Exploration of Transition Strategies in Dutch Refineries and Organic Chemicals Industry for Climate Policy

TNO Public ⟩ TNO 2024 R11075
9 September 2024

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TNO 2024 R11075 – 9 September 2024

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Refineries and the large volume organic chemicals industry

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Classification report	TNO Public
Number of pages	78 (excl. front and back cover)
Number of appendices	4
Project name	KVE 23 Industrie weglekeffecten
Project number	060.55401

This project has been funded as part of the Energy Transition Studies research program under the directorate general Energy and Climate of the Ministry of Economic Affairs and Climate (EZK) (with the new name Ministry of Climate and Green Growth) with the aim of providing knowledge for energy policy.

Summary

The heavy industry sector, particularly the petrochemical industry, relies on fossil fuels for a variety of processes, both energy and non-energy applications. Non-energy fossil fuel use refers to raw materials derived from fossil fuels, such as naphtha and other feedstocks that are essential for manufacturing processes, accounting for nearly 50% of the total energy use in industry. In alignment with combating climate change and meeting the objectives of the Paris Agreement, the Dutch government has set the national ambition to become climate-neutral by 2050. Additionally, the Dutch government expressed its aspiration for the country to become fossil free and circular by 2050. Achieving these goals will require substantial changes in industrial processes that currently depend on fossil fuels.

This study aims to support the Ministry of Climate and Green Growth[1] of the Netherlands and serve as a starting point for broader discussions on future developments within the heavy industry sector. It focuses on the significant changes required in industrial processes to become climate-neutral by 2050. Thus, this study assumes a scenario in which the ambition to reach carbon neutrality by 2050 will be reflected globally in national policies. The study focuses on the refineries and the large volume organic (LVO) chemicals industries. Another study has been conducted for the iron and steel industry and the fertilizer industry, with the results of that study reported separately.

This research employs a desk-study approach, utilising both qualitative and quantitative assessments of possible industry retrofits and the demand for renewable resources. This was supplemented by scenario modelling to project the industry's transformation within the framework of a carbon-neutral energy system. The study also considers the potential risks of value chain relocation to other regions where renewable resources are more abundant and cost-effective. However, it excluded an analysis of carbon leakage issues and the broader competitiveness of the industrial sectors. Possible environmental impacts or effects on human capital of both adaptation strategies and the relocation risks were also beyond the scope of this analysis. Instead, the focus was on the availability of renewable feedstocks necessary for the sector's transformation.

A brief overview of the results for the refineries and LVO chemical industries can be found below. A more detailed summary of these findings is presented in the subsequent sections.

Refineries
Dutch refineries, which contribute significantly to European capacity and production, are likely to face significant challenges in the transition towards climate neutrality by 2050. Future scenarios involving climate policy implementation project a significant reduction in demand for fossil fuels, which could lead to downsizing or conversion of existing facilities, but much will depend on key factors such as the development of renewable fuels, geopolitical dynamics, and the industry's ability to adapt to shifting market conditions.

The review of company plans indicates that while Dutch refineries acknowledge the need for long-term transitions towards renewable fuel production, their efforts have been limited and reactive, driven more by current market conditions. This underscores the need for a more

[1] Previously, this ministry was named Ministry of Economic Affairs and Climate Policy

robust and forward-looking approach to ensure the successful transition of the refining sector.

The adaptation strategies for refineries involve the integration of additional steps in the value chains, with biomass co-processing emerging as a transitional solution. This approach could help refineries gradually shift towards producing renewable fuels. While the potential for biomass as a sustainable feedstock appears sufficient, the mobilisation of these resources and the establishment of tradable bio-oil commodities that are produced from various types of biomass feedstocks has been lagging. This lag presents a challenge to the transition of refineries.

Another challenge relates to the limited research on the effectiveness of co-hydrotreatment of bio-oil with petroleum streams. This knowledge gap hinders the development of comprehensive retrofit strategies and the efficient use of existing refinery infrastructure. Therefore, further research is needed to explore the potential of these technologies and their implications for refinery operations.

Despite the challenges associated with retrofitting existing refineries, there is significant strategic value in developing fully integrated biomass-to-fuel refineries in the Netherlands. These refineries could not only support the country's transition to a carbon-neutral energy system but also provide essential biogenic products, such as naphtha for the chemical industry and biogenic CO2 for negative emissions or synthetic fuel production.

In summary, the future of Dutch refineries lies in their ability to adapt to a rapidly changing energy landscape. While the risk of relocating existing refineries diminishes, the need for strategic adaptation and addressing potential bottlenecks becomes increasingly critical.

Large volume organic(LVO) chemicals
The Netherlands is a key player in the European organic chemical industry, strategically positioned within the Antwerp-Rotterdam-Rhine-Ruhr-Area (ARRRA).

The industry is navigating a complex regulatory environment where current EU policies aim to reduce emissions but do not explicitly mandate a transition to circular feedstocks, leaving uncertainties about how to shift from fossil to renewable feedstocks. Consequently, current company strategies focus on reducing direct greenhouse gas emissions and exploring electrification, with slow progress on renewable feedstocks. While plastic pyrolysis is a promising alternative and explored more by the companies, its expansion is uncertain due to potential limitations on plastic waste.

The LVO chemical sector is closely intertwined with the refinery sector, and any transformation in the latter is expected to influence this industry significantly. Transformations in refineries, particularly if they produce bio- and synthetic naphtha in significant quantities, would create a renewable naphtha market and reduce possible relocation risks in these industries. However, the oil refineries also produce aromatics. The downsizing of oil refineries could create the risk that the production of aromatics from these processes may shift elsewhere.

The relocation risk mainly relates to new processes, like bioethylene production from bioethanol, as they may be located in regions with abundant biomass. Current leading bioethylene production is in countries like Brazil, India, China, and the USA. Similarly, methanol-to-olefins and biomass-to-aromatics production may also be situated in resource-rich areas. Nevertheless, the easy transportation of polymer pellets allows the displacement of semi-finished product supply and the downstream processing plants can continue producing final plastic products in the Netherlands.

Further research needs
Further research is needed to address several key areas, including the suitability of individual refinery sites in the Netherlands for conversion, hydrogen needs and costs to retrofit these sites, the mobilization of biomass resources from other regions and the set up of efficient logistics, and synergies between biomass and renewable power-to-fuel production.

When it comes to the LVO chemicals industry, a thorough techno-economic assessment of polymer pellets production from alternative value chains in various global regions is needed. This will support understanding the future markets for renewable polymer pellets and the role Dutch companies may play, particularly in the downstream processes. In addition, further evaluation of the potential of novel polymers to replace conventional ones, including scalability and market introduction, requires further research.

Refineries

Today, Dutch refineries contribute approximately 6% of the European installed capacity and 10% of the production. Overall, 55% of the production serves the Dutch market and the remaining portion is exported. Within the Dutch manufacturing sector, refineries represent the second-largest greenhouse gas (GHG) emitting industry, after the basic metals industry. The Dutch government has been in the process of establishing tailor-made agreements with refineries to ensure that they reduce their annual operational CO_2 emissions (referred to as scope 1) by 2030 and share their long-term visions.

The refineries will need to adapt to changing market conditions as the demand for oil products is projected to be significantly reduced when stringent climate policies are implemented.
The majority of the refinery products are used as transportation fuels, and the demand for these products will undergo significant changes as a result of the policy instruments within the Fit-for-55 package. While the European Emission Trading Scheme (EU ETS) and the Dutch CO_2 tax aim to reduce GHG emissions that occur during processing, other policies, particularly the transport sector related climate change mitigation policies, will affect the demand for fossil oil products. Consequently, looking beyond 2030, crude oil refineries may need to substantially downsize their throughput or face the risk of shutting down their processes. Achieving Paris Agreement goals and pursuing climate neutrality by 2050 will result in a global oil product demand reduction. This reduction can be up to 75% globally (IEA, 2023), and 90% within the EU (EC, 2018). Given that the majority of the refinery product slate relates to transport fuels, this will require refineries to adapt their business models to align with evolving market conditions.

The refinery adaptation strategies will involve the creation of additional steps in the value chains and biomass co-processing could be a transitional choice.
Depending on the site's complexity, some refineries can retrofit their existing units to produce renewable fuels, and biomass co-processing could be a transitional choice. Bio-oils can be processed with crude oil, and existing assets, particularly the hydroprocessing units can be utilised for this. The key advantage of these units relates to generating product slate better suited for heavy-duty transport, aviation and maritime sectors.

In the Netherlands, refineries are equipped with hydroprocessing units, and supplying just 5-10% of hydrotreatment feed from bio-oil will suffice for 10-20% of current maritime bunkering demand. Scaling up to 50% supply of hydrotreatment feed could meet the entire maritime bunkering demand, though, such intensive co-processing would require substantial revamping and a significant increase in hydrogen demand.

Sustainable biomass potential appears to be sufficient but the mobilisation of these feedstocks and the creation of tradable commodities, for instance, bio-oils, is lagging behind. Retrofits in Europe predominantly focus on the use of lipids, such as vegetable oils, used cooking oils (UCO) and animal fats. However, there are policy limitations and caps on the use of these feedstocks, therefore, their future role will be more limited. Conversely, there are significant amounts of lignocellulosic feedstocks both in Europe and globally.

Based on the most recent update of sustainable biomass potential in Europe eligible for biofuel production under the Renewable Energy Directive (REDIII) (COM, 2024), about 1% of the lignocellulosic biomass potential in Europe appears to be sufficient to meet 5 to 10% co-processing in hydroprocessing units in the Netherlands. Converting hydrotreater units to

50% co-processing, or fully converting existing hydrocrackers, would require approximately 5.5% of the sustainable lignocellulosic biomass potential in Europe.

As previously mentioned, current retrofit initiatives use lipids, which are tradable commodities. Biomass-to-oil supply chains that use lignocellulosic feedstocks, particularly wastes and residues from agriculture and forestry will need to be established. Refinery retrofits, regardless of whether they are co-processing or full retrofits, will require the mobilisation of significant amounts of biomass resources. Given the limited domestic biomass availability, biomass will need to be supplied from elsewhere and the biomass harvesting and conversion to bio-oils supply chains will need to scale up to satisfy the existing hydroprocessing capacities. Two thermochemical technologies emerge as pivotal in this context: biomass pyrolysis, which is fully commercial but whose implementation is still limited, and Hydrothermal Liquefaction (HTL), which is on the brink of commercialisation.

Furthermore, while lipid co-processing in existing hydroprocesses appears to be a low-cost option, there is limited research on the use of hydropocessing units and co-hydrotreatment of bio-oil with petroleum streams.
Literature review indicates a potential saving of 30% to 50% in capital expenditures when bio-oil is co-processed, however, the levelized cost of producing biofuels from co-processing in comparison to stand-alone processes has not been sufficiently covered. Therefore, further research is needed to assess the use of existing hydroprocessing units, where the specifics of different refineries and the functioning of various hydrotreaters are taken into consideration. In that way, the revamp requirements can be better detailed.

While retrofitting existing refineries and supplying bio-oil from other regions could contribute to achieving a carbon-neutral energy system in the Netherlands, there is a strategic value in fully-integrated biomass-to-fuel refineries in the Netherlands.
For instance, stand-alone biomass gasification followed by Fisher-Tropsch synthesis not only provides diesel and kerosene for the transport sector, but also biogenic naphtha for the chemical industry and also biogenic CO_2, which can be stored for negative emissions and/or used for the production of carbon carrying synthetic fuels.

The review of company plans highlights that oil refineries act and react to the existing market conditions and their efforts towards the long-term transition to producing renewable fuels and feedstocks are limited.
While nearly all companies that own Dutch refineries have set the ambition to become carbon-neutral by 2050, their strategies for 2030 have been changing each year. Biomass co-processing in existing refineries in the Netherlands has not been considered due to the complexity and methodological uncertainty of tracing biogenic carbon in refineries and determining the renewable content of the product to be counted towards the renewable target within the Renewable Energy Directive[2]. Currently, the methodology is defined by Commission delegated regulation (EC(2023)3513), which may influence refinery perspectives.

An important aspect that needs further attention is the knock-on effects of shifting from oil refineries to renewable refineries. The refineries are closely integrated with their surroundings, delivering naphtha and several basic chemicals, as well as steam and refinery gases. While these integrations have previously been seen as a competitive advantage, they may also pose bottlenecks in the transition process.

[2] Based on the communication with stakeholders

Further research needs and recommendations

- Each refinery has a different configuration and product slate, therefore, individual sites should be studied in detail to identify whether they are suitable for conversion to a renewable refinery. Additionally, depending on the biomass type and the bio-oil characteristics, bio-oil co-processing in existing refineries will require additional hydrogen. The total volume , the availability and the cost of hydrogen need further research.
- A detailed study for the Dutch refineries should be complemented by an EU- wide study that covers European refineries. This can provide an optimal use of existing refining capacities in Europe and the relative importance of Dutch refining.
- Timely supply of biomass resources in large quantities will be essential not only for refinery conversions, but also to attain transport sector-related climate mitigation objectives. While the current studies indicate significant amounts of biomass resources, their mobilisation has been slow. There is a need for good understanding of mobilisation strategies and the related investment needs.
- There is strategic value of having fully integrated biomass-to-fuel refineries in the Netherlands. This strategic value relates not only to the supply part of the transport fuels, but also to providing biogenic naphtha to the chemical industries and to biogenic CO_2, which can be stored for negative emissions and/or used for the production of carbon carrying synthetic fuels.
- Further research on synergies between biomass to fuels and feedstocks and renewable power to fuels and feedstocks is needed to identify better business models.
- Related to the topics above, in retrofits, the hydrogen demand will increase significantly, and the availability and affordability of this green hydrogen will be one of the key considerations.
- In addition, in the medium-to-long term, e-fuels value chains will require biogenic CO_2, highlighting again the importance of biorefineries.

Large Volume Organic (LVO) chemicals industry

The Netherlands hosts a significant organic chemical industry, strategically located with strong connections to other industrial clusters in the Antwerp-Rotterdam-Rhine-Ruhr-Area (ARRRA) region. The total production capacity of olefins and aromatics, also referred as high value chemicals, comprises approximately 16% of the EU's production capacity. Among basic chemicals, ethylene and propylene are the most relevant in terms of export activity, especially within the EU, and exports of polyethylene pellets are significantly higher compared to other semi-finished products.

Overall, the base organic chemicals industry faces a complex regulatory framework with unclear directions regarding feedstock transition.

The sector heavily relies on fossil fuels as energy sources for processes and fossil feedstocks, particularly naphtha, to produce olefins and aromatics. Numerous EU policy initiatives affect this industry; while policies such as the Emission Trading System (ETS), the Dutch CO_2 tax, and REDIII (Hydrogen Obligation for Industry) aim to reduce direct process emissions, they do not directly require transitioning from fossil feedstocks to circular and sustainable alternatives. There are various policy initiatives which provide guidelines and identify actions for a green, digital, and resilient chemical industry, as well as dedicated directives specifying plastic use types with the aim of promoting circularity, and regulations that focus on the end-of-life to minimize environmental impacts, requiring production of more durable and reusable products. For instance, a recent policy, the sustainable Carbon Cycles communication (COM(2021)8000) introduces ambitions to source 20% of the carbon used in chemical and plastic products from sustainable non-fossil sources.

Within this complex landscape, assessing the possible relocation aspects of transitioning to renewable feedstock becomes quite challenging.
Reviews of company strategies and the current plans indicate that companies primarily focus on reducing direct GHG processes emissions (Scope 1) and on exploring electrification opportunities (both direct and indirect electrification). The transition towards renewable feedstocks is slow as these multinational companies continue to expand their fossil manufacturing capacity worldwide to meet growing demand. Among the options for circular feedstocks, the focus lies mainly on plastic pyrolysis with intentions to co-process in Europe and in the Netherlands. However, the expansion of such alternatives in the future is still uncertain due to possible limitations on plastic waste availability for pyrolysis.

Given the complex policy framework and uncertainties surrounding decarbonisation pathways, TNO has conducted scenario modelling aimed at achieving a climate-neutral energy system in the Netherlands (Scheepers et al, 2024). Within this modelling, two scenarios were constructed with varying ambitions for GHG emission reductions in international bunkering and ambitions for achieving circular carbon in the base chemicals industry. The relevant conclusions for this study are as follows:

- **The LVO chemical sector is closely intertwined with the refinery sector, and any transformation in the latter is expected to influence this industry significantly. Provided that renewable refineries produce bio- and synthetic naphtha and these become tradable commodities, there will be no direct relocation risk to existing processes.**
  Steam crackers can replace fossil naphtha with renewable naphtha. Bio and synthetic refineries supplying renewable fuels to the transport sector can also provide feedstock co-products for the organic chemicals industry. Depending on the available volumes and the composition of bio- and synthetic naphtha, these could replace fossil naphtha. Naphtha is a tradable commodity, which companies already import to the Netherlands currently, therefore, in the case of using renewable naphtha, the current processes would not face any relocation risk. This, however, should not be mixed with the current pressure industry is facing due to increasing energy and feedstock prices and affecting their competitive position against their peers elsewhere.
- **This also applies to plastic pyrolysis, there will be no relocation risk at the downstream processes**
  While the production of pyrolysis oil from plastics may occur elsewhere, following hydrotreatment, these feedstocks can also be fed into existing crackers, not affecting downstream processes. The potential for replacing fossil naphtha input with pyrolysis oil depends on the availability of plastic waste.
- **The downsizing of oil refineries will affect aromatics production as these are integrated and produced in oil refineries, creating the risk that they may locate production elsewhere.**
  To compensate for the downsizing of oil refineries aromatics will need to be produced stand-alone. The modelling results indicate biomass-to-aromatics production as a promising option. However, whether these new processes will locate in the Netherlands or elsewhere carries a large uncertainty.
- **(Re)location becomes more pronounced for new processes, such as the production of bioethylene from bioethanol.**
  The modelling results indicate this route becoming a promising low-cost option, and this value chain may be situated in regions with abundant biomass feedstocks and larger bioethanol production facilities. In fact, the largest commercial production of bioethylene

is in Brazil, followed by countries like India, China, and the USA. Other value chains appearing in the scenario modelling include methanol to olefins and biomass to aromatics. Again, these value chains may occur in regions with abundant renewable resources, impacting on the competitiveness of Dutch polymers in the market. The easy transportation of polymer pellets allows the displacement of semi-finished product supply. Post-processing plants can flexibly import more polymer pellets to produce final plastic products, further facilitating the use of imported materials. Regulations, such as carbon pricing through mechanisms like the Carbon Border Adjustment Mechanism (CBAM), will play a crucial role in shaping the competitive landscape.
These results should not be mixed up with the current pressure on the competitiveness of industry due to rising energy and feedstock prices.

Furthermore, there is the possibility of substituting conventional polymers with new materials. Conventional polymers, well-established synthetic materials, have predictable properties and widespread applications. In contrast, novel polymers are relatively new materials with unique properties and potential advantages. Universities, research organisations and the private sector actively develop novel polymers to address specific challenges and enhance performance. The EU policy initiatives focus on eco-design principles, including recyclability and reduced environmental impact, encouraging the adoption of materials aligned with these goals. If novel polymers meet EU criteria, they could disrupt the plastics value chain by gaining traction in the European market. Dutch manufacturers must keep pace with developments to avoid losing out to imported novel polymers.

However, the current market competitiveness of these new polymers remains a challenge, and their business case may not yet attract major players. While relocation risks associated with novel polymers are relatively low at present, vigilance is essential as the industry evolves.

Further research needs and recommendations
Given uncertainties about the LVO chemical sector's future, a thorough assessment is crucial to evaluate potential relocation risks and their implications for the Dutch LVO chemicals industry. Therefore, a thorough assessment combining technical, economic, and environmental, aspects can bring meaningful insights on the sector's future development.

The following topics are recommended to be evaluated by future research:
- Assess in detail the production costs of polymer pellets via these alternative value chains in diverse global regions, in order to evaluate the competitiveness of the Dutch polymers pellets.
- Evaluate how likely novel polymers could replace conventional polymers, assessing their scalability, challenges and opportunities to be introduced in the plastics market and how the Netherlands positioning itself in the development of such emerging materials.
- Similar to the refinery industry, timely supply of biomass resources in large quantities will be essential for the transformation of the chemical industry. There is a need for good understanding of mobilisation strategies and the related investment needs.

Contents

1 Introduction

Background

The Netherlands has a significant heavy industry sector, with large refineries, chemical clusters, and base metal companies. This is thanks to various factors, such as abundant and affordable natural gas reserves, strategic coastal positioning that facilitates easy access to European markets via large seaports, and a well-developed infrastructure with excellent inland connections or connections within Europe for the transit of raw materials, semi-finished products and products.

The heavy industry sector relies on fossil fuels for various processes, both for energy and non-energy purposes. Non-energy fossil fuel use covers raw materials derived from fossil sources, such as naphtha and other feedstocks that are vital for manufacturing processes. In achieving the Paris Agreement and combating climate change, the European Union (EU) and the Netherlands have set the goal of becoming climate neutral by 2050. In addition to climate neutrality, the Netherlands has expressed its aspirations for a fossil-free and circular economy by 2050 (Coalitieakkoord, 2022; NPE, 2023). Meeting these ambitions and adapting to changing conditions will require substantial changes in industrial processes, significantly reducing the use of fossil fuels for both energy and raw material purposes and replacing them with renewable and circular resources. These changes could profoundly alter the landscape of industrial activities.

The Dutch government has initiated the National Program Sustainable Industry (NPVI) to address challenges for the industry and remove uncertainties about sustainable conditions (i.e., availability of electricity, hydrogen, permits). This program aims to accelerate investments for a sustainable industry. The Dutch government collaborates with the largest industrial emitters to implement sustainable technologies that will lead to substantial reduction of fossil fuel use and CO_2 emissions. The so called “customized agreements (maatwerkafspraken)” cover, among other industries, refineries and large volume organic chemicals industries in the Netherlands.

The current efforts have been mostly focused on the energy use and reduction of direct emissions from industrial processes. The replacement of non-energy use of fossil fuels, which comprises almost half of the total energy use in industry, with renewable and sustainable supply options requires further attention and research.

Objectives of this study

Shifting from fossil fuels to renewables, particularly replacing them with carbon from renewable/circular sources, presents significant challenges for heavy industry. This study focuses on refineries and the large volume organic chemicals, that are heavily dependent on hydrocarbons and assesses their future transformation.

This study aims to support the Ministry of Economic Affairs and serve as a starting point for a wider discussion on the future transformation of Dutch industry. The specific questions that are formulated and addressed in this study are the following:

- What are the main policy drivers affecting these sectors?

- What are the decarbonisation options for refineries and the organic chemical industry and what are the individual company strategies in this regard?
- What are the industry adaptation options to replace non-energy use and how much renewable resources are needed?
- Which processes within each industry may face relocation risks, given that renewable feedstocks, particularly biomass, are limited in the Netherlands? It is important to note that this question is different from carbon leakage issues, where industries lose competitiveness due to different policy interventions and move to other world regions. Nor should it be confused with questions regarding the competitiveness of industries in general.

While the main aspects studied are the costs and the availability of renewable feedstocks reallocation risks relate to many other factors such as the investment climate, distance to customers down stream in the value chain, and the EU policies regarding "strategic" goods. These aspects are beyond the scope of this study.

