a sustainable carbon future

Feedstock Transition for Harbor Industrial Cluster Rotterdam

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As the energy transition is gaining scale and speed, the feedstock transition to replace crude oil for a mix of sustainable carbon sources poses an even greater challenge for Rotterdam's Harbor Industrial Cluster (HIC) for decades to come.

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Preface

Background

The *Port of Rotterdam* aims to reach net-zero CO_2 emissions by 2050, which will require the energy and feedstock supply to transform into a sustainable mix. The Harbor and Industrial Complex (HIC) is exploring ways to transition from using crude oil to sustainable feedstocks for its refined fuels and petrochemical products.[1]

A clear picture does not yet exist as to the potential of sustainable carbon feedstocks for replacing fossil-based feedstocks at the HIC, of which crude oil is by far the dominant flow. These sustainable carbon feedstocks are expected to become a limited resource in the future. Furthermore, most of the commercial and industrial products produced (e.g., chemicals, plastics, shipping and aviation fuels) at the HIC will continue to require carbon-based feedstocks.

The *Province of Zuid-Holland* asked *Deltalinqs* and *Power2X* to obtain a realistic picture of the potential future feedstock mix to achieve CO_2 neutrality in the HIC. This investigation was further supported by the *Port of Rotterdam*. The outcome of this study is one of multiple feedstock studies that are being executed from different angles, leading up to the creation of a *Port of Rotterdam* Future Climate Neutral Feedstock Vision document. This study therefore forms a starting point for the decision-making and action that will shape the feedstock transition at the HIC.

Main definitions

The energy and feedstock transition to achieve climate and energy security goals will present a major transformation challenge for decades to come and affect many companies at the HIC Rotterdam.

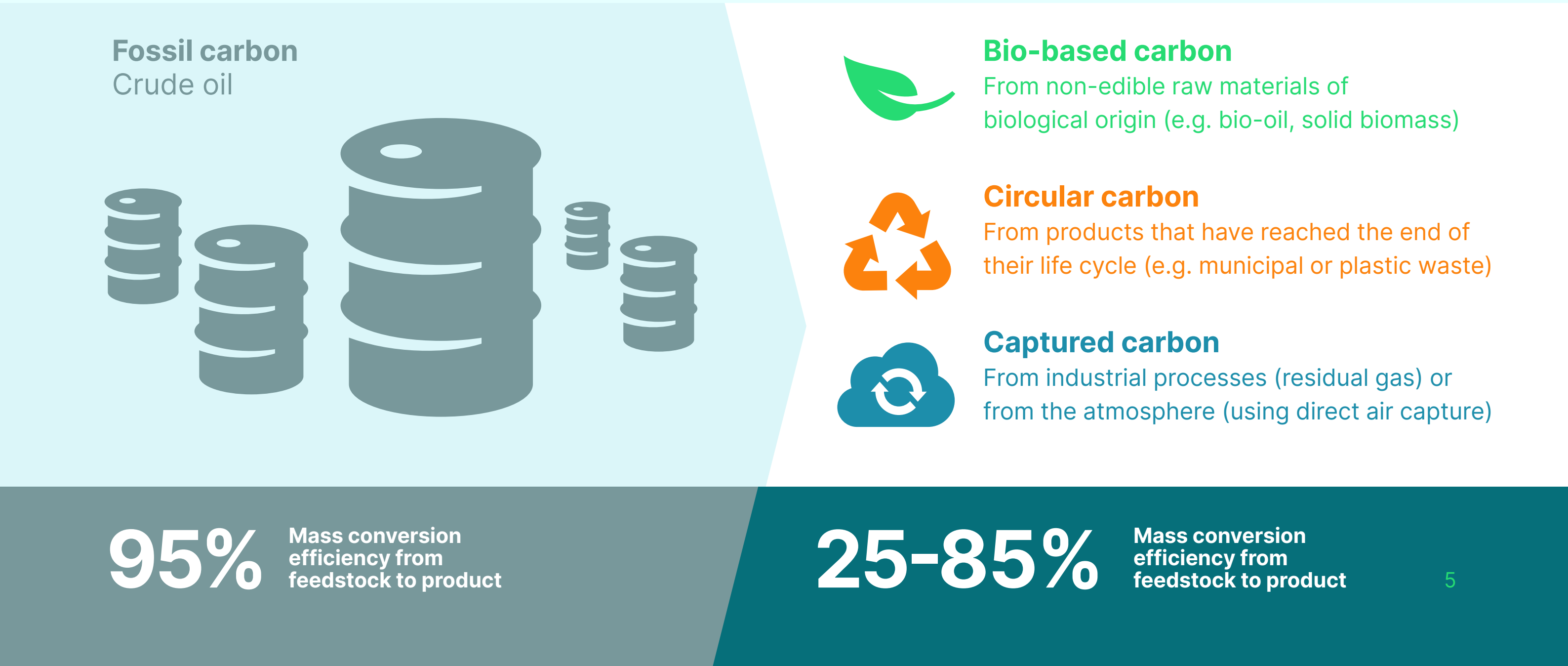
- **The energy transition** aims to replace fossil-fuels with low-carbon renewable energy sources. At its heart is the need to reduce energy-related CO_2 emissions to limit climate change.
- **The feedstock transition** aims to replace fossil-feedstocks (crude oil, naphtha, coal, natural gas) with sustainable (carbon) feedstocks from bio-based, circular and captured sources.

In the context of this study, **sustainable feedstocks** refer to those feedstocks that recycle carbon rather than adding to it. These feedstocks can come from different sources:

- **Bio-based** (biogenic): from non-edible raw materials of biological origin (e.g. solid biomass or residual vegetable oil, animal fat or used cooking oil (UCO));
- **Circular**: from products that have reached the end of their life cycle (e.g. municipal or plastic waste); and
- **Captured**: from industrial process (residual gas) or from the atmosphere (using direct air capture).

These feedstocks can be transformed to products using mature technology and could become available at sufficient scale. However, all are inherently less efficient to convert into useful end-products and less versatile compared to crude oil.

Feedstock transition from fossil carbon to sustainable carbon sources



Scope

Today, roughly 200 megatons of crude oil (equivalent, incl. naphtha, natural gas, coal)[2] pass through the HIC every year, of which ~150 megaton is transshipped and used in other locations (out of scope for this study). The remaining 50 megaton of crude oil is processed in the cluster (focus of this study) to produce fuels, Naphtha and base chemicals such as olefins and aromatics. The base chemicals are further used to produce downstream chemicals (e.g. glycols, benzaldehyde) which are out of scope for this study. Our analysis is based on the basic assumption to maintain HIC Rotterdam current production output of fuels and base chemicals and to replace ~50 megaton of crude oil equivalent per annum. Major shifts in demand for fuels and chemicals are expected in the future but are beyond the scope of the study. For example, electrification of transport will have a substantial impact on the demand for road fuels such as gasoline and diesel, which will decline in the next decade.

