based on a reversible hydrogenation / dehydrogenation process, whereby hydrogen can be transported in a liquid under ambient conditions. This would make it possible to scale up hydrogen transport by sea-going vessel with the use of existing liquid bulk assets in the port.

A consortium led by Vopak is investing in development of international hydrogen infrastructure on the basis of LOHC technology[xxxii]. LOHC can be transported by sea-vessel, discharged to inland vessels and trucks, and transported in containers to tank stations. LOHC could be a quicker solution than liquid hydrogen. However, when hydrogen transportation will increase worldwide, liquid hydrogen will grow rapidly in volumes.

Also, sodium borohydride is being tested as carrier of hydrogen in Plant One, a test center for innovative technologies in the port. However, this technology is still in lower technology readiness levels.

Green methanol and ammonia will probably be the first green hydrogen carriers to be transported overseas in big volumes, mostly however for direct use in industries.

Inland transit of hydrogen

With industry in the port and hinterland (oil refining, chemicals, steel) as launching customers, the transport chain could be developed further with logistics service providers and grid operators via inland shipping and pipelines.

Both in the Netherlands and in Germany, there are plans for a national hydrogen pipeline infrastructure to enable development of a hydrogen market. Recently, German industrial companies announced development of the first publicly accessible hydrogen network, 130 km from Lingen to Gelsenkirchen, under the name of GET H2 Nukleus[xxxiii]. With refineries in Lingen and Gelsenkirchen, BP is key player in this development. The companies aim to be ready to operate the network and a 100 MW electrolyser in late 2022. The project is set to become the first hydrogen network in the regulated sector with non-discriminatory access and transparent prices.

Companies ask the government for planning and regulation, with the aim to develop a nationwide network with standardized transportation specifications and regulated use, including implementation of tradable guarantees of origin that provide information on the decarbonization contribution of hydrogen and can be offset against CO_2 reduction targets.

In the Netherlands, grid operator Gasunie is taking steps to have an open access hydrogen grid available by 2030, connecting all major industrial clusters, by converting existing gas pipelines and making new connecting pipelines, and integrating hydrogen storage in salt caverns. For industries, it is important that the hydrogen network will be well integrated with neighboring countries, since industrial clusters in Netherlands, Belgium and Germany are already very well connected in the so-called ARA-Ruhr Cluster. This requires cross-border planning by national governments, as well as cooperation between grid operators and industry.

In its vision on hydrogen, The Dutch government acknowledges the possible hub function of the Netherlands for supply of hydrogen to its neighboring countries, with special attention for Germany.

The Dutch government already made a reservation for a pipeline trajectory from Rotterdam to Germany via Chemelot, the Limburg industrial park. This is a strategic connection for Rotterdam for hydrogen and CO_2 pipeline infrastructure.

Hydrogen as transport fuel

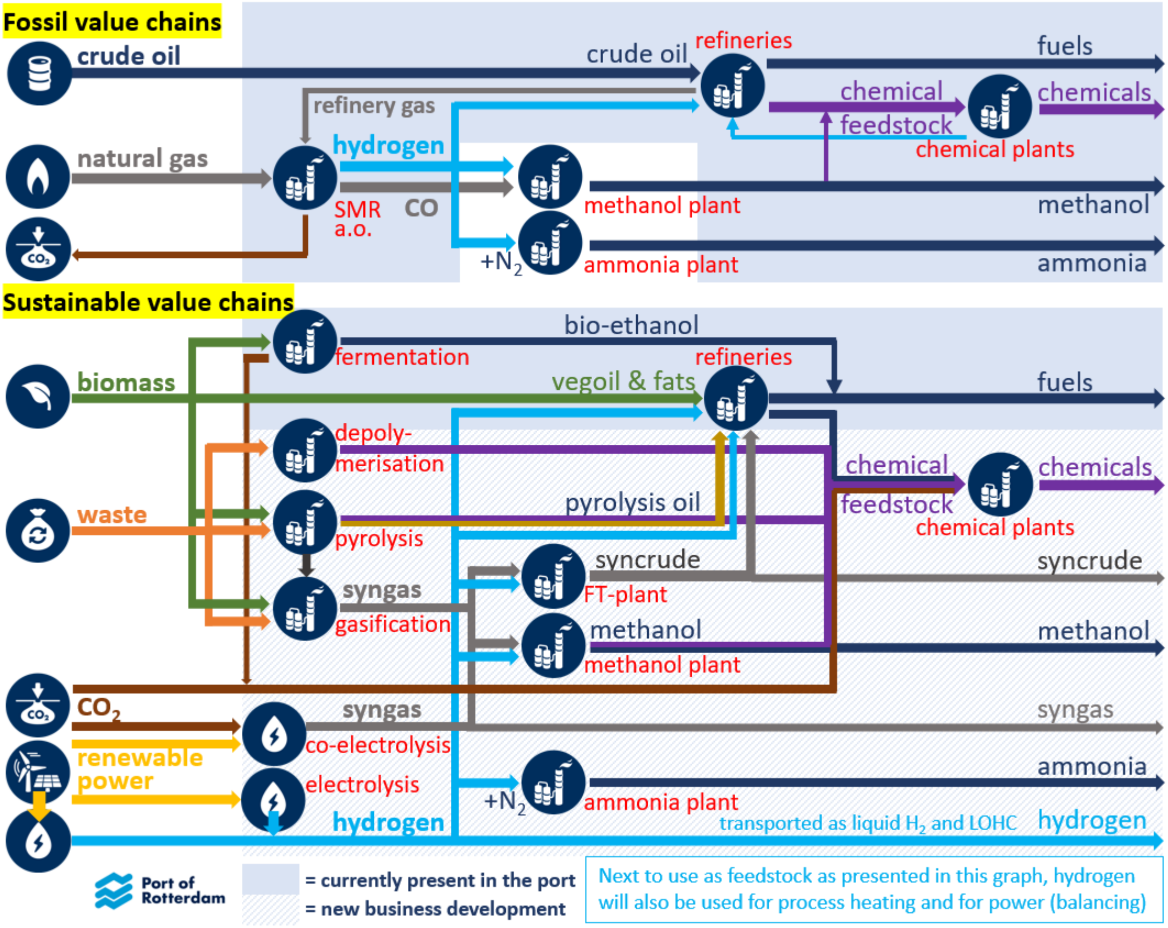
Not only transport of hydrogen, but also transport with hydrogen as transport fuel needs to be developed. Just like it was the case with liquified natural gas (LNG), PoR and port companies lead the way and, together with other stakeholders, support development of bunker stations for inland shipping (RH2INE project), tank stations for trucks (Hytruck) and hydrogen based fuels for aviation (pilot Rotterdam The Haque Airport).