Approach

The study approach consists of literature review, stakeholder interviews and scenario modelling. Based on the literature and the interviews with relevant stakeholders, information regarding the decarbonisation plans and plans for moving to renewable resources are identified. Company plans and strategies at a corporate level are collected from publicly available open sources. When publicly available, their specific project plans regarding renewable and circular production pathways are presented. The company official announcements are kept as the main source; when needed, other credible and publicly available data were used. This information is presented to suggest the significant importance of Dutch processes among the company processes in Europe and globally and to provide their decarbonisation plans, which may provide hints regarding their possible relocation plans.

TNO scenario modelling has been exploring different pathways to achieve a carbon neutral energy system in the Netherlands. The OPERA model, which is a technology rich, cost-optimisation energy system model, has been used for these purposes. The study has paid particular attention to heavy industry in the Netherlands. The results related to refineries and the organic chemicals industry are included in this report. In order to examine the low-cost decarbonisation options, particularly the substitution of fossil feedstock with renewables. The modelling framework, the main assumptions and the full results covering the whole energy system are presented in Scheepers, et al. 2024.

Outline

The report is outlined in 4 chapters. Chapter 2 delves into the refinery sector, starting with an overview of the current status of refineries in the Netherlands. This is followed by the introduction of the key policies that will have the largest impact on this sector up to 2050. Section 2.3 provides a summary of decarbonization options for refineries and outlines individual company plans and strategies. In Section 2.4, the future outlook explores the demand for oil products in both the transport sector and the chemical industry. Section 2.5 delves into the risks of relocation within the industry, with a specific focus on the necessary adaptations for oil refineries. The following section of this chapter introduces broader discussion aspects not covered in the assessment, provides sector specific conclusions and recommendations, where future research needs are highlighted. Chapter 2 follows a similar structure, shifting its focus to sectors involved in the production of olefins and aromatics in the Netherlands, particularly the steam cracking. Chapter 3 also presents the main conclusions and further research needs.

2 Refineries

2.1 Current status of Dutch refineries

There are 6 refineries in the Netherlands with a nameplate crude oil capacity of around 67 Mt per year (2861 PJ[3]) (PoR, 2017) (Olivera & Schure, 2020). Gunvor, one of these refineries, has recently stopped its oil processing operations. The remaining five refineries contribute to around 5.7% of the total European primary capacity (Concawe, 2023)[4] and account for approximately 10% of European production[5]. Five of them are in the Rotterdam/ Europoort region and one is located in Zeeland. The port of Rotterdam receives crude oil from the North Sea region and variouse areas, including Russia, and the Middle East. Around 80-85% of the refinery products relate to fuels and the remaining 15-20% consists of naphtha, base oils, and bitumen (CBS, 2023a).

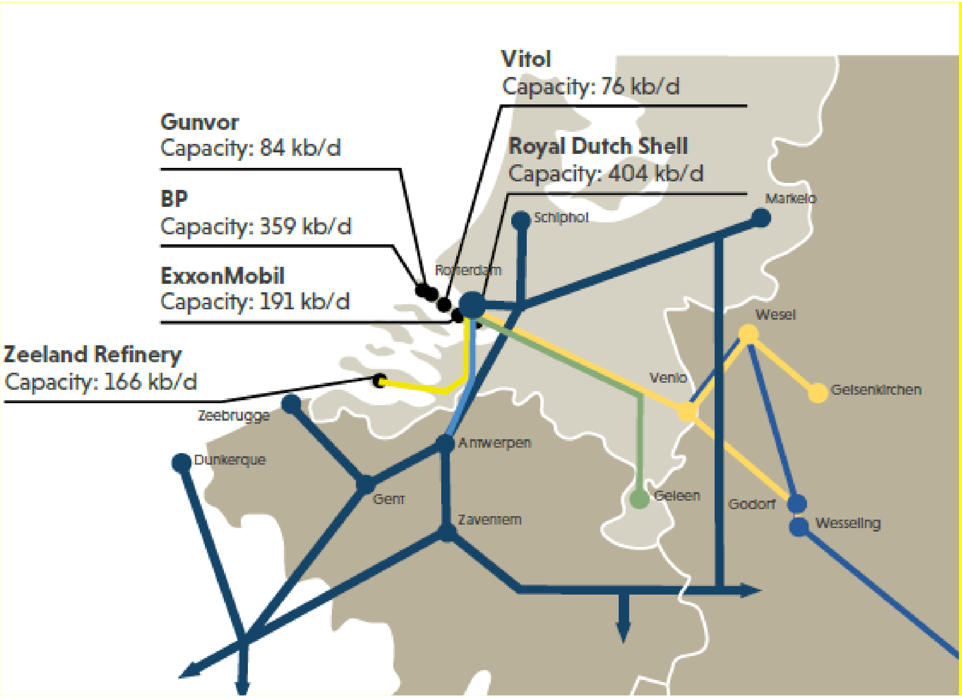

Figure: 2.1 Location of refineries and their throughput capacity (VNPI, 2020)
kb: Thousand Barrels per day

Figure 2.2 illustrates the average balance of petroleum products in the Netherlands from 2015 to 2022. This figure shows that the country has been the net importer of petroleum coke, liquefied petroleum gas (LPG), aromatics, naphtha, and refuse fuel oil (RFO), with naphtha emerging as the largest commodity. Significant volumes of kerosene, gasoline, and diesel have been exported to other countries. Overall, approximately 45% of the total production appears to be exported. However, factoring in the maritime and aviation

[3] Calculated based heating value of 42.7 MJ/kg.
[4] The average contribution between 2009-2022.
[5] blg-876198.pdf (officielebekendmakingen.nl)

bunkering in the Netherlands, the net export volume reduces to around 25% of the total production.

The main destinations of refined petroleum exports from Netherlands in 2021 were Germany, Belgium, the United States, Nigeria and France (CSBS, 2023b; OECD,2023).

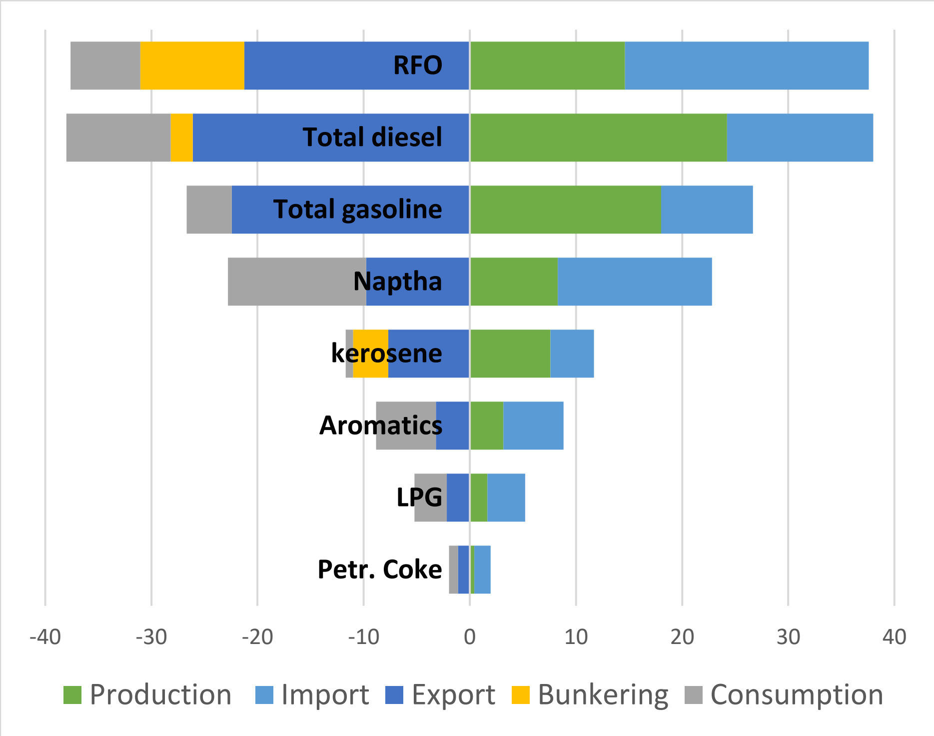

Figure 2.2: Petroleum product balance between 2015-2022 in the Netherlands (CBS, 2023a)

Petroleum refineries are the second-largest contributor to GHG emissions among base manufacturing industries in the Netherlands. Figure 2.3 provides a comparison of direct GHG emissions of refineries with those from other major industries in the Netherlands in 2020. It also shows the total emissions of each refinery. Shell Pernis accounts for the majority of GHG emissions due to its large throughput capacity and high complexity.

In line with the climate goals of the Paris Agreement and the ambition to become climate-neutral by 2050, the refineries will go through a fundamental transformation.

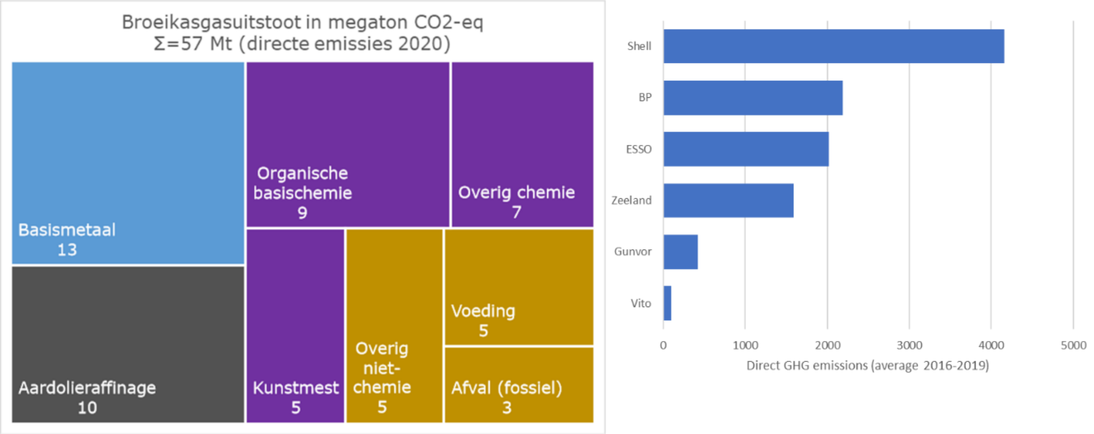

Figure 2.3: Manufacturing sector GHG emissions broken down to different industries (left) and GHG emissions of refineries in the Netherlands (right)

2.2 Key drivers for transformation– the policy landscape

This section briefly introduces the key policy instruments and summarises their impacts to the refineries in Table 2.1.

The Renewable Energy Directive (REDIII)

The REDIII, amended in 2023, sets out specific goals for both the industry and transport sectors by 2030, in addition to the overall renewable energy objective. According to REDIII, by 2030, at least 42% of the hydrogen used in industry should come from renewable fuel of non-biological origin (RFNBO), such as green hydrogen or hydrogen energy carriers produced via electrolysis. This shift aims to reduce reliance on fossil fuels and lower GHG emissions in industry. Weeda and Segers (2020) note that a significant portion of hydrogen in industry, approximately 37%, is used in oil refineries for processes like desulphurization and hydrocracking, excluding its use as fuel. The directive encourages refineries to transition their hydrogen production from fossil fuels to renewable hydrogen.

Moreover, REDIII introduces specific renewable energy sub-targets and also an overall GHG emission intensity reduction target for the transport sector. Consequently, there will be a shift in demand from conventional oil products to renewable alternatives. Detailed information on these transport-related targets and the expected demand for renewable fuels in the Netherlands can be found in a recent study by Uslu (2024).

Aviation and Maritime regulations

The Fit-for-55 package included two major regulations for the aviation and maritime transport sectors; the FuelEU Maritime and the ReFuelEU Aviation regulations, both entered into force in October 2023. The ReFuelEU Aviation regulation introduces mandatory volume-based targets for sustainable aviation fuels starting from 2030 up to 2050. By 2050, at least 70% of the aviation fuel should be from sustainable aviation fuels (SAF). Thus, the fossil kerosene contribution will be limited to 35% of the total demand. The FuelEU Maritime regulation introduces a GHG intensity reduction target for ship owners of more than 5000 gross tonnages. They will need to reduce the GHG intensity of energy used on board by 6%

in 2030, increasing to 80% in 2050, compared to a reference intensity figure. While this regulation covers 100% of energy voyages between EU ports, it covers half of the voyages where the arrival or departure port is outside the EU. The international maritime organisation (IMO) also adopted a strategy in 2023, which envisages carbon intensity reduction of international shipping by at least 40% by 2030 and reaching net-zero GHG emissions by 2050.

New rules CO_2 emission standards for cars and vans
The EU has adopted an amendment to its light-duty vehicles (LDV) CO_2 standards, mandating that all newly registered cars and vans from 2035 onwards must be 100% CO_2 -free. Additionally, the CO_2 reduction targets for 2030 have been strengthened to -55% for cars and --50% for vans, compared to a 2021 level. These measures aim to boost the adoption of electric vehicles.

Furthermore, a provisional agreement on CO_2 emission standards for heavy-duty vehicles was reached in February 2024. This policy introduces a 100% zero-emission target for urban buses by 2035, covering trucks (over 5 tonnes), city buses, long-distance buses (over 7.5 tonnes), and trailers. The proposal outlines a gradual reduction in CO_2 emissions from these vehicles, aiming for a 45% reduction from January 1, 2030, a 65% reduction from January 1, 2035, and a 90% decrease from January 1, 2040 onwards, compared to 2019 levels.

EU Emissions Trading System (EU ETS)
The new regulation of the EU ETS involves gradually phasing out the free allocation of EU ETS emission rights, known as EU Allowances or EUAs, currently granted to the industry. Economic sectors covered by the EU ETS, such as power production and designated energy-intensive industries, including refineries, are required to reduce their combined emissions by 62% by 2030, compared to 2005 levels. To ensure success, the phase-out of free EUAs will be accompanied by an annual reduction in the total number of available EUAs for these sectors. This reduction will be set at 4.3% per year from 2024 to 2027 and 4.4% per year from 2028 to 2030, resulting in no EUAs in 2040.

The EU ETS also extends its coverage to maritime transport, while a separate ETS 2 will be established for buildings, road transport, and fuels. Starting in 2026, maritime sector GHG emissions must be surrendered as allowances in the subsequent year, with interim targets set for 2024 (40% of CO_2 emissions only) and 2025 (70% of total GHG emissions). No free allowances are allocated to the maritime sector, and each non-compliant allowance will incur a penalty of €100 per tonne of CO_2eq. Failure to comply for two consecutive years may result in restrictions on calling at EU ports.

Initially, the refining sector will not be shielded by a Carbon Border Adjustment Mechanism (CBAM), exposing European players to higher carbon costs compared to their international counterparts. Nevertheless, this setup creates a strong incentive for decarbonizing existing operations.

CO_2 levy
Under the Climate Agreement, it has been agreed that the industry will reduce annual CO_2 emissions by 14.3 Mt CO_2 by 2030. The CO_2 levy came into effect on January 1, 2021 to ensure that this objective is achieved.

Table 2.1: Key policy instruments and their impacts to the refinery sector.

Policy instrument	Content	Effects to existing refineries
Amendment of the Renewable Energy Directive (REDIII)	Sets GHG intensity reduction target and also renewable fuels sub-targets for the transport sector up to 2030. Introduces RFNBO obligation to industry	• Reduced fossil fuel demand • Shift to renewable fuel supply • Encourages use of green hydrogen in its processes
FuelEU Maritime Regulation proposal	Introduces GHG emissions intensity reduction targets up to 2050.	• Reduces fossil fuel demand. • Shift to low carbon/ renewable fuel supply
ReFuelEU Aviation Regulation proposal	Introduces a SAF obligation up to 2050, with sub-target for RFNBO	• Reduces fossil fuel demand. • Shift to low carbon/ renewable fuel supply
CO_2 standards for cars and vans	Zero-emission vehicles	• Reduces fossil fuel demand. • Shift to Batter Electric Vehicles (BEVs) and H_2 use via Fuel Cell Electric Vehicles (FCEVs)
EU ETS amendment	Gradually reduces free allowances given to industry up to 2034.	• Refinery direct emissions will need to be zero before 2040.
Extension of EU ETS	EU ETS will also cover maritime sector emissions. ETS 2 will be set to cover building and road transport	• Impacts CO_2 prices[6] • Further incentivises low-carbon fuel use
CO_2 levy	Industry shall reduce annual CO_2 emission by 14.3 Mt by 2030	• Refinery direct emissions will need to be reduced.

In conclusion, the current policy process will significantly affect the refineries. On the one hand, direct emissions of the refinery processes will need to reach net zero. On the other hand, the majority of the refinery products are used as transportation fuels, and the demand for these products will undergo significant changes as a result of the policy instruments within the Fit-for-55 package. With the rise of electrification and improvements in vehicle efficiency, the demand for fuel in road transport is expected to decrease notably. Additionally, over the coming decades, there will be a shift in demand from fossil fuels to low-carbon alternatives in aviation and maritime sectors.

2.3 Refinery decarbonisation options and the company plans

Refinery decarbonisation options were introduced in the MIDDEN report (Olivera and Schure, 2020). These are recapped in Table 2.2. Among the possible options, implementing carbon capture and storage (CCS) and switching to renewable energy to meet the energy demand would address direct process emissions (scope 1) and emissions due to utilities (scope 2). While these measures would contribute to reducing GHG emissions in the industry sector, particularly under the EU ETS, they do not address emissions associated with the combustion of refinery products, particularly fossil fuels as transport fuels.

[6] ETS1 and ETS2 will be separate systems. Therefore ETS2 will have its own CO_2 price

However, a significant proportion of emissions across the entire value chain is related to the use of refinery products. To address these emissions, options such as substituting conventional fossil feedstocks with renewable alternatives and transitioning to renewable refineries can be considered.

Given the focus of this study on the potential impact of renewable energy supply options and the possibility of process relocations outside of the country, discussions on CCS and fuel switch options are not included in the rest of the document.

Table 2.2: Refinery decarbonisation options highlighted in MIDDEN.

	Technology	Relevant process	Scope
CCS/CCU		Mainly for H_2 production unit, FCC and gasification unit Also applicable to all stacks	Reduction of scope 1 emissions
Fuel switch	Use of electric furnaces Electric boilers Electric shaft equipment Blue/green H_2 as fuel	Applicable to all process that use gas-fired equipment (atmospheric distillation, cracking, reforming) Replacing steam boilers Replacing steam turbines All processes that use gas-fires equipment	Reduction of scope 1 and when renewable electricity is used also scope 2
Feedstock substitution	Co-processing • biolipids and/or • stabilised pyrolysis oil, and/or • Fischer-Tropsch (FT)-wax	Co-feed in Fluid Catalytic Cracking (FCC) (only 2 refineries have this process) Co-feed to hydrocracking and hydrotreatment Demand for additional H_2	Reduction of limited scope 1 and limited scope 3
	Blue/green H_2 as feedstock for process	Desulfurization, hydrotreatment, hydrocracking	Scope 2 emissions
New process rebuilt	Bio and e-refineries		Scope 1, 2 and 3

2.3.1 Company plans and announcements

The refineries in the Netherlands are owned by multinational companies that have many operations across the world, with global strategies. Even though the diverse operations, different markets and regulatory environments will factor into their decisions for different regions, they will likely align with their global strategy. Therefore, this section introduces current company plans regarding their decarbonisation strategies and shift to renewable fuel and feedstock production.

Table 2.3 provides an overview of the companies that have operations in the Netherlands. It shows the relevance of Dutch refineries in comparison to the global and European refining capacities. This is to give some indication of how significant the Dutch production processes are within the overall portfolio of company-owned refineries. In addition, it introduces their announced plans as indications of their decarbonisation strategies.

Shell has been updating its main energy transition targets[7] and re-evaluating its refinery business and the five clusters strategy (Shell, 2023a). In its energy transition strategy in 2024, Shell announced that it will remain committed to reaching net zero emissions by 2050 (Shell, 2024). However, it has abandoned its 2035 net carbon intensity target due to uncertainty regarding changes across countries and the broader energy transition (Shell, 2024a). According to this new strategy, it will keep oil output stable up to 2030 (Argus, 2023). It wants to "high grade" the European cluster, possibly targeting value over volume. In the Netherlands, Shell has announced a final investment decision to build an 820 kt/year biofuel facility at the Pernis Refinery. For comparison, Shell's refinery nameplate capacity in the Netherlands is 21,000 kt/year. In addition, Shell took the final investment decision to build a 200 MW electrolyser and to produce 60 tonnes of renewable hydrogen per day, to replace hydrogen produced from natural gas (grey hydrogen) that is used for its oil refining processes. The renewable electricity will come from offshore wind in the North Sea.

Similarly, BP announced its vision to become carbon-neutral by 2050 and had plans to reduce its oil and gas output by 40% in 2030, compared to 2019 (BP, 2020), but according to recent announcements (BP, 2024), it has rolled back its plans to cut oil and gas output. In a recent communication, BP indicated an aim for a 50% reduction in scope 1 and 2 emissions, a 20-30% reduction in the emissions associated with the carbon in upstream oil and gas production (scope 3) by 2030, and to reduce the average carbon intensity of products to net-zero by 2050. The main focus is set to replace its own grey hydrogen consumption with green hydrogen (hydrogen produced from renewable electricity using electrolysers). For bioenergy, BP aims to grow its global biofuels production to around 100 000 barrels per day by 2030 and increase its supply volumes of biogas (BP, 2023). BP plans five major biofuel projects across existing facilities, with the Rotterdam refinery among them. However, there has been no final investment decision yet for the Rotterdam refinery. BP already co-processes biofuels at three refineries in Germany, Spain, and the US (Chery Point).

ExxonMobil's primary focus lies within the United States with a significant portion of its operations driven by the incentives provided by the US Inflation Reduction Act (IRA). The main focus is on CCS technologies. The company is engaged in the development of a low-carbon hydrogen production facility from natural gas, with carbon capture located in Texas. In addition, ExxonMobil has plans to enhance renewable diesel production at its Imperial Oil refinery near Edmonton, Alberta (Canada). ExxonMobil is also involved in co-processing trials to produce lower-emission fuels, including sustainable aviation fuel (ExxonMobil, 2024).

TotalEnergies has transformed its La Mède refinery in France into a biorefinery with a capacity of 500 kt of hydrotreated vegetable oil (HVO)-type biofuels per year. TotalEnergies currently transforms its former Grandpuits refinery site in France into a zero-crude platform for biofuels and bioplastics. It will construct a renewable diesel unit, producing aviation fuel. This unit is planned to be commissioned in 2024, to process 400 kt per year, of which 170 kt is Sustainable Aviation Fuel (SAF), 120 kt is renewable diesel and 50 kt renewable naphtha. The unit will process mainly animal fats from the EU and used cooking oil, supplemented with other vegetable oils like rapeseed. In addition, TotalEnergies has a joint venture with Corbion to produce poly lactic acid (PLA) (a substitute for fossil polymers) from sugar in the

[7] In the first update to its main energy transition targets since 2021, Shell said it will target a 15%-20% cut in the net carbon intensity of its energy products by 2030 compared with 2016 levels. It had previously aimed for a 20% cut by 2030. The company said it now plans to reduce the net carbon intensity of the energy products it sells by 9-12% by 2024, 9-13% by 2025, 15-20% by 2030, compared to 2021 and 100% by 2050 (S&P Global, 2024; Shell 2024).

EU, following their plant in Thailand. TotalEnergies will be constructing France's first chemical recycling plant with Plastic Energy (TotalEnergies 60%, Plastic Energy 40%) (TotalEnergies, 2023;2020).