Methodology

This study identifies the key sustainable feedstocks and the quantities that are available and can be processed in the cluster for each feedstock. An initial top-down perspective was created supported with in-depth analysis of bottom-up process flows for the largest companies including Neste, Shell, BP, ExxonMobil, Lyondellbasell, Vopak, VTTI, EVOS, ShinEtsu and Lanxess and further substantiated through interviews with these companies and experts active on this topic such as AVR, GidaraEnergy, Huntsman, Gert Jan Kramer and Coby van der Linden.

To assess the potential future feedstock mix, each feedstock has been evaluated along three key dimensions:

- **Compatibility:** feasibility to implement, based on 1) supply chain maturity and 2) compatibility with fuels and chemicals value chain infrastructure and assets.
- **Feedstock availability:** potential to scale up, based on current and long-term feedstock availability.
- **Space, energy and hydrogen requirements:** required space, energy (heat and power) and hydrogen (feedstock) for processing sustainable feedstocks into useful end products compared to crude oil.

A realistic share of each feedstock in a potential future feedstock mix is estimated along with short term actions for developing feedstock value chains. Finally, a roadmap of actions for different stakeholders is identified for achieving speed and momentum for the sustainable feedstock mix in HIC Rotterdam.

1 — The main products of the HIC, and particularly its petrochemicals cluster, are plastics, chemicals and refined fuels for road transport, shipping and aviation.
2 — Source: Facts & Figures on the Rotterdam Energy Port and Petrochemical Cluster.

Executive summary

Feedstocks

The feedstock transition at the HIC is still in its early stages. Many challenges need to be overcome before crude oil can be replaced by sustainable feedstocks. The large-scale use of sustainable carbon-based feedstocks is difficult to implement cost competitively. The current share of sustainable feedstock represents less than 10% of total feedstock flows, and no clear picture of the target feedstock mix exists yet for the HIC Rotterdam. Feedstock availability may be limited in the future. Preparations therefore need to start early to secure feedstocks and to retain a vital industry in a globally competitive market during the transition.

Four main sustainable feedstock pathways are expected to shape the future fuels/chemicals value chains:

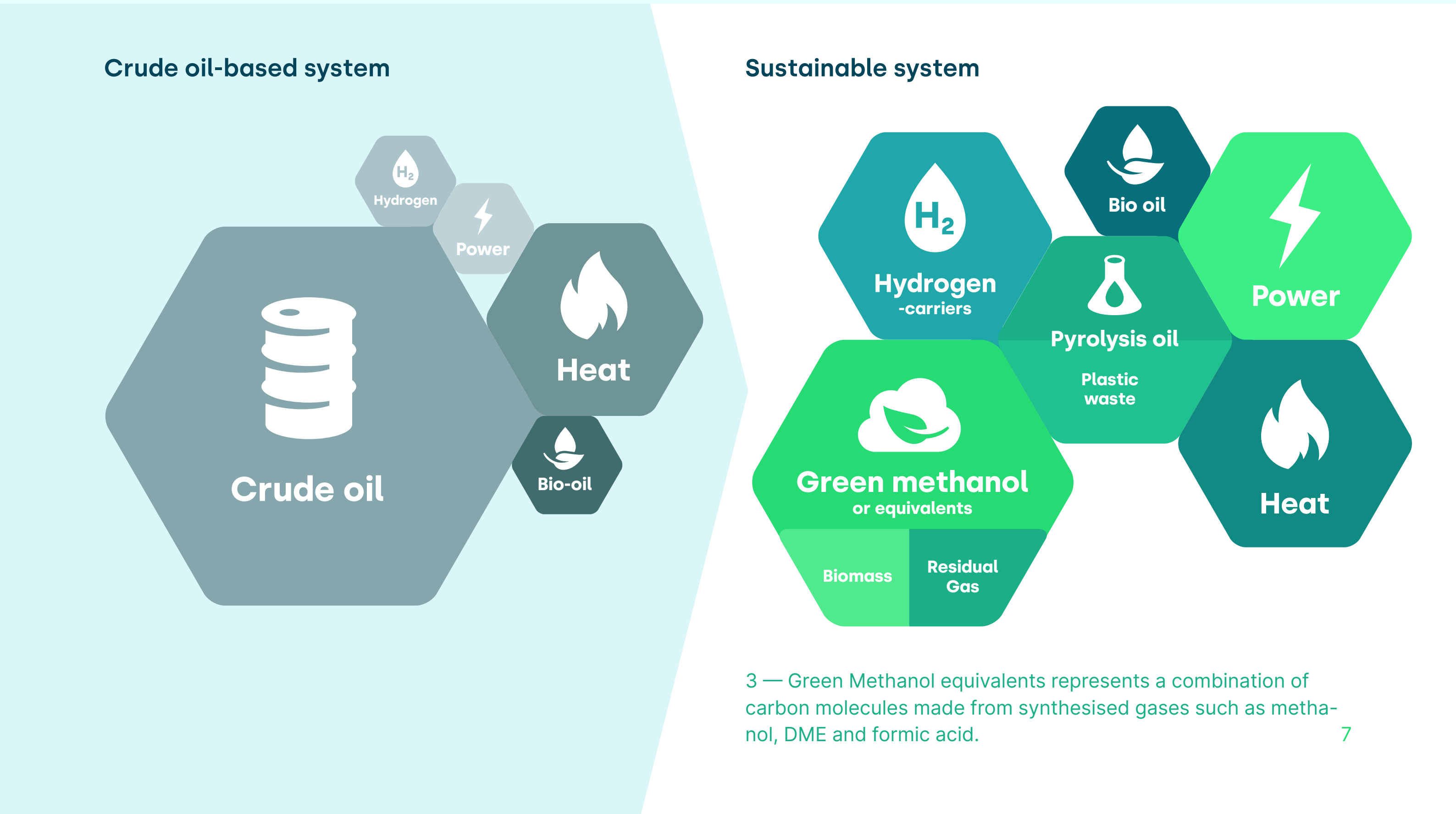
- Bio oils, imported or produced locally from e.g. residual vegetable oil, animal fat or used cooking oil (UCO);
- Pyrolysis oil, imported or produced locally from plastic waste;
- Green methanol$_{eq}$[3], imported or produced locally from hydrogen and biomass or residual gas; and
- Hydrogen (or hydrogen carriers), as a key enabler for processing sustainable carbon feedstocks.

Compatibility

Liquids (bio/pyrolysis oils) are easiest to implement, while solids (waste, biomass) and green methanol$_{eq}$ require major changes to the existing supply chain infrastructure and asset base.

- Bio oils and pyrolysis oils are more compatible with existing fuels and chemicals infrastructure and assets, and require the least amount of space and energy.
- Solid feedstocks (plastic waste, biomass, etc.), require the development of new supply chains, along with more energy and space. They could be pre-processed elsewhere and imported as liquids instead.
- Residual gases, though already available in large quantities in the HIC, will need large amounts of hydrogen and new processing assets for conversion to fuels and chemicals
- Green methanol$_{eq}$[3] has a relatively low conversion efficiency compared to other feedstocks and requires major changes to replace naphtha in chemicals production. As an advantage, methanol is a proven raw material and fuel.

