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NARRATIVE

Transition to e-fuels: a strategy for the Harbour Industrial Cluster Rotterdam

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TRANSITION TO E-FUELS: A STRATEGY FOR THE HARBOUR INDUSTRIAL CLUSTER ROTTERDAM

Narrative



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CONTENT

01	Introduction	6
1.1	Setting the scene	6
1.2	Economic and logistic position	7

02	A strategy for the transition to e-fuels in the Harbour Industrial Cluster Rotterdam	10
2.1	Goal of the strategy	10
2.2	SWOT analysis	10
2.3	Basic strategy	13

03	A roadmap for implementation	22
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04	Scenario analysis: robustness of the strategy	25
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05	Key take-aways	27
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06	References	29
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Introduction

1.1 Setting the scene

The energy transition, needed to realise climate goals, will have a major impact on all actors involved in the transport value chain. This includes end users, refineries and other fuel producers, port operators, vehicle suppliers, refuelling infrastructure providers, storage providers and all connected value chains. Large reductions in CO₂ emissions are necessary to maintain a “license to operate”. Battery-electric vehicles will play a key role in reducing CO₂-emissions from passenger cars, vans, buses, and urban and regional distribution trucks. For heavy-duty, long haul road transport, shipping and aviation, however, batteries will not suffice. For these sectors, therefore, (nearly) emission-free fuels will have to be produced and stored. Besides green hydrogen, biofuels will play a significant role. However, biomass may not be sufficiently available to meet worldwide demand for sustainable fuels. Therefore, e-fuels, produced from green hydrogen, will most likely supply a considerable share of the demand for sustainable fuels. E-fuels are expected to start playing a role in sustainable transport from 2030. E-fuels¹ and green hydrogen, and their potential role for the Port of Rotterdam in the transition to a sustainable logistics and energy hub, are the topic of this study.

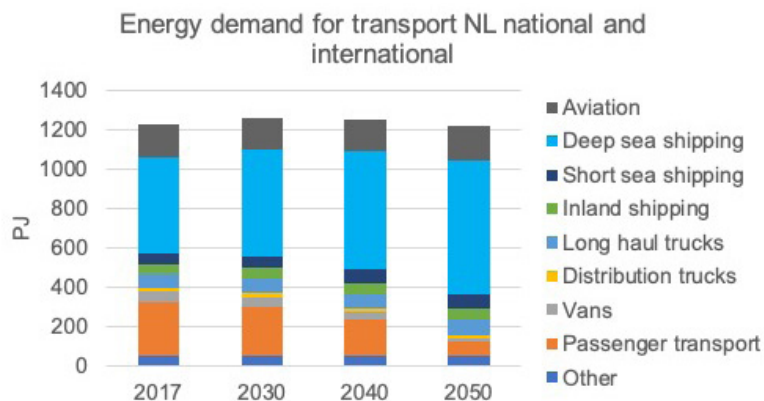


Figure 1: Energy demand in NL for national and international transport modalities, fuelled/bunkered in NL, and an approximate distribution of the most logical option(s) to make these modalities sustainable. The high energy efficiency of battery-electric vehicles (BEV) compared to vehicles with a combustion engine causes a significant reduction in energy demand for a.o. passenger transport, vans and distribution trucks.

In the Power2Fuels project [1] a mapping of suitable e-fuels per transport modality was prepared, and for each modality the techno-economic performance of different e-fuels was compared. In another study, space requirements were determined of an e-fuel production cluster large enough to supply all fuel demand in the Netherlands from long haul road transport, shipping and aviation (approx. 600 hectares, of which 2/3 for direct air capture) [2]. Space in the Harbour Industrial Cluster (HIC) Rotterdam

¹ E-fuels are defined as fuels, based on green hydrogen and CO₂ or nitrogen. Other synthetic fuels, e.g. synthetic fuels based on biomass or recycled carbon like CO, are not in scope of this study.

is scarce, which raises the question whether the production of the (e-)fuels should and can take place in Rotterdam [3]. Next to that, space for the landing of offshore wind power is limited, and the Dutch (renewable) electricity production capacity also has limits. On top of that, countries with abundant renewable energy sources can provide electricity at lower costs. At the same time, Rotterdam has for decades been an important fuel and (petro-) chemical cluster with good infrastructural connections and a good location for the landing of wind energy (until 2030, a total of 7.4 GW could land at Maasvlakte).

These challenges and their impact on the existing cluster prompted SmartPort and Voltachem to ask TNO and a group of stakeholders from different parts of the value chain to consider the following questions²: What would be a logical role for HIC Rotterdam in the e-fuels value chain? What is the best way for HIC Rotterdam to distinguish itself from other clusters? Which part of the value chain can best be attracted to Rotterdam (production, storage, infrastructure)? This report presents a summary of the results of the CHAIN project. The underlying analysis can be found in the background report. [7]

1.2 Economic and logistic position

In order to answer these questions, the analysis started with an assessment of the current economic and logistic position of the Port of Rotterdam. For the economic position, data shows that the Rotterdam port provides direct employment for about 100,000 employees, which is about 1% of employment in The Netherlands. [4] The total contribution of the Port of Rotterdam to the Dutch GDP is about 2% (CBS and [4]).

The analysis of the logistic position shows that the Port of Rotterdam is a global maritime hub: it is the 1st port of Europe and the 10th worldwide. Also, Rotterdam is home to the 2nd largest fuel cluster in the world. Currently, a very large amount of fuel for national and international modes of transport is produced and bunkered in the Rotterdam port area. The role of the fuel cluster is significant; it accounts for 45% of the total maritime throughput. Only 26 mln ton is used in the Netherlands (see Table 2). A large share of the throughput consists of crude oil that is refined locally. Maritime imports in Rotterdam are transhipped to the hinterland via road, inland waterway and pipeline. Main competitors of the port are Antwerp (refineries, chemical industry and oil storage and distribution) and Amsterdam (oil storage and distribution).

Table 1: Rotterdam maritime liquid bulk throughput statistics in 2019 (million ton) [5]

	Inbound	Outbound	Total
Crude Oil	103	1	104
Mineral oil products	36	32	68
LNG	7	1	7
Other liquid Bulk	19	12	32
Total liquid bulk	165	46	211

2 This has been a cooperative project with stakeholders from the industry. The following partners participated in the project: BP, Deltalinqs, Gate Terminal, Nouryon, Port of Rotterdam, Shell, Sohar Port/Freezone and Vopak.

Table 2: The NL fuel and bunker market in 2019 totals 26 mln ton [6]

Modality	Fuel type	mln ton
Road transport	Petrol	6.5
	Diesel	4.3
	LPG	0.1
Rail transport	Diesel	0.0
Aviation	Kerosine	3.9
Shipping	Fuel Oil (high and low sulphur)	8.4
	Gas Oil	2.8

The role of Rotterdam as a major global logistics hub is of great significance to the Dutch economy. The transport volumes associated with the fossil fuel cluster and the related availability of affordable bunker fuels are important pillars for Rotterdam's dominance as logistics hub. Defining a well-thought-out strategy for the transition to e-fuels is therefore of major importance. Our analysis of the economic and logistics position of the Port of Rotterdam provides important elements for a strategy towards e-fuels. It shows that the German hinterland could be an important market for green hydrogen and e-fuels³. Since the energy transition creates a new era in the fuel and chemical market, being a fast mover is of strategic importance. Also, being able to offer these new fuels at competitive prices is important. Supplying e-fuels at a price level competitive with other countries/ports requires strategic alliances with countries that have access to abundant, low-cost renewable energy. The construction of (hydrogen) pipelines will also contribute to creating strategic advantages. In terms of creating employment and value added, wholesale trade services and transport and storage services seem to contribute most.

³ Germany is, after Singapore and Belgium, the third country in the world that is expected to have a shortage of renewable energy to fulfill national energy demand. The Netherlands is fourth. [18]



A strategy for the transition to e-fuels in the Harbour Industrial Cluster Rotterdam

The proposed strategy is the result of input from workshops and discussions between the project partners, supported by analysis from TNO (SWOT, economic analysis).