Vitol and Gunvor Groups are among the largest commodity trading companies with some investments in refining. In the Netherlands, Gunvor Group acquired the Rotterdam refinery in 2016, however, it closed its two crude processing units, one in 2019 and the other in 2020 (S&P, 2021). Its operations now focus on the desulphurization of high-sulphur products and the production of gasoline. Currently, Gunvor intends to renovate its existing oil refinery facilities in Europoort Rotterdam and make them suitable for the processing of vegetable and animal oils and fats into renewable fuels, mainly SAF and renewable diesel. The plan is to construct two production trains each with a production capacity of 350 kt/year. Each train corresponds to around 7.5% of the fossil refinery nameplate capacity[8]. The facilities are planned to be built on the previously decommissioned lubrication oil plant. Gunvor has also agreed to partner with petrochemical group Dow to purify pyrolysis oil feedstocks derived from plastic waste, using an existing unit at its refinery site in Rotterdam. Next to that, Gunvor has signed an agreement with Air Products for a green ammonia supply terminal. The VPR refinery in Rotterdam has been acquired by the Vitol Refining Group. Vitol's focus has been more on supplying biofuels rather than on investing in the production processes.

Review of the company plans highlights that the oil refineries react to the existing market conditions and their efforts towards the long-term fundamental transition to producing renewable fuels and feedstocks are limited. Biomass co-processing in existing refineries in the Netherlands has not been considered by the companies due to the complexity regarding tracing biogenic carbon in refineries and determining the renewable content of the product to be counted for renewable targets within the Renewable Energy Directive[9]. Until 2023, the methodology to determine the share of biofuel via co-processing was not set. Currently, this methodology is defined by the Commission Delegated Regulation (EC (2023)3513).

IEA (2023) indicates that the oil and gas industry has not taken a leading role in the global transition to clean energy systems. It states that clean energy investment by the oil and gas industry as a whole represented 2.7% of its total capital spending in 2022 and 1.2% of total investment in clean energy. More than 60% of this came from four companies: Equinor, TotalEnergies, Shell and BP, which spent each around 15-25% of their total budgets on clean energy (IEA, 2023).

Table 2.3: Review of the decarbonisation plans of companies that have refinery operation in the Netherlands.

	Relevance of the Dutch refinery	List of known project plans
Shell	• 44% of the company's total refining capacity in Europe[10] • 25% of the company global refining capacity in 2022	*Germany* • Rheinland refinery plans: Expand electrolysers capacity to 100 MW, produce SAF using renewable power and biomass, and develop a bio-LNG plant. • Miro Karlsruhe refinery: Add synthetic fuels to product slate of around 50 kt/y. • Plans to establish two state of the art biomethane production facility in Karstaedt and Steinfeld, to fulfil up to 5% of Germany's present consumption (Shell, 2024b).

[8] Name plate capacity of Gunvor was mentioned as 4500kt/y.
[9] Based on the communication with stakeholders.
[10] In case of joint Ventures, the refining capacity is corrected based on the joint venture share (i.e. for MIRO refinery in Germany and Trecate refinery in Italy.

	Relevance of the Dutch refinery	List of known project plans
		The Netherlands • FID to build 820 kt/a biofuel facility in Rotterdam. • Bio-LNG plant with Nordsol and Renewi in Amsterdam Westport (3.4 kt/y). • Green H_2 plant in Shell Pernis refinery. *UK* • With Quarter Energy blue and green H_2 plant.
BP	• 46% of company refining capacity in Europe. • 25% of the company global refining in 2022	• Globally invest in five major biofuel projects, of which three of them adjacent to existing refineries and up to two conversions of existing refineries. *Germany* • In Lingen refinery: green H_2 production of 50 MW in 2022 to 100 MW in 2024, comprising around 20% of the H_2 from natural gas in Lingen. *The Netherlands* • H_2-fifty, 250 MW plant to produce green H_2 (45 kt/y) to desulphurization, replacing grey hydrogen. No FID yet. *Spain* • At Castellon refinery: Develop a 20 MW electrolyser with further expansion to 115 MW, with the aim to replace grey hydrogen production.
TotalEnergies (owner of 55% of Zeeland Refinery[11])	• 6% of the company capacity in Europe • 5% of the company global refining capacity in 2022	• Total has chosen biofuels as its target market. The company projects renewable diesel production of nearly 5 mln tonnes per year by 2030 and aims to become a market leader in renewable diesel, reaching 15% share of the biofuel market. *France* • La Mede: a 500 kt/y HVO plant, where it recently began SAF production. • Grandpuits facility: Converting it from 93,000 b/d into a 400 kt/y biorefinery to start up in 2024. • Plans to add 300 kt/y of HVO capacity in Europe from co-processing at existing facilities. *Belgium* • TotalEnergies' Antwerp refinery: considers adding co-processing biofuel units with capacity of 150 kt/y, processing UCO&AF. *The Netherlands* • Zeeland refinery: with H2ero project, a 150 MW electrolyser to produce renewable H_2. *Germany* • Refinery in Leuna : TotaEnergies and Sunfire investing in a project to produce methanol from green hydrogen and highly concentrated CO_2 from the refinery production processes.
ExxonMobil (Esso refinery)	• 16 % of the company European capacity	• Focus on scope 1 and 2 emissions and to become net-zero in 2050. • Lower emission investment plans through 2027.

[11] Zeeland refinery is currently a joint venture between oil companies Total (55%) and Lukoil (45%). Since Total has a larger share, information about this company is illustrated in the table.

	Relevance of the Dutch refinery	List of known project plans
	• 4% of the company global refining capacity in 2022	• Renewable diesel – Strathcona, Canada and Slagen, Norway. • Bio co-processing – Sarnia, Canada. • Baytown low-caron hydrogen, ammonia and CCS project plan 2027-2028.
Vitol	• A trading company, acquiring five refineries globally. • 55% of the company refining capacity in Europe[12]	
Gunvor	• A trading company that acquired three refineries • Only Gunvor Refinery Ingolstadt is operational	*The Netherlands* • An HVO/HEFA plants, with a total production capacity of 700 kt/y. *Spain* • Gunvor acquired/invested in a biofuel plant in Spain (Gunvor Biofuel Berabtevilla; built in 2008) which has a 400,000 Mt/y capacity based on transesterification/esterification/distillation. • Additionally, Gunvor invested in the biofuel plant Heulva, built in 2012. The plant was built to refine vegetable oil. Gunvor is upgrading it to allow for UCO and fatty acids.

- Refining capacity in Europe is based on the Concawe dataset. When the refinery is part of a joint venture, the capacity is corrected by the joint venture share.
- Global refining capacities of companies are based on the Statista, Global refining capacity of key oil majors 2022.

2.4 Outlook

2.4.1 Reduction of fossil oil demand for transport

As stated previously, the future strategies of the oil refineries will depend on many factors, most importantly the petroleum product demand in the future. It is evident that the demand for the transport sector will decrease, especially in Europe. However, the pace of this decrease will depend on policy implementation and is highly uncertain. This difficulty can be addressed with energy modelling and related projections, which can provide valuable information regarding demand reductions within a pre-determined scenario framework.

A recent study from the IEA explores the outlook for oil and natural gas producers based on two scenarios: the Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050 (NZE) Scenario (IEA, 2023). These scenarios set out global transition pathways aligned with regional and global net-zero targets respectively, and assess what this would mean for oil and gas companies and producer economies. The APS scenario sets the framework based on the announced pledges by individual countries. It assumes that all climate commitments made by governments and industries around the world as of the end of August 2023, including Nationally Determined Contributions (NDCs), will be met. The NZE scenario sets out

[12] Vitol owns the VPR refinery in Rotterdam and is co-owner of a smaller refinery in Cressier, Switzerland.

a pathway for the global energy sector to achieve net zero CO_2 by 2050. While both scenarios are exploratory scenarios, they are well aligned with the Paris Agreement goals, and the EU goal of carbon neutrality by 2050, particularly the NZE scenario.

Figure 2.4 illustrates the projection results. The IEA scenarios show an overall oil product demand reduction of 45% and 75% by 2050 compared to 2022 for the APS and NZE scenarios, respectively. Transport fuels, such as gasoline, diesel, and kerosene, are projected to undergo significant decline over the coming decades. The decline in gasoline demand is particularly pronounced, with a share of 25% today, declining to 15% by 2050 in the APS, and to almost zero in the NZE Scenario. Diesel and kerosene are projected to decline significantly in the NPE scenario as the decarbonisation of long-distance transport and aviation sectors takes effect. In contrast, demand for petrochemicals feedstocks (such as ethane, LPG, and naphtha) is expected to remain more stable according to these projections. The share of product demand is projected to exceed 50% by 2050 in the NZE scenarip, up from 22% today. This shift highlights the significant importance of strategic adjustment by the refining industry to align with future markets.

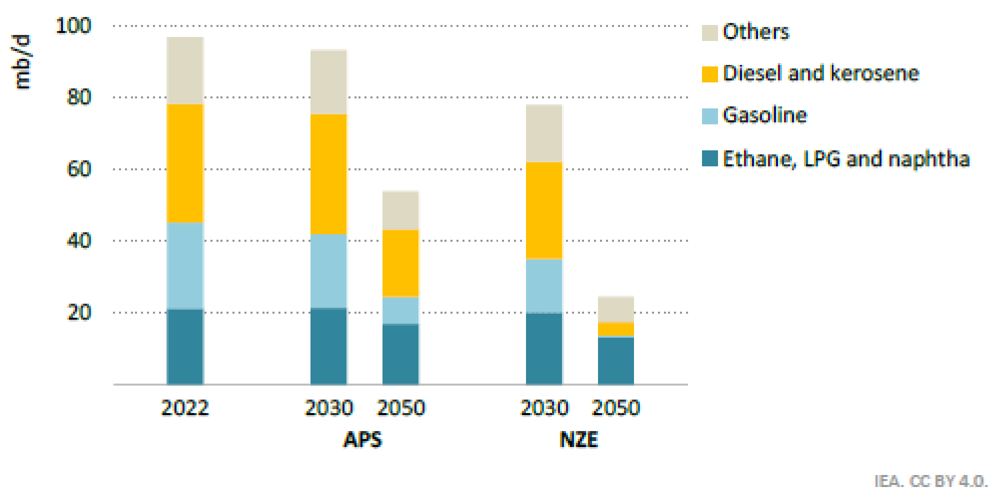

Figure 2.4: Oil product demand in the APS and NZE Scenario [IEA, 2024] the oil and gas industry in net zero transition

The European Commission Communication (EC, 2018): “A clean Planet for all- A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy” introduced sectoral and economy-wide low carbon energy transformation pathways. The model-based quantitative analysis explored eight different scenarios achieving different levels of emission reduction, contributing to the Paris Agreement’s temperature objectives of keeping global temperature increase to well below 2ºC, and pursue efforts to achieve a 1.5ºC temperature change, thus reaching net-zero GHG emissions. Figure 2.5 illustrates the transport sector oil demand results related to scenarios achieving GHG emissions reduction close to 90% by 2050 compared to 1990 and reaching net-zero GHG emissions by 2050. Results are presented for the transport sector excluding EU international maritime fuel demand and for international maritime fuel demand. The overall demand for oil products is projected to be reduced by approximately 75% and 90% in 2050[13] compared to 2015. It is important to highlight that the international maritime sector

[13] The low range is based on the comparison of combination of COMBO scenario for inland transport, including aviation and 50% emission reduction scenario for the EU international maritime sector with 2015. The 90%

GHG emission reductions were set at 50%, 60% and 70% at the time of these projections, whereas International Maritime Organisation has introduced a recent strategy in 2023 to pursue efforts towards phasing out GHG emissions from international shipping entirely by the middle of this century.

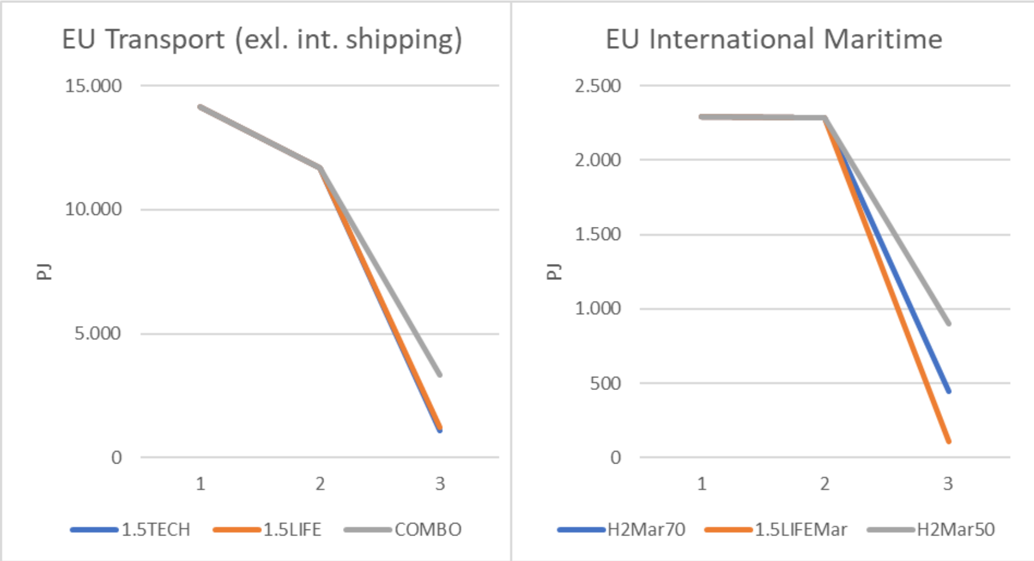

Figure 2.5: EC scenario projections for the fossil fuels consumed in transport sector(excl maritime) and international shipping in the EU

TNO has defined two scenarios for energy system in the Netherlands: ADAPT and TRANSFORM. Both scenarios are based on a framework for achieving carbon neutrality in the Netherlands. However, they differ in aspects regarding the total energy demand for transport sector and the emission reduction objectives for the aviation and maritime bunkering in the Netherlands. ADAPT follows the Climate and Energy Outlook (KEV) projections from PBL (2023) and assumes that the aviation and bunkering-related emissions will be reduced by 50%. TRANSFORM considers aviation and the maritime bunkering to reach zero emissions by 2050. In addition, due to the assumed behavioural changes of consumers, the demand for aviation and maritime fuels is lower in TRANSFORM than in ADAPT. Within the framework of this scenario modelling, the demand for oil products for transport sector is projected to reduce by more than 85% in ADAPT and more than 95% in TRANSFORM, compared to 2019 (see Figure 2.6). Further details of this scenario modelling can be found in Scheepers et al, 2024.

reduction refers to 1.5 ºC scenario, combined with 70% GHG emission reduction in EU international maritime sector.

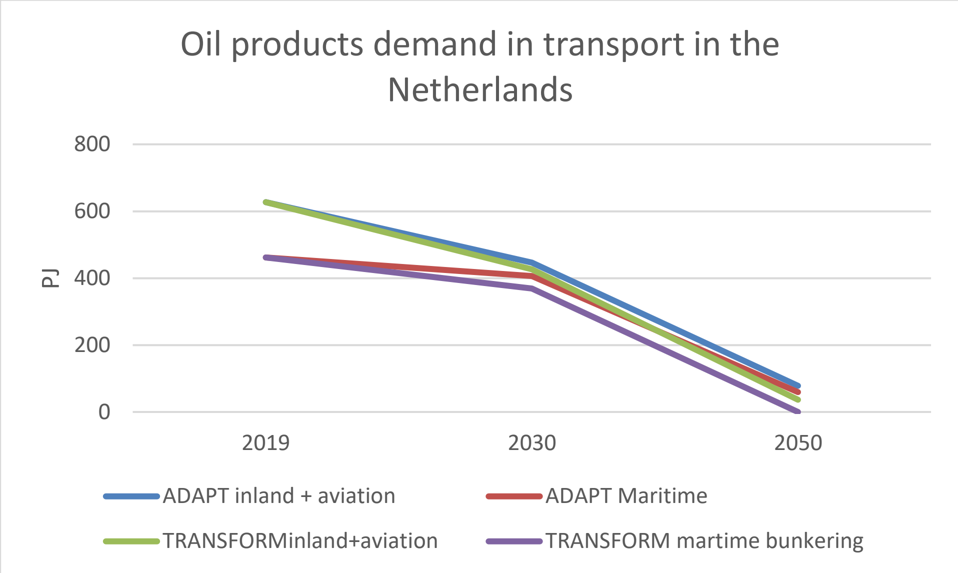

Figure 2.6: Oil product demand in the Netherlands according to ADAPT and TRANSFORM scenarios

2.4.2 Demand for petrochemical intermediates

Crude oil refineries do not just produce fuels for transport, but also petrochemical intermediates for the base chemical industry, such as naphtha, LPG, ethane and reformates for aromatics. These products may turn into the main sources of demand growth for refineries.

The future demand for petroleum feedstocks like naphtha and LPG will be influenced by, among other things, policies affecting plastics production and demand, such as the implementation of circularity. However, the policy formation on this topic is currently less concrete than it is for the transport sector-related policies (see section 3.1.1), therefore the future demand for fossil feedstocks is more uncertain. For instance, the IEA (2023) projects an almost 20% reduction in petroleum feedstock demand by 2050 compared to 2022 in its APS scenario and a 37% decline in the NZE scenario.

Another study that underpins the EC communication on “Clean Planet for All” (EC, 2018), indicates that fossil naphtha consumption may increase by 25% in 2050, compared to 2015 when CCS is implemented to reduce GHG emissions of the chemical industry (ICS & Fraunhofer, 2018). Another scenario variant that considers a significant amount of biomass and biogas use, next to plastic recycling, results in 80% reduction of fossil naphtha in the EU in 2050 compared to 2015.

This uncertainty about the future market demand for petroleum feedstocks adds an additional layer of complexity to the refinery sector.

2.4.3 Possible company responses

The companies will set their strategies for the coming period, and depending on the business case and the refinery type, they may decide one of the below options.

- *Hold their investment levels and/or milk their previous investment*: Due to high margins[14] in the short-to-medium term, companies may decide to hold onto their assets. They may decide not to re-invest or go for major maintenance but instead keep the refining running until the operational cash flow is below salvage values. Current company plans, introduced in Section 2.3.1, indicate this trend, at least up to 2030.
- *Shrink selectively and shift to chemicals*. Companies may seek niche markets with the highest value and longer time duration. They may change their individual process units, change the mix of process units, or build more direct crude-to-chemicals plants (Fitzgibbon et al., 2022).
- *Shut down and divest*: Companies may decide to close many of the oil processing units and look for opportunities to shift to renewable refineries.

Petrochemical integration with oil refineries has been considered as one of the key parameters in determining refinery resilience to competition. Refineries that have some chemical-oriented process and supporting processes[15] can adapt to shifting demand from transport fuels to chemicals (Fitzgibbon et al., 2022; CIEP 2017). This may provide a financial safeguard against declining demand for diesel and gasoline and a competitive advantage over non-integrated refineries. However, as stated in the previous section, this option depends heavly on future policy formation regarding circularity and emission reduction objectives for the chemical industry.

Table 2.4 presents the most relevant processes that can increase the feedstock yield, such as naphtha, for the chemical industry. This table also shows the Dutch refineries where these processes are available.

- Fluid catalytic cracker (FCC): This process converts higher-molecular-weight (heavy) hydrocarbons into lighter products. The products usually consist of high-octane gasoline, light fuel oil and olefin-rich light gases (Olivera & Schure, 2020). This process can be redesigned to produce higher petrochemical yields, resulting in increased production of olefins, aromatics, and LPG & naphtha for the steam crackers.
- Hydrocrackers: Hydrocrackers yield diesel, jet fuel, and steam cracker feed such as LPG and naphtha. Refineries may boost petrochemical output while still keeping diesel and jet fuel production by increasing the hydrocracker capacity and shifting towards higher yield of light-ends feedstocks (Fitzgibbon et al., 2022).
- Naphtha reformers: Refineries can reduce gasoline production and maximise aromatics production by adopting reforming process.

Table 2.4: Units that are most relevant for chemicals production within the Dutch refineries (derived from table 3 in Olivera & Schure, 2020)

	Naphtha Reformer	Hydrocracker	FCC
BP	X		X
ESSO	X	X	
Gunvor			
Shell	X	X	X
Vitol			
Zeeland	X	X	

[14] i.e., increased profit margins due to tight market and high fuel prices.
[15] Such as hydrogen generation, aromatics separation and handling, and light ends storage.

2.4.4 Possibility to shift to renewable fuels

The possibility to shift to producing renewable fuels could offer an alternative for refineries. The refinery transition to renewable fuels can be grouped under four general implementation routes (CONCAWE, 2019). These are:

- Refinery integration: this refers to integration of renewable fuels with the existing crude oil refinery.
- Refinery conversion: existing refineries can be adapted to process 100% renewable feedstocks.
- Refinery co-location: renewable refineries can be built stand-alone, for instance adjacent to fossil refineries and use some of the existing logistics and infrastructure, or
- They can be fully self-containing, greenfield projects.

Existing fossil refineries can be integrated with produce renewable fuels and feedstocks. At present, several refineries in Europe are either retrofitted to produce 100% biofuels or co-process lipids alongside traditional crude oil with limited or no modifications to the existing processes[16], as demonstrated by for instance Preem, Cepsa, and Repsol. Preem, one of the world's leading co-processing companies, co-processes up to a 30% ratio of lipids, including tall oil methyl ester (Egeberg et al., 2011). In a recent announcement, Preem together with Haldor Topsoe, has achieved up to 85% co-processing in its Gothenburg refinery (Bioenergy international, 2021). Table 3.2 in Appendix A introduces the list of current and planned retrofitted fossil refineries in Europe.

Co-processing can occur at different injection points within refineries, with two most common being the hydroprocessing units and the Fluid Catalytic Cracking (FCC) unit. A simplified flow diagram of a refinery with the two main insertion points are illustrated in Figure 2.7. The FCC products usually are: high-octane gasoline, light fuel oils, and olefin-rich light gases (Olivera & Schure, 2018).The hydroprocessing unit comprises two major operations: i) hydrotreatment, which aims at removing sulphur, nitrogen and oxygen, next to other undesirable metals, and ii) hydrocracking, where the heavier petroleum intermediate products such as heavy gas oil and vacuum gas oil into is cracked to lighter products by catalytic cracking and hydrogenation. These result in gasoline and diesel range fuels that meet the environmental regulations. The Dutch Petroleum Industry Association (VNPI)[17] indicates the total refinery hydrotreatment capacity in the Netherlands as 24 Mt/y and the hydrocracking capacity 12 Mt/y for fuels production in the Netherlands (VNPI, 2022). Detailed hydroprocessing capacity per refinery to produce fuels is presented in Appendix B.