Feedstock mix transformation from a crude oil-based system to a sustainable energy and feedstock system



3 — Green Methanol equivalents represents a combination of carbon molecules made from synthesised gases such as methanol, DME and formic acid.

Availability

Bio oils and pyrolysis oil may have limited availability in the long term. Eventually, there may not be enough sustainable carbon feedstocks available to fully replace the large amount of fossil-based carbon we use today. Ultimately, green $methanol_{eq}$ produced from green hydrogen and biogenic CO_2, or from atmospheric carbon sources by using direct air capture (DAC), could contribute to solving this challenge. This will take substantial time and technology and cost breakthroughs. Based on our analysis of availability of sustainable feedstocks, we have identified their potential for replacing crude oil as follows:

- Bio oils and pyrolysis oil could potentially replace up to 20%.
- Residual gases could potentially replace up to 10%.
- Solid biomass and plastic waste could potentially replace up to 20%.
- In the long term, in order to fully replace crude oil, up to 50% of the balance will need to come from additional sources. Green $methanol_{eq}$ could potentially fill this gap.

Space requirements

The lower energy densities and conversion efficiencies of sustainable feedstocks compared to crude oil create the need for higher storage and throughput volumes. Depending on the ultimate feedstock mix, the space required for processing sustainable feedstocks could double or triple compared to the current infrastructure for crude oil. Land constraints will therefore be a dominant limitation in the feedstock transition, as space is already scarce in the HIC.

Energy and hydrogen feedstock requirements

Energy requirements in the form of heat and electricity and hydrogen feedstock could also be multiple fold higher for processing sustainable feedstock than for crude oil processing. Most sustainable feedstocks such as bio oils, residual gases, waste, CO_2 require significantly more hydrotreatment and energy than crude oil. Depending on the ultimate feedstock mix, the use of hydrogen feedstock may shoot up to 10 times and the use of energy could go up 2–3 times from the current requirements for processing crude. Subsequently, the energy infrastructure required for the feedstock transition is expected to be significantly more than currently planned for the energy transition.

Action plan

Actions can be started across all feedstocks today, optimized in an overarching vision and masterplan for HIC Rotterdam. Firstly, sustainable carbon feedstocks can already be secured (and prioritized for the hardest-to-abate products). Secondly, a feedstock- and energy transition masterplan should maximize economic viability through site integration synergies and opportunities to build world-scale assets. Thirdly, expanding the energy infrastructure to increase baseload supply is likely a no regret in any scenario.

Introduction

1

Net-zero CO_2 ambition

The HIC Rotterdam is one of the largest fuels and chemicals clusters in the world. It processes ~50 megatons of crude oil per year into fuels and chemical products, which are then transported around the world. In line with the Paris Climate Agreement, the Port of Rotterdam (POR) has set the ambition to reach net-zero CO_2 emissions by 2050. This requires realizing an energy and feedstock transition to replace fossil-based fuels and feedstocks with sustainable alternatives.

The energy transition at the HIC has gained momentum, and plans are being executed to achieve emissions reduction targets (e.g. energy supply and infrastructure for renewable electricity, green hydrogen, carbon capture, etc.). Strong policies, mandates and subsidy support are available to achieve these climate targets. Recent energy security concerns have further increased the urgency to reduce dependency on fossil fuels and move towards sustainable alternatives.

Scope of the challenge

The transition from crude oil to more sustainable feedstocks will be an extensive process. It involves transforming the fuels and chemicals value chain and the interconnected system of large-scale assets that has been built over the past century. This feedstock transition is still in its early stages, and many challenges need to be overcome before this can be achieved. For one, sustainable alternatives are less efficient to convert to useful end-products. They also require more energy and space, along with major new investments in supply chain infrastructures and assets. The regulatory and legislative framework to support investments and business cases is still emerging. For example, no ETS system, scope 3 targets or taxonomy for circular feedstocks yet exist. Existing mandates currently prioritize the available sustainable carbon feedstocks for use in low-carbon fuels instead of in products with a longer life cycle, such as plastics where there are no definite mandates. Ultimately, if the current trend continues, there will likely be strong global competition for securing sustainable carbon feedstock to replace all the crude oil we use today. Securing access to scarce green carbon molecules will be vital.

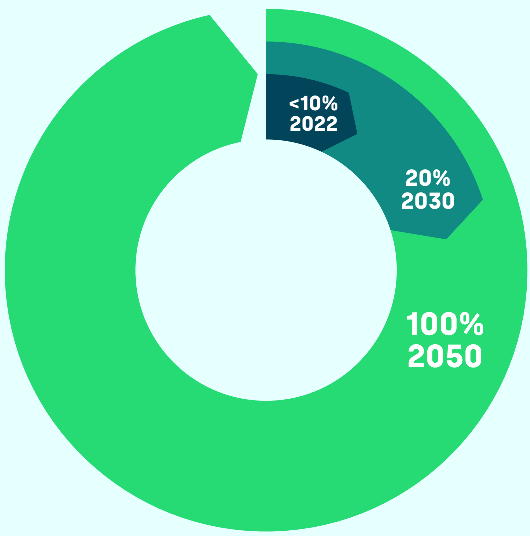
Preparations and roadmap

Companies in the HIC Rotterdam are aware of the opportunities and risks of being a front-runner in the feedstock transition. Some companies are taking initial steps and are starting to integrate new/sustainable feedstocks in their processes. Although the required technology largely exists, it is currently mostly deployed at relatively small scale. The share of sustainable feedstock today represents less than 10% of total feedstock flows[4] in the HIC Rotterdam. There is not yet a clear picture of the target feedstock mix nor the speed at which we want (and need) to achieve it.

Preparations must start early and new coalitions need to be formed to establish the new sustainable value chains. This paper is intended as a starting point for further action and to inform the key choices to be made regarding:

- the target ambition level and the speed at which we want to achieve it;
- which sustainable feedstocks to prioritize and for which applications;
- what to do locally in the HIC Rotterdam and what to import from other locations;
- how to fit it all given space and energy system constraints; and
- how to retain a vital industry in a global competitive market during the transition.

Targets for achieving sustainable feedstock mix for HIC



4 — Currently production includes ~2.3 mtpa biofuels from Neste, Vittera and Alco Energy. Announced projects from Shell and Neste amount to additional ~2 mtpa biofuels. Total of 4.3 mtpa, which is roughly 8% of current capacity.

Sustainable pathways

2

Four sustainable pathways are expected to shape the future feedstock system.