In January this year 17 parties[xxxiv] signed a letter of intent with the aim to develop transport over waterways, roads and railways in the so-called Rhine-Alps corridor on the basis of hydrogen. PoR is a driver in this initiative under the name RH2INE (Rhine Hydrogen Integration Network of Excellence). In order to create a stable market environment for a hydrogen corridor, sufficient infrastructure with bunker locations and tank stations is crucial for bringing demand and supply in balance. Also, in the field of safety and regulation much has to be done yet, to which PoR will contribute in RH2INE. In the first phase, RH2INE will focus on realization of bunker locations for hydrogen along the Rhine between Rotterdam and Cologne, resulting in 10 to 15 inland tankers sailing on hydrogen the next few years.

Hydrogen for industry

Driven by the necessity to reach climate goals, it is expected that hydrogen will grow rapidly as feedstock for refining and chemicals in the thirties and forties, replacing crude oil more a more. In which form this hydrogen will arrive at the port will be dependent on the position of the port in the value chain.

In fossil value chains, the port is well positioned with its petrochemical complex, where crude oil is converted into fuels and chemicals, whereas methanol and ammonia are imported. In sustainable value chains, the port is positioned with a bio-ethanol plant and a bio-refinery, converting solid and liquid biomass into biofuels.



In new sustainable value chains, by 2050 Rotterdam could also be positioned from climate neutral carbon and hydrogen to fuels and chemicals, provided that pyrolysis oil, green methanol and Fischer-Tropsch syncrude would be produced and processed into products in the port. However, this will require large new production installations.

The location of such facilities will depend to a large extent on availability of sufficient and cost effective volumes of climate neutral carbon and hydrogen. So, in order to attract such investments, Rotterdam will have to develop into a large import hub for biomass, waste, CO_2 and hydrogen. However, sustainable biomass may not be there at enough scale.

In the longer term, direct air capture (DAC) of CO_2 may become an alternative. If this could become cost effective and available in sufficient volumes, hydrogen may be transported combined with CO_2 in the form of syngas, or synthetic methane, using existing LNG infrastructure. Then, refineries in the port could convert the syngas into syncrude with a new FT-plant, and then into e-fuels, using existing hydrocrackers.

Presence of E-refineries in the port would bind hydrogen and syngas as cargo flows to the port. Without such plants less hydrogen and more synthetic fuels, green methanol and green chemicals will be imported. Rotterdam would then be competing for this cargo with other ports, without the advantage of local industry binding the cargo to Rotterdam and attracting other industry.

Rotterdam, and the Netherlands in general, should create an investment climate for retaining and attracting industry that uses and converts sustainable feedstocks into products, thereby creating added value and employment. Otherwise, The Netherlands would only retain its logistics function. This calls for industry policy, not just energy policy. At local, national and European levels. The industrial clusters that will survive will be very efficient – in energy and CO_2 – and very well integrated, locally and (EU)regionally. Local and national industry policy should focus on nurturing this. European industry policy should focus on security of supply, by establishing relations with countries with big potential to produce cheap renewable electricity.

Therefore, it is of strategic importance to develop the hydrogen hub through the whole value chain: attracting hydrogen import and production, realizing inland transport chains, and retaining and attracting industry that uses hydrogen and circular carbon as feedstock.