[16] Around 5-10% co-processing of renewable feedstock
[17] VNPI changed its name to Association of Energy for Mobility and Industry (Vemobin)

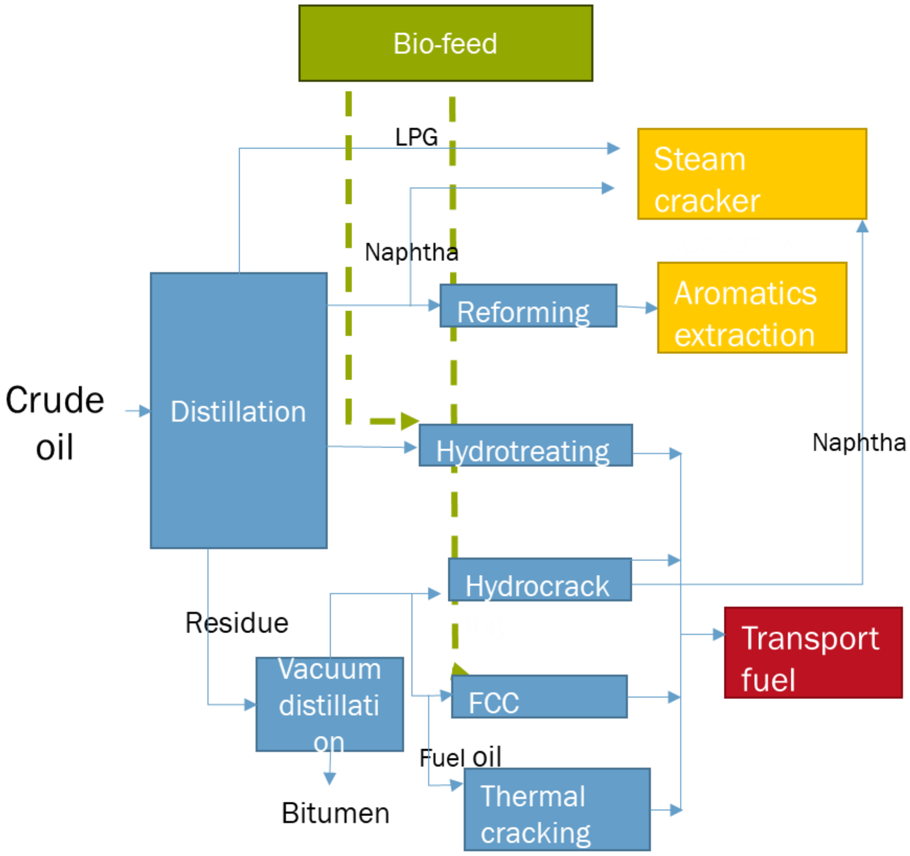

Figure 2.7: Simplified flow diagram of a generic refinery with biomass co-processing

Co-processing can be considered as a near-term option as the oil demand will be significantly reduced in the medium to long term (see Chapter 2.4.1). Therefore, the possibility to expand the renewable feed to 100% and establish stand-alone co-located biorefineries appear as the promising next steps. In Europe, the repurposing of existing refineries and the conversion to Hydrogenated Vegetable Oil/ Hydro-processed Esters and Fatty Acids (HVO/HEFA) have been happening. For instance, ENI has been repurposing its oil refineries in Italy (Portho Marghera in 2014, Gela in 2019) into stand-alone, renewable facility (ENI,2024). The conversion was estimated to cost about one-fifth to one-fourth of the cost of establishing a new greenfield facility due to use of existing infrastructure (ENI, 2014). TotalEnergies refinery La Mède in France was converted to biorefinery between 2015 and 2019 (TotalEnergies, 2024). In the Netherlands, Gunvor refinery has decided to produce HVO from used cooking oil, animal fats and other vegetable oils. The refinery has already been processing some limited amount of biofeed in its existing hydrotreatment facility. With this new plan, next to the existing reactor a new installation for hydrotreatment is planned. By doing so, existing other process installations will be used, such as the amine recovery installation, the acid water stripper, hydrogen supply, the petrol factory, connections to the tank farm for the storage of renewable fuels and utility systems such as water, steam, electricity, nitrogen, refinery gas and sewage.

In 2021, Shell announced its final investment decision to build a biofuel plant adjacent to its refinery in Rotterdam, in which it will convert vegetable and animal oils and fats into biofuels. The plant will produce 820 kt biofuels, of which more than half will be sustainable aviation fuels and the rest renewable diesel. The feedstock base is reported to consist of used cooking oil, waste animal fats and other industrial and agricultural residue products. In addition, a range of certified sustainable vegetable oils, such as rapeseed, will supplement the feedstock input (Shell, 2021).

2.4.5 Feedstock use and availability

Almost all of the commercial plants are currently based on vegetable oils (such as palm, rapeseed, or soybean), animal fats, and used cooking oils. However, use of these feedstocks to produce biofuels are either banned[18] (i.e. use of biomass feedstocks with high indirect land use change (iLUC) impacts, such as palm and soy oil) or capped by the renewable energy directive (REDII) due to sustainability concerns (i.e. used cooking oil and animal fats, and food and feed crop based biomass)[19].

Alternative feedstocks with significant potential for co-processing include bio-oils generated through thermochemical processes like fast pyrolysis, catalytic pyrolysis, or hydrothermal liquefaction (HTL). Unlike fats and oils, these can be derived from abundant sources like forest or agricultural residues. However, it's important to note that these technologies are at different stages of technology readiness. Fast pyrolysis is a commercial technology, but pyrolysis oil from woody biomass contains high water and oxygen and is not compatible with fossil fuel oils to be directly co-processed. The product from HTL technology, biocrude, has lower water and oxygen content making it more advantageous to transport and co-feed. However, HTL technology is less advanced than fast-pyrolysis oil. Appendix D introduces the technology status of pyrolysis and HTL.

Since the pyrolysis technology is already commercial, its use as refinery feedstock has been investigated the most (Seiser at al., 2022; Lammers et al., 2019; Dyk et al, 2019, 2022). Its poor thermal stability and the high oxygen content requires pyrolysis oil to undergo a hydrotreatment to remove some of the oxygen and make it more stable. This so called mild hydrotreatment can be done back-to-back with the pyrolysis process, and improve the transportation costs, or this can be done at the refinery, making use of existing installations.

Table 2.5 provides indicative refinery integration options in the Netherlands and related biomass feedstock demand if the existing hydrotreating and hydroprocessing units for transport fuels are to be utilised. Two options are examined. Option 1 refers to refinery adaptations using lipids. Option 2 refers to converting lignocellulosic biomass into pyrolysis oil and use of this pyrolysis oil in exiting refinery processes. This table shows the order of the magnitude feedstock demand compared to the sustainable biomass potential in Europe. The sustainable biomass potential is based on a recent publication by DG RTD (EC, 2024). This study has updated the European sustainable biomass potential for energy markets and indicates the total biomass supply potential to be in the range of 310-836 million dry tonnes for 2030 and 294 - 892 million dry tonnes in 2050. The European biomass potential, across different sectors can be found in Appendix c. This Appendix also shows a comparison of this study results with other biomass potential assessment studies.

[18] The revised Renewable Energy Directive (RED II) introduced a new approach to address the issue of the iLUC effect. It sets limits on high iLUC-risk biofuels, bioliquids and biomass fuels which pose a high risk of indirect land-use change and are therefore associated with significant GHG emissions. Article 26(2) of RED II provides for a progressive phasing out of high iLUC-risk biofuels mainly from palm oil and soybean oil by 31 December 2030.

[19] Biofuels produced from food and feed crops are limited to their supply in 2020. Biofuels from feedstocks listed in annex IX, part B of REDII are capped to max. 1.7% of transport fuel demand. It is important to note that FuelEU aviation regulation does not introduce any or limitation to the use of biofuels produced from annex IX, list b for the aviation sector.

5-10% co-processing in existing hydrotreaters in the Netherlands would demand approximately 1.3 to 2.9 Mt of lipid input[20], provided that the fuel throughput stays comparable to current level. A full conversion would require almost 29 Mt lipids. To put these numbers into perspective, the sustainable supply potential of UCO and animal fats is estimated to be around 3.9 Mt in Europe in 2030 and 2050 (EC, 2024). Thus, the demand for these biomass resources exceed the sustainable potential in Europe (above 100%), according to the calculated potential by the recent study (EC, 2024). In 2022, however, the EU consumption of UCO and animal fats was exceeding this potential already, with imports from outside Europe, totalling to approximately 5.2 Mt (USDA,2023) and the global consumption of UCO for biofuels was around 10 Mtonnes[21]. In 2022, more than 70% of the UCO based biofuels supplied to the Dutch market was from outside of Europe, China contributing the largest (Nea, 2022). It is important to note that existing installations, whether co-processing or stand alone, currently use other vegetable oils such as rapeseed and sunflower oil, palm and soy oil, next to UCO and animal fats. Nevertheless, we can conclude that this route, regardless of where it is in the form of co-processing or 100% conversion, will be limited.

Co-processing via pyrolysis route appears to demand approximately 3.5 to 7 Mt lignocellulosic feedstocks. The total supply potential of sustainable lignocellulosic biomass in Europe is estimated to be in the range of 380-650 Mt, according to medium and high mobilisation scenarios (EC, 2024). Thus, in average 0.7-1.5% of the European lignocellulosic feedstock potential would suffice to meet the demand. However, when 50% conversion of hydrotreaters is considered, up to 7.5% of the sustainable biomass potential in Europe may be needed to satisfy this. This 50% conversion corresponds to fuel substitution of more than 80% of the aviation and maritime bunkering in the Netherlands in 2019, or more than 20% of the EU international aviation fuel consumption[22] in 2015.

It is necessary to note that these figures are indicative, assuming use of clean wood for the pyrolysis oil integration. A more detailed analysis, where different biomass feedstock compositions are taken into consideration, next to the refinery specifics, will be necessary to provide a more robust understanding.

[20] Applying the lipid conversion of 83% for co-processing in exiting hydrotreatment (Concawe, 2019).
[21] See Global Supply and Trade of Used Cooking Oil (cleanfuels.org)
[22] In 2015, aviation fuel consumption is estimated to be 53.5 Mtoe.

Table 2.5: Integration of biomass use with the existing refineries in the Netherlands[23]

	Hydrotreatment		Hydrocracking	
Hydro treatment capacity in the Netherlands (Mt/y)[1]	24		12	
Co-processing ratio(%)	5%	10%	50% of base capacity	100% of base capacity
Renewable fuel (Mt)	1.2	2.4	6.0	12.0
Option1. Lipid demand (Mt)[2]	1.5	2.9	7.4	14.8
Share as total UCO and AF potential in Europe (%)[3]	37%	74%	190%	380%
Option 2. Raw pyrolysis oil demand (Mt)[4]	2.5	5.0	12.5	25.0
Option 2. Woody biomass demand (Mt)[5]	3.5	7.2	17.9	35.7
Share as lignocellulosic feedstock potential in Europe (%)[6]	0.6-0.9%	1.1-1.9%	2.7-4.7%	5.5-9.4%
Refinery implicates	• Demand for “on-purpose H_2” increased 25 to 100%. • Re-optimisation of existing fossil units. • Moderate reduction in fossil diesel production and slight loss of crude capacity.		• Demand for “on-purpose H_2” increased x2 to x4. • Major reduction in fossil diesel production and major loss of crude capacity with closure of many fossil process units.	

1 the total Dutch hydrotreatment and hydrocracking capacities are derived from VNPI, 2022

2 lipid hydrotreatment efficiency is assumed as 83%; lipid hydrocracking 81% (derived from Concawe, 2019)

3 European potential is 3.9 Mt (see EC, 2024)

4 pyrolysis oil hydrotreatment efficiency is set to 48%

5 pyrolysis oil yield from woody biomass is assumed as 70%

6 lignocellulosic biomass potential to be in the range of 650-380 Mt_{dry} based on high mobilisation versus medium mobilisation scenario of EC, 2024.

There are other ways to produce biofuels from lignocellulosic feedstocks but their compatibility with current refineries is somewhat limited or non-existing. These are:

- Lignocellulosic ethanol pathway: consists of biomass pre-treatment, hydrolysis to fermentable carbon sugars, sugar fermentation, and distillation of ethanol to fuel grade. This pathway has only limited scope for refinery integration, mainly via common use of utilities and logistics.
- Biomass gasification, followed by Fischer Tropsch (FT) synthesis to hydrocarbons pathway: the FT synthesis results in a product, called wax that undergoes further processing steps to produce a number of products such as naphtha, diesel, and kerosene. A low-level co-processing via use of refinery hydrocrackers, or unit transformation, use of utilities including heat, power and hydrogen, or using existing

[23] Follows the Concawe, 2019 calculation method.

FCC for upgrading, product handing, blending and logistics are considered as possible integrations with the existing refineries (Concawe, 2019). Currently, there are no commercial plants that produce biofuels via FT synthesis.

An alternative route to syngas production is the power-to product (PtX) pathways. These pathways involve conversion of CO_2 into syngas using hydrogen from electrolysis using renewable electricity. This e-syngas would get through FT synthesis producing e-wax, and similar integration as the biobased route could be considered.

Biomass gasification followed by methanol synthesis and power-to-methanol pathways are not touched upon here on as these are considered under the chemical sector, even if they can be used for transport. Their integration with the chemical industry appears as a more logical option. Table 2.6 recaps the evaluation of refinery integration of various renewable based value chains.

Table 2.6: Refinery integration of various renewable feed based value chains (adapted from Concawe, 2019)

	Refinery integration	Additional investments	Feedstock availability	Level of integration
Lipids	Diesel hydrotreaters or hydrocrackers can be utilised, resulting in CAPEX savings. Alternatively, FCC unit can be utilised for co-processing.	Requires storage and pre-treatment, resulting in additional hydrogen demand.	Sustainable feedstock availability is limited	Significant
Biomass pyrolysis oil	Use of existing hydrotreaters and hydrocrackers Alternatively, FCC unit can be utilised for co-processing.	Special oil storage for raw bio-oil. Raw pyrolysis oil will need to go under a mild treatment to be stabilised. This will require additional investments and hydrogen demand. In addition, biomass to-pyrolysis oil value chain will need to be established.	Sufficient feedstock	Significant
Biomass gasification	FT can be further processed in existing hydrocrackers.	Biomass to FT wax processes will need to be established. Storge units for FT wax.	Sufficient feedstock	Moderate
E-FT	FT wax can be fed into existing hydrocrackers.	E-FT process will need to be established. Storge units for wax.	Depends on availability of hydrogen and carbon	Moderate

2.4.6 Costs

As stated, current co-processing at refineries is limited. One of the reasons relate to the suitability of biofeed to the existing processes. Bio-oils have different characteristics such as chain length, number of double bonds and the amount of free acids versus triglycerides, which require special treatment during processing (Dyk et al., 2022). This extra processing necessitates higher hydrogen consumption and storage of feedstocks, adding to the overall investment required. Whether this approach is economically viable depends on various factors, including feedstock availability and costs, the potential value of renewable products, and the specific conditions at each refinery.

Although there is limited information available about the investment costs associated with co-processing, it is reported to be significant due to the need for infrastructure, feedstock reception, storage, reactor feeding, and other equipment requirements. Hamelinck et. al. (2021) assumes these costs to be roughly half of a greenfield HVO plant. ENI has estimated the conversion to cost about one-fifth to one-fourth of the cost of establishing a new greenfield facility due to use of existing infrastructure. However, none of these estimates are based on bio-oil from lignocellulosic biomass. CONCAWE (2019) indicates the capital expenditure for feed pre-treatment to be alone approximately 0.05 €/ kt and the full costs to exceed this by a factor of 5.

An IEA study (2020) calculates biofuel production cost via the pyrolysis route, using lignocellulosic feedstocks, comparing the co-processing route with the stand-alone route. This study highlights that the figures are based on Rough Order of Magnitude (ROM) calculations. Data is generally not available, and refineries are different in terms of their investment needs and processing capabilities such that a generic figure cannot be estimated. According to this study, the capital expenditures of a stand-alone system appear to be lower than the co-processing route[24]. There is no detailed clarification behind these numbers. The relatively low production costs of a stand-alone facility may be explained by the higher conversion efficiency assumption (68%), compared to the co-processing biomass conversion efficiency (29%). Yanez et. al. (2020) studies a number of co-processing case studies in an oil refinery located in Colombia, with an average capacity of 250 kbpd. In Yanez et. Al. (2020), the capital cost of refurbishing is assumed to be about 50% of the cost of adding a new unit. While this study acknowledges the uncertainties surrounding such comparison due to different technology readiness levels and related cost entailments, it shows the fast pyrolysis co-feed to the refinery with a max of 10% co-feed as the low cost option, among the different co-processing options. This study indicates that higher pyrolysis oil co-feed, with esterification of pyrolysis oil increases the production cost significantly. Unfortunately, this study does not include a stand-alone process to make a comparison between the co-feed versus stand alone. TNO has also conducted an analysis of levelized cost of biofuels production via biomass pyrolysis, followed by two stage hydrotreatment, thus considering a stand-alone process. This resulted in approximately 28-30 €/GJ, which falls within the IEA (2020)calculation range. The main assumptions regarding the financial parameters used in these studies can be found in Table 2.7.

In conclusion, while 5-10% co-feed may be the low cost option, for higher levels of co-feed detailed techno-economic analysis will be needed, where the refinery specifications are taken into account.

[24] The specific investment of a co-processing value chain is highlighted to be in the range of 2250 - 4000€/kW, whereas a dedicated stand alone upgrading total investment was mentioned as 2340 €/kW.

Table 2.7: Comparison of bio oil co-processing with stand-alone production of biofuels via pyrolysis and HTL

Literature	Pathway	Co-feed rate	Biomass price	**Biofuel production cost**	Of which bio oil production	Of which bio oil co-processing
			€/GJ	**€/GJ**	€/GJ	€/GJ
IEA (2020)	Co-processing		2,8	21,9	10.8	1,7
			5,6	38,6	18.1	1,7
E. Yanez, et al. (2020)	FPOtoFCC	10%	3,4	17,0	5,2	12,0
	FPOe[1]toFCC	20%	3,4	31,0	24,8	5,8
	FPOe[1]toHDT	20%	3,4	25,0	20,5	4,2
	HTLOtoHDT	15%	3,6	21,0	12,7	8,0
IEA (2020)	stand-alone	100%	2,8	22,8	-	-
		100%	5,6	35,3	-	-
TNO	stand-alone	100%	5,00	28-30	-	-

1 this includes esterification of fast pyrolysis oil for the co-processing.
FPO: fast pyrolysis oil; FCC: Fluid Catalytic cracking; FPOe: Fast pyrolysis oil that is esterified: HTLO: Hydrothermal liquefaction oil; HDT: Hydro-processing

2.5 Process relocation due to de-fossilisation

It is highly uncertain how the companies strategies will evolve and what pathways the Dutch refineries will follow. Nevertheless, they will need to transform and adapt to the changing market conditions. Oil refining will shrink but this trend will also occur in other countries and regions under the assumption that the Paris Agreement goals are pursued globally. Under this consideration, new supply chains based on renewable resources will emerge and they may occur elsewhere. This relates to the limited availability of biomass resources in the Netherlands, when compared with the order of the magnitude demand to retrofit existing hydroprocesses and cracking processes, or the demand for the large bunkering in the country.

Figure 2.8 illustrates the possible options to consider, provided that the existing assets in the Netherlands are to be used. Within the first two options, the (re)location refers to feedstock collection and their conversion to a transportable commodity. Alternative three refers to the possibility of importing solid biomass. In these options, the relocation is limited to the collection and densification of solid biomass and its transportation. Solid biomass has already been traded in the form of wood chips and wood pellets. In 2021, the total woody biomass import to the Netherlands was approximately 3 million tonnes (dry) for energy production, and exports were approximately 0.9 million tonnes (CBS, 2023c)[25]. The last

[25] Nationale balans vaste biomassa, 2021

option refers to the possibility of importing the end product, thus biofuels, from elsewhere. This case refers to a full relocation of the value chain.

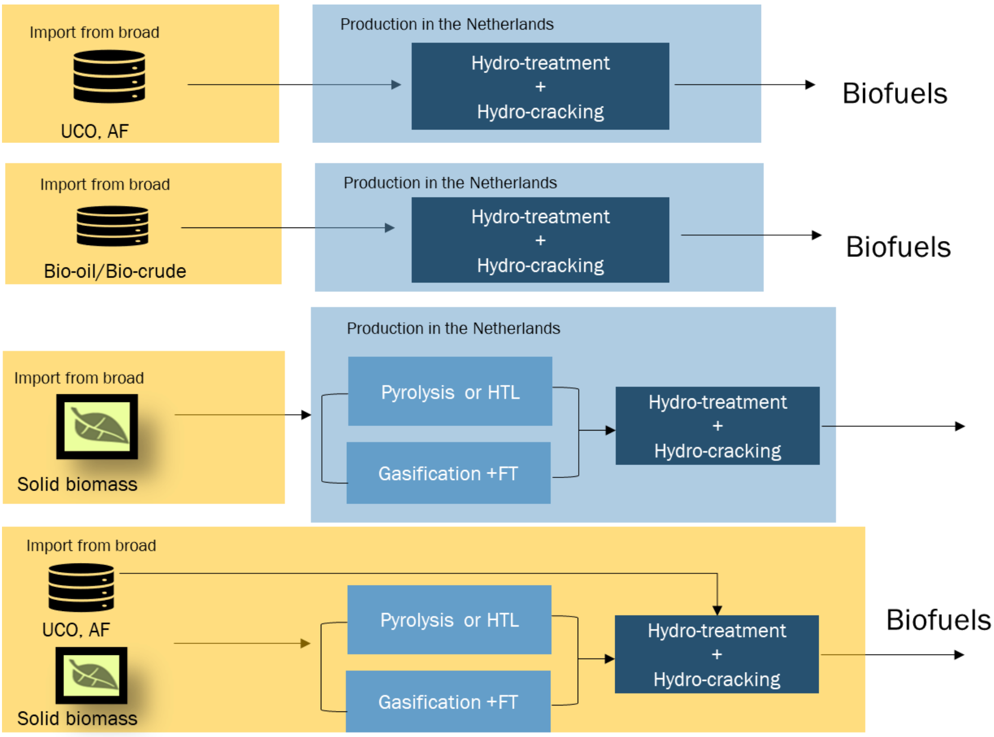

Figure 2.8: (Re)location risks related to the adaptation of existing assets to produce biofuels

The following aspects are of importance in analysing the likelihood of each value chain:

An important factor relates to the establishment of biomass (intermediate) supply chains and related costs to the Netherlands and, once they become tradable commodities, the market prices of these renewable materials should also be considered in this analysis. In addition, costs associated with the adaptations needed to integrate those value chains with the existing assets, and the selling price of renewable fuels will be key parameters for decision making. Mobilising biomass feedstocks in sufficient quantities with affordable prices will be important both for adapting existing refineries and for establishing stand-alone biorefineries. The low bulk density of many different biomass feedstocks, combined with their divergent chemical compositions, will necessitate pre-treatment and densification. Thus, conversion of primary biomass into intermediate energy carriers in close proximity to the feedstocks will be needed.

- There is already a commodity market for wood chips and wood pellets. Bioethanol and biodiesel have been traded globally. In addition, fats, oils and greases including used cooking oil are collected globally and have been used to produce biodiesel or renewable diesel, and traded volumes have increased.
- However, there is need for establishing new bio-based commodity markets to enable mobilisation of biomass feedstocks with low energy density, such as agricultural residues.
- As stated in the previous section, biomass pyrolysis and hydrothermal liquefaction are suitable feedstocks for existing refinery integration and promising routes to convert biomass into tradable commodities. However, these technologies need to

be scaled up and implemented commercially for different types of biomass feedstocks.