Based on the different bio-based and circular raw materials that are available at relatively large scale and for which mature technology already exists, we have identified four main pathways that are expected to shape the future sustainable feedstock system at the HIC Rotterdam:

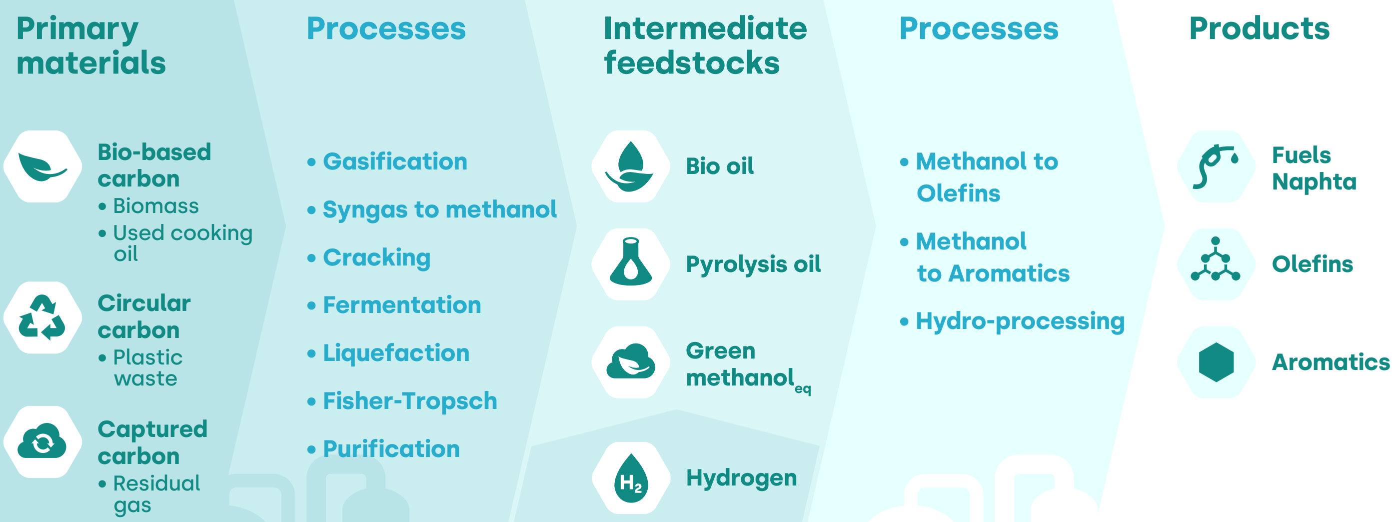
Bio oils
imported or produced locally from e.g. used cooking oil (UCO), residual animal fats or residual vegetable oil

Pyrolysis oil
imported or produced locally from plastic waste

Green methanol$_{eq}$
imported or produced locally from hydrogen and biomass or residual gas

Hydrogen (carriers)
as a key enabler for processing sustainable feedstocks (limited use as a feedstock)

Primary pathways for conversion of feedstocks to base products



Bio oils

are made from second-generation biomass, used cooking oil (UCO), residual vegetable oil, residual animal fats or other biogenic waste streams. They can be processed into biofuels directly or used as co-feed in refineries. These days they can be used in most oil processing installations and are already used to produce biodiesel, SAF and bio-naphtha. Demand for these products is expected to grow significantly due to tightening EU regulations and mandates, such as REDII.

Pyrolysis oil

is produced by the slow heating of plastic (waste) material, which is currently incinerated or landfilled. It can be used to replace crude oil as a (circular) co-feed in existing refineries and petrochemical sites. Pyrolysis oil is liquid, making it a highly suitable match for most oil process installations. Converting plastic waste into pyrolysis oil requires significant heat and power. The first projects for producing pyrolysis oil for fuels have been announced, and a cluster is being developed at the HIC Rotterdam. However, pyrolysis oil is expected to be largely imported from other locations where the solid waste is collected and processed into pyrolysis oil. This process requires significant heat, power, space, as well as the sourcing of plastic waste, which is highly decentralized.

Green methanol$_{eq}$

is produced from green hydrogen and biogenic or atmospheric carbon. Gray methanol is already used as a fuel additive and in the production of various fuels and chemicals (e.g. aviation and shipping fuels, MTBE, aromatics and olefins). In addition to its end-use flexibility, green methanol can be synthesized from green hydrogen and multiple carbon feedstocks:

- **Residual gas** is a by-product from industrial processes (CO_2, CO, CH_4, H_2) and is currently used primarily as a combustion fuel (e.g. in process furnaces and steam boilers). Residual gas can be used as a carbon feedstock to produce green methanol instead of as a fuel (for which green hydrogen or electricity can be used). An estimated 5–10 Mtpa is available at the HIC today that could potentially be redeployed. The main source of carbon feedstock at the HIC now comes from crude oil processing, yet this can shift in the future towards green carbon sources with the increased processing of biogenic, circular and captured carbon. To justify the required investments, policy and taxonomy changes must recognize the carbon emission savings.
- **Solid biomass** is 2nd generation material that does not compete with food production and is gasified to produce biogenic syngas. This process requires significant amounts of space, hydrogen and power. Biogenic carbon will ultimately be a limited resource globally.
- **Atmospheric carbon (direct air capture (DAC))** can be captured from the atmosphere and as such is essentially an unlimited resource. DAC technology is still very costly and consumes large amounts of energy and space. Significant cost breakthroughs are required to make it commercially viable.

Hydrogen

from renewable electricity sources will play a key role in decarbonizing the HIC Rotterdam. Green hydrogen and its derivatives (e.g. ammonia) can replace fossil fuels and feedstocks as a source of energy in making selected products, i.e., those that do not contain carbon molecules, such as fertilizers. It is also a key input for converting sustainable carbon feedstocks into useful end products. Whether used to hydro-process bio oil feedstocks or to convert CO_2 into syngas (CO + H_2) for further support in Fisher-Tropsch synthesis or methanol synthesis processes, green hydrogen will be required in large quantities to enable the feedstock transition.

Compatibility

3

While liquids (bio- and pyrolysis oils) are easiest to implement, all new feedstocks will require major changes to the fuels and chemicals value chains.

Asset base requirements

The HIC's current asset base is highly geared towards processing liquid and gaseous hydrocarbons. The cluster's existing distillation and separation columns, gas treatment equipment, gas and liquid heat exchangers, pumps and compressors are most compatible with sustainable feedstocks that have similar physical and chemical properties. In comparison, solid feedstocks – especially biomass – are much less compatible with the current fuels and chemicals value chains and require much higher investments in infrastructure and pre-processing assets.

The extent of asset transformation needed for sites focused on producing fuels may be very different from that for sites which mainly produce chemicals. For example, fuel production sites might choose to focus on maximizing their existing hydrotreatment assets to upgrade sustainable feedstock, while chemical sites may opt for upstream integration in sourcing naphtha-like feedstocks so that they can continue using their downstream infrastructure (perhaps including their cracker infrastructure). The compatibilities of the different feedstocks with the existing assets are described below.

Connecting the feedstocks and the supporting energy flows with the processing assets will require a transformation of the infrastructure as well. The current fossil-focused infrastructure and integrated fuels and petrochemicals set-up will shift to multiple sustainable carbon feedstocks that will be imported on a large scale. This requires major investments in new supply chain infrastructure to be able to import, store and distribute different liquid and gaseous fuels and feedstocks.