2.1 Goal of the strategy

The key driver for a transition to e-fuels is to reduce GHG emissions from hard-to-abate transport modes like aviation, maritime shipping and heavy-duty, long haul road transport. E-fuels will lead to significant changes in production and import value chains, which will have a large impact on HIC Rotterdam as a fuel cluster. Therefore it is important to design a strategy in which the current economic and logistic position of HIC Rotterdam is maintained or even strengthened. Therefore the two main goals for the strategy are:

1. Reduction of CO₂ emissions in heavy duty transport (long haul road transport, shipping and aviation, to be CO₂ neutral in 2050), by application of e-fuels and green hydrogen, in order to achieve the Paris climate targets.
2. Maintain or strengthen the economic and logistic position of HIC Rotterdam and of value chain partners, to contribute to societal welfare by creating new value chains and as such maintaining employment.

The strategy consists of three pillars, answering the following questions:



Figure 2: The three pillars of the strategy

2.2 SWOT analysis

Before filling in the three pillars of the strategy, it is important to consider the strengths and weaknesses of the HIC Rotterdam, and the opportunities and threats in the market. Therefore a SWOT analysis of the HIC Rotterdam regarding the transition to e-fuels, and the production and application of e-fuels has been made, with input from the project partners. Figure 3 summarizes the results of the SWOT analysis.

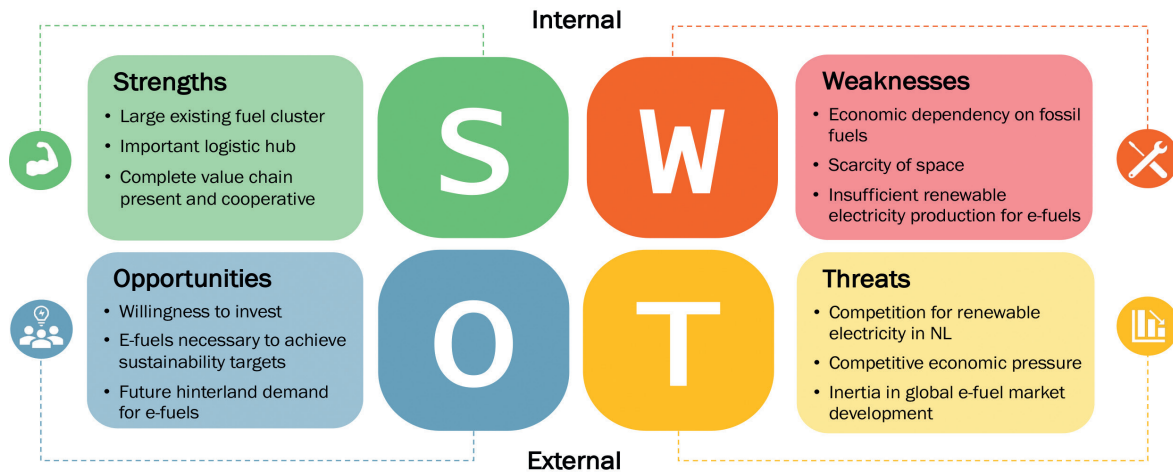


Figure 3: Summary of results of the SWOT analysis

Next, the elements of the SWOT are combined in a so-called *confrontation matrix* (see Figure 4), in which a weight has been assigned to each of the cells in the matrix. Strategic directions were formulated based on the cells with the heaviest weights. In particular, the darker coloured components in the confrontation matrix require attention in the strategy. These components provide the key strategic directions.

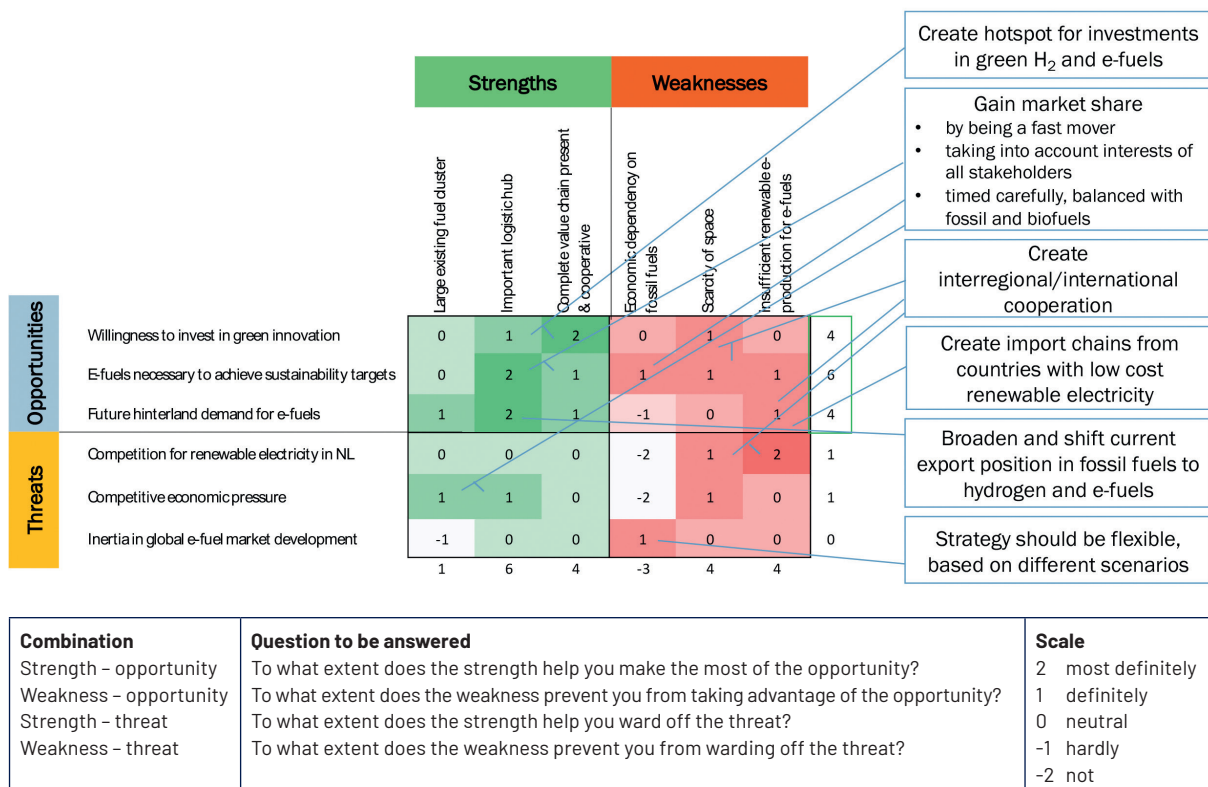


Figure 4: SWOT confrontation matrix provides strategic directions

Based on the SWOT analysis and the confrontation matrix, the following input for the strategy has been formulated:

Rotterdam can respond to the expectations for a significant e-fuels market by using its strength as major logistics hub. When Rotterdam starts offering e-fuels, a significant volume can be built up quickly. At the moment, the willingness to invest in sustainable technology is high⁴. This offers an opportunity to create a position in Rotterdam in the field of e-fuels.

Especially the strengths “important logistic hub” and “complete value chain present” make HIC Rotterdam an attractive hotspot for investments in green hydrogen and e-fuels. Furthermore, similar developments are taking place in the chemical sector. This offers opportunities to strengthen development in terms of shared infrastructure, joint development of an innovation ecosystem, skilled workforce, co-siting, and other potential synergies. This position can be used by the region to attract investments.

Actors from the entire value chain are already present in HIC Rotterdam. Access to markets is well-established and a lot of existing infrastructure (such as pipelines) and logistic connections can be reused for the supply of e-fuels. By being a fast mover, Rotterdam can build up a position here. However, ports like Antwerp and Hamburg have similar plans.

The current economic interests in fossil fuels could also have an inhibiting effect on building a position as e-fuels producer. Therefore, it is important that fossil fuel producers are stimulated to take a stake (role) in the transition to e-fuels. Another obstacle is the lack of locally generated sustainable electricity. Furthermore, space in the port area is scarce and expensive. By setting up import chains with countries where electricity from sustainable sources will be available in abundance, at lower prices than in Europe, the lack of locally generated sustainable electricity can be overcome. The import of hydrogen (carriers) and e-fuels can also partially overcome the problem of lack of space. In addition, it is important to work together with other regions for the storage of hydrogen in salt caverns.