- While densification could reduce transportation costs, additional costs associated with this step, along with decreased overall mass and energy yield, would influence the overall economic performance. Jong et al (2017) have studied cost reduction strategies for biofuel production, where integration with existing industries, and distributed supply chain configurations (i.e., supply chains with an intermediate pre-treatment step to reduce biomass transport cost), have been looked into. HTL was used for the analysis of a supply chain with intermediate HTL crude production and transport versus centralised biofuel production (thus HTL crude and further upgrading to biofuels in a centralised location). The study results showed that distributed supply chain configurations do not provide a significant cost benefit, when compared with the centralised supply chain. This is because, producing HTL crude and transporting this to the upgrading (final conversion) locations results in loss of synergies between the HTL and upgrading processes (i.e., off gas integration and shared utilities). Thus, the lower transportation costs are outweighed with the integration benefits. Nevertheless, a distributed bio intermediate supply chain will involve many other benefits, such as utilising a wider variety of different types of biomass feedstocks, access to larger volumes, increasing local experiences with feedstock handling. In this regard, a more comprehensive assessment taking wider system aspects is needed.

In 2024 TNO has explored different future visions, where the Dutch energy system would achieve carbon neutrality by 2050. The TRANSFORM scenario described a future vision where the energy system in the Netherlands will become carbon neutral by 2050. In addition, the GHG emissions from international bunkering (both aviation and maritime shipping) will be zero by 2050. The TNO energy optimisation model OPERA has been deployed to illustrate the cost optimal way of achieving the set targets. Further details of this scenario modelling can be found in Scheepers et al, 2024.

Figure 2.9 presents the TRANSFORM scenario modelling results concerning the transition of refineries in the Netherlands. As oil refining diminishes, renewable refineries emerge, continuing to produce both transport fuels and feedstocks for the chemical industry. Renewable refineries cover biomass and renewable electricity based renewable fuel and feedstock production facilities, excluding renewable methanol and ammonia. These two commodities are grouped under the chemicals in this scenario modelling even when they are used for the transport sector.

Up to 2030, biomass value chains appear as the cost-effective option, maintaining stability until 2050. In 2030, almost half of the biofuel production relates to HVO from UCO, highlighting the integration opportunities with the existing hydrotreatment processes. Beyond, while HVO/HEFA continues to play an important role, biomass gasification followed by the FT synthesis to produce kerosene becomes equally important. This value chain supports the deployment e-FT kerosene production by supplying biogenic CO_2.

Due to limited supply of sustainable biomass feedstocks[26] and increasing competition for chemicals production, there is a shift towards deploying synthetic fuels and feedstocks. An essential factor here is the availably of biogenic carbon for synthetic fuels production. Therefore, a biomass-to-fuels and feedstocks value chain, with biogenic carbon captured within the process, becomes favourable. This biogenic carbon can be partially stored for

[26] The study assumes the solid biomass import of 650 PJ, of which 550 PJ from the EU.

negative emissions and partially utilised for synthetic fuels production. Thus, the low cost in terms of capital expenditures and operation expenditures versus low cost in terms of a full system optimisation may mean different things.

It is important to note that this is not a forecast, but a scenario projection within a pre-determined framework and Dutch circumstances.

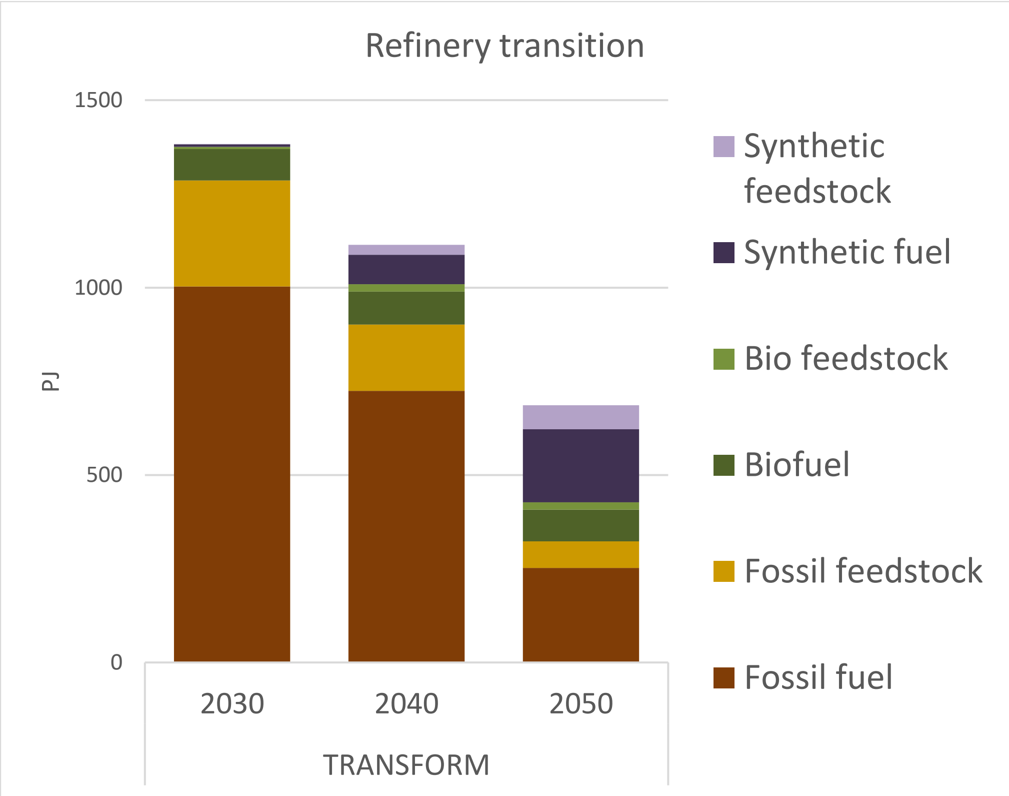

Figure 2.9: TRANSFORM scenario results relevant for the refinery transition

2.6 Discussions, conclusions, and further research needs

2.6.1 Discussions for this sector

This study examines the potential risks associated with relocating certain refinery processes due to the shift towards renewable energy resources in line with the efforts to reduce industry's reliance on fossil fuels and achieving net zero emissions by 2050. It serves as a starting point for broader discussions on transforming the refining industry in the Netherlands, focusing on developments beyond 2030.

The current policies primarily target reducing GHG emissions from industrial processes to meet the national Climate Agreement, REDIII and EU ETS goals. Achieving GHG emission reduction targets does not necessary require refineries to switch to renewable energy carriers. Alternative carbon reduction options, such as carbon capture and storage can also be utilised. However, this study does not delve into all possible options for reducing direct emissions or associated relocation risks. Related to this, the aim of this study should not be confused with the carbon leakage issue. Carbon leakage refers to production shifting to other countries as a consequence of the cost implications of climate policies. This could result in a rise in their overall emissions and certain energy-intensive industries, such as refineries, are particularly vulnerable to this risk.

European refineries already face several challenges, including overcapacity and intense competition, leading to downsizing or shutdown of several refineries. Since 2009, out of close to 100 refineries operating in Europe, 26 refineries (threshold > 30 kbbl/d or 1.5 Mt/y) were closed or transformed (Concawe, 2024). Thus, the focus has not been on the future leakage risks associated with the competitiveness of individual refineries.

This study reviews the current decarbonisation plans of companies owning refineries in the Netherlands, to understand their future strategies. However, the information is limited to their announcements and publicly available data. While we draw some indicative conclusions regarding their strategic importance relative to the overall capacity of these companies' refineries, this is not sufficient to make any concrete conclusions. For instance, the Dutch refining capacity of Shell and BP appears more than 40% of the companies European refining capacity and approximately 25% of the companies global refining capacity. This information alone cannot be translated into willingness to use their existing assets and retrofit to renewable refineries in the Netherlands. At the same time, they play a strategically important role due to their integration with the chemical clusters in the ARRRA region (Antwerp-Rotterdam-Rhine-Ruhr-Area).

The availability and sustainability of biomass for energy have long been debated, with studies offering wide-ranging estimates of biomass potential in Europe and globally (i.e., S2Biom, 2018, JRC, 2018; Calipolies et al., 2021). While this study doesn't extensively analyse biomass potentials, it acknowledges the complexity of quantifying biomass supply potential for the Netherlands due to differing study results and the diverse nature and dispersion of biomass feedstocks. For instance, a PBL study (2020) indicates the sustainable biomass potential in Europe to be 14.9-29.7 EJ in 2030 and 16.8 EJ in 2050, whereas the recent EC study (2024) mentions the biomass potential for biofuels to be 5-13.6 PJ in 2030, and 4.8-14.6 EJ in 2050 in Europe. Next to that, large-scale, centralized biorefineries are considered cost-optimal for producing biofuels due to economies of scale and integration opportunities, but mobilizing biomass feedstocks requires careful consideration as they are diverse in their chemical composition and are dispersedly located.

The document introduces possible refinery adaptations for transitioning to renewables, particularly biomass. However, each refinery in the Netherlands has different configurations and production capacity and retrofitting some of these refineries may prove to be very challenging and costly. Therefore, a case-by-case assessment should be done in close collaboration with the refineries.

The outlook for fossil refineries is presented based on the scenario projections. The general trend observed is that they will shrink, but at what level is uncertain. Nevertheless, such a shrink will have significant implications to the surrounding environment of refineries. Shell Pernis, for instance, is connected to the Shell Nederland Chemie site in Moerdijk delivering naphtha and several basic chemicals. Shell Nederland Chemie converts product streams of the refinery into products such as propylene, Methyl tert-butyl ether (MTBE) and polyether polyols. Shell Pernis refinery is also closely linked in terms of energy with the Shell Nederland

Chemie Pernis. In addition, the surrounding companies such as Hexion, Shell Nederland Chemie and Shin-Etsu are strongly dependent on steam and refinery gas supply from the refinery. Esso refinery is also closely connected to the ExxonMobil chemicals. This refinery is also linked to the Rotterdam aromatics plant (RAP) and the Rotterdam plasticizers plant (RPP). At some distance in Europoort Rotterdam Esso is connected with the oxo-alcohols plant (ROP). Air Products has its hydrogen facility on this site to deliver hydrogen to the refinery hydrocracker unit. This 300 t/day steam methane reformer (SMR) plant uses on average 60-70% of refinery gas input, and additionally uses natural gas. A relatively large share of the products is sold to the petrochemical sector (steam crackers, aromatics). Fuel gas and steam are delivered to ExxonMobil RAP and ExxonMobil RPP, and some fuel gas to Air Liquide. Moreover, these refineries are connected with the other industrial clusters in the ARRRA. These connections allow oil and refinery product (such as naphtha and multiple other petroleum products) transportation to and between refineries and steam crackers.

2.6.2 Conclusions

Dutch refineries are well-placed due to their large seaports allowing for the import of fuels and raw materials, along with a robust infrastructure with excellent inland connections for transporting materials. Additionally, their integration with the petrochemicals industry, both locally and regionally, positions them favourably to adjust to evolving supply-demand dynamics.

However, meeting the goals of the Paris Agreement and achieving climate neutrality by 2050 will significantly impact oil refineries, especially regarding policies aimed at decarbonizing the transport sector. This will lead to a decrease in demand for oil products, particularly demand for transport fuels.

Globally, there can be a substantial reduction in fossil fuel demand by 2050, with Europe to see a decrease of 75-90%, within the carbon neutrality framework. This will likely result in significant reduction of refinery throughputs and closures unless they can adapt to changing market conditions by shifting towards producing feedstocks for chemicals and renewable fuels.

Thus, fossil fuel refineries will need to transform and begin producing renewable fuels using existing assets and infrastructure. In the short term, this can be achieved through biomass co-processing, while in the mid-to-long term, refineries can undergo conversion to fully utilize renewables. Access to biomass resources will be crucial, considering the limited availability of domestic resources. While there is a market for lipids like vegetable oils and used cooking oils, competition for these feedstocks is already high. Mobilizing other biomass feedstocks such as agricultural and forestry wastes and residues will be necessary to achieve higher volumes.

Although this study provides a rough estimate of the biomass needed to utilize key assets in the Netherlands, each refinery has unique characteristics that must be considered. Configurations, product slates, and site-specific factors vary, and not all sites may be suitable for adaptation. Further research is required to determine the appropriate scale for upgrading in each refinery, considering factors like access to available hydrogen.

Relocation risk within refinery transitions is tied to biomass resource supply, pre-treatment processes like densification or liquefaction, and transportation. While full relocation of the value chain from biomass supply to biofuel production is possible, it may not be the most strategically favourable option. Biorefineries offer various benefits to countries, including enhancing energy security, providing feedstocks for the chemical industry, supplying CO_2 for renewable electricity-based refineries (power-to-X), and achieving negative emissions through CCS.

2.6.3 Further research needs-recommendations

This study has been part of a wider study related to heavy industry in the Netherlands and the supply of renewable resources. Therefore, it stays as explorative, and more research is needed to provide sound policy recommendations. The recommendations regarding further research need are as follows:

- Each refinery has different configurations and the product slate, and they should be studied in detail to identify whether they are suitable for conversion to renewable refineries.
- A detailed study for the Dutch refineries should be complemented by an EU-wide study where the European refineries are covered. This would investigate the optimal use of existing refining capacities in Europe and the relative importance of Dutch refining.
- Timely supply of biomass resources in large quantities will be essential not only for refinery conversions but also to attain transport sector related climate mitigation objectives. While the current studies indicate significant amounts of biomass resources, their mobilisation has not been happening. There is a need for good understanding of mobilisation strategies and the related investment needs.
- There is a strategic value of having fully integrated biomass-to-fuel refineries in the Netherlands. This strategic value relates not only to supply part of the transport fuels, but also provide biogenic naphtha to the chemical industries and the biogenic CO_2, which can be stored for negative emissions and/or used for the production of carbon carrying synthetic fuels.
- Further research on synergies between biomass to fuels and feedstocks and renewable power to fuels and feedstocks is needed to identify better business cases.
- Related to above, in retrofits, the green hydrogen demand will increase significantly, and the availability and affordability of this hydrogen will be one of the key considerations.
- In addition, in the medium-to-long term, e-fuels value chains will require biogenic CO_2 highlighting again the importance of biorefineries.

3 Large volume organic (LVO) chemicals

3.1 Current status

There are three companies that produce High Value Chemicals (HVC) in the Netherlands. Table 3.1 summarizes the production capacities of the steam cracker facilities located in the country. The total capacity represents 16% of the total EU+UK ethylene production capacity (total production capacity of the EU countries and UK is based on data retrieved from CEFIC, 2013).

Table 3.1 - Production capacity in the Netherlands for the main HVCs (Petrochemicals Europe, access 2023 & Heino et al., 2017)

	Capacity (kt/yr)			
Site	Ethylene	Propylene (calculated)*	Butadiene (calculated)*	Aromatics (calculated)*
SABIC (Geleen)	1310**	616	187	400
Shell (Moerdijk)	910	428	130	278
Dow (Terneuzen)	1825	858	260	558
Total	4045	1903	576	1236

* Ethylene production capacity values are original numbers from the Petrochemicals Europe database extracted in 2023. Propylene, butadiene and aromatics capacities were estimated considering the production ratios for a typical naphtha steam cracker, as described by the Best Available Techniques report from the Joint Research Center (Heino et al., 2017)

**This value does not consider the possible closure of one of the steam crackers as announced by SABIC in January 2022 (Argus, 2022)

The feedstocks used by Dutch steam crackers consist of naphtha and LPG and, in some cases, recycled ethane and propane. The average naphtha use was 302 PJ (6.9 Mt) between 2017-2022 in the Dutch petrochemical industry; this number was 94 PJ (2.1 Mt) for LPG (CBS, access 2023d).

The steam crackers have a strategic location and are heavily connected to other industrial clusters in the Antwerp-Rotterdam-Rhine-Ruhr-Area (ARRRA). Figure 3.1 shows the main pipeline systems that allow feedstocks and chemicals transport between different industrial sites in the ARRRA. Notably, crude oil, naphtha and ethylene are the main materials transported.

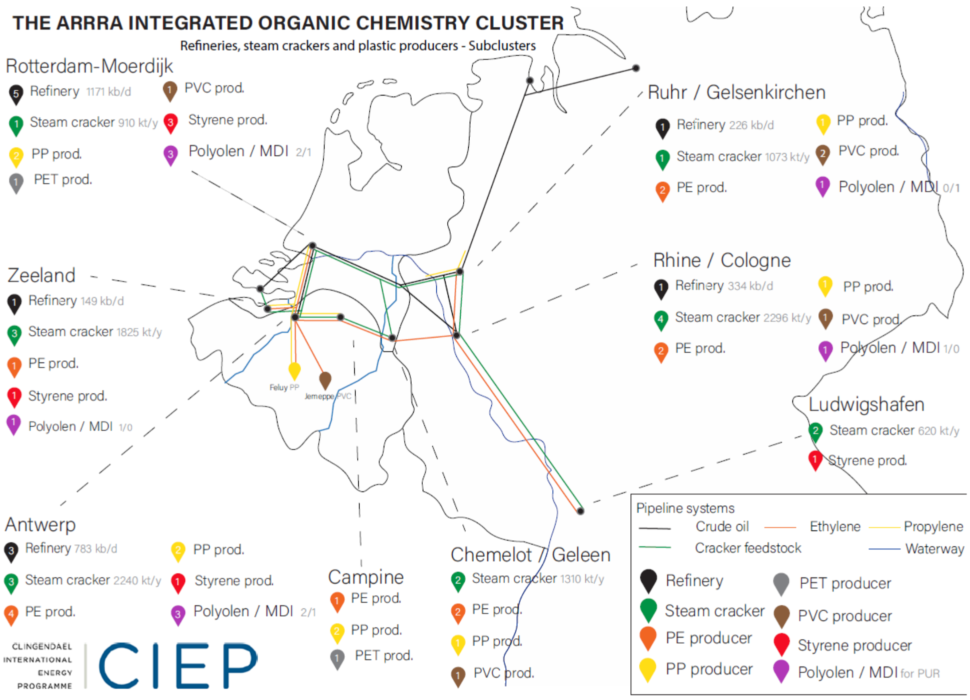

Figure 3.1 - Refineries and steam cracking sites in the ARRRA region and the main pipeline infrastructure (CIEP, 2021)

Olefins and aromatics together known as high value chemicals (HVC) are relevant for the production of a wide range of materials that are used for different applications, as illustrated by Figure 3.2. The chemical sector supply chain can be quite complex; therefore, this study will focus on the most relevant chemicals in terms of volume and on those parts of the value chain with higher risk of relocating.

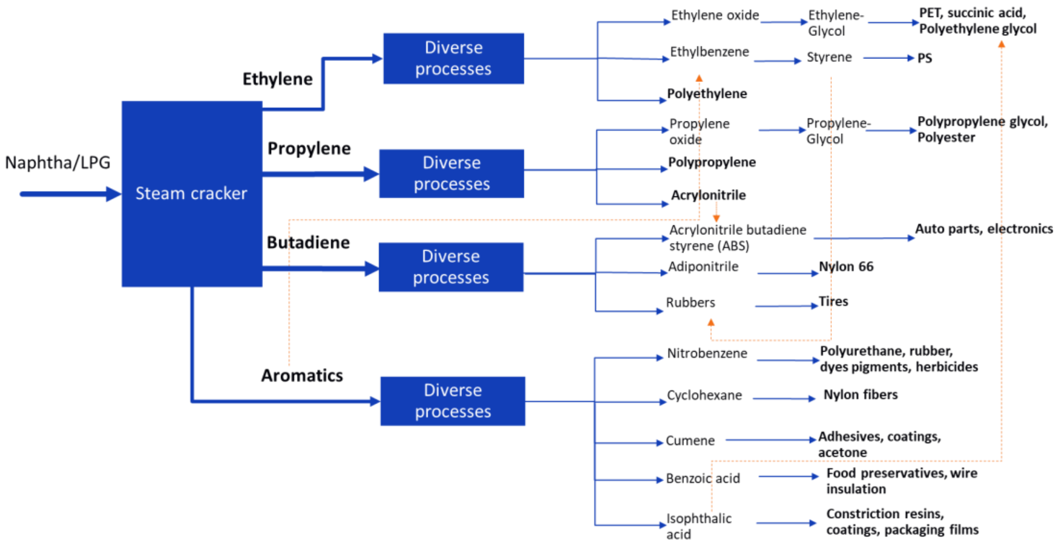

Figure 3.2 - Current value chain of basic chemicals and polymers

Figure 3.3 and Figure 3.4 summarize the trade flows from and to the Netherlands in 2021 of those chemicals that are key in terms of production volume within the presented value chain. The trade flows are relevant to assess the exchange dynamics of such materials and helps to identify which activities from the value chain are more prone to relocation.

The figures below show that, among the basic chemicals, ethylene and propylene are the most relevant in terms of export activity, specially within the EU and exports of polyethylene are by far the highest when compared to other semi-finished products. Regarding imports, propylene, benzene and polyethylene present the highest volumes. Imports and exports to/from the Netherlands and from/to other countries outside the EU are smaller compared to the numbers within the EU. Due to physical properties, long distance transport (e.g., via ships) of ethylene and propylene is difficult, however, the robust pipeline infrastructure around the ARRRA region facilitates trading activities of these chemicals within the EU. The semi-finished products present in Figure 3.4 are normally transported in form of pellets, which the transport via ships is possible, facilitating imports and exports from/to overseas.

In short, although ethylene, propylene and butadiene are traded within the EU, their transit is limited to the current pipeline infrastructure and the import overseas is not practical, which diminishes the risk of importing these olefins from other countries. On the other hand, the long-distance transport of polymers pellets is easier and could increase if Dutch pellets become less competitive in the market, allowing relocation of part of the value chain. Examples of how the relocation of polymers pellets production could take place is explored in section 3.2.

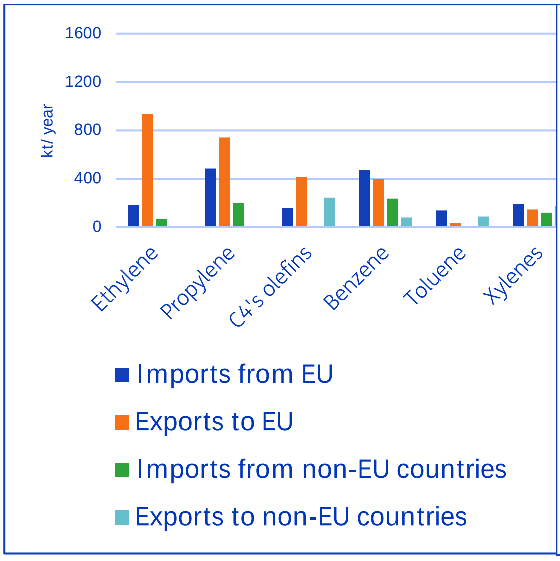

Figure 3.3 - Trade volumes from/to the Netherlands in 2021 of basic chemicals (CBS, access 2023e)

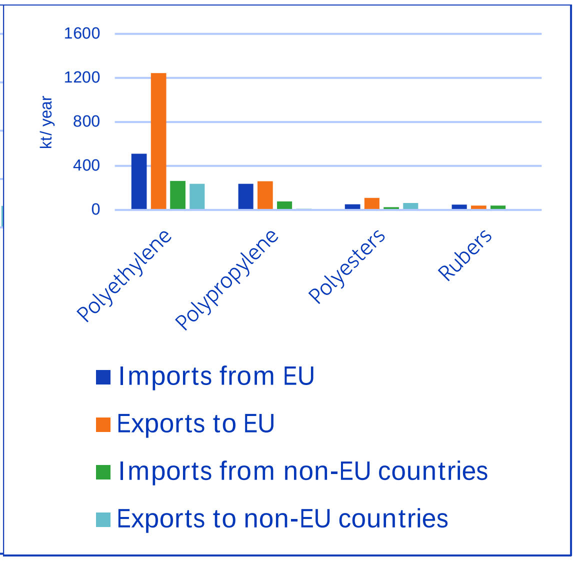

Figure 3.4 - Trade volumes from/to the Netherlands in 2021 of semi-finished products (CBS, access 2023e)

3.1.1 Policies relevant for LVO chemicals value chain

The main policies and communication that could influence the value chain of plastics and, therefore, the large organic chemicals are listed in this section. There is still quite a lot of uncertainty of how these policies will concretely take place and how the market will react, this summary intends to give some light of the main factors that could impact to significant changes in the value chain studied.