Feedstock compatibilities

Each feedstock will have their own specific fit within the respective fuels and chemicals value chains:

- Refining will need a mix of low-carbon (hydrogen-based) feedstocks for processing industry and road transport, as well as sustainable carbon-based feedstocks that be converted into fuels suitable for shipping and aviation.
- Chemicals can include sustainable and circular carbon pathways that are able to produce pure base chemicals such as olefins and aromatics.

Therefore, these value chains are expected to focus on different pathways and have their own timelines. This may ultimately lead to the decoupling of refining and chemicals activities.

Bio oils and pyrolysis oil

can be implemented relatively easily with the existing refinery assets and infrastructure. Some, such as vegetable oils, are already co-processed in hydrotreating and -cracking units in some of the HIC refineries. These feedstocks are highly compatible with the current refinery asset base, and securing them at large scale should therefore be prioritized. Chemical plants, however, will require additional hydrotreating units to pre-process these feedstocks, limiting direct compatibility with this value chain.

Plastic waste and biomass

are solid feedstocks and require significant investments in pre-processing units that produce high(er) energy-density liquid intermediate feedstocks before they can be converted into useful end products. For plastic waste, there are synergies with existing waste handling companies, and the required investments across the fuels and chemicals value chain are expected to be modest. Biomass, on the other hand, will require much higher investments in pre-processing. Removing the water content and other impurities (e.g. oxygenates) from biomass will involve gasifiers and liquefaction- and/or fermentation units.

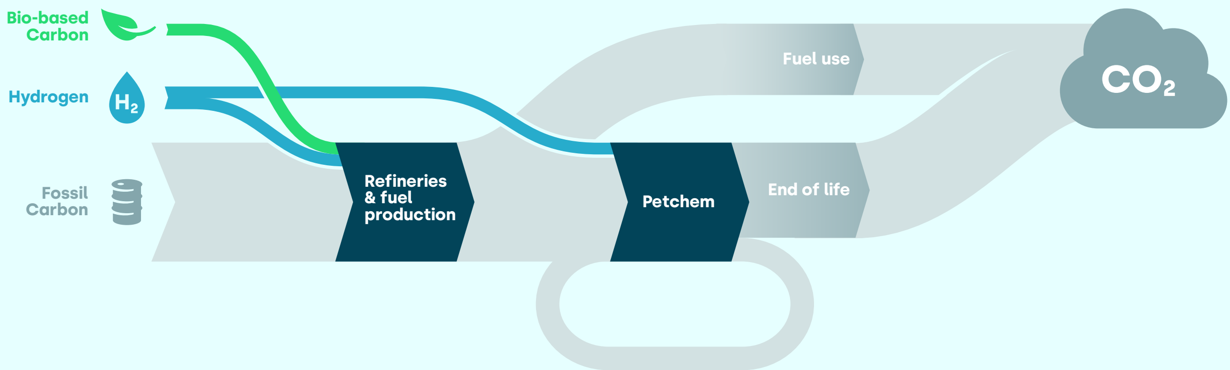
Residual gases

are by-products of existing industrial processes in the HIC and need to be converted to useful syngas before they can be used as a feedstock. This requires substantial investments and new asset and conversion infrastructure, particularly when the energy content in these gases is very low. Higher CO_2 content requires more hydrogen-intensive conversions to convert it into syngas (CO plus H_2). This needs to be followed by Fisher-Tropsch or methanol synthesis units to convert the syngas into carbon products that meet the requirement of having an energy density comparable to that of crude oil. In addition, if residual gas is to be used as a feedstock source, investments will be needed to switch the fuel supply (from residual gas to e.g. hydrogen or electricity).

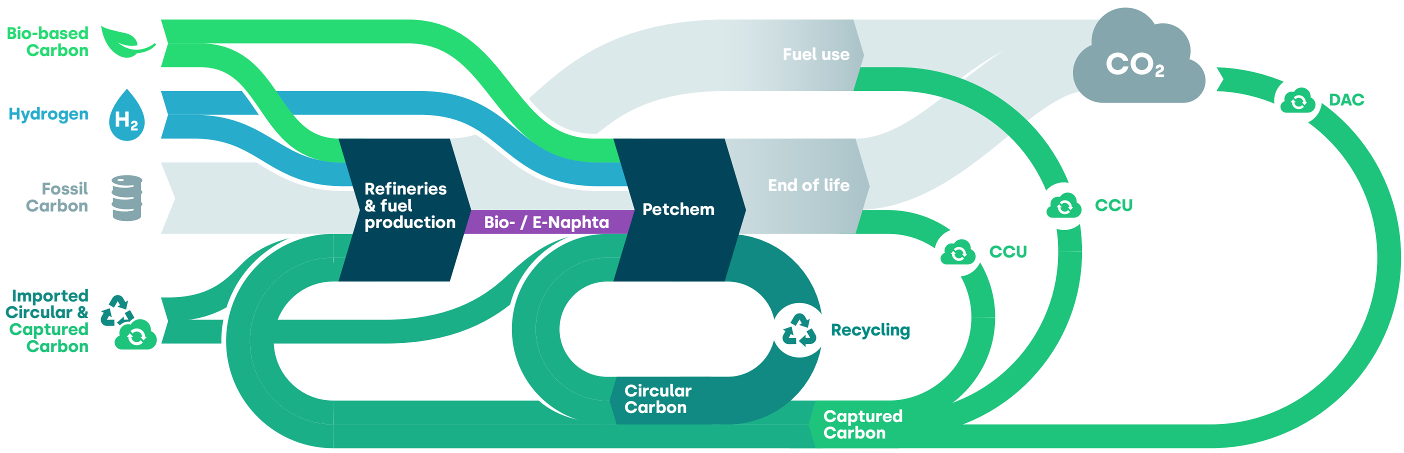
Green methanol$_{eq}$

and its derivatives lie somewhere in between the solids and the other liquid feedstocks in terms of asset compatibility. It shares the benefits of bio oils and pyrolysis oil in being a liquid feedstock, which is an advantage in terms of storage, transport and general product handling. Its main challenge, however, lies in the fact that methanol-to-product conversion requires specific chemistry, making it significantly different than the refining of crude oil and also limiting its compatibility with traditional refining units. However, for specific chemical products, methanol can offer unique flexibility: once the methanol has been converted in e.g., olefins and aromatics, downstream chemical units–which already use these molecules as a feedstock–can still be used.

Today's (fossil) system



Future sustainable system



Size of the flows are not representative of actual flows

Availability

4

Bio oils, plastic waste and pyrolysis oil may have limited availability in the long term; green methanol$_{eq}$ will ultimately be required on a large scale.