An example of the latter is the waste-to-chemicals consortium of PoR with Nouryon, Air Liquide, Enerkem and Shell with the aim to realize production of 220 kton green methanol in the port. Further extension of this production will go hand-in-hand with attracting climate neutral hydrogen to the port.

In the study of Wuppertal Institut into decarbonization pathways of the port industry[xxxv] it was assumed that by 2050 base chemicals in the port would no longer be produced from fossil naphtha, but from 6 Mt green methanol, for which 0.8 Mt climate neutral hydrogen would be needed.

In the new raw materials study of Wuppertal Institut (2020) in one scenario it is assumed there will be a Fischer-Tropsch plant located in the port by 2040-2050, which produces FT-crude from biomass and 4.2 Mt hydrogen, which is processed into synthetic fuels in the existing hydrocrackers at refineries in the port.

It is expected that within Northwest Europe Rotterdam is best positioned for a syngas and FT plant, thanks to the presence of hydrocrackers, storage capacity and pipeline connections to the hinterland, as well as the potential to import biomass and hydrogen in large volumes.

Fischer-Tropsch technology is mature, as evidenced by the Gas-to-Liquids plant of Shell in Qatar, which produces 140,000 b/d (7 billion liters per year) liquid fuels from natural gas. However, climate neutral syngas and hydrogen as feedstocks for an FT-plant are still in their infancy.

In Dresden a Fischer-Tropsch demo plant is located, that produces 1 b/d synthetic fuels from CO_2 and hydrogen from renewable electricity, with a total energy efficiency of 65%. The owner Sunfire aims to start up an E-fuels plant in Norway with a capacity of 10 million liters (8 kton/year), which will be fed by 20 MW electricity from hydropower[xxxvi]. So, also here we see a need of huge upscaling and cost reduction. According to Concawe, an e-fuel still costs € 7/ltr, and would only be produced with comparable costs as fossil fuels by 2050[xxxvii].

IEA points out that still a lot of technology development will be needed to increase the overall efficiency of the conversion chain, since around 45-60% of the electricity used for production of e-fuels is lost during the process[xxxviii].

Rotterdam hydrogen trading hub

In Rotterdam, hydrogen will be developed in the twenties by combining the existing application as feedstock with application in process heating. Whereas blue hydrogen could rapidly lead to considerable reduction of CO_2-

emissions, green hydrogen could contribute to stabilizing the electricity grid, since electrolysers are extremely flexible to switch up and down. A combination of blue and green hydrogen would be able to give security and reliability to both large consuming industries and electricity producers and grid operators. Hydrogen is convertible in different forms. Especially in the thirties and forties, hydrogen will be used more and more as replacement for crude oil in producing climate neutral feedstock and fuels. Although every conversion step will cost energy, hydrogen could be of considerable added value by coupling of energy, fuels and feedstock systems and markets.

By the fact that hydrogen is already widely used in the petrochemical industry, Rotterdam has the unique possibility to combine use, transport, production and transit, thereby forming a first trading hub for hydrogen.

A Rotterdam H_2-quote could be very supportive: trade attracts trade, makes longer term physical and paper exchange possible, and will be beneficial for price-setting and stability. In December 2019 S&P Global Platts launched the first independent hydrogen price assessments, with California and the Netherlands as benchmarks locations. Rotterdam should aim to be renowned in the future as price-setting location for hydrogen as it is now for oil products.

Annex 1:

Klimapfade für Deutschland, Boston Consulting Group for Bundesverband Deutsche Industrie, 2018

Der 95 %-Klimapfad auf einen Blick

ABBILDUNG 12 | Wesentliche Entwicklungen im 95 %-Klimapfad

ELEKTRIFIZIERUNG VERKEHR UND WÄRME
Verkehr und Wärme werden umfassend elektrifiziert – v. a. durch 33 Mio. E-Pkw, 8.000 km Lkw-Oberleitungen, 16 Mio. Wärmepumpen und 15 GW_{el} PtH in der Fernwärme.

GASNETZ ALS NEUER VERBRAUCHER
Nullemissionen im Strom lassen sich nur durch 100 % synthetisches Gas in den flexiblen Kraftwerken (GuD, GT, Motoren etc.) erreichen – das Gasnetz wird zum saisonalen Speicher.

KONZENTRATION BIOMASSE
National verfügbare Biomasse wird in der Industrie konzentriert, um dort biogenes CO_2 zur Power-to-Gas-Erzeugung mit Systemnutzen recyceln zu können.

AUSBAU ERNEUERBARE
Durch die neue Nachfrage würde der Strombedarf auf ~ 715 TWh steigen – um diesen emissionsfrei zu bedienen, wäre eine deutliche Beschleunigung des EE-Ausbaus nötig.

ERHEBLICH MEHR FLEXIBILITÄT
Zur Abdeckung kurzfristiger Schwankungen in der Stromerzeugung ist deshalb auch mehr „direkte" Flexibilität im System nötig – Im-/Export, Speicher, flexible Verbraucher etc.