EU transition Pathway for the Chemical Industry
In 2023, the European Commission published this plan, co-developed together with industry stakeholders and NGOs. This document brings guidelines and identifies the actions and conditions needed to achieve green and digital transition and improve resilience in the chemical industry. The strategy presents a high-level transition pathway for the chemical industry towards sustainable future and one of the topics covered refers to circularity, which is quite relevant for the LVO chemicals value chain. The document also highlights which regulation and communication directives are relevant for the sector, such as Single-use plastic directive (SUPD) and sustainable carbon cycle (SCC) which are briefly described in this chapter.

(EU) 2019/904 Single-Use Plastics Directive
The directive focuses on promoting circular approaches that prioritize re-usable products and recycling rather than single-use products. Among other categories, this directive applies to certain single-use plastics, such as cutlery, plates, straws, stirrers, cotton bud sticks, and specific plastic packaging items. The aim is to reduce the impact of certain products on the environment, some of the measures include:

- action from member States to reduce use of single-use plastics by defined targets by the countries.
- member states should include restrictions on placing single-use products on the market, prohibiting specific products (e.g., plastic plates, cutlery, food containers);
- product requirements: specific guidelines on how improve sustainability of certain single-use products, such as PET bottles should have at least 25% of recycled plastic in their composition.

The mentioned measures indirectly affect the high-value chemicals industry, including propylene and ethylene production, as they drives demand for alternatives to traditional plastics.

Sustainable Carbon Cycle - (COM(2021) 800)
This is a communication document that focuses on the short-term actions to upscale carbon farming as a business model, motivate practices on natural ecosystems that increase carbon sequestration, and promote new industrial value chains that target sustainable capture, recycling, transport, and storage of carbon. The focal point of this communication to boost activities that either reduce GHG emissions or remove carbon from the atmosphere. It discusses the establishment of a regulatory framework which identifies of the activities that remove carbon from the atmosphere and can decrease the atmospheric CO_2 concentration. This framework should also cover the certification of carbon removals, based on robust accounting methodologies, for high-quality sustainable carbon removals from both natural ecosystems and industrial solutions. Because one of the discussed measures in this communication is the reduction of industry dependency on carbon by promoting circular economy, the framework would impact directly LVO chemicals value chain, especially if sustainable carbon targets towards 2050 are set for the industry sector. Alternative

feedstocks and technology that rely on circular carbon would be favoured by the framework measures.

Packaging and packaging waste, amending Regulation (PPWR)
This regulation aims to minimize the environmental impact of packaging and packaging waste. It sets targets for the recovery and recycling of packaging materials, promotes the use of reusable and recyclable packaging, and establishes requirements for the management of packaging waste. Among other measures, the regulation includes restrictions for substances/additives in packaging (e.g., restrictions on the presence of lead). Furthermore, all packaging would have to be recyclable (designed for recycling by 2030 and can be recycled at scale from 2035). The proposal also introduces minimum recycled content in plastic packaging from 1 January 2030 (e.g., 30 % for single use plastic beverage bottles), with some exemptions (e.g., for medical devices), the percentages would increase from 2040. Depending on how these targets are eventually put into practice in the EU, the impacts on the LVO chemicals value chain may differ, especially in relation to recycling rates and feedstock use.

Ecodesign for sustainable products regulation (ESPR)
Proposed regulation lays down rules applying to all products placed on the EU market (including those imported to the EU), with the aim of boosting circularity. The focus of the regulation requirements go beyond energy efficiency, to aspects such as recycled content, carbon and environmental footprints, product repairability, reusability and the presence of chemical substances that creates barriers for recycling will also be covered. The regulation also introduces the concept of a “digital passport”, in which information about the product’s sustainability would be available to authorities and consumers. It is expected that the regulation also covers plastics products, therefore, it would impact several aspects of the LVO chemicals value chain, such as carbon sourcing.

Carbon border adjustment mechanism (CBAM)
The EU’s Carbon Border Adjustment Mechanism (CBAM) is a tool designed by the European Commission, aiming to put a fair price on the carbon emitted during the production of carbon intensive goods that are imported by EU countries. CBAM will apply in its definitive regime from 2026, until then the transitional phase is taking place, which is aligned with the phase-out of the allocation of free allowances under the EU Emissions Trading System (ETS). This pricing scheme will initially apply to imports of selected goods: cement, iron and steel, aluminium, fertilisers, electricity and hydrogen, which were identified by the Commission as presenting high risk of carbon leakage in the short term. The objective of the transitional period is to serve as a pilot and learning period for all stakeholders (importers, producers and authorities) and to collect useful information on embedded emissions to refine the methodology for the definitive period. It is still uncertain whether such a scheme will be extended to plastics value chains, however, depending on how the transition period goes, there is a possibility that such products will be added to the CBAM mechanism after 2026.

Other energy related policy instruments, such as EU ETS and REDIII (see Section Current status of dutch refineries 2.1) focuses on reducing direct emissions in industry, including the LVO chemicals industry.

3.1.2 Decarbonisation of high-value chemicals production and the company plans

The MIDDEN (Manufacturing Industry Data Exchange Network) database includes reports for the steam cracking sites of SABIC, DOW and Shell Moerdijk, which describe a series of decarbonisation options for the sector. These options are summarized in the following paragraphs (Wong, L & Van Dril, T., 2020; Oliveira, C. & Van Dril, T., 2021; Eerens, H. et al., 2022):

1. Electrification: Electrification of cracking furnaces refers to the use of electricity to meet the process heat demand, substituting the conventional gas-fired furnaces. The technology development follows two different approaches: retrofitting existing steam crackers and replacing gas-fired burners with electric heating systems; the other route focuses on entirely new methods of electric heating and radical innovation of the cracking technology. This entails, for instance, the development of novel techniques for direct heating, such as the production of ethylene via plasma technology using methane as feedstock. Brightlands, the research centre located in the Chemelot cluster, is working on developing such technology in the so-called Plasma Lab. The lab presents a small-scale pilot reactor for experiments. The first approach is more likely to be ready for commercial application sooner than the second. When furnaces are electrified, there will be a significant amount of fuel gas (methane-rich by-product from cracking reactions) available, which is normally used as furnace fuel in the conventional process.

   Electrification of steam driven compressors: the major compressors in a steam cracking facility are driven by steam turbines (e.g., cracked gas compressor), the substitution of such equipment by electrical machines would significantly reduce the steam consumption on site. Also, companies see this application as an important step to stablish electric cracking systems.

2. Hydrogen as fuel: The aim of this option is to replace the fuel gas by hydrogen as energy source for the steam cracking furnaces. Hydrogen combustion generates only water, therefore, its use in replacement of natural gas and/or fuel gas in fired processes results in reduction of direct CO_2 emissions. To avoid carbon leakage, the hydrogen used should be produced through a low CO_2 process. In principle, the application of hydrogen as a fuel would require changes in the operating conditions related to the combustion itself and the installation of burners that are capable to burn gas with high concentration of hydrogen. Also, hydrogen combustion releases exhausted gases with high concentration of NO_x components, being necessary the addition of a NO_x abatement device to the exhaustion system.

3. Alternative feedstock: Bio-naphtha: as a substitute for fossil feedstock to steam crackers, bio-naphtha can be supplied via different production routes, such as a by-product from the manufacture of Hydrotreated Vegetable Oil (HVO) or from biomass gasification followed by Fischer-Tropsch. This biobased feedstock has already been used by the major players from the petrochemical sector. The largest European producer of bio-naphtha is located in the Netherlands (Neste with nameplate capacity of 1.3 Mt/year) (S&P Global, 2021). Plastic solid waste (PSW) can be used as feedstock in steam crackers via pyrolysis, a process that converts the waste into a fuel oil that can be upgraded to naphtha level. Pyrolysis can be defined as thermal cracking process in an inert atmosphere, under controlled temperatures. The raw pyrolysis oil most likely will need to be hydrotreated in order to be used as naphtha replacement. This option has been explored by the major

players in the petrochemical sector. SABIC, together with PlasticEnergy are building a 20 kt/yr (input) pyrolysis plant in Geleen, The Netherlands.

4. Alternative processes:

   a. Dehydration of bioethanol: this option allows the production of bio-based ethylene. The bioethanol is normally produced via fermentation of sugars (sugar cane, for instance). However, there is also the possibility of obtaining ethanol via fermentation of lignocellulosic biomass.
   b. Methanol to olefins: catalytic conversion of methanol into olefins (ethylene, propylene, and butadiene). Currently it is widely applied in China with coal-based methanol. However, the future projects intend to use renewable methanol as feedstock (bio and/or e-based).

5. CCS/CCU: Carbon capture from exhausted gases leaving the steam cracking furnaces. The concentration is normally low (8-10% vol.), which increases the cost of capture. A relevant aspect for CCS is the location of the site, since its proximity to CO_2 infrastructure and storage location under the North Sea influences the feasibility for CO_2 storage. For instance, sites located far from the coast could face limitations regarding CO_2 transportation.

A summary of main strengths and weaknesses for the application of each technology is presented in Table 3.1.

Table 3.1 - Technology options strengths and challenges HVCs sector

Technology	Strengths	Weaknesses	Technology readiness level	Emissions scope/ relevance to renewable feedstock supply
Post-combustion CCS in steam crackers	No major changes in current assets are needed. Infrastructure for CO_2 transport is being currently developed in some locations close to industrial clusters (PORTHOS). Relevant for scope 1 emissions reduction.	CO_2 concentration normally is quite low in flue gases. CO_2 transport can be challenging if site is not located close to the sea. Storage limitation Policies might limit the fossil products market.	TRL range 5-7, this technology has been developed and tested at significant scale, but it hasn't yet reached full commercial deployment.	Reduction of direct process emissions (scope 1). Not relevant to renewable feedstock supply.

Technology	Strengths	Weaknesses	Technology readiness level	Emissions scope/ relevance to renewable feedstock supply
Electric cracking	Scope 1 emissions reduced completely. Companies are building consortiums to develop electrification technology. Reduction of scope 1 and when renewable electricity is used also scope 2. However, the residual fuel gas should be repurposed	Excess of fuel gas requires sustainable destination, otherwise it could lead to carbon leakage. If electricity supply is not renewable, the scope 2 emissions are high and the overall GHG emissions impact is higher than the conventional process. Requires significant amount of renewable electricity. Little flexibility in operation when it comes to electricity supply fluctuation, reliable supply of electricity is crucial.	Still in early stage of development (TRL 3-4), being the main challenges related to the electricity provision infrastructure and availability of renewable electricity. However, most steam cracking companies envision the application of such technology as relevant to reach net zero emissions in the long term (2040-2050).	Reduction of direct process emissions (scope 1) and when renewable electricity is used also related emission (scope 2). However, the residual fuel gas should be repurposed. Not relevant to renewable feedstock supply.
Methanol to olefins (MTO)	High efficiency towards olefins, when compared to steam crackers. Commercially available technology. Diverse projects being developed in the Netherlands focusing on renewable methanol production/imports. Long distance transport of methanol is doable.	It does not produce the other HVCs besides olefins, such as aromatics (unless if dedicated technology as methanol to aromatics -MTA). Competition with other sectors for renewable methanol supply.	Commercially available, several installations in China (TRL 8-9). However, the challenge relies on the availability of renewable methanol. For instance, biomass to methanol process has a TRL falls under the range of 7-8.	Potential to reduce scope 1, 2 and 3 depending on the type of methanol used and its origin. Relates to renewable feedstock supply.
Bio-ethylene via bioethanol dehydration	Use of renewable carbon in the value chain Less energy demand compared to fossil ethylene. Bio-ethanol catalytic dehydration technology commercially available and competitive. CO_2 tax and other policy measures such as CBAM could make this option more attractive economically Development of bio-ethanol production via lignocellulosic feedstock. Long distance transport of bioethanol is doable.	Highly dependent on biomass availability Price gap with fossil ethylene. The production via sugarcane is difficult to replicate in EU. Bioethanol used for bio-ethylene could compete with fuel sector. Dependent to the mobilisation of sustainable biomass . Careful consideration of sustainability of biomass feedstocks used.	TRL 6-7 late stages of development, with pilot-scale validation and readiness for commercialization, however, further scaling and integration into large-scale industrial facilities are necessary to achieve full commercial deployment.	Reduction of scope 1 and scope 3 emissions Relates to renewable feedstock supply

Technology	Strengths	Weaknesses	Technology readiness level	Emissions scope/ relevance to renewable feedstock supply
Bio/e-naphtha as feedstock	No pre-treatment required prior feeding to crackers.	Availability in the market.	Depends on how the bio-naphtha is obtained. Bio-naphtha can be a by-product from HVO process and it is commercially available. Bio-naphtha via biomass gasification followed by Fischer-Tropsch conversion.	Reduction of scope 1 and scope 3 emissions. Relates to renewable feedstock supply.
Plastic waste pyrolysis oil as feedstock	Alternative for recycling mixed plastics streams.	Hydrotreating required to reach naphtha level quality prior feeding to crackers. Highly dependent on collection and sorting of plastic waste.	TRL 6-7 late stages of development, with successful pilot-scale demonstrations and readiness for commercialization, however, further scaling and integration into large-scale industrial facilities are necessary to achieve full commercial deployment.	Potential to reduce scope 3 emissions due to the circular aspect of this value chain. Relates to circular plastic supply.

3.1.2.1 Company plans

Dow Terneuzen

In 2021, Dow Terneuzen announced its roadmap to reduce the site's CO_2 emissions by 40% in 2030. The plan presents three phases. The first phase includes the construction of an autothermal reformer (ATR) plant to convert the fuel gas from the crackers into hydrogen and CO_2. The hydrogen could be used for fuel substitution in the steam crackers furnaces and the CO_2 could be captured and stored. The company explores also alternatives to use CO_2 instead of storing it. The hydrogen plant is expected to start up in 2026 and the company states that this measure would enable the Terneuzen site to reduce CO_2 emissions by approximately 1.4 million tonnes per year. The first phase also includes additional investments in infrastructure for CO_2 transport and storage, oxygen production and hydrogen distribution.

In the second phase, Dow plans to capture CO_2 from its ethylene oxide plant and to replace a number of gas turbines with electric motors by 2030. The company estimates that additional 300,000 tonnes of CO_2 emissions per year could be avoided. In the final phase, Dow plans to replace completely the use of fuel in the steam crackers by renewable electricity. Together with Shell, Dow is currently developing electric cracking technologies (Dow, 2021). The two companies completed the construction of an e-cracking furnace experimental unit in 2022, which is located at the Energy Transition Campus Amsterdam. The experimental unit will be used to test a theoretical electrification model developed for retrofitting the gas-fired steam cracker furnaces used today (Sustainable Plastics, 2022).

Globally, Dow announced partnership with New Energy Blue for the construction the New Energy Freedom site, a new facility in Iowa, United States, that is expected to process 275 kt of corn residue per year and produce commercial quantities of second-generation ethanol and clean lignin. Nearly half of the ethanol will be turned into bio-based ethylene feedstock for Dow products (Dow, 2023). The completion year for this project was not mentioned by the company.

SABIC Geleen

SABIC is currently focusing on the construction of a plastic waste pyrolysis plant. The technology is provided by Plastic Energy and the unit will be able to process 20 kt/year of plastic waste. The intention was to start up the facility in the second half of 2022, the company's CEO disclosure in January 2023 that the unit is still under construction, but near completion (Industry & Energy, 2023). SABIC is also constructing a hydrotreating unit to upgrade the raw pyrolysis oil as feedstock to the steam crackers, which should also be able to treat imported pyrolysis oil in the future.

The authority of the Chemelot cluster, where SABIC's crackers are located published the main cluster's plans for 2030. The expansion of bionaphtha use by steam crackers is included, as well as electrification; however, the publication does not specify which units in Chemelot would be electrified. Still, SABIC already exposed the company's wish to electrify the major compressors and to explore electrification technologies for the steam crackers. In 2021, the company signed a joint agreement with BASF and Linde to develop solutions for electric steam crackers (SABIC, 2023).

Recent news mentions the closure of one of the company's crackers (Olefins 3). The unit stopped operation this year due to maintenance reasons and will not return to operation when the turnaround period is over. This is the oldest cracker from SABIC and presents lower energy performance than Olefins 4 (Industry & Energy, 2024). This unit presents an ethylene production capacity of 595 kt/year (Oil & Gas journal, 2015).

Worldwide, SABIC continues to develop fossil-based projects. Together with ExxonMobil, the company established a joint venture (Gulf Coast Growth Ventures) in Texas, United States. The new manufacturing facility started operation in 2022. It includes an ethylene production unit with an annual capacity of 1.8 million tonnes, which will feed two polyethylene units with annual capacity of about 1.3 million tonnes and a monoethylene glycol unit with annual capacity of about 1.1 million tonnes (ExxonMobil, 2022)

Shell Moerdijk

In 2022, Shell Moerdijk announced their main plans for achieving net-zero emissions by 2032. The site is investing in a pyrolysis oil upgrading unit, with capacity of 50 kt/year (input) and it is expected to start production in 2024. Shell also mentioned the intention to build a hydrogen production plant on site, which would use fuel gas from steam crackers as feedstock and the produced hydrogen would be used as fuel in the cracking furnaces. Similar to Dow Terneuzen, Shell Moerdijk plans to capture and store CO_2 output from the hydrogen plant. Additionally, Shell is building a biofuels plant in Rotterdam which production is planned to start in 2024; this facility would be able to provide bio-based feedstock to the Shell Moerdijk steam crackers (Shell, 2022).

In 2020 the company also announced that 16 old furnaces would be replaced by eight new units at Shell Moerdijk site, which are more energy efficient. The installation started in 2022 and it is planned to be completed by 2025. The company claims that the operation of the new furnaces contributes to the reduction of carbon emissions due to higher efficiency, but no specific reduction targets were disclosed.

Shell Moerdijk has plans to install an upgrading unit for plastic pyrolysis oil. The company's intention is to start co-processing pyrolysis oil with naphtha in the steam crackers for olefins production. The production capacity of this new unit was not disclaimed.

Similar to other petrochemical major players, Shell is expanding fossil production worldwide. In June 2016, Shell Chemical took the final investment decision to build a major petrochemicals plant in Pennsylvania, United States. In November 2022, Shell commenced operations at the plant which consists of an ethylene cracker with a polyethylene derivatives unit. The plant uses ethane from shale gas and has a designed output of 1.6 million tonnes of polyethylene annually (Shell, 2023).

ExxonMobil

ExxonMobil does not have steam crackers in the Netherlands; however, it has relevant activity worldwide in the chemical sector. ExxonMobil has completed in 2022 the initial phase of a plant trial of a advanced recycling process for converting plastic waste into raw materials for production of HVCs. The plant is located at the company's existing facilities in Baytown, Texas. Upon completion of the large-scale facility (2026), the operation in Baytown will have an initial planned capacity to recycle 30,000 tonnes of plastic waste per year.

Braskem

Braskem's activity in Europe is limited to two polypropylene units in Germany; however, the Brazilian petrochemical company was the first to start bio-ethylene (in 2007) production via bio-ethanol from sugar cane. Braskem started in 2022 to expand production capacity at its green ethylene plant in Rio Grande do Sul (Brazil), from 200 kt/year to 260 kt/ year. The petrochemical technology licensor, Lummus Technology and Braskem, have joined forces in 2022 to develop technologies for two ethanol-to-green ethylene production units to be set up in North America and Asia.

In summary, the petrochemical companies focus mainly on reducing direct GHG processes emissions (Scope 1) and explore the electrification opportunities. In terms of changing the feedstock base, the focus is mostly on plastic pyrolysis with the intention to co-process. Because the major players are multinational companies and climate regulations differ significantly in different parts of the world, these companies are still expanding their fossil manufacturing capacity worldwide. Also, in Europe, regulations regarding carbon crediting for circular biobased chemicals is still incipient and uncertain, therefore, the shift from fossil to renewable feedstocks is rather limited.

3.1.3 Demand for plastics and LVO Chemicals production

As already exposed in Figure 3.2 basic chemicals production is highly interlinked to the plastics market. Therefore, evaluating the current and future trends of the market is key to understand possible changes in LVO chemicals demand and relocation activities.

In 2021, the global plastic production was 390.7 Mt and the EU27 was responsible for 15% of it, while China reached almost one third of the total. The European production share was higher in 2017 (19%), which indicates the rapid growth of Asia in plastics production capacity. Also in 2021, polyolefins (polyethylene – PE and polypropylene- PP) represent the majority of the global production (46.2%) and the main market application was on packaging and buildings & construction (Plastics Europe Facts, 2022).

In Europe, there was a total polyolefins production of 23.2 Mt in 2021, which represented almost 13% of the global polyolefins production. Regarding trading from and to the EU, both the USA and China were the main trade partners of the EU27 plastics industry together responsible for nearly 27% of total imports to the EU27 and 22% of the exports from the EU27 (Plastics Europe Facts, 2022).

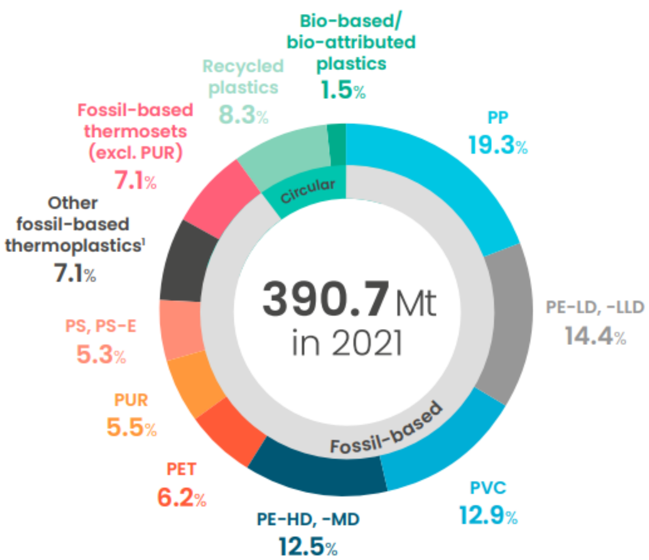

Figure 3.5 – Distribution of the global plastics production by type (extracted from Plastics Europe Facts 2022)

The Global Plastics Outlook report from OECD presents 3 scenarios: Baseline, Regional action and Global action (OECD, 2022). The Baseline is a business-as-usual scenario and considers only the impact of current policies and the modelling projections indicate that the plastics use could almost triple globally by 2060, mainly due to economic and population growth, especially in emerging countries. The Regional action scenario focuses on the impact of policies that aim to improve the circularity of plastics use while still allowing economic growth, being the implementation of such policies being stronger for the countries within OECD. In this scenario, the plastic waste decreases by almost a fifth below the Baseline by 2060, mainly due to the implementation of a tax on plastic use. The most ambitious scenario, Global action, considers a very stringent policy package that aims to reduce plastic leakage to the environment near to zero by 2060; the policies considered are the same as in the Regional scenario, but with more ambitious targets. In the Global scenario, the plastic waste reduced by a third below the Baseline by 2060, being both taxation and recycling the main reasons for this result.