In addition to bunkering and refuelling markets in Rotterdam, there will also be a sales market for e-fuels in the hinterland. Currently, Rotterdam is already a major supplier of fuels to the hinterland (mainly Germany). It is expected that the demand for fossil fuels and oil will gradually shift towards a demand for sustainable fuels and green hydrogen.

A threat is the potential loss of competitiveness, due to the (for now) significantly higher cost levels of e-fuels compared to fossil fuels and biofuels. In the transition period, e-fuels will therefore have to be offered alongside fossil and biofuels. The speed of the transition to e-fuels ultimately depends largely on external factors. If development in other regions is too slow, Rotterdam can accelerate locally using its important position as a logistics hub, and its transition power due to the presence of almost the entire value chain. If this happens too soon, part of the logistics chain will seek out competing ports. A constant balancing act is therefore required, based on the interests of the various players and on the growth in demand for sustainable fuels from the logistics sector. Meanwhile, companies will only invest in e-fuels when market demand justifies the investments. To increase market demand, incentives are needed to persuade companies to no longer use fossil fuels. Besides that it is important to find customers with willingness-to-pay, either because they are early adopters and/or because they operate in markets with above average sustainability requirements.

4 See e.g. the European Green Deal, and the number of sustainable energy projects that are initiated by industry consortia. Nouryon/BP/HbR plans for 250 MW elektrolyser [21] and Shell has plans for a 200 MW plant at Maasvlakte 2, starting in 2023 [22].

2.3 Basic strategy

Local production and import

The first pillar in the strategy concerns import and local production of hydrogen and e-fuels. Currently, a large amount of energy is imported in the Port of Rotterdam in the form of crude oil. It is expected that import of energy will continue to play a significant role after the energy transition, but in the form of sustainable feedstock, fuels and hydrogen (carriers).

Though costs are not the only factor to take into account when deciding on import or local production, it is a factor that will have major impact. To answer the question which e-fuels and hydrogen carriers are economically attractive and which can (partly) be produced in HIC Rotterdam, an economic analysis has been carried out on import of various e-fuels and hydrogen carriers from countries around the world. E-ammonia (NH_3), e-methanol (MeOH), liquid hydrogen (LH_2) and a liquid organic hydrogen carrier (LOHC) are incorporated in the analysis. The cost of import of e-ammonia and e-methanol are compared to the cost of local production in HIC Rotterdam. Liquid hydrogen and LOHC are assumed to be used as gaseous hydrogen in Rotterdam. Therefore the costs of LH_2 and LOHC are compared to the cost of local production of gaseous green hydrogen in HIC Rotterdam. The main assumptions for the analysis are presented in Table 3. A more detailed elaboration of underlying assumptions can be found in [7].

Table 3: Main assumptions for economic analysis of import and local production ^{5, 6, 7, 8}

For all chains: • Comparison of import of ammonia, methanol, LOHC and liquid hydrogen for 8 countries and ammonia, methanol and gaseous hydrogen for NL • Sustainable production from renewable energy sources and CO_2 from DAC • During offpeak hours conversion plant needs to keep running, so stored renewable energy is used as energy source (LCoE + storage costs) • LCoE, distance and local interest rate are main country differentiating factors • Transport by ship • Ammonia and methanol are assumed to be used as fuels / feedstock directly, without conversion back to hydrogen											
Country-specific parameters	Reference	Unit	Netherlands	Canada	Morocco	Australia	Oman	UK	South Africa	Namibia	Chile
LCoE, wind & solar power (where applicable) in 2030	Multiple LCoE reports	€/MWh _{el}	74	37	59	26	37	28.2	33.3	47.9	43.6
Cost of stored electrical back-up power in 2030	LCoE + storage costs 60 €/MWh ₅	€/MWh _{el}	134	97	119	86	97	88	93	108	104
Shipping distance (one way to PoR)	Ports.com	nm	0	3,400	1,700	13,188	6,765	524	8,157	6,605	9,730
Local interest rate	HyChain, WACC used	%	7.2	8	13	10	10	7	12	13	11

5 The accuracy of the cost estimates may be up to ~50% per process block. However, since basic assumptions for each of the routes are the same, the overall comparison between routes is more accurate.

6 LCoE and FLH (full load hours) per country are based on literature. The method applied to determine LCoE and FLH is described in [7]. Though this method may lead to some outliers (e.g. UK seems to be too low compared to NL, partly explained by the fact that UK renewable energy supply (RES) is based on onshore wind and solar, where NL RES is based on offshore wind), consequent application of the method has prevailed in the analysis.

7 <https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/>
Currently large scale storage starts at about 120 EUR / MWh, the assumption is that this cost is reduced by a factor of two by 2030.

8 LCoE: Levelised Cost of Energy is an average price of electricity per MWh, based on CAPEX and OPEX of the energy generating asset.

The examples of the cost breakdowns for import and Dutch production of e-ammonia and LOHC respectively, shown in Figure 5 and Figure 6, indicate that the local costs of renewable hydrogen production are a major determinant in the cost comparison.

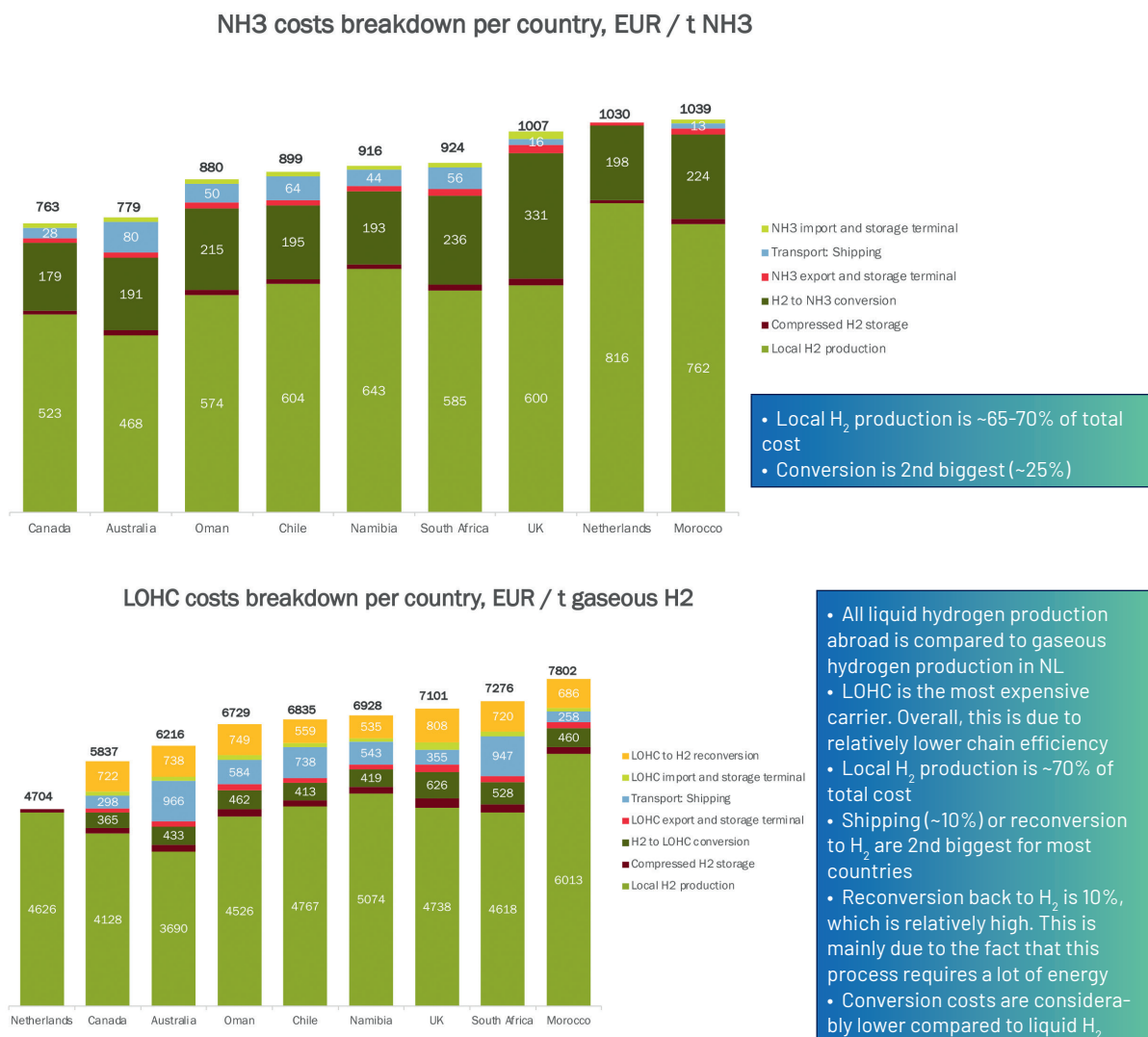
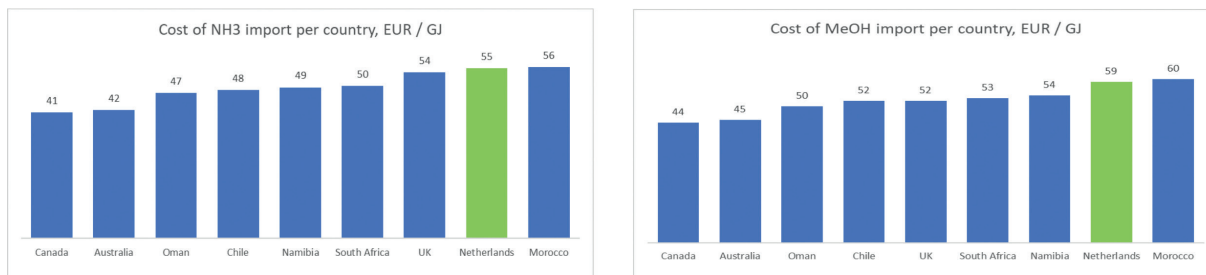