IMPORTE PtL UND PtG
Trotz allem bedienen Kraftstoffe auch 2050 noch > 60 % des EEV im Verkehr – dafür und für Teile des Backup-Stroms werden überwiegend synthetische Brenn-/Kraftstoffe aus Ländern mit besserer EE-Verfügbarkeit importiert.

CCS NÖTIG
CCS ist nach heutigem Stand nötig, um Emissionen in der Zementproduktion und der Müllverbrennung zu eliminieren – und ist auch für Stahl, Dampfreformierung und Raffinerien die günstigste Option.

BEITRAG DER LANDWIRTSCHAFT
Energie, Verkehr und Gebäude sind 2050 fast emissionsfrei, dennoch ist zur vollständigen Zielerreichung wohl die Reduzierung von Emissionen im Tierbestand nötig (~ 30 % bis 2050).

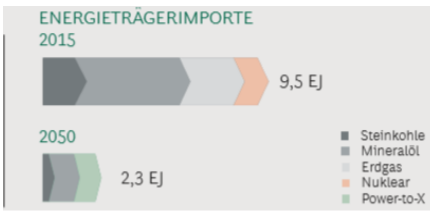
Anmerkung: EE = erneuerbare Energien, EEV = Endenergieverbrauch, GT = Gasturbine, GuD = Gas und Dampf, PtG = Power-to-Gas, PtH = Power-to-Heat, PtL = Power-to-Liquid
Quelle: BCG

Umfangreicher Import erneuerbarer Power-to-X-Kraft-/-Brennstoffe erforderlich

Insgesamt wären zur Bedienung des verbliebenen **Kraftstoffbedarfs** im 95 %-Klimapfad in 2050 etwa 100 TWh synthetischer Kraftstoffe und 25 TWh Wasserstoff für die nationalen Verkehre notwendig. Hinzu kommen noch einmal etwa 143 TWh, falls auch von Deutschland abgehende internationale Verkehre vollständig emissionsfrei gestellt werden sollten, außerdem etwa 100 TWh synthetisches Gas für Stromsektor und Industrie.

Allein für die Produktion dieser 368 TWh synthetischer Brennstoffe wäre im Jahr 2050 eine erneuerbare Stromerzeugung von insgesamt etwa 740 TWh erforderlich. Diese Menge ist höher als die gesamte Nettostromerzeugung Deutschlands im Jahr 2015 (610 TWh) und im Inland nicht realistisch darstellbar.

In der Studie wird unterstellt, dass Deutschland knapp 20 Prozent seines nationalen Bedarfs an Power-to-Gas für die Strom- und Fernwärmeerzeugung aus Gründen der Versorgungssicherheit sowie den Wasserstoffbedarf verbrauchsnah national erzeugt. Damit ergibt sich in 2050 zur Erreichung eines 95 %-Ziels ein **Importbedarf** für etwa 340 TWh synthetische Brenn- und Kraftstoffe aus Ländern mit besseren Bedingungen für erneuerbare Energien.[74] Um diese Mengen 2050 verfügbar zu haben und zu möglichst niedrigeren Kosten produzieren zu können, müssten die ersten großtechnischen Anlagen schon Mitte/Ende der 2020er Jahre in Betrieb gehen. Dazu wären bereits in den nächsten Jahren erhebliche Anstrengungen hinsichtlich Technologieerprobung und -skalierung sowie Projektentwicklung und -finanzierung notwendig.



Insgesamt würden im Vergleich zu 2015 **Brenn- und Kraftstoffimporte** dennoch um mehr als 75 Prozent zurückgehen (bezogen auf Menge und Energieinhalt), weil außer zur stofflichen Nutzung in der Chemie und der Stahlproduktion fast keine fossilen Mengen mehr importiert werden müssten.

Calculation: import 340 TWh x 3.6 = 1,224 PJ / 120 MJ/kg = 10 Mt H2

Annex 2:

Roadmap Chemie 2050, Dechema/Future Camp for Verein Chemische Industrie, 2019:

Referenzpfad (Pfad 1): Die Unternehmen produzieren weiterhin ausschließlich mit den heutigen Technologien. Ihre Investitionen bleiben auf dem gegenwärtigen Niveau von 7 Milliarden Euro pro Jahr und dienen der Erhaltung und Effizienzsteigerung der Anlagen. Die Unternehmen setzen zudem auf mehr Recycling. Durch das angenommene Ende der Kohleverstromung in Deutschland 2038 wird die deutsche Stromversorgung kontinuierlich emissionsärmer, was sich auch auf die Chemie auswirkt.