Despite the difference in results for plastic waste volume and plastic leakage to the environment, all three scenarios considers that plastics demand will grow worldwide by 2060 (with less intensity to the most ambitious scenarios), mainly because of emerging economies. Also, plastics are an important input for many economic activities, which highlights how the economies around the globe will remain significantly dependent on plastics. The plastic demand development behaves differently depending on the world region. In fast-growing emerging economies, the plastic use grows by higher pace than in Europe in all scenarios. For Europe specifically, the plastic use is projected to increase around 110% in 2060 (compared to 2019 volume) for the Baseline scenario, being the increase around 90% and 80% for the Regional and Global scenarios, respectively (OECD, 2022).

In summary, the main takeaways from the trends and current production levels are:

- Production in the EU27 is quite relevant worldwide, especially for trading of packaging plastics.
- It is expected that emerging economies will develop their production capacity for plastics, as well as their plastic demand.
- The plastic demand in Europe is expected to grow for the next 40 years, however, other regions in the world will present a faster and more relevant growth.
- Recycling is increasing its role in the plastic market.
- It is uncertain what will happen with the chemical sector in Europe, mainly due to lack of clear regulations around materials.

The trends presented in this study help to highlight that the plastic economy will most probably continue to grow and that the European plastic demand market will become less relevant than it is currently due to emerging economies. All these factors combined are relevant when looking into possible relocation of the Dutch plastic manufacturing value chain.

3.1.4 Pathways to de and re-carbonising LVO Chemicals production in the Netherlands

The most recent study on Sustainable Scenarios for the Netherlands examines possible long-term development pathways for the Dutch energy system, with the goal to achieve carbon neutrality by 2050 (Scheepers et al, 2024). It includes the low-cost decarbonation options for the chemical industry from a systems perspective. This study involves two scenarios with the common goal of achieving a carbon neutral energy system in the Netherlands. They differ in future demand projections and targets introduced for international bunkering. In addition, they differ from each other in regard to introduction of circular carbon target for the chemical industry.

- ADAPT scenario assumes a future that is in line with the Climate & Energy Outlook projections (PBL, 2023) up to 2040 and continues growth beyond. The GHG emission reduction target for international bunkering is set to 50%. No circular carbon target is introduced for the chemical industry, however, due to increasing biofuels production and, therefore, growing bio-naphtha availability, the share of biogenic carbon in chemicals also increases.
- TRANSFORM scenario considers a future, where society is better aware of sustainability and therefore there are some demand reductions. The international bunkering is assumed to produce zero emissions by 2050. In addition, this scenario introduces a circular carbon target of 80% in 2050 to feedstock use in the chemical industry, particularly for the production of high value chemicals (see Scheepers et al., 2024, forthcoming).

The modelling results show that the TRANSFORM scenario drives a significant shift of the chemical industry towards alternative feedstocks, especially bio-based feedstock. Next to the circular carbon target, reasons for such transformation is the considerable shrink of fossil refineries (85% in 2050) and growth of renewable refineries. The production of e/bio-kerosene increases the availability of e/bio-naphtha to steam crackers because the latter can be a by-product of Fischer Tropsch and HVO/HEFA processes. Also, the considerable shrink from the fossil refinery sector in the TRANSFORM scenario directly affects aromatics production. With lower production of reformates/aromatics by fossil refineries, alternative ways of production are needed, the bio route being the most relevant one. However, it is important to highlight that no imports of chemicals were considered in this scenario.

Technology selection

In the more ambitious scenario, electrification of steam crackers appears as the most relevant technology to produce olefins in 2050 in both scenarios, followed by bioethanol dehydration. Methanol to olefins has smaller presence mainly due to limited availability of renewable methanol to be used in the chemical sector. Similar situation occurs for the use of pyrolysis oil as feedstock in crackers, the lower availability of plastic waste for recycling limits its contribution to the sector. For ADAPT, the production volume of olefins is higher because of the demand assumptions set in this scenario; also, pyrolysis oil from plastic waste has less participation than in TRANSFORM.

For aromatics production, biomass to aromatics becomes the most relevant production route in TRANSFORM. Fossil refineries shrink in 2050 decreases the production of aromatics and reformates (conventional feedstock for aromatics production). Because of the limited availability of alternative technology for aromatics, the bio-based route becomes responsible for meeting the 2050's volumes demand. In ADAPT, refineries are still quite active in 2050, which allows more fossil aromatics production.

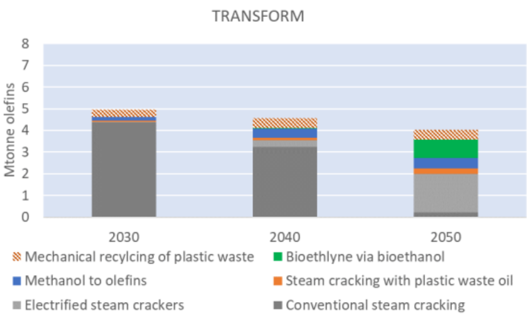

Figure 3.6 - Olefins production for TRANSFORM (technology selection)

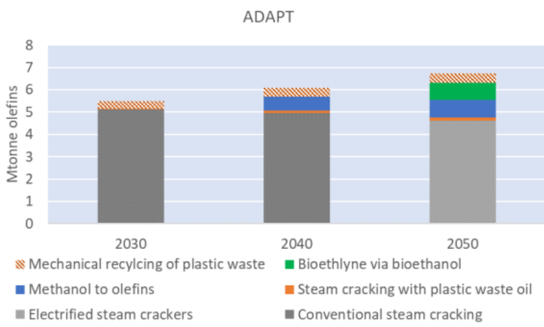

Figure 3.7 - Olefins production for ADAPT (technology selection)

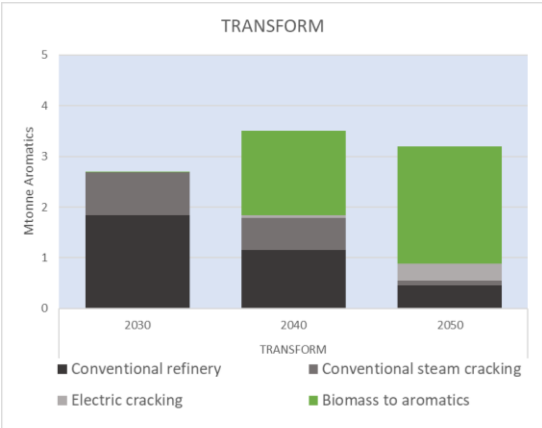

Figure 3.8 - Aromatics production for TRANSFORM scenario (technology selection)

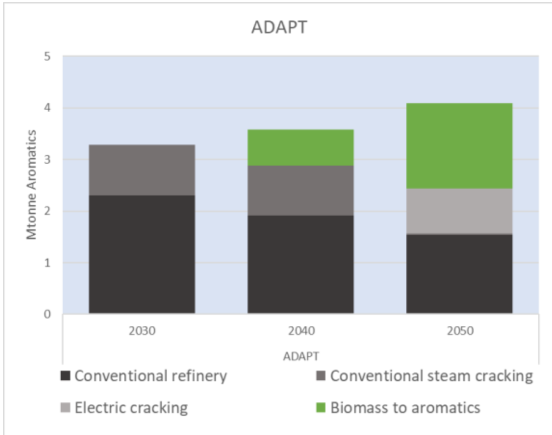

Figure 3.9 - Aromatics production for ADAPT scenario (technology selection)

Feedstock selection

In TRANSFORM, biobased materials are the most relevant feedstocks in 2050 for the overall LVO chemicals production. This is mainly due to the standalone production of aromatics via biomass gasification. Synthetic feedstocks also become more prominent in 2050 because of higher availability of e-naphtha as by-product from synthetic fuels production from renewable refineries. When looking closely at steam crackers, both bio and e-based naphtha are similarly relevant. Circular feedstocks are limited to domestic availability only, therefore, their use in 2050 is restricted.

In ADAPT fossil feedstocks still play an important role in both olefins and aromatics production. Also, synthetic naphtha presents much lower share as feedstock for steam crackers, when compared to TRANSFORM, especially due to lower availability in the system. These results can illustrate how interlinked the refinery and LVOCs sectors are and how sustainable targets may affect the choices regarding technology and feedstock use.

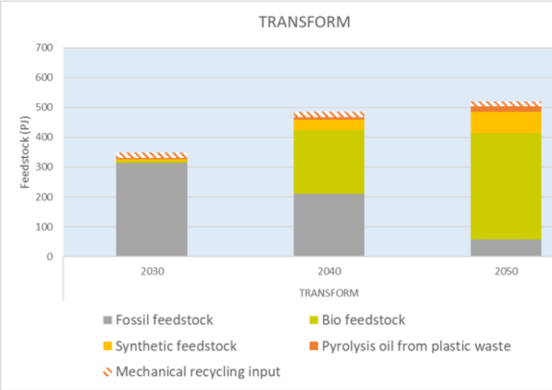

Figure 3.10 - Feedstock input for LVO Chemicals for TRANSFORM scenario

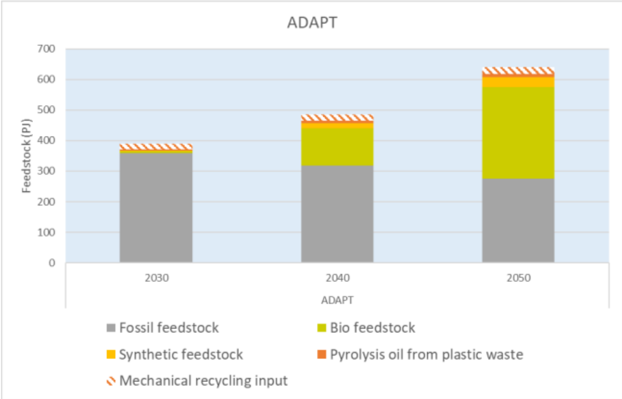

Figure 3.11 - Feedstock input for LVO Chemicals for ADAPT scenario.

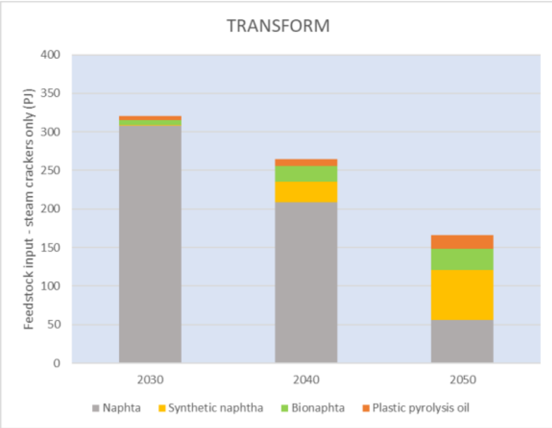

Figure 3.12 - Feedstock input to steam cracker in TRANSFORM scenario

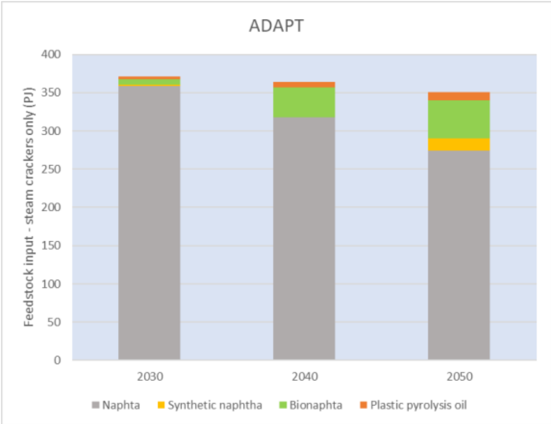

Figure 3.13 - Feedstock input to steam cracker in ADAPT scenario.

3.2 Process relocation due to de-fossilisation

There are several possibilities on how the olefins value chain in the Netherlands can change considering the decarbonisation options mentioned in the previous sections. Shifting to renewable feedstock alternatives, for instance, can increase (re)location risks in these industries. Figure 3.14 presents the first group of alternative value chains, which relates to bio and/or e-based feedstock. Considering the current assets, imports of bio/e-naphtha from other countries would not result in modifications to steam crackers and the current olefins value chain would remain unchanged, provided that these have the same chemical composition as fossil naphtha (thus drop-ins) and they become tradable commodities. This consideration, of course, is valid within the framework of implementing Paris Agreement goals globally and providing the level playing field in terms of implementing circularity.

The alternatives that include the use of bio/e-naphtha would rely mostly on the refinery sector transformation, where oil processing will likely reduce up to 2050, and be replaced by renewable refineries. As both bio and e-naphtha are by-products of renewable refineries, these feedstocks could be supplied to the current steam crackers.

Other alternatives are the import of bioethanol for bioethylene production in the Netherlands via dehydration or the import of bio/e-methanol as feed for methanol to olefins (MTO) process. Both processes are currently non-existent in the Netherlands, however, there are some project plans:

- The project called Blue Circle Olefins, for instance, aims to produce olefins using only renewable methanol and the installation location is the Port of Rotterdam (Blue Circle website, access 2024). This project started in cooperation with the Dutch research institute TNO to realize the first circular methanol-to-olefins production facility.
- There is a recent announcement indicating the intentions to build the first plant for production of ethylene from bioethanol in Europe, located at the Chemelot Industrial Park in Geleen, the Netherlands. The production capacity is mentioned to be 100 kt (syclus, 2023[27]).

Nevertheless, the potential for new investments is mostly in other regions of the world where biomass availability is higher, such as North and South Americas.

It is important to note that neither bioethanol dehydration nor methanol to olefins processes are able to produce the full range of products that a steam cracker is capable of, therefore, these technologies cannot fully replace a conventional steam cracker. For instance, the production of aromatics is not possible with these two new technologies. Such characteristic is also relevant when assessing relocation risks.

[27] See PRESS RELEASE 2023 07 03 (syclus.nl)

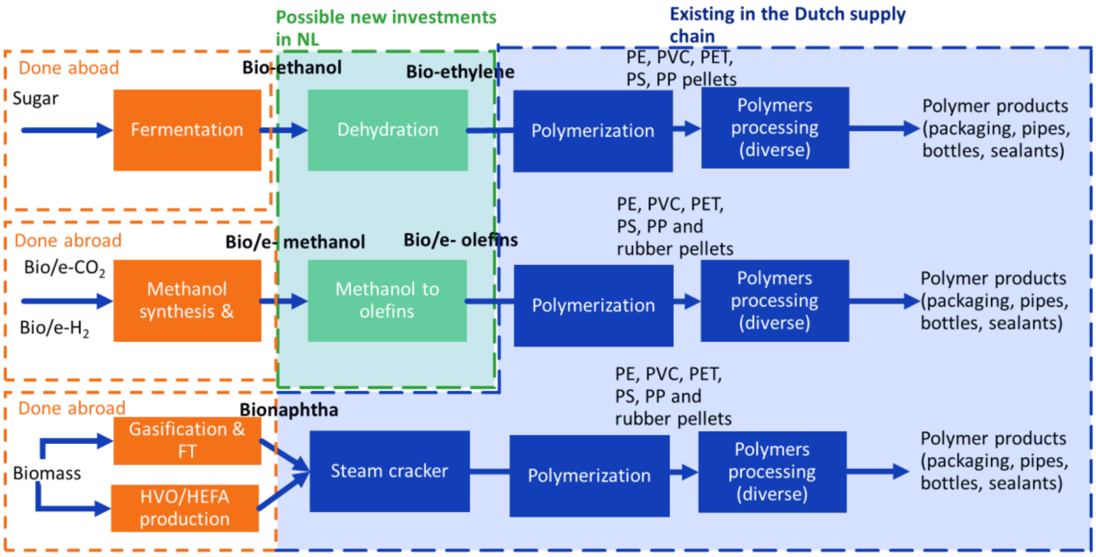

Figure 3.14: Renewable feedstock import alternatives

When it comes to circular feedstocks, the private sector has been showing significant interest in importing pyrolysis oil to be used in the current assets in the medium term. Companies such as Shell and SABIC are investing in new hydrotreaters to upgrade such oil to be used as naphtha substitute. The expansion of pyrolysis oil use in steam crackers is highly dependent on plastic waste collection and sorting, therefore, regulations and policies around recycling would directly affect the availability of pyrolysis oil in the market. Also, as mentioned in the previous chapter, this option would require new investments in hydrotreaters facilities.

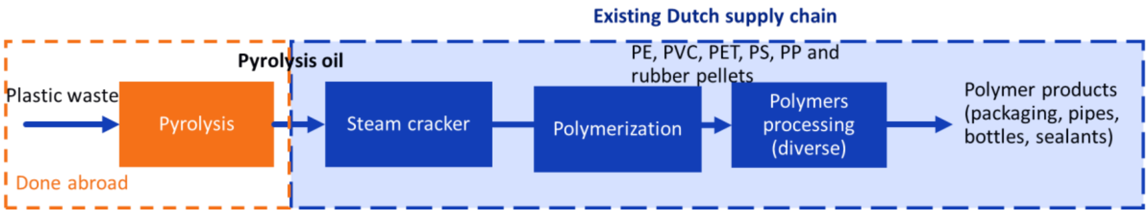

Figure 3.15: Circular feedstock import alternative

The alternative value chains mentioned in the previous paragraphs could also occur abroad up to the production of polymer pellets, which are easily tradable overseas (Figure 3.16 and Figure 3.17). These imported materials would compete directly with the Dutch polymer pellets and, therefore, could significantly impact the olefins value chain in the Netherlands. The demand for olefins from the conventional steam crackers assets could be reduced significantly. On the other hand, the polymer processing units present in the country would not be directly affected because the imported material would still serve as feedstock for further processing into plastics products.

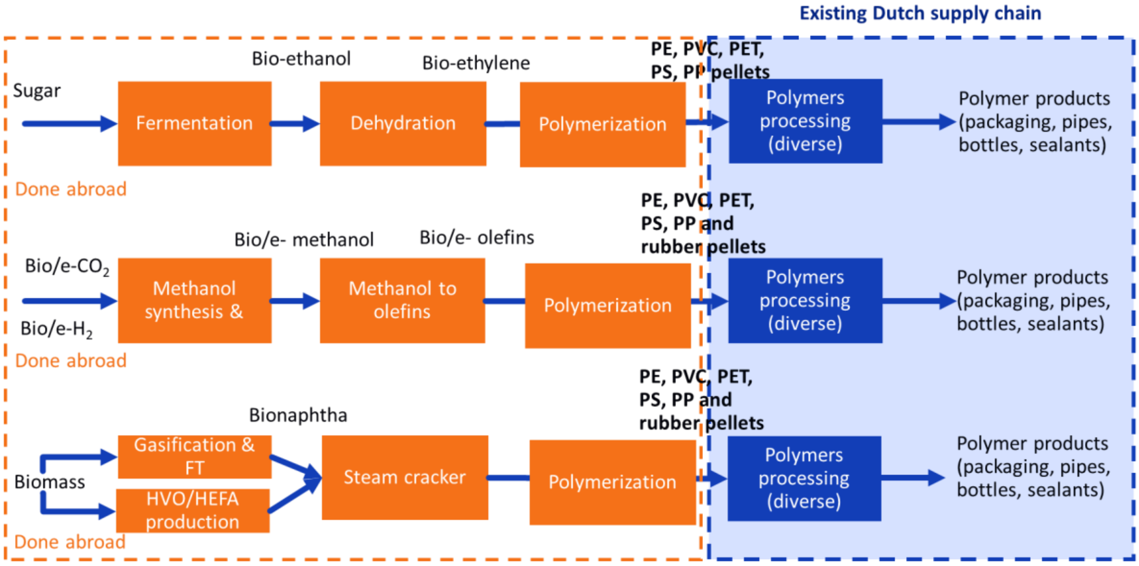

Figure 3.16 – Renewable semi-finished products import alternatives

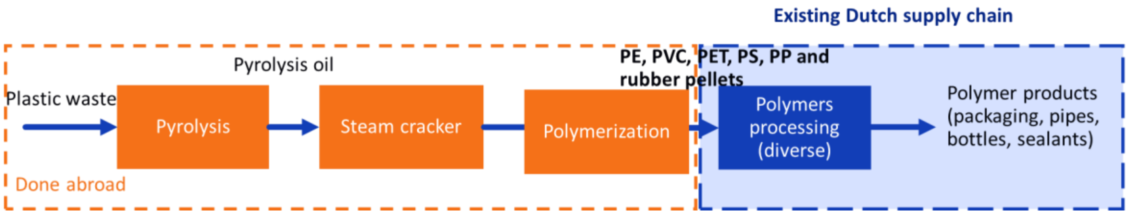

Figure 3.17 - Circular semi-finished products import alternative

One important remark is the fact that the polymers processing step in the value chain would not be impacted in any of the alternatives explored above, therefore, the relocation risk of such activity can be considered lower than relocating other steps of the LVO chemicals value chain. The possibility of importing finished plastic goods exists; however, the higher flexibility and lower costs of trading polymers pellets in comparison to finished goods could make the occurrence of such imports less attractive.

Figure 3.18 illustrates quite a different concept when compared to the alternatives already presented. In this case, novel polymers with different chemical compositions might substitute for conventional polymers pellets. For instance, well-known Polyethylene terephthalate (PET) pellets could be replaced by PEF (Polyethylene 2,5-furandicarboxylate) in the confection of beverage bottles. PEF's manufacturing process requires different technology and feedstocks when compared to PET, however, it presents similar mechanical properties as PET. PEF is 100% plant-based, recyclable and biodegradable plastic, being considered more sustainable than PET (Avantium website,2024). Polylactic acid (PLA) is another example, which is a biodegradable substitute for polystyrene (PS) and can be applied to produce food containers.

Emerging polymers exhibit properties that are in some cases either equivalent to or superior when compared to conventional polymers. These novel materials can be chemically recycled more easily and may incorporate safer additives and chemicals in their composition, as highlighted by the CIEP (2022). Their adoption could potentially impact the existing LVO chemicals production in the Netherlands, leading to relocation risks. If these polymer pellets become widely available and are primarily imported, they could serve as feedstock in the final stage of the plastics value chain, potentially reducing the demand for conventional polyolefins. Nevertheless, it's important to note that introducing novel chemicals and polymers is often a complex and resource-intensive process. Convincing all stakeholders in the value chain of the advantages of the new product and preparing production lines to meet the increasing demand are critical considerations. For example, the introduction of PLA by Dow and Cargill took between 20-30 years before the product became profitable (CIEP, 2022). Therefore, the challenging process of introducing novel polymers into the market may reduce the mentioned re-location risk of conventional LVO chemicals production.