Future constraints

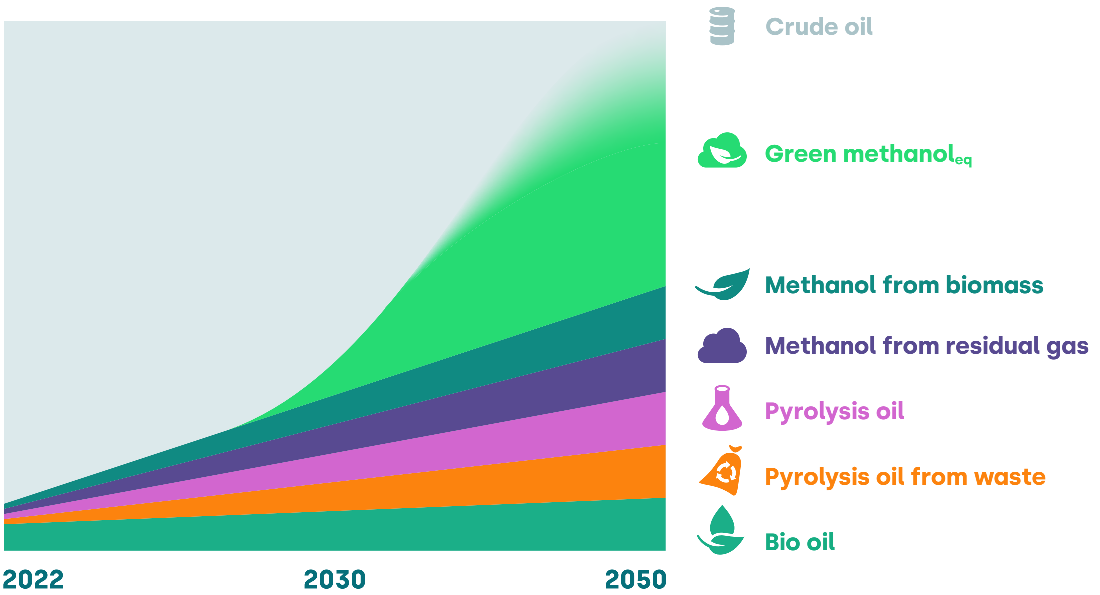
Increasing demand in many sectors (food, construction materials, energy, chemicals, etc.) is placing significant pressure on the future of the world's sustainable resources. In the long term, there may not be enough sustainable carbon feedstocks available to fully replace the large amount of fossil-based carbon we use today.

Current prioritization

Sustainable carbon feedstocks which are closest to crude oil composition and which can be sourced to the HIC Rotterdam in short term must be prioritized, i.e., bio oils, pyrolysis oil and residual gases. Ultimately, green methanol$_{eq}$ (which is produced from green hydrogen), together with biogenic or atmospheric (i.e., direct air capture, or DAC) carbon sources, could contribute to solving this challenge. However, it will still take quite some time before green hydrogen is available at a large scale, and DAC technology is still very costly and requires large amounts of energy and space.

A potential ramp up of sustainable feedstock mix[5]

As crude oil equivalent (COE)



5 — Excludes non-carbon feedstock sources, such as hydrogen.

Bio oils

Bio oils could potentially replace up to 20% of current demand for crude oil at the HIC:

— Currently, 5%–10% of feedstocks can be considered sustainable or are expected to become sustainable based on publicly announced plans, which are mainly based on bio oils and pyrolysis oil.

— The further upscaling of bio oils is expected to add a maximum of 5%–10% above current levels, due to the limited availability of suitable raw materials.[6]

Pyrolysis oil and plastic waste

Pyrolysis oil and plastic waste could be processed into liquid feedstocks, potentially replacing 10% to 20% of current demand for crude oil at the HIC:

— Solid materials require significant extra space and energy to convert into useable feedstocks and would require a major expansion of the HIC Rotterdam or a reduction in production output.

— The vast majority of chemicals and plastics produced at HIC Rotterdam are exported globally. As a result, demand for plastic waste also far outweighs what is available in the local region.

Green methanol$_{eq}$

Substantial volumes of green methanol$_{eq}$ will potentially be required to fully replace crude oil. The green methanol$_{eq}$ can be obtained from three primary sources:

1. Residual gases

— Residual gases are expected to contribute a maximum of 5%–10% to the feedstock mix, given that these are by-products from other processes and are therefore inherently limited in supply.

— Residual gases are expected to have a lower carbon footprint over time and evolve from being gray to becoming blue and then green (as industrial processes change from using crude oil, natural gas, etc. to using carbon capture, green electricity, green hydrogen and sustainable carbons).

2. Biomass

— Production of methanol from biomass (from second generation biomass or bio-waste) is already planned for deployment in HIC Rotterdam.

— Biomass feedstock is estimated to contribute ~10% to the feedstock mix. Handling, storage and processing of biomass requires more space than liquid feedstocks.

3. Green methanol imports

— Depending on the demand evolution for carbon based feedstocks, a balance of up to 50% of green methanol$_{eq}$ would be required to serve as a gap filler to fully replace crude oil. Currently, green methanol$_{eq}$ is not yet available on a large enough scale, nor is it economically attractive.

— Large quantities of green methanol$_{eq}$ will likely need to be imported and are expected to come from locations where green hydrogen is cheapest and biogenic CO/CO_2 is available. This can take many years to develop; as such, large scale green methanol$_{eq}$ can only be considered as a scalable solution in the long term.

6 — CE Delft (2020). *Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa* (link).

Space requirements

5

Space will be a dominant constraint in the transition, as sustainable feedstocks require much more space, and this is already scarce at the HIC.

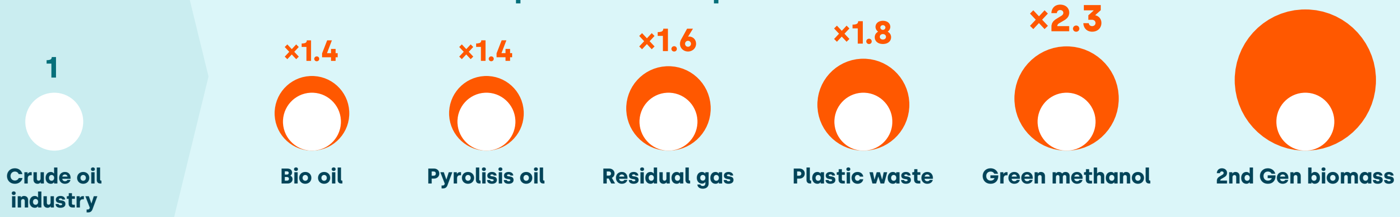
Long-term constraints

After 2030, space constraints will become a dominant limitation to realizing the feedstock transition. The HIC Rotterdam is a large industrial area of closely interconnected assets and companies, with very limited space for expansion.[7] Currently, the fuels and chemicals cluster occupies 1,100 hectares within the HIC Rotterdam (around one-third of the total). Depending on the ultimate feedstock mix, more than double the space could be required to fully replace crude oil with sustainable alternatives. The 1,100 hectares of fuels and base chemical cluster space in Rotterdam can accommodate 35%–55% of current products outputs when chosen to be done by a potential feedstock mix described earlier in the availability section. Hence, the current space would require a decline of 20–30 mtpa of product output which may come from future decline in fuels demand.