Technologiepfad (Pfad 2): Es wird dargestellt, wie weit die Chemie beim Klimaschutz kommen kann, wenn sie zusätzlich in neue Produktionstechnologien für Basischemikalien wie Ammoniak und Methanol investiert. Dabei unterliegt sie aber in diesem Pfad betriebswirtschaftlichen und technischen Restriktionen: Es werden maximal 225 Terawattstunden (TWh) erneuerbarer Strom im Jahr 2050 als für die chemische Produktion zur Verfügung stehend angenommen. Zudem ist das zusätzliche Investitionsbudget auf 1,5 Milliarden Euro pro Jahr begrenzt. Neue Technologien zur CO_2-Minderung werden eingeführt, sobald sie wirtschaftlich sind. Zudem spielen erneuerbare Energien in der Eigenenergieversorgung und eine verstärkte Kreislaufführung kohlenstoffhaltiger Produkte durch chemisches Recycling eine Rolle.

Pfad Treibhausgasneutralität (Pfad 3): Nahezu 100 Prozent weniger Treibhausgase durch maximale Investitionen für alternative Verfahren mit 11-fachen Strombedarf im Jahr 2050.

Um die deutsche Chemie 2050 weitgehend treibhausgasneutral zu stellen, müssen die im Technologiepfad beschriebenen Anstrengungen noch intensiviert werden. Technologien werden in diesem Pfad zum Beispiel schon dann eingeführt, wenn sich aus ihrem Einsatz eine CO_2-Ersparnis ergibt, ohne Rücksicht auf die Wirtschaftlichkeit. Von 2035 bis 2050 werden so alle konventionellen Verfahren der Basischemie durch alternative Verfahren ohne CO_2-Emissionen ersetzt. Die größten CO_2-Minderungen würden allerdings auch dann erst in den 40er-Jahren erbracht, wenn die Technologien in der Breite wirken und der deutsche Strommix weitgehend dekarbonisiert ist.

Die Kehrseite der Medaille: Die neuen, strombasierten Verfahren lassen den Strombedarf der deutschen Chemie ab Mitte der 2030er Jahre auf 685 TWh jährlich steigen, was mehr als der gesamten deutschen Stromproduktion von 2018 entspricht.

Tabelle 33: Gesamtergebnisse des Pfads Treibhausgasneutralität 2020 bis 2050; die einhergehenden Änderungen zwischen 2020 und 2050 sind in den letzten beiden Spalten ausgewiesen.

	Einheit	2020	2030	2040	2050	Änderung 2020-2050	
						absolut	prozentual
Rohstoffmenge fossil	Mt/a	19,1	17,4	14,3	1,5	-17,6	-92 %
Rohstoffmenge Biomasse	Mt/a	2,5	7,6	11,0	11,4	+8,9	+355 %
Rohstoffmenge Kunststoffabfälle	Mt/a	0	0,9	1,9	2,8	+2,8	+100 %
Rohstoffmenge CO_2	Mt/a	0,04	0,04	3,9	41,0	+41,0	+100 %

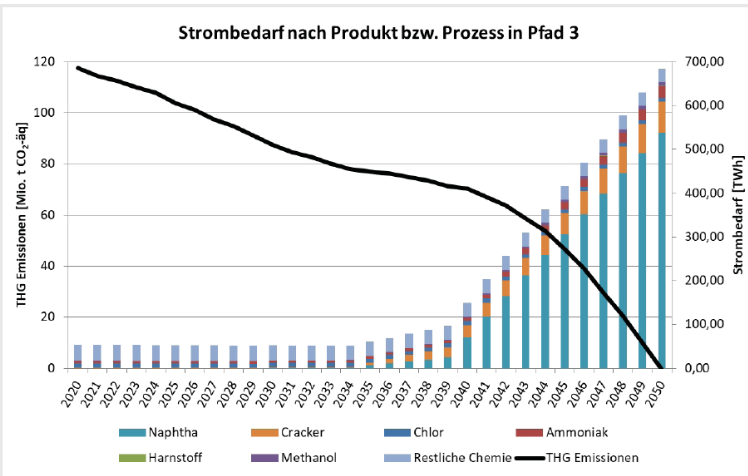


Abbildung 27: Strombedarf in Pfad 3 nach Produkten bzw. Prozessen (Balken) und Verlauf der THG Emissionen zwischen 2020 und 2050 (schwarze Linie). Nicht-betrachtete Basischemie- und Spezialchemieprodukte sind als „restliche Chemie" zusammengefasst.

Calculation: 685 TWh – 70 TWh E for cracker furnaces = 615 TWh for H2: 51,6 MWh/t H2 = 12 Mt

Annex 3:

CONCAWE: Refinery 2050: Conceptual assessment.