Figure 5: Cost breakdown of e-ammonia import per country and production of e-ammonia in NL

Figure 6: Cost breakdown of LOHC import per country and production of gaseous hydrogen in NL

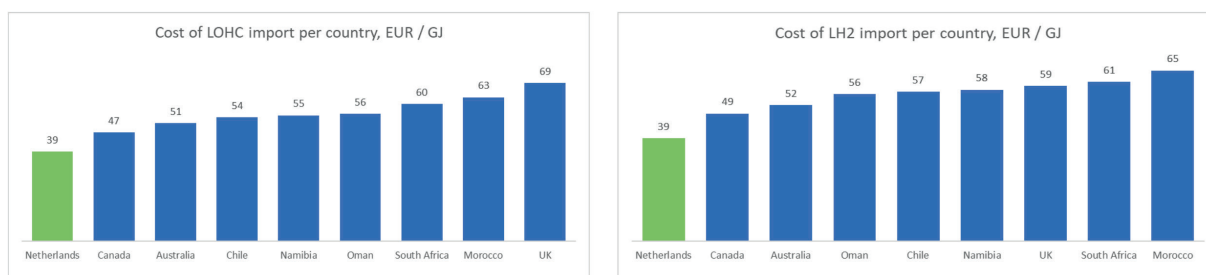
Under the assumptions included in the analysis, import of ammonia and methanol as fuels for use in the Netherlands is sensible from a cost perspective (Figure 7). Though not too much value must be attached to the exact sequence of the countries, the lower LCoEs abroad result in lower cost for import of ammonia and methanol, compared to production in the Netherlands.



- Import of NH₃ and MeOH is economically more attractive than local production in NL
- Overall, MeOH is more expensive because of high Direct Air Capture CAPEX and lower chain efficiency
- In NH₃ and MeOH cases their use as fuels was assumed, so no cracking back to hydrogen in NL was included in the cost

Figure 7: Comparison of import costs per country and production in NL of e-ammonia (left) and e-methanol (right)

For hydrogen the results are opposite: import of LOHC and liquid hydrogen is significantly more expensive than production of gaseous hydrogen in the Netherlands. Obviously this is mainly a consequence of the energy consuming processes of producing LOHC from hydrogen and liquefaction of hydrogen, besides other costs in the value chain that are omitted by production in the Netherlands.



- Producing hydrogen in NL is more attractive than importing it as liquified hydrogen or LOHC, when used as gaseous hydrogen in Rotterdam.
- However, if NL sees a very high hydrogen demand that cannot be covered by domestic production or import by pipeline, this could be an interesting option. Also for direct use in transport or for further transportation import of LOHC or LH₂ may be interesting options.
- LOHC is the most expensive carrier of all four

Figure 8: Comparison of import costs per country for LOHC (left) and liquid hydrogen (right) and production of gaseous hydrogen in NL

An alternative to import of e-fuels could be the import of intermediates. For the HIC, an important aspect is to maintain economic activity around the production of fuels. It is therefore useful to also consider chains in which raw materials and/or intermediate products are imported and the final fuels are produced in HIC Rotterdam: what are the possibilities and how would they fit into the strategy for the transition? In particular, e-diesel and e-kerosene are candidates for this. Detailed results of an economic analysis of production of e-diesel and e-kerosene from imported intermediates can be found in [8]. The results of that study are summarized below.

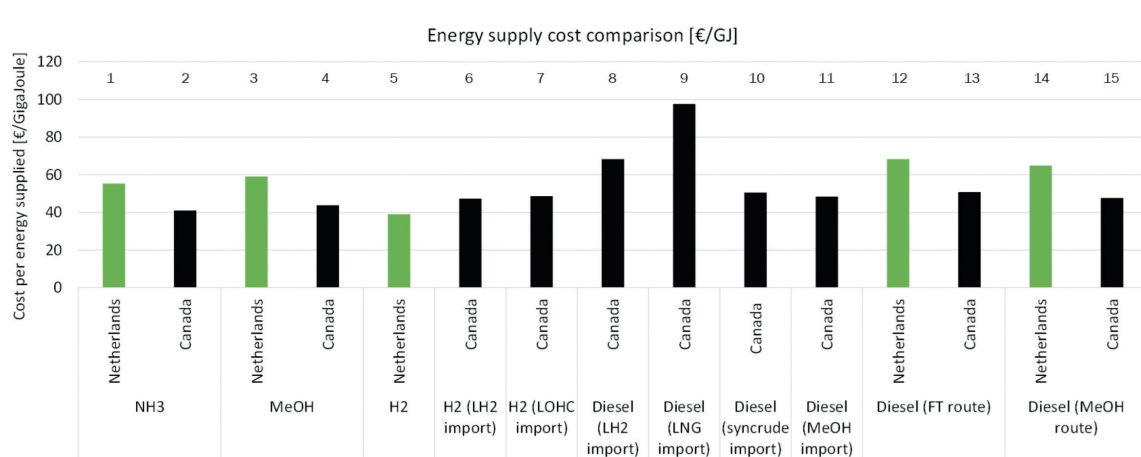
E-diesel and e-kerosene can be produced in a Fischer-Tropsch plant that uses FT-crude as feedstock. The FT-crude is produced from hydrogen and CO₂. An alternative to a Fischer-Tropsch plant is the production of e-diesel or e-kerosene from e-methanol or e-LNG.

In Figure 9 the results of the economic analysis of local production of e-diesel⁹ from intermediates is compared to import (from Canada) and local production in Rotterdam of different e-fuels and hydrogen.

For the production of e-diesel (and e-kerosene) the methanol route is found most efficient and results in lowest cost. Cost of production via Fischer-Tropsch is close to cost of the methanol route. Especially the e-LNG route is inefficient and costly, and also import of liquid hydrogen to produce e-diesel in Rotterdam is significantly more costly.

Import of e-diesel (and e-kerosene) is slightly more cost effective than producing the fuels locally from imported intermediates, such as methanol or FT-crude. However, import of FT-crude presents technical challenges. Also, the step from intermediate to e-diesel (and e-kerosene) results in a higher value product, while the additional expenses are fairly limited. It seems therefore logical that the producer of FT-crude converts it into the final diesel (and kerosene) product. Import of green methanol to produce diesel and kerosene, on the other hand, seems more rational, since methanol is also a platform molecule for the chemical industry and a global methanol market already exists. Therefore local production of e-diesel and e-kerosene from imported green methanol is considered a serious alternative to import of e-diesel and e-kerosene.