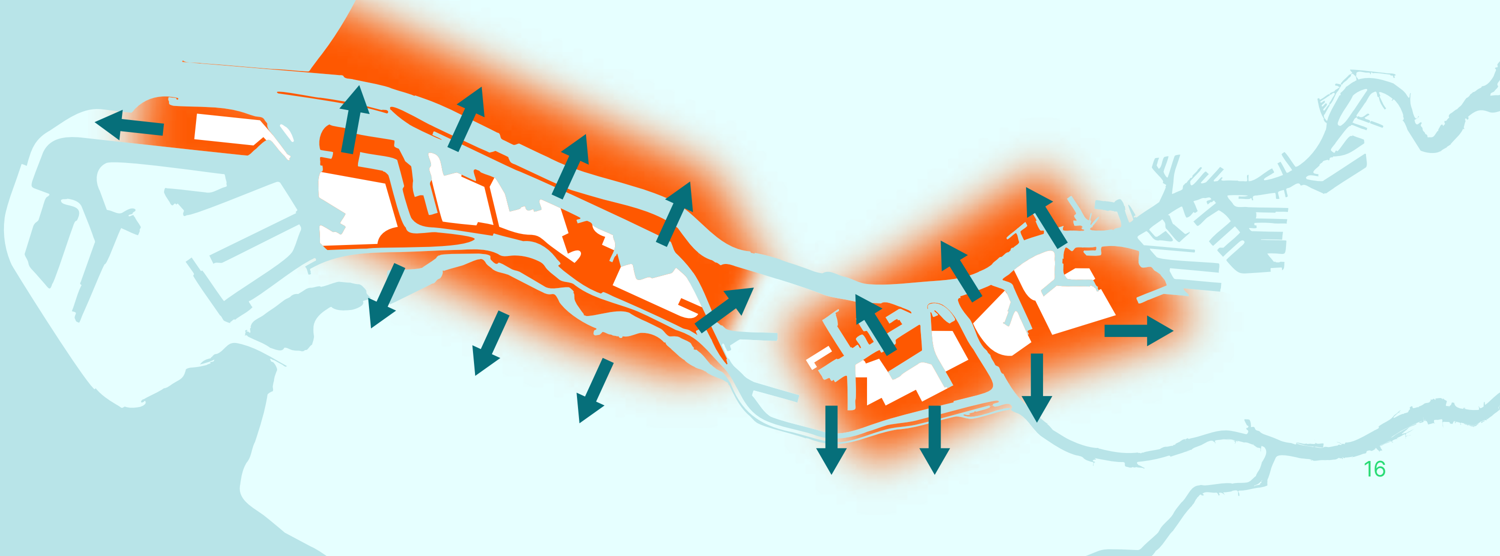
Careful choices

Conscious choices need to be made as to which feedstocks, at what scale and which processing steps should be prioritized at the HIC Rotterdam. Solids such as biomass, wastes and plastics require much more space for storage and processing. In terms of scale, building one large unit is more space efficient than building several smaller units.

All sustainable feedstocks require more space



Fully sustainable fuels cluster with available feedstocks will require 2-3x space



Imports and storage

Significantly more amounts in mass and volume will be imported as sustainable feedstocks are less energy dense and have lower conversion efficiency compared to crude oil. More tons of sustainable feedstock therefore needs to be stored and distributed (e.g., through pipelines) to produce the same end-product output compared to crude oil.

- More than double the amount of sustainable feedstocks quantities could be required depending on the ultimate feedstock mix.
- Storage and pipeline capacity will need to increase substantially along the value chain to accommodate the larger volume flows to achieve the same end-product output.

Space

Sustainable feedstocks also require additional conversion steps.

- Liquid feedstocks are preferred over solid waste and biomass, as the former require far less space for storage and conversion steps.
- Bio oils and pyrolysis oil require ca. 40% more space than crude oil, whereas green methanol$_{eq}$ requires more than double the space.
- To save space and energy, solid biomass and plastic waste can be collected in locations elsewhere and preprocessed into higher value intermediate feedstocks that can then be used at the HIC Rotterdam.

7 — CIEP & SmartPort (2021). The energy and feedstock transition in the Port of Rotterdam Industrial Cluster.

Energy and hydrogen feedstock requirements

6

The need for hydrogen feedstock, power & heat could double or triple.

System-wide demand increases

The Dutch energy infrastructure is already congested, and the energy transtion is placing further pressure on the system. The feedstock transition could further excerbate the situation, with energy demand increasing beyond already steep projections. Currently, the HIC Rotterdam consumes ca. 200 PJ of energy per year in the form of electricity, heat/steam and hydrogen to process 50 Mtons of crude. Processing sustainable feedstocks requires even much more energy; the HIC Rotterdam's energy demand could double or even triple depending on the ultimate feedstock mix.[8]

Climate neutral power and heat

Currently, circa 4.3 GW of electricity and heat is used in the Port of Rotterdam. To process sustainable feedstocks, the demand for electricity and heat could increase by a factor of 2 to 3, depending on the ultimate feedstock mix.

— To be processed, all sustainable feedstocks require *more (green) electricity* than crude oil. Bio oils, pyrolysis oil and green methanol$_{eq}$ require 6 to 7 times more, plastic waste circa 14 times more, and residual gas and biomass more than 30 times more.

— However, less heat is required to process most sustainable feedstocks, with the exception of green methanol$_{eq}$, which requires circa 3 times more compared to crude oil. Residual gases, bio oils and pyrolysis oil need 50% to 90% less heat, as the processing of biomass generates heat in itself.