A LOOK INTO EU-WIDE SCALE

Key messages

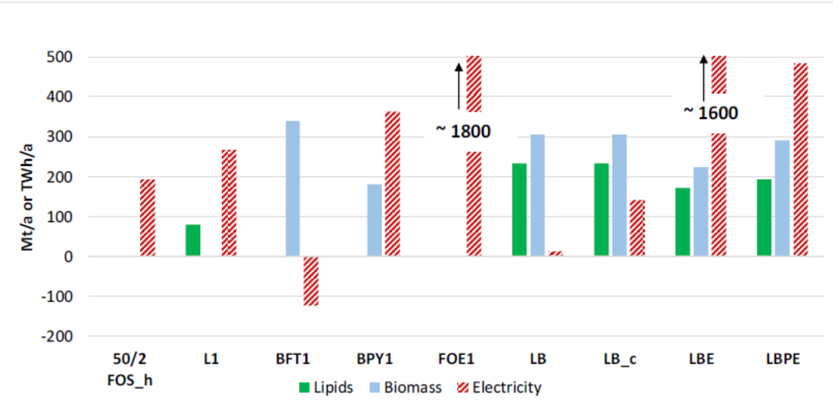
- When introducing alternative feedstocks, the main objective would not be to reduce emissions at the refinery site but indeed to reduce the carbon intensity of the final products contributing to a low carbon future in Europe.
- The cases described above could imply supply of up to 8 Mt/a biomass or 5 Mt/a lipids to a single site which would present significant challenges. If applied to the whole industry up to 200 Mt/a of lipids or 300 Mt/a of wood would be required.
- Large scale production of e-fuels would imply electrical consumption equivalent to a significant fraction of total EU consumption today.
- A combination of reduced demand, electrification and CO_2 capture could reduce the EU-wide industry emissions from 120 Mt/a to about 30 Mt/a. Outside CO_2 capture, use of alternative feeds would still result in sizeable fossil emissions at refinery sites, unless those feeds were fully renewable.
    - A combination of reduced demand, electrification and CO_2 capture at the refinery could reduce the EU-wide total emissions from main fuel products from about 1400 Mt/a to about 900 Mt/a in the fossil cases and down to 200 Mt/a with alternative feeds.
    - When the 2050 scenarios are compared with CO_2 emissions at 1990 level, the CO_2 reduction savings range from -50% up to -90% (direct emissions). Additional carbon sinks can be created when *Carbon Capture and Storage* solutions are combined with the biomass cases (BECCS) achieving negative emissions compatible with the EU long-term strategy (*A Clean Planet for all*).

Table 8.1.2-1 Hydrogen production (kt/a)

Case	50/2 FOS_h	LB	LBE	LBPE
SMR (general purpose)	0.8	54.6	50.6	48.8
Electrolysis (general purpose)	29.0	30.0	14.0	68.0
Electrolysis (e-fuels)	0.0	0.0	383.7	64.5
Total	29.8	84.6	448.3	181.3

Hydrogen production of an average refinery in the EU, production volumes adjusted to lower market demand in 2050; 80 refineries, so
80 × 448 kton = 36 Mt hydrogen, of which 398 kt = 32 Mt hydrogen with electrolysis in LBE-case
L=Lipids; B=Biomass (lignocellulosic), E=E-fuels, P=Pyrolysis

Figure 9.1-2 EU-wide alternative feedstock supply requirements



Note. As a reference, net electricity generation in EU-28 ~3100 TWh in 2016 (Source: Eurostat).

Large scale production of e-fuels would imply electrical consumption equivalent to a significant fraction of total EU consumption today

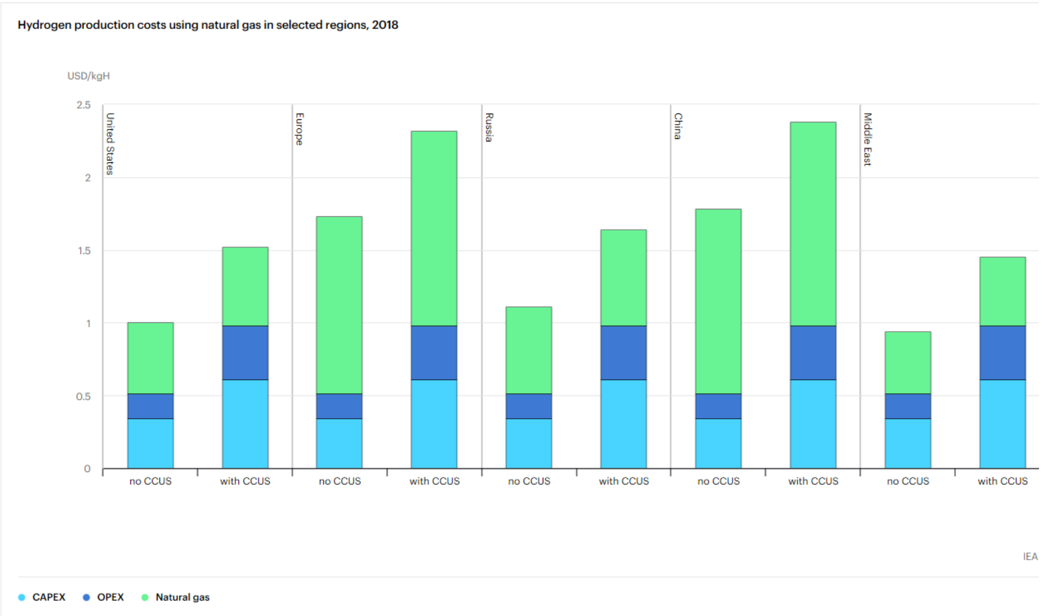
Annex 4:

Hydrogen production costs

Future of Hydrogen, International Energy Agency, 2019 (prices 2018):

Production costs hydrogen in Europe in 2018: capex 0.34 + opex 0.17 + nat.gas 1.22 = 1.73 $/kg = 2.04 €/kg

with CCS (blue hydrogen): capex 0.61 + opex 0.37 + nat.gas 1.34 = 2.32 $/kg = 2.74 €/kg



However, the Dutch TTF gas price has almost halved between Q4-2018 and Q4-2019, which resulted in considerably lower production costs of hydrogen:

Platts Hydrogen assessment (prices December 2019)

Production costs hydrogen in Europa end 2019: capex 0.47 + CO_2 0.27 + nat.gas 0.80 = 1.54 €/kg

Onderwerp: EMEA Hydrogen assessments, Dec 18

		Hydrogen Prices - Eu/kg				
8	Type of Hydrogen	Symbol	Close	Previous	Change	Change (%)
9	Hydrogen Netherlands SMR (H2 99.9%) w/o CCS MA	HWNMA00	0.7978	N/A	#VALUE!	#VALUE!
10	Hydrogen Netherlands SMR (H2 99.9%) w/o CCS (inc. CAPEX) MA	HXNMA00	1.2722	N/A	#VALUE!	#VALUE!
11	Hydrogen Netherlands SMR (H2 99.9%) w/o CCS (inc. Carbon) MA	HYNMA00	1.0673	N/A	#VALUE!	#VALUE!
12	Hydrogen Netherlands SMR (H2 99.9%) w/o CCS (inc. CAPEX & Carbon) MA	HZNMA00	1.5418	N/A	#VALUE!	#VALUE!

S&P Global Platts

In Q1 2020 the Dutch TTF gas price decreased another quarter. This means in April 2020 the hydrogen production costs of hydrogen are around 1.30 €/kg.

Notes:

[i] International Energy Agency, *The Future of Hydrogen*, June 2019

[ii] Waterstofcoalitie, *Tijd dringt voor groene waterstof*, November 2019

[iii] www.bmwi.de/Redaktion/DE/Dossier/wasserstoff

[iv] Ministry of Economic Affairs & Climate, *Kabinetsvisie Waterstof*, 30 March 2020

[v] Hydrogen Europe, Ad van Wijk, *Green Hydrogen for a European Green Deal, A 2x40 GW Initiative*, April 2020

[vi] Topsector Energy, TKI New Gas, *Contouren van een Routekaart Waterstof*, 2018

[vii] Institute for Sustainable Process Technology, research Hychain-1: *Energy carriers and Hydrogen Supply Chain: Assessment of future trends in industrial hydrogen demand and infrastructure*, 2019

[viii] Boston Consulting Group, *Klimapfade für Deutschland*, 2018, for Bundesverband der Deutschen Industrie

[ix] DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., and FutureCamp Climate GmbH, *Roadmap Chemie 2050*, 2019

[x] Concawe, *Refinery 2050: Conceptual assessment. Exploring opportunities and challenges for the EU refining industry to transition towards a low CO2-intensive economy*, september 2019

[xi] Mineralöl Wirtschafts Verband, Jahresbericht 2019: Rohöl- und Produkteneinfuhr 125 Mt in 2018
Verein der Kohlenimporteure, Importe von Steinkohle in 2018: 44 Mt
From Rotterdam to Germany in 2018: crude oil appr. 16 Mt, oil products appr. 16 Mt, coal appr. 22 Mt
⇨ Share Rotterdam in German import oil and coal: 54 / 169 = appr. 1/3

[xii] 20 Mt hydrogen = 2,400 petajoule (PJ) hydrogen. Then, with expected 75% efficiency of electrolysers in 2050 (now still 67%) 3.200 PJ electricity would be needed. 3.200 PJ electricity = almost 900.000 GWh electricity.
With 4.500 full load hours offshore wind this is: 900,000 GWh / 4,500 h = 200 GW necessary offshore windcapacity

[xiii] *CBS Elektriciteitsbalans, aanbod en verbruik*: Net electricity consumption in 2018 in Netherlands 112.7 TWh;
Climate Agreement: ambition electricity production wind at sea in 2030: 49 TWh from 11.5 GW; 49/112.7 = 43%
Net electricity production in 2018 in Netherlands 110.1 TWh, of which coal 28.8 TWh, natural gas 56.5 TWh;
(28.8+56.5)/110.1 = 77%

[xiv] *Klimaatakkoord*, Den Haag, 28 juni 2019, page 160: *afspraken en randvoorwaarden voor het realiseren van de 49%, eventuele versnellingsopties, het 55% scenario en de verdere doorgroei van wind op zee na 2030.*

[xv] EU, *A clean planet for all*, November 2018

[xvi] WindEurope; *Our energy, our future*, November 2019

[xvii] PBL, *De toekomst van de Noordzee*, 2018

[xviii] Berenschot en Kalavasta, *Climate neutral Energy Scenarios 2050*, a scenario study for the integral infrastructure exploration 2030-2050, April 2020

[xix] www.rotterdamccus.nl: news 2 December 2019: *Porthos a step closer: four companies prepare CO_2 capture.*

[xx] www.deltalings.nl/h-vision: Feasibility Study Report H-vision: *Blue hydrogen as accelerator and pioneer for energy transition in the industry*, juli 2019. Annexes to the H-vision Main Report: Costs of CO2 transport and storage, pages 80-81: capex storage, compression en transport in reference-case reduced by base case
[xxi] For H-vision the reference case is taken, but without power plants, so only oil refineries and cogen.