When taking into account all considered e-fuels and hydrogen, in terms of costs per GJ of fuel, local production of hydrogen (column 5 in Figure 9) has lowest costs. However, costs of storage, distribution, tank infrastructure and vehicles are significantly higher for hydrogen than for e-fuels [7]. Of all the e-fuels that are analysed, ammonia has lowest cost per GJ.



- Lowest production cost per GJ of fuel are via H2 production in NL (39 €/GJ H2), column 5.
- Lowest production cost per GJ of fuel imported are via NH3 supply (41 €/GJ NH3), column 2.
- Lowest cost to supply e-diesel (column 8-15) is via the methanol route with e-diesel import (48 €/GJ Diesel), column 15.
- Lowest e-diesel supply costs are 9% higher per GJ fuel compared to MeOH import from Canada (column 15 vs column 4).

Figure 9: Comparison of import and local production costs of different e-fuels (column 1-4 and 12-15) and hydrogen (column 5-7) with local production of e-diesel from imported intermediates produced from renewable energy (column 8-11).

9 The costs of production of e-kerosene will be approximately the same as of e-diesel. Fractions can be tuned depending on process conditions.

For the strategy the following conclusions can be drawn:

Local production and import

Import of e-fuels from countries with low cost renewable electricity

Production of e-fuels in HIC Rotterdam will be significantly more expensive than import, which favours an import strategy for e-fuels. Costs are, however, not the only important factor that affect market prices; in case of scarcity, willingness-to-pay will highly influence market prices. If market prices are high enough, a positive business case for e-fuels production in Rotterdam might come within reach. But there is another reason to import e-fuels: Electricity from renewable energy sources (RES) will not be sufficiently available to produce the amount of e-fuels and hydrogen that would be needed for heavy-duty, long haul road transport, shipping and aviation [9]. Therefore *import of e-fuels* will be necessary. However, to initiate the transition to e-fuels, HIC Rotterdam, as one of the first, should develop a *strategic e-fuel production capacity*, albeit on a limited scale. As such, HIC Rotterdam, and possibly also the rest of the EU, will not become a major producer, but can be the first in its class to innovate, develop technologies (that could later potentially be exported) and produce e-fuels. Besides that, a local strategic production capacity can reduce geopolitical dependence. For e-diesel and e-kerosene, local production from imported green methanol may be considered as an alternative to import.

Local production of H₂, as far as enough RES is available; complement with import

Transport and storage of hydrogen are complex. Therefore it is necessary to convert hydrogen to LOHC or liquid if transported by ship. These conversions require a lot of energy and are costly. Therefore, hydrogen can best be produced locally as much as possible¹⁰. This conclusion might be different when there is a demand for specific LH₂ or LOHC (instead of H₂ in gaseous form). For such applications import is likely to become interesting. One could, for instance, tank liquid hydrogen directly into a ship [10]. An alternative to transport by ship is transport of gaseous hydrogen by pipeline from nearby countries¹¹. This option was, however, not considered in this analysis.

Positioning and role of HIC Rotterdam

The second pillar of the strategy concerns the position and role of HIC Rotterdam during and after the transition towards e-fuels. Based on the SWOT analysis and input from project partners, the following strategic directions are recommended:

Broaden and shift current position in fossil fuels to a hub position for hydrogen and e-fuels

Though HIC Rotterdam will most likely not produce e-fuels at the current scale of fossil fuel production, it has many competitive advantages that can be used to broaden and shift its current role as a hub for fossil fuels to a hub position for hydrogen and e-fuels, both for delivery to the transport sector and to the hinterland. Rotterdam has extensive experience with the transit of fuels, existing customer contacts, already operating strong value chains and valuable infrastructure that can be reused.

Landing of large quantities of electricity from offshore wind

The production of hydrogen and e-fuels requires large amounts of electricity. This electricity from renewable energy sources is not only needed for more sustainable transport, but also for making industry and other sectors more sustainable. For hydrogen production alone, Port of Rotterdam

¹⁰ This is of course dependent upon the availability of space and electricity from RES and could be a limiting factor in this respect.

¹¹ The Gas for Climate consortium analysed possibilities for a European hydrogen backbone [23].

foresees a need of 4 GW off shore wind in 2030 already. [11] Offshore wind farms could play an important role in providing this large amount of electricity and making the region more sustainable. Landing as much offshore wind as possible in Rotterdam should therefore be an essential part of the strategy. It should be noted, however, that Rotterdam has limited space to accommodate the landing of such large amounts of electricity. Storage (of electricity and/or hydrogen) will also be of crucial importance, since the demand side often has a continuous profile in contrast to the intermittent generation of energy from wind.

Cooperation throughout (existing and new) value chains

The production, transport, storage and use of hydrogen and e-fuels require many different actors, from producers of electricity to users of fuels in logistics. With a shift to new fuel types, new international value chains will emerge, involving both existing and new parties. Based on its current position (logistically, economically and knowledge base), HIC Rotterdam can play an initiating role for these new chains and lead the way globally.

Create interregional/international cooperation

In order to accommodate the transition towards lower CO₂ emissions, the Rotterdam region can benefit from cooperation with other regions, for example with the Northern part of the Netherlands for storing hydrogen in salt caverns or for space consuming DAC. Furthermore, in the light of the need to import energy carriers, good international trade relations are important, since geopolitical dependence on countries to import from may arise. This is an important element to take into account in the choice for countries to import from.

Integration with chemical cluster

There is good potential for integration of e-fuels with the chemical cluster. Here e-fuels are not only suitable for the production of heat and power but also as feedstock for products. Green hydrogen as fuel produces high-temperature heat while as feedstock it can be used to upgrade oxidized forms of carbon like CO₂ back to marketable products. Green ammonia can be used as fuel, and is also the basis for fertilizers and functional chemicals that are the basis for a myriad of products. Green methanol or Fischer-Tropsch liquids can be a source of circular carbon that can be converted to more complex carbon-based products that are today based on the naphtha fraction from oil refining. The exploitation of circular carbon is also important in the chemical industry: circular carbon from waste or biomass would likely displace naphtha in the same way that e-fuels displace fossil fuels. This provides opportunities for synergies to strengthen innovation, development and integration in both fuels and chemicals production. This could be in terms of re-use or development of new infrastructure, development of an innovation ecosystem, skilled workforce and co-siting.

Transition

The third pillar is about the *transition* from fossil fuels to e-fuels, concerning choices around speed of changes, types of fuel, investment in new infrastructure and reuse of existing assets, integration and consequences of choices made.

Be a fast mover

Though it is not always necessary to be a *first* mover, which requires significant upfront investments and brings the risk of betting on the wrong horse, companies in the Rotterdam region do have the ambition to be a *fast* mover. Fast movers may avoid mistakes made by the first mover, they can reduce their own investment requirements as well as their risks, can identify areas of improvement left by the first mover, adopt new and more efficient processes and technologies, and scale up production to reduce costs. By being a fast mover HIC Rotterdam can speed up the transition to hydrogen and e-fuels in a robust manner.

Rotterdam region as a hotspot for investments in green hydrogen and e-fuels

Given the high willingness of governments and businesses to invest in green hydrogen and e-fuels, the momentum should be used to attract investments to HIC Rotterdam. This would be a stimulus for creating a future position in the production, use and transit of hydrogen. Even though in the long term the lion's share of e-fuels will be imported, it is desirable to also build up (limited) strategic production capacity for e-fuels. This can stimulate the development of innovative production technology for e-fuels and hydrogen, that can be exported in a later stage. This development has already started with the various pilots for sustainable fuel production and the realization of electrolysis capacity currently taking place.

Refineries: transition of modern refineries into integrated energy and chemical sites

As e-fuels and electricity displace fossil fuel products, circular-carbon resources will displace fossil resources for chemical products and fuels. This will in the long run (2030-2050) substantially reduce the required crude oil fractionation capacity of the Rotterdam cluster. The throughput of unit operations related to the first processing steps, physical fractionation of the crude oil, will therefore structurally diminish. Selected unit operations related to chemical conversion further downstream processing may be of good use to integrate circular-carbon resources from waste and bio-materials:

- Unit operations that would eventually phase out while shifting away from crude oil are e.g. the crude distiller, vacuum distiller and visbreaker.
- Unit operations that might be of good future use could e.g. be the gasifier, catalytic reformer, hydrocracker and hydrotreater.
- New assets in a cluster could e.g. be water-electrolysers for local hydrogen and oxygen production and plants for conversion of circular-carbon raw materials to olefins.