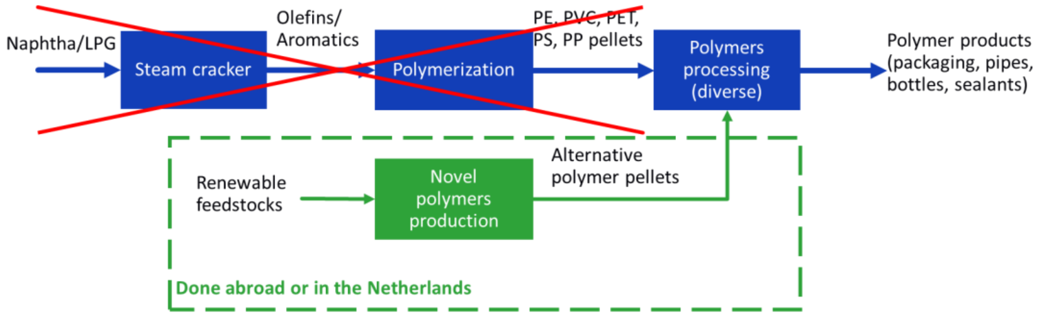

Figure 3.18 - Novel types of polymers as substitution to conventional materials

3.3 Discussions, conclusions and further research needed

3.3.1 Discussions and conclusions

This section highlights the main factors associated with potential relocation risks for certain activities of the LVO chemicals production value chain due to the transition of the chemicals sector towards sustainable resources, aiming to achieve net zero emissions by 2050. Similar to the assessment of the refinery sector, this analysis serves as a starting point for broader discussions on transforming the base chemicals industry in the Netherlands, focusing on developments beyond 2030. Therefore, it should not be considered as an extensive review of all possible relocation risks of such value chain.

The current plans from the leading LVO chemical companies show that the primary focus of the private sector remains on reducing direct process emissions, also refereed to scope 1 emissions (e.g., electrification of steam crackers, use of sustainable hydrogen as fuel). This is due to the robust policy framework and GHG emission reduction obligations introduced for the industries within EU ETS. However, regulations targeting certification of carbon removal and circularity aspects of the value chain are still incipient and uncertain. For this reason, the companies are taking rather incremental steps ("wait and see" approach). Furthermore, many of these companies operate globally and have assets in diverse regions, including countries where climate policies lag behind those of the European Union. Additionally, some regions may have more abundant and cost-effective natural resources, such as biomass. This circumstances pose some challenges for the viability of new value chains, as companies strive to remain competitive in the market.

The absence of clear EU regulation and specific targets related to carbon sourcing in this sector introduces significant uncertainty about its future behaviour. Consequently, assessing relocation risks becomes challenging due to the lack of concrete guidelines. Nevertheless, the transition from fossil refineries to renewable refineries would impact the LVO chemicals production sector. The availability of fossil naphtha would be limited, leading to increased relevance of alternative feedstocks such as biomass, synthetic naphtha, bionaphtha and, synthetic methanol, bio-methanol and pyrolysis oil. Strategically, when renewable refineries have significant development in the Netherlands, the LVO chemicals manufacturing sites would have easier access to sustainable feedstocks.

However, if other regions of the world offer more cost-effective manufacturing of polymer pellets, it could impact the competitiveness of Dutch polymers in the market. This cost-effectiveness might arise from factors such as access to cheaper and sustainable feedstocks or weaker climate policies in those regions. Due to easy transportation of polymer pellets, displacement of supply of semi-finished products is possible. Processing plants are flexible to import more polymer pellets to produce final plastics products, this flexibility also makes use of imported material easier. Regulations play a crucial role here, for instance, if imported polymers become subject to carbon pricing (for example through CBAM), it could further influence the competitive landscape.

Researchers in the public and private sectors are keen on developing novel polymers to address specific challenges and enhance performance. The EU has been proactive in promoting eco-design principles, including recyclability and reduced environmental impact of materials, being plastics products one of the targeting groups. This focus may encourage the adoption of materials that align with the mentioned goals. If novel polymers meet the EU's criteria for eco-design and recyclability, they could gain traction in the European market and the large-scale production of these materials could disrupt the plastics value chain, potentially affecting existing manufactures. If Dutch manufacturers fail to keep pace with developments, the might lose out to imported novel polymers.

However, it is important to highlight that the current market competitiveness of these new polymers remains a challenge and their business case may not yet attract major players. Considering the current landscape, the relocation risks associated with novel polymers are relatively low. But vigilance is essential as the industry evolves.

3.3.2 Further research needs and recommendation

Given the uncertainties surrounding the future of the LVO chemical sector, a comprehensive assessment is essential to evaluating potential relocation risks and their implications for the Dutch LVO chemicals industry. For instance, conducting a systemic techno-economic and environmental impact assessment of the emerging value chains and the traditional production methods for large volume organic chemicals (including alternatives involving drop-in replacements) would provide valuable insights into how production costs of fundamental chemicals might vary. Additionally, this comparison should encompass scenarios where these alternative value chains operate in diverse global regions.

Furthermore, there is a research need to study novel polymers and evaluate how likely these novel polymers could replace conventional polymers, assessing their scalability, challenges and opportunities to be introduced in the plastics market and how the Netherlands positioning itself in the development of such emerging materials.

The future transformation of refineries and their structural effects on the chemical industry has been studied for the Netherlands, using the OPERA model. Such structural effects should also be studied at the European and global level. These will provide valuable insights regarding the optimal locations and the possible relocation risks.

Conducting an in-depth analysis of emerging EU policies would provide valuable insights into the evolving policy landscape and its potential impact on the studied sector, not only within the Netherlands but across the entire European Union.

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Appendix A
Operational and planned HVO/HEFA retrofits in Europe

Table 3.2: Operational and planned HVO/HEFA retrofits in Europe(BioFitHandbook_EN_2ndEdition_2022-03-15.pdf (biofit-h2020.eu))

Owner/Operator	Location	Type	Feedstock	Main product	Main product capacity (t/year)	Status
PREEM	Sweden (Gothenburg)	Retrofit	Tall oil, also triglyceides	HVO	220,000	Operational
PREEM	Sweden (Gothenburg)	Retrofit		HVO	1,080,000	Planned
BP	Spain (Castellon)	Retrofit		HVO/HEFA	80,000	Operational
Repsol	Spain	Retrofit	Palm oil	HVO/HEFA	200,000	Operational
Cepsa	Spain (La Rabida)	Retrofit	UCO	HVO	43,000	Operational
Cepsa	Spain (San Roque)	Retrofit	Bio-oil	HVO	43,000	Operational
ENI	Italy (Venice)	Retrofit (100%)	Bio-oil	HVO/HEFA	300,000	Operational
ENI	Italy (Gela)	Retrofit (100%)	Bio-oil	HVO/HEFA	600,000	Operational
ENI[28]	Italy (Livorno)	Retroffit (100%)	Vegetable waste and residues	HVO	500,000	Planned
Total	France (Grandpuits)	Retrofit		HVO/HEFA	400,000	Planned
Total	France (Le Mede)	Retrofit	Bio-oil	HEFA	100,000	Operational
Gunvor	Netherlands (Rotterdam)	Retrofitt		HVO/HEFA	350,000	planned

[28] Eni moves ahead with conversion of the Livorno refinery into a bio-refinery

Appendix B
Refinery specific hydrotreatment capacity

Table B.1: Hydrotreatment capacities of existing refineries in the Netherlands that are dedicated to fuel production (derived from worldwide refining survey 2018)

	Gasoline desulfurization	Kerosine/Jet desulfurization	Diesel desulfurization	Other distillate desulfurization	Other hydrotreating	Total
	kt/y	kt/y	kt/y			Mt/y
BP refinery	0	7712.4	4059.1	744.2	433.0	13
ExxonMobil	0	1095.6	1967.1	0	0	3
Gunvor	0	528.9	1098.1	0	293.8	2
Shell	460.7	1429.3	2490.0	0	1679.3	6
Vitol	0	0	0	0	0	0
Zeeland	0	0	0	0	0	0
Total	460.7	10766.2	9614.3	744.2	2406,0	24

Appendix C
Sustainable biomass availability

A recent publication by DG RTD (EC, 2024), indicate the total European biomass potential available for the energy market, to be in the range of 310-836 million dry tonnes for 2030 and 294 to 892 million tonnes in 2050. Figure c.1 presents the European[29] biomass potential, across sectors.

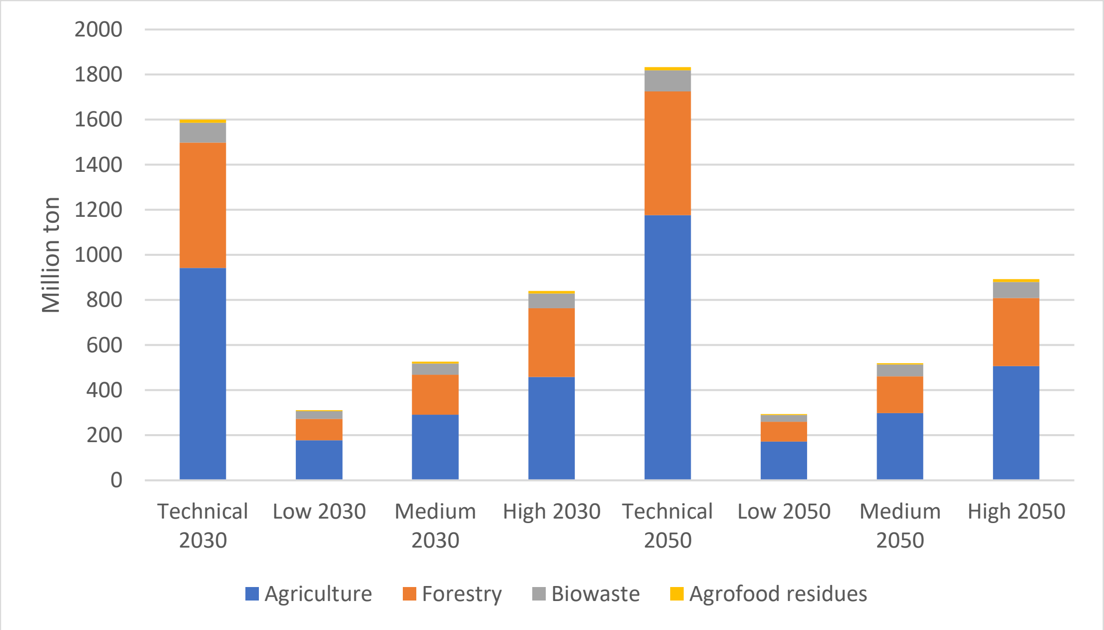

Figure C.1: Total biomass potentials in Technical, low, medium, and high mobilization scenarios in 2030 and 2050 in million dry tonnes (EC,2024)

- The 'technical potential' refers to the European biomass potential that complies with REDIII. In the low mobilization scenario, it is assumed that only 20% and 16% of the technical potential in 2030 and 2050, respectively, will be available for energy uses such as heat, electricity, and biofuels. In the medium mobilization scenario, these shares increase to 34% and 33% for 2030 and 2050, respectively. In the high mobilization scenario, the percentages rise to 55% and 54% for 2030 and 2050, respectively.

Figure c.2 and Figure c.3 compare the EC (2024) study results with the former scenario studies by JRC-Times, DG-RTD and Concawe (Imperial College (IC), Panoutsou, 2021). The potential assessment in this recent study, particularly the low mobilisation, are providing more conservative results. One of the important factors for these differences relates to the implementation of competing uses and the feedstock mobilisation factor. Next to that, all studies apply different assumptions and data inputs ranging per mobilisation scenario and

[29] European potential includes from EU regions and Associated countries.

per biomass type. Yield increase assumptions have large influence on agricultural potentials from both primary field residues (e.g., straw) and from dedicated crops on unused, degraded lands and in cover and intermediate cropping systems. The very low potential resulting from the low mobilisation scenario is very conservative where no priority is given any more to directing biomass towards bioenergy and biofuels.

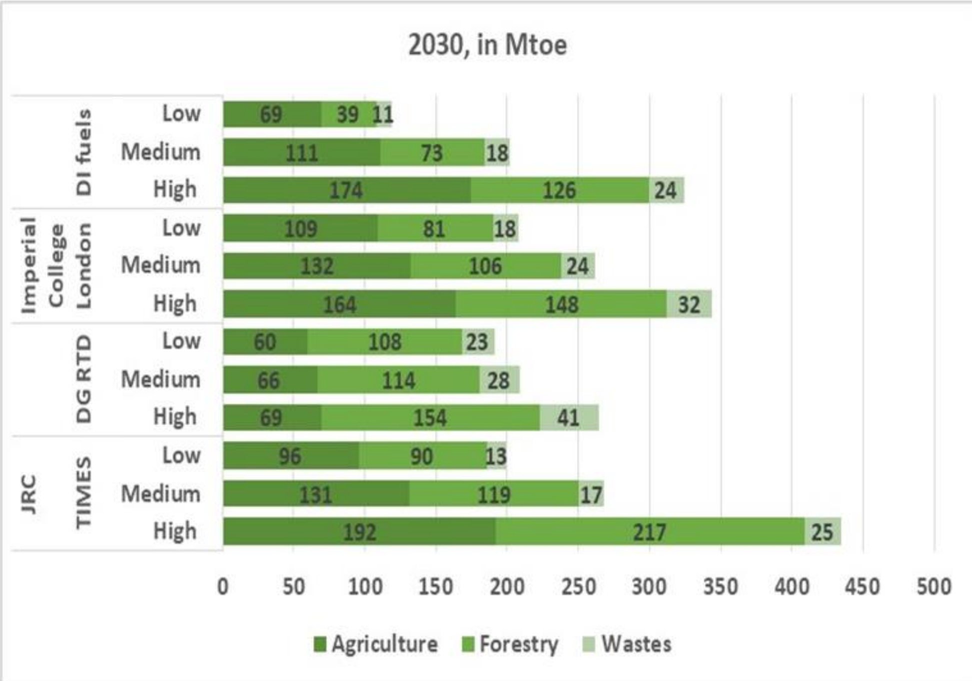

Figure C.2: Comparison of European biomass feedstock potential assessments for 2030

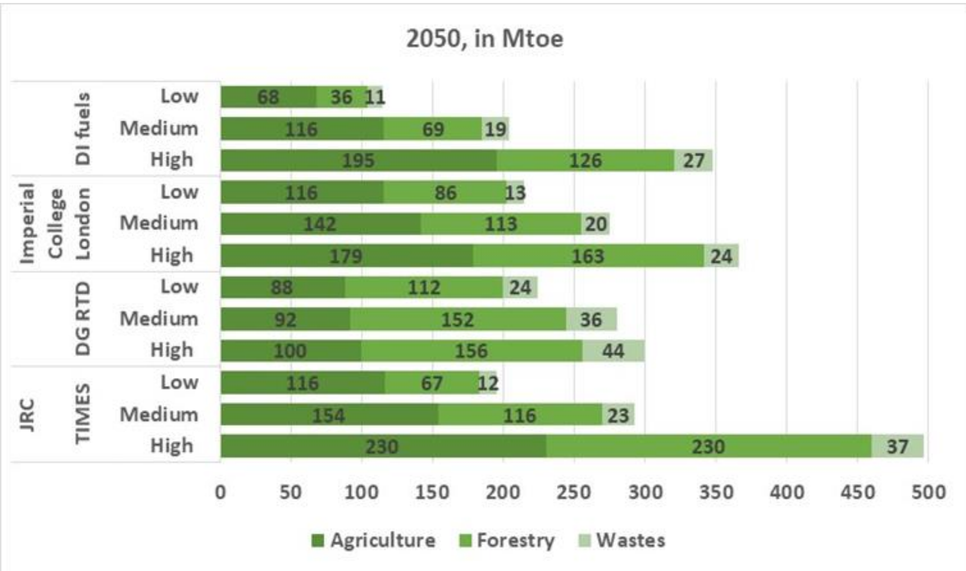

Figure C.3: Comparison of European biomass feedstock potential assessments for 2050

Biomass import to the Netherlands

Currently biomass trade occurs in the form of wood chips, wood pellets and waste wood. Figure c.4 shows the biomass balance for energy purposes between 2013 and 2020. As shown, import of solid biomass in the form of wood pellets has increases significantly in 2020 for the co-firing purposes. Next to solid biomass, liquid biomass resources such as vegetable oils, used cooking oil and animal fats have been traded. The Neste plant in Rotterdam has an annual production capacity of a maximum of 1.4 Mt. In 2022, roughly 95 percent (92 percent in 2021) of the feedstock used by Neste to produce renewable diesel consisted of waste and residue feedstocks. The waste and residues consist of animal fats, used cooking oil (UCO), palm fatty acid distillate (PFAD), palm effluent sludge, bleaching earth oil, and technical corn oil (co-product of corn ethanol production). Neste is expanding its refinery in Rotterdam increasing capacity roughly by 1.3 Mt of renewable diesel/SAF. This investment brings the total annual renewable (biofuels and intermediate feedstocks) production capacity in Rotterdam to 2.7 Mt, of which roughly 1.5 billion litres of SAF. The company's target is to start up the new production unit during the first half of 2026 (USDA, 2023)[30].

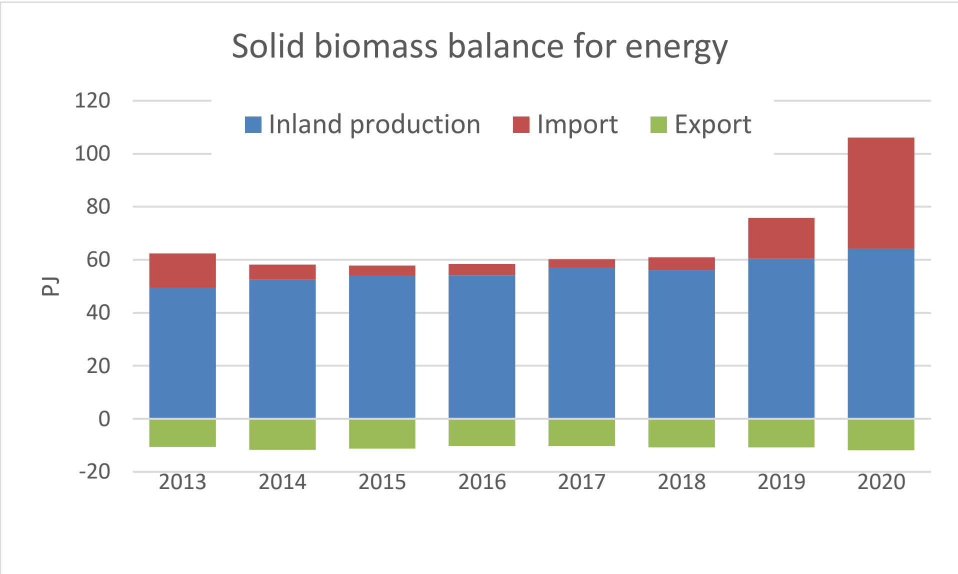

Figure C.4: Solid biomass balance for energy in the Netherlands (CBS, visited 2024)

[30] DownloadReportByFileName (usda.gov)

Appendix D
Biomass feedstock conversion to dense bio-intermediates for co-processing

The low bulk density of many different biomass feedstocks, combined with their divergent chemical composition, will necessitate densification. The pre-treatment and densification methods can ease transportation and handling and also provide uniform intermediates to be co-processed with existing refineries. For refinery integration, literature focuses on liquid intermediates that can be feed into the refineries FCC units and the hydrotreatment units. The intermediates most commonly studied are (used) vatable oils, bio-oil via fast pyrolysis or catalytical fast pyrolysis, upgraded bio-oil, dehydrodeoxygenated bio-oil , and bio-crude via hydro thermal liquefied crude oil (Prastyo et. al., 2020; Magrinie et. Al., 2021). The research focus has been developing bio-oil intermediates for injection into the existing refineries with the most impact. The incretion points are set to fluidised catalytical cracking, hydrotreatment and hydrocracking units.

Technology status
While lipid-based co-processing has been implemented commercially, co-processing of bio-oil intermediates has not been commercially demonstrated in refineries. There has been some pilot scale work based on 10% bio-oil feed into the Fluid catalytic cracking (FCC) units (i.e. pilot work by ENSYN and Petrobras). This relates to the fact that there has been no large-scale supply of bio-oil from biomass feedstocks. While biomass pyrolysis is a commercially proven technology, the production is still limited and the produced bio-oil is used to produce heat and electricity. There are currently 6 operational commercial plants, which can add up to 136 million litre bio-oil per year globally, if all these plants are assumed to produce full capacity (IEA, 2023. The current practices, however, relate to converting woody feedstocks into bio-oil. Various other feedstocks, for instance agricultural residues with large potential, have not yet been fully proven on commercial scale.

HTL is a thermochemical process that converts wet biomass (i.e. sewage sludge, food waste, wood, algae) into a high energy density liquid fuel, called biocrude, under high temperature (250 ºC to 400 ºC) and pressure (up to 25 MPa). HTL is not fully commercial yet. There have been some pilot-scale operations aiming to carry this technology to commercial scale in the future. IEA (2023) reports 6 demonstration plants, and a start of the first commercial plant by 2023 in Canada. This facility is also planned to be based on wood.

Table D.1: Commercial status of direct thermochemical liquefaction technologies (IEA Bioenergy, 2023)[31]

Owner	Country	Technology	TRL level	Capacity	Feedstocks	Status
Ensyn, Suzano S.A.	Brazil	Fast pyrolysis	TRL 8	83 ML/y		Under development
Arbios Biotech	Canada	HTL	TRL 7-8	8 ML/y	Forestry residues and waste	Under development
Bioenergy AE Côte-Nord	Canada	Fast pyrolysis	TRL 9	338 Ml/y	Wood residues from a sawmill	Operational
Kerry Group	Canada	Fast pyrolysis	TRL 9	11 ML/y	Mill and forest wood residues	Operational
Onym Group	Canada	Fast pyrolysis	TRL7-8	6 ML/y	Wood residues, including bark	Under development
Green Fuel Nordic Oy	Finland	Fast pyrolysis	TRL 9	20 ML/y	Sawdust and wood residues	Operational
Circa Group AS	France	Catalytic pyrolysis	TRL 7-8	0.8 ML/y	Waste cellulosic biomass	Under development
Twence	The Netherlands	Fast pyrolysis	TRL 9	20 ML/y	Clean woody biomass	Operational
Pyrocell AB	Sweden	Fast pyrolysis	TRL 9	21 ML/y	Sawdust	Operational
Ensyn	USA	Fast pyrolysis	TRL 8	76 ML/y	Mill wood residues, forest residues	Under development
Kenny Group	USA	Fast pyrolysis	TRL 9	20 ML/y	Wood residues	Operational
Circa Group AS and Norske Skog	Tasmania	Catalytic pyrolysis	TRL 6	40 kL/y	Lignocellulosic biomass	Operational
Arbios Biotech	Australia	HTL	TRL 6-7	1.6 ML/y	Post-consumer and biomass residues	Operational
Metro Vancouver	Canada	HTL	TRL 6-7	2 dryt/day	Primary and secondary sewage sludge from wastewater treatment plant	Under development
Shanxi Yingjiliang Biomass Company and Shanghai Jiao Tong University	China	Fast pyrolysis	TRL 6-7	8 ML/y	Rice husk	Operational
Crossbridge	Denmark	HTL	TRL 7	4000 dry t/y	Wet	Under

[31] Commercial status of direct thermochemical liquefaction technologies IEA Bioenergy: Task 34 June 2023

Owner	Country	Technology	TRL level	Capacity	Feedstocks	Status
Energy					wastewater sludge	development
Fraunhofer UMSICHT	Germany	Intermediate pyrolysis and integrated reforming	TRL 7	500 kg/hr	Biomass, biogenic residues	Operational
Shell Catalysts & Technologies	India	Catalytic hydropyrolysis	TRL 7-8	5 t/day	Forestry, agricultural, and urban waste	Operational
MASH MAKES A/S	India	Pyrolysis	TRL 7-8	3000 t/y	Agricultural residues	Operational
Reliance Industries Limited	India	Catalytic HTL	TRL 8	80 l/day	Algae, food waste and sludge	Operational
Silva Green Fuel	Norway	HTL	TRL 7