[xxii] According to one of the oil companies

[xxiii] Hydrogen Council, Path to hydrogen competitiveness, January 2020

[xxiv] CE Delft, Gasunie and Nuon, *Waterstofroutes Nederland*, 2018.
In this study, for blue hydrogen natural gas from and CO_2-storage in Norway is assumed.

[xxv] WoodMackenzie, *Green hydrogen production, landscape, projects and costs*, October 2019

[xxvi] International Energy Agency, *The Future of Hydrogen*, June 2019, page 54

[xxvii] IRENA, *Hydrogen, a renewable energy perspective*, September 2019:

Considered Load factors and levelized cost of electricity are:

2030: Wind best: Load factor: 47%. LCOE: 23 USD/MWh.
Wind Average: Load factor: 34%. LCOE: 55 USD/MWh.
PV Best: Load factor: 27%. LCOE: 18 USD/MWh.
PV Average: Load factor: 18%. LCOE: 85 USD/MWh.
2050: Wind best: Load factor: 63%. LCOE: 11 USD/MWh.
Wind average: Load factor: 45%. LCOE: 23 USD/MWh.
PV best: Load factor: 27%. LCOE: 4.5 USD/MWh.
PV Average: Load factor: 18%. LCOE: 22 USD/MWh.

[xxviii] BloombergNEF, Hydrogen: *The molecule to power a clean economy?*, August 2019

[xxix] Hydrogen Council, Path to hydrogen competitiveness, January 2020

[xxx] HySTRA = CO_2-free Hydrogen energy Supply-chain Technology Research Association, of Kawasaki Heavy Industries, Shell, J-Power, Iwatani, Marubeni, JXTG Nippon Oil & Energy, "K"Line

[xxxi] Kawasaki Heavy Industries, Ltd: *World's First Liquefied Hydrogen Carrier SUISO FRONTIER Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-free Society*, Dec. 11, 2019. Pilot project ship size:

Overall length	: 116.0 m	Gross tonnage	: 8,000 tonnes
Overall width	: 19.0 m	Vessel speed	: 13 knots
Depth	: 10.6 m	Draft	: 4.5 m
Maximum crew	: 25 persons	Tank capacity	: 1,250 kL

[xxxii] Royal Vopak, Mitsubishi Corporation, Covestro and AP Ventures invest Euro 17 million into Hydrogenious LOHC Technologies GmbH and its Liquid Organic Hydrogen Carrier (LOHC) technology for hydrogen logistics.

[xxxiii] GET H2 Nukleus: BP, Evonik, Nowega, OGE and RWE Generation sign a Letter of Intent to develop a hydrogen network from Lingen to Gelsenkirchen, March 2020

[xxxiv] Parties in RH2INE: province South-Holland, Bundesstaat Nordrhein-Westfalen, Ministry of Infrastructure and Water, Province Gelderland, Port of Rotterdam Authority, Port of Duisburg, RhineCargo, BCTN, EICB, Nouryon, Covestro, Air Products, Future Proof Shipping, HTS Group, NPRC, AirLiquide, Koedood.

[xxxv] Wuppertal Institut, *Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam*, 2016

[xxxvi] https://www.sunfire.de/en/company/news/detail/first-commercial-plant-for-the-production-of-blue-crude-planned-in-norway

[xxxvii] Concawe, *Role of e-fuels in the European transport system - Literature review*, January 2020:

Currently, e-fuel costs are relatively high (up to 7 euros/litre). Some authors forecast their decrease over time due to economies of scale, learning effects and an anticipated reduction in the renewable electricity price, leading to, in 2050 around 1-3 euros/litre (without taxes)[7]. Therefore, cost of e-fuels could range from one to three times higher than fossil fuels by 2050[8].

[7] Sources: [dena 2018], [Cerulogy 2017], [Frontier Economics 2018], [FVV 2018a], [Dechema 2017], [Shell 2018].

[8] Electricity costs currently ranging from 4 ct/kWh (North Africa - Photovoltaic) to 10-13 ct/kWh (North and Baltic Seas - Offshore wind), and by 2050 expected to range from 1-3 ct/kWh (North Africa - Photovoltaic) to 4-8 ct/kWh (North and Baltic Seas - Offshore wind). Source: [Frontier Economics/Agora 2018b].

[xxxviii] International Energy Agency, *The Future of Hydrogen*, June 2019, figure 20, page 56: 45-60% electricity lost in electrolysis, synthesis and used in direct air capture