The scale of operation at complex refineries is very large compared to chemical sites. Therefore the chemical conversion-assets of these complex refineries today are by their scale well-positioned to be re-purposed into large centralized and cost-efficient facilities for the production of intermediates from bio-derived and recycled materials. For example, Shell already made plans in this direction [12]. Two of the five refineries in Rotterdam have extensive conversion capabilities that may eventually be re-purposed to produce cracker-feed from circular-carbon resources. Such integrated sites offer potential for synergy and optimization. Efficiency in both energy use and carbon conversion to products will be key for the performance of these sites as a whole. Since resources for circular carbon, which must replace carbon from crude oil, are critical for the cluster, it is of strategic importance for the Port of Rotterdam to facilitate or even secure access for its industries by building on its role and position of global logistics hub.

Prepare for ammonia and methanol as transport fuels for maritime

At the moment, ammonia and methanol seem to hold the best cards as a transport fuel for the maritime sector. Several consortia around the world are investing in production of ammonia for export. Also several big shipping companies like Maersk [13] see ammonia as promising. A big advantage of ammonia is that it is not a carbon fuel. So there is no need to invest in expensive, energy- and space-intensive DAC installations. However, extra attention will have to be paid to safety, since ammonia is gaseous and toxic, and to the associated NO_x emissions when ammonia is used in an internal combustion engine.

Methanol, on the other hand, has the advantage that it is easier to handle, since it is a liquid. It also requires less modification on the ship itself. Furthermore, the possibility to use methanol as a platform molecule in chemistry, in addition to its direct application as a fuel (for e.g. shipping and long haul road transport) and the possibility to make kerosene and diesel out of it, offers the potential to scale up faster. Many (pilot) projects for the production of sustainable methanol and also for the application of methanol as fuel for shipping are running worldwide. Interesting to know is that bunkering of methanol has already taken place in Rotterdam. [14], [15]

Besides ammonia and methanol (and e-diesel produced from methanol), hydrogen (particularly for inland shipping) and other e-fuels, such as e-LNG, could also play a role for shipping. Since maritime shipping is the largest consumer of fuels in Rotterdam, it is important to quickly get the transition in this modality off the ground. For this purpose it is important to set up pilots with ammonia and methanol for use in the maritime sector.

Spatial integration

Availability of space is an important topic in a transition towards a new energy cluster. New energy carriers potentially require more (storage) space than current carriers, since their energy density is much lower. Additionally, adjustment of current assets to make them suitable for new fuel types or building new infrastructure takes time, so companies face a period in which both old and new assets will co-exist and as such will require more space. Furthermore, space is required for the integration of offshore wind and for the production of H₂.

This means that choices will need to be made in terms of production versus import of energy carriers and/or fuels, given the availability of space or potential to free up space. Also the use of alternative locations (i.e. outside the port area) should be considered, such as using salt caverns in the north of the Netherlands for storage of hydrogen and potential (off shore) locations for DAC.

Reuse of existing infrastructure

HIC Rotterdam has many existing assets that can be (re)used in the transition to e-fuels. Examples are (fuel) pipelines (both within the region, and to clusters outside the region, e.g. to Germany), existing refineries, bunker infrastructure, jetties, etc. Storage tanks will become available when fossil fuels are phased out. Furthermore, there is an LNG terminal in the Port of Rotterdam, which can be expanded with other cryogenic fuels through the development of additional infrastructure. Liquid hydrogen is particularly important in this respect. Additionally, connection to the planned national hydrogen backbone is important, which could be very realistic if existing gas pipelines will be used for this backbone.

Flexibility

Because uncertainty is inherent in a transition, staying flexible is key, especially regarding the following subjects:

- which e-fuels: there is still a great deal of uncertainty as to which technologies will be used, particularly for shipping. But also for road transport: how big is the gap that cannot be filled with battery-electric and hydrogen vehicles and which e-fuels will fill this gap?
- geopolitical dependence: make sure not to be dependent on production in a single country, i.e. spread your risk. Value chains need to develop, so at this stage it is still unsure which countries are most attractive to import from. Therefore, a broader focus than just costs is important in the selection of supplying countries.
- speed of scaling up: it is still unknown how fast the transition will take place. Will countries meet the Paris targets on time, late or not at all? How soon will fossil fuels be phased out? At what pace will market demand for e-fuels develop? How big will the role for biofuels be? It is important to be able to flexibly respond if things change faster or slower than expected.

Overview

The strategy resulting from the analysis and the contents of the three pillars described in this chapter is represented in Figure 10:

Local production and import	Positioning and role of the Rotterdam area	Transition
• Local production and import • Import of e-fuels from countries with low cost renewable electricity; develop limited strategic production capacity. • Local production of H₂, as far as enough RES is available. Complement with import.	• Broaden and shift current position in fossil fuels to a hub position for hydrogen and e-fuels, both for delivery to the transport sector and to the hinterland • Landing of large quantities of electricity from offshore wind is of vital importance for the cluster • Cooperation throughout the (existing and new) value chains • Create interregional/international cooperation • High level of integration with chemical cluster	• Be a fast mover: learn from first movers, move fast to gain market share and scale up • Position Rotterdam as a hotspot for investments in green H₂ and e-fuels • Refineries: transition of modern refineries into integrated energy and chemical sites • Prepare for ammonia and methanol as transport fuels for maritime • Prepare for spatial integration of new clusters • Reuse of existing infra • Flexibility, to be able to cope with different scenarios

Figure 10: Summary of the three pillars in the basic strategy

A roadmap for implementation

Now the basic strategy has been determined, the transition path towards realization of the strategy can be outlined. The roadmap shows how the strategy translates into actions over time and is made up of several layers: energy supply, local production, import chains (to Rotterdam), export chains (from Rotterdam to the hinterland), and application in heavy duty transport. For each of these layers, a distinction has been made between actions needed in terms of R&D, infrastructure (distribution, storage, refuelling infrastructure), production, regulation, trade and application of e-fuels. Figure 11 shows the roadmap and its different layers. Each individual layer will be discussed in the next sections.