Climate neutral hydrogen

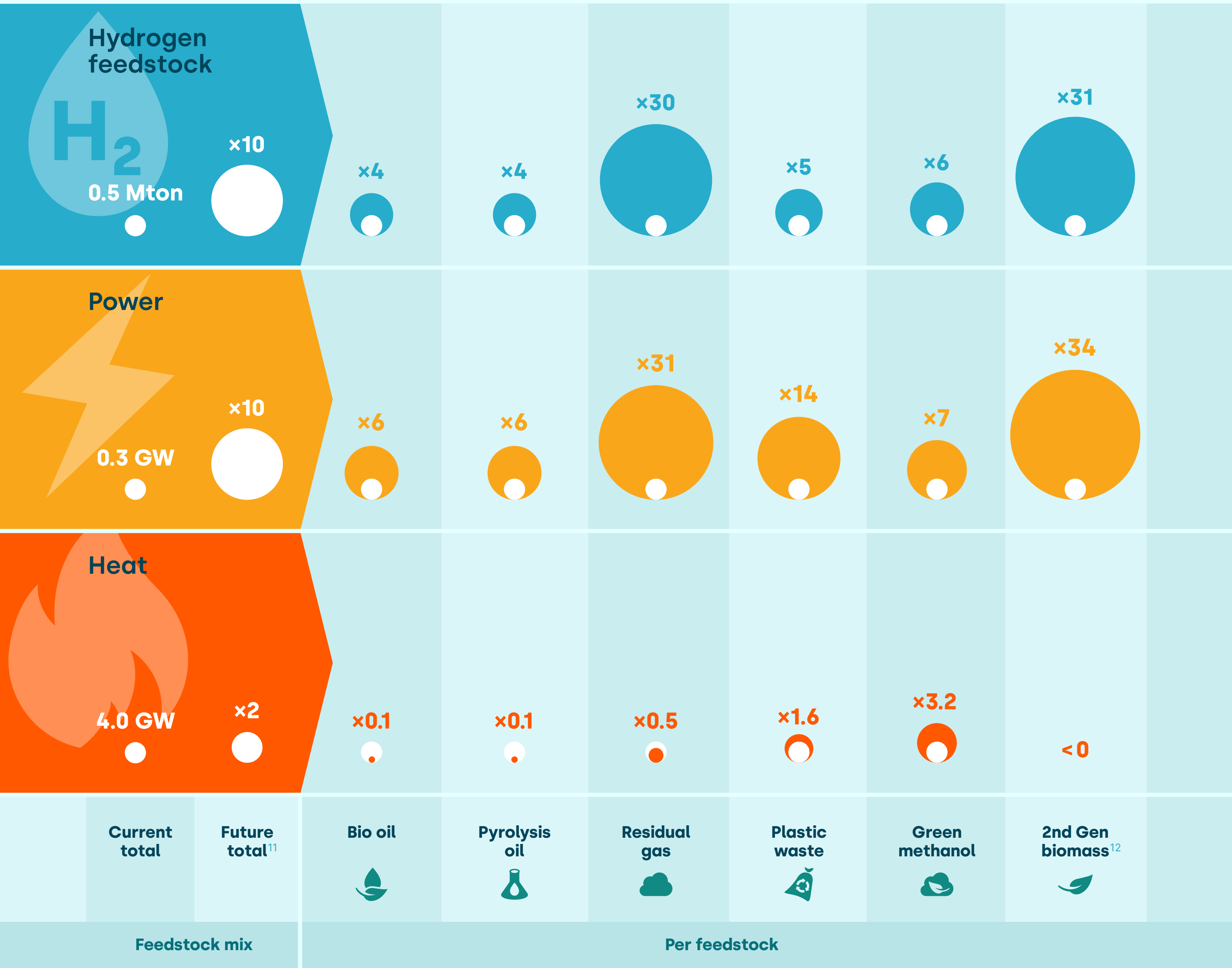
Currently, 0.4 to 0.6 Mtons of hydrogen (currently mostly gray) is used at the Port of Rotterdam each year in fuels and chemicals production.[9,10] Processing sustainable feedstocks into useful end products requires much more hydrogen than crude oil does (in addition to the hydrogen needed for the energy transtion). Residual gases and biomass require ~30 times more hydrogen, bio oils, pyrolysis oils and green methanol$_{eq}$ 4 to 6 times more, and plastic waste ~2 times more. Initial indicative estimates suggest that projected hydrogen requirements for the feedstock transition could be in line with what the Port of Rotterdam is currently targeting (~4 Mtons of hydrogen usage for local fuels production in 2050).[8]

Energy infrastructure

The seemingly ambitious targets now in place for green hydrogen imports and renewable electricity from offshore wind may still not be sufficient for the full requirements of the feedstock transition. Plans to expand the energy infrastructure to transport additional gigawatts of green electrons, hydrogen and heat may fall short of what is required. Energy supply and grid expansion plans therefore need to be critically reviewed and potentially be upgraded to avoid incremental improvements where large step changes are needed.

8 — Power2x analysis on requirements per feedstock compared to crude, based on data based on TNO (link 1 & 2), TNO & PBL (link) IRENA (link), Neste (link), Zhao (link)
9 — Port of Rotterdam Hydrogen vision 2020 (link)
10 — The Dutch hydrogen balance, and the current and future representation of hydrogen in the energy statistics 2020 (link)

Future hydrogen feedstock and energy requirements



11 — Based on weighted average of expected feedstock mix shown on page 12 multiplied by individual feedstock requirements on this page

12 — Biomass conversion to products results in net heat release and thus less than 0

Roadmap and actions

7

Actions can be taken across all sustainable pathways and optimized in an integral masterplan for the HIC Rotterdam

All sustainable feedstock pathways will play a role in the future feedstock mix of the HIC Rotterdam and there are actions which we can start today:

— Set ambitions and 2030 targets to start building speed and momentum (supported with policies and incentives to ensure resilience and competitiveness)

— Develop masterplan for fuels and chemicals value chains, integrating mass and energy flows, conversion and repurposing of sites and building world-scale assets (not everything will fit if current 50 Mtpa of output is to be maintained)

— Start securing sustainable carbon feedstocks at large scale across the globe to ensure competitive and secure supply (incl. from locations with GW-scale green hydrogen export plans)

— Invest in new energy and feedstock infrastructure which are considered no-regrets in any scenario (e.g. for power, heat, CO_2, hydrogen, and new product flows)

Per pathway, several no-regret opportunities have emerged on which action can and should be taken today in order to be able to meet the HIC's net-zero goal for 2050:

Bio oil

Secure bio oil sources (such as UCO) from regional waste collecting companies and imported from abroad to achieve economies of scale.

Pyrolysis oil

Stop exports of plastic waste and aggregate pyrolysis oil from regional processing centers.

Green methanol$_{eq}$

Re-route existing residual gas streams to produce low carbon methanol$_{eq}$, develop plans for large scale imports and integrate 2nd generation feedstocks in existing assets (e.g. biomass in gasifiers).

Hydrogen (carriers)

Increase its usage as it is a key enabler for processing sustainable carbon feedstocks.

Actions can be taken now on all stakeholder levels

NL and EU

- Setting the **ambition and targets** for the feedstock transition
- Ensuring green carbon **supply security** and **resilience**
- Maintaining **competitive industries** during the transition
- **Policy and incentives** for new assets and infrastructure

Value chains/ Company

- Maximizing use of **sustainable carbon for materials** not fuels
- Redefining **global supply chains** from off-take to sourcing
- Establishing **new (technology) partnerships**
- Securing competitive **sustainable carbon** at large scale early

HIC Rotterdam

- Developing the **masterplan** to optimize value per hectare
- Estimating **energy and feedstock infrastructure** needs
- Building large scale and global **access to scarce feedstocks**
- Enabling coalitions to **accelerate** new value chain **projects**

Site

- Building **world-scale assets** for optimal capex efficiency
- Creating **feedstock/product optionality** (grey, blue, green)
- Maximizing **integration with nearby sites** and infrastructure
- Freeing up space, co-siting with **new technology partners**

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Power2X is a project developer and consultant for industrial energy transition, specialized in realizing next generation energy assets and infrastructures at industrial scales. Together with industry-leading partners around the globe, we advise companies and develop and invest in new energy projects.

Deltalinqs

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Deltalinqs promotes the common interests of over 95% of all logistics, port and industrial enterprises in the harbor and industrial cluster (HIC) Rotterdam. As a whole, the HIC accounts for 8.2% of the Dutch gross national product and provides work to over 565,000 people, either directly or indirectly. This feedstock mix study is a key pillar in the Deltalinqs Climate Program.

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