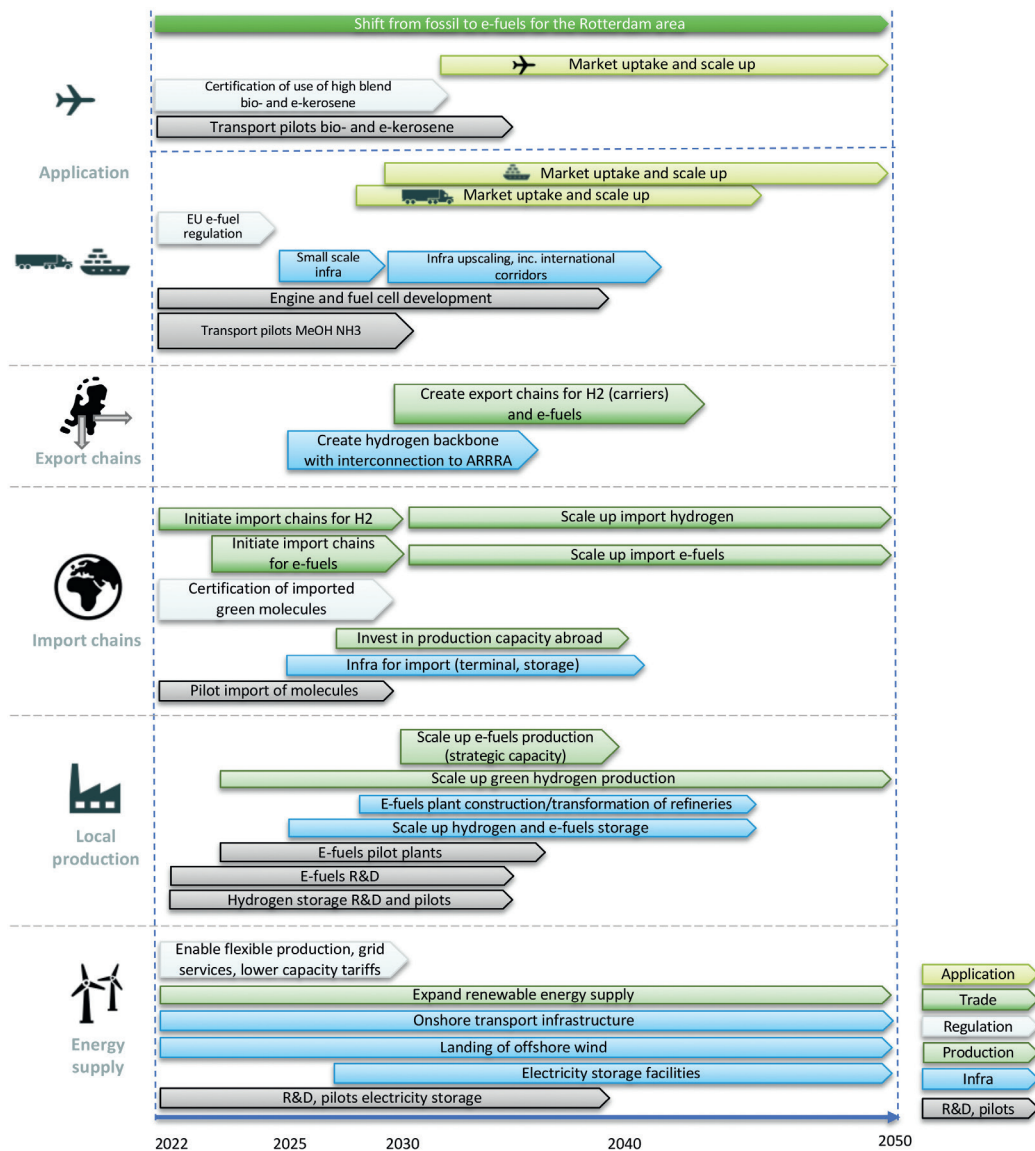


Figure 11: Roadmap for the transition to e-fuels in the HIC Rotterdam

Renewable energy supply

Since massive amounts of electricity are needed for the production of hydrogen and e-fuels, creating a large capacity of particularly offshore wind energy is essential¹². It is preferred to locate hydrogen production near the landing point of offshore wind to minimize the need for costly and space consuming onshore transport infrastructure for electricity.

The production of e-fuels is a high-CAPEX process that cannot be easily interrupted and needs a continuous flow of hydrogen. This means, that either the electricity supply has to be continuous or large amounts of hydrogen have to be stored. The development of large scale electricity (and also hydrogen) storage requires further R&D and pilots.

Local production

As explained in the strategy, it is important to ensure that HIC Rotterdam develops e-fuel production facilities, albeit on a limited scale, in order to maintain a strategic position. It would be good to start with the production of hydrogen¹³, followed by e-fuels. E-fuels production locations will be determined by the location of existing infrastructure in HIC Rotterdam that can be reused. Also access to hydrogen supply via pipeline is necessary.

It is important to keep in mind that different feedstocks and products have a different time course. Currently, in terms of regulation, there are already opportunities for recycled carbon fuels (see RED II) where Rotterdam has a location advantage¹⁴ and could produce affordably at large scale, with the possibility to switch to DAC on the long term.

For e-fuels production, existing technologies like Fischer-Tropsch and Haber-Bosch synthesis can be utilized, but R&D is still needed to arrive at optimal production processes. In addition, research is needed into CO₂ utilization for carbon fuels. On short term biogenic CO₂ can be used. In the long run however, it is expected that DAC will play a major role when large-scale use of carbon e-fuels will take place.

In terms of storage, R&D investments will have to be made primarily in the storage of hydrogen and possibly ammonia. For ammonia, LNG storage tanks could be reused when available. Cooperation with the Northern Netherlands, where empty salt caverns seem to offer a good option for hydrogen storage, is important here¹⁵. After a while, in the scaling-up phase, but also dependent on price levels, e-fuels should be imported from outside the EU, given the limited production capacity in the port area and the EU as a whole. It is therefore important to start building relationships with other clusters and countries around the world.

12 Future quantities of hydrogen needed (and therefore how much RES is needed for production) are still uncertain, depending on the speed of the sustainability transition and the role of hydrogen in it. In the Hydrogen Vision report of the Port of Rotterdam the following quantities are mentioned:

2030: 2 GW hydrogen, so 4 GW off shore wind to be connected

2040: 18 to 24 GW off shore wind

2050: 100 GW hydrogen, of which a substantial part is transit

13 Pilots for large scale hydrogen production will start: Nouryon/BP/HbR plans for 250 MW elektrolyser [16] and Shell has plans for a 200 MW plant at Maasvlakte 2, starting in 2023 [17]

14 Recycled carbon streams with high utilization potential, like CO, can be a transition step to manufacture synthetic fuels and on longer term integrate biogenic CO₂, and CO₂ from DAC when technologies for those become mature.

15 Gasunie has begun with a pilot for storing hydrogen in a salt cavern in Zuidwending. If successful, Gasunie plans to make the storage facility operational by 2026. [19]

Import chains (import of e-fuels from abroad to Rotterdam)

For e-fuels import is the most viable option, besides a strategic local production capacity. Dependent on the pace of the transition, the use of e-fuels is expected to take off from 2030, so import chains must be initiated by now. The same holds for hydrogen. Imports of e-fuels and hydrogen will be needed for transit to the hinterland, and import of e-fuels (and possibly hydrogen) is also needed for local use. For imports of both e-fuels and hydrogen, it is important to start pilots in a timely manner, and make infrastructure suitable for the molecules that will be imported. Storage tanks for fossil fuels that become available can be reused. Regarding regulation, certification of green molecule imports should be arranged by the EU.

Export chains (export from Rotterdam to the hinterland)

For export to Germany, and possibly Belgium, a connection to the planned hydrogen backbone is essential. For transit of e-fuels and LOHC barges can be used, and for export at larger scale existing pipelines can be reused. Since The Netherlands does not have enough RES to meet its own needs for hydrogen, import is necessary and could, as such, form a basis for transit.

Application

Trucks & ships

For road transport, the use of hydrogen is expected to be the main option where battery electric vehicles (BEV) do not suffice. Where hydrogen does not suffice either, carbon-based e-fuels such as e-methanol and e-diesel can play a role. For shipping, hydrogen can play a role particularly in inland navigation and for ferries. In maritime shipping, methanol and ammonia are expected to play a major role. It is therefore important to set up pilots for the use of ammonia and methanol in the maritime sector. Although there is still much uncertainty about which e-fuels will eventually win, it is necessary to take steps now to achieve the sustainability targets for 2050. Regulation and policy (e.g., financial incentives, obligations, and especially for ammonia also safety protocols and permitting) are important instruments to enable the use of e-fuels.

Tank and bunkering infrastructure must be created for hydrogen and (new) fuels such as ammonia and methanol, initially on a small scale and expected to be scaled up from 2030 onwards. For e-diesel and e-LNG, use can be made of existing bunker infrastructure. Particularly for the application of hydrogen (especially for trucks and inland shipping), it is important that international corridors with refuelling or bunkering stations are created. In the maritime sector, at the beginning of the transition, dual fuel engines will be used in part. Also, development of internal combustion engines and fuel cells is needed for the use of new fuels and attention will have to be paid to the storage tanks in the vehicles, especially for ammonia and hydrogen.

Scaling up of e-methanol and e-ammonia in shipping is expected from 2030 onwards. Upscaling of biomethanol in shipping and the uptake and scale-up of hydrogen, particularly in truck transport, are expected before 2030.

Aviation

For long haul aviation, in general, only bio- and e-kerosene are seen as having a role as a fuel by 2050. Certification is necessary for the use of new types of kerosene. The market uptake of e-kerosene is not expected before 2030. Until then, mainly bio-kerosene will play a role in the market and e-kerosene will have to be piloted.

Scenario analysis: robustness of the strategy

Now that the basic strategy and the roadmap towards realization of the strategy have been determined, the time has come to see which external factors, such as decisions taken in other sectors, policies and innovations, should be taken into consideration. They can strongly influence the speed of the transition. This speed will have a great impact on the strategy to be followed for the period 2030-2050 and the preparation period until 2030. Given the fact that there are many more uncertainties in a transition to e-fuels, a scenario analysis was carried out to check the robustness of the strategy. The choice was made to define scenarios in which: 1) the speed of GHG emissions reduction and 2) whether or not climate targets are met in the EU and at the global level, are leading. These factors are presumed to have large impact, but are highly unpredictable. The scenarios are presented in Table 4.

Table 4: Scenario description

	High ←	Achieving climate goals	→ Low
	High ←	Cooperation	→ Low
	Acceleration	Frontrunners	Inertia
Description	EU and RoW (rest of the world) achieve climate goals	EU achieves climate goals, as well as some other countries, regions and cities; RoW does not	EU and RoW do not achieve climate goals
Characteristics	High drive towards sustainability; cooperation between countries and businesses	EU cooperates with countries and regions that strive for sustainability; other countries let economic/ fossil interests prevail	Everyone for himself, economic interests prevail over sustainability
Development of RES in Europe	quick	quick	slower, but still economic driver (dependent on CO ₂ tax for fossil)
Development of RES abroad	quick	slower	slower, based on economic driver
Adoption of e-fuels in Europe	quick	quick	slower
Adoption of e-fuels RoW	quick	slower	slowest
Availability of biomass	shortage	higher availability for Europe	no shortage on short term

The scenarios are defined qualitatively. The scenario-analysis is not about the exact speed of decarbonization, but about the impact that an acceleration or deceleration has on the strategy to be followed. A detailed analysis of the scenarios can be found in [7]. Based on the scenario-analysis, the following conclusions can be drawn:

1. The elements of the strategy for the base case scenario are important in all scenarios, but with different accents and at a different pace.
 - a. In the Acceleration scenario, the demand for e-fuels will develop at a higher pace, which makes an accelerated implementation of the elements in the strategy urgent. This reaches from the setup of value chains for import to the implementation of a hydrogen backbone. Both market uptake of relatively higher TRL technologies, like green hydrogen and e-methanol production, and the development of new technologies, like ammonia fuel cells, should be accelerated.
 - b. In the Frontrunner scenario, biofuels will initially have a higher share in the sustainable fuel mix compared to the Acceleration scenario. It seems logical, but not necessarily required, to focus the development of value chains for import on cooperation with frontrunner countries. This scenario offers a great opportunity for Europe to also become a frontrunner in technology development related to e-fuels, and export these technologies to the rest of the world. Modern refineries may continue to produce fossil fuels longer, to meet the demand for fossil fuels outside Europe, if they are allowed to by governments. Making global logistic value chains, like for maritime shipping and aviation, more sustainable, will be more complicated in this scenario. The coexistence of both fossil and sustainable production capacity and related infrastructure will complicate spatial integration.
 - c. In the Inertia scenario, the transition to sustainable fuels will be a slow process. For a longer period, the availability of biomass for sustainable fuels will meet demand, resulting in a slower development and uptake of e-fuel related developments regarding technology development, implementation of production capacity and related infrastructure and the development of value chains for import. It is expected that the adoption of sustainable hydrogen will go on, but with a bigger role for blue hydrogen. The mix of blue and green hydrogen will offer more possibilities for flexibility. Local production of hydrogen will meet demand for a longer period, so import of hydrogen at large scale will be postponed.
2. Flexibility is key in all scenarios. In the Acceleration scenario, flexibility is especially needed to scale up at a high pace, whereas in the Inertia scenario, uncertainty regarding which e-fuels will win will remain longer. Avoiding geopolitical dependence will be even more important in this scenario, since countries will tend to let their own economic interests prevail over global sustainability goals.

Key take-aways

Now all building blocks have been discussed and the questions around the impact of the transition to e-fuels on HIC Rotterdam have been answered, in conclusion the following main lessons are identified as key take-aways from the different elements of the analysis:

Basic strategy

HIC Rotterdam is well positioned to play a significant role in the transition to e-fuels. Hydrogen will be one of the main feedstocks in this transition. From a strategic and economic point of view, hydrogen will be produced locally as much as possible. Due to the fact that a conversion to a carrier like LOHC or to liquid hydrogen is not needed when hydrogen is produced locally, it will be more economic than import. For e-fuels, the creation of limited strategic production capacity is important, but in the long run the lion's share of e-fuels, other than hydrogen, will probably be imported. There are two main reasons for importing a large share of the e-fuels needed. First of all, the Netherlands itself does not have enough energy available from renewable sources. In addition, the production of e-fuels in the Netherlands is considerably more expensive than importing them from abroad. Geopolitical independence is a point of attention in the choice of countries from which to import.

With the transition to e-fuels, HIC Rotterdam will be able to retain its hub function for energy streams. However, unlike now, this will be less from its role as a fuel producer, but mainly as a transit port for hydrogen and e-fuels to the hinterland.

For implementing the strategy, the availability of sustainable electricity is seen as the greatest challenge¹⁶. Other challenges are spatial integration, market acceptance of more expensive e-fuels, creating the necessary flexibility in the energy system and setting up international value chains.

Roadmap

To actually get the transition to e-fuels off the ground, cooperation throughout the entire chain, and from regional to global level, is essential. An integrated approach, i.e. timing and implementation based on dialogue between the stakeholders of the various components, must be adopted, ensuring coherence between the components of the roadmap.

An example is storage capacity in the value chain: because fuel production needs a practically constant supply of hydrogen, the creation of large-scale storage facilities for electricity and/or hydrogen is crucial.

Scenario's

The elements of the strategy for the base case scenario are important in all scenarios, but with different accents and at a different pace. The share of e-fuels in the mix of renewable fuels will initially vary considerably per scenario.

¹⁶ Based on a poll among market representatives during a workshop organized in the context of the CHAIN project.

Flexibility in the strategy is crucial. This applies equally to the choice of e-fuels, geopolitical (in)dependence and the speed of scaling up.

The speed of implementation of the transition towards e-fuels will impact the duration of need for coexistence of both fossil and sustainable production capacity and related infrastructure. The longer it takes, the more complicated spatial integration will be.

Concluding, it can be stated that the transition to e-fuels will face HIC Rotterdam with lots of challenges, but when all stakeholders unite forces they can pave the way towards a future in which transport has become sustainable and in which HIC Rotterdam can maintain its role as major energy hub.

Challenges

The transition to e-fuels will face several challenges. A number of these challenges are discussed in this report, but the study also gives rise to new questions that need attention in follow-up research. For HIC Rotterdam, especially the following questions are relevant:

1. What will be the impact on Rotterdam as a bunker port?

Currently, Rotterdam has a very strong position in bunker fuels, partly because of the very competitive price that Rotterdam can offer due to its position as fossil fuel production cluster. When Rotterdam will import the lion's share of fuels, this will change drastically. What will be a good strategy here?

2. How will feedstock streams for the petrochemical cluster change?

As described in the report, circular carbon will be an important but scarce feedstock, not only for carbon e-fuels, but also for chemicals. What will be the impact on the Rotterdam cluster, when fossil production will be phased out? Is it a desirable option to reuse fossil carbon during the transition? How much carbon from biogenic and waste sources will be available? Will these developments result in a shift of chemical products produced in HIC Rotterdam?

3. Transition in the hinterland

Currently a large share of fuels produced in Rotterdam is transhipped to the hinterland. In the defined strategy Rotterdam will stay a logistics hub for delivery of (imported) fuels to the hinterland. How this position will develop in the future is, however, dependent on development in the hinterland: what are their plans with respect to the transition to e-fuels and other sustainable energy carriers, especially in the ARRR cluster? And what are the implications for HIC Rotterdam?

4. What are potential game changers for the strategy?

The designed strategy in this study is based on future developments that are nowadays expected. Besides that, robustness of the strategy was challenged in the scenario analysis with respect to the speed of the transition. However, game changers might arise in the future, that give reason to adjust the strategy. For example, when a revolutionary breakthrough in battery technology is achieved, the need for e-fuels will be different. It will be important to create a broad picture on potential game changers for all PESTLE (political, economic, social, technological, legal, environmental) factors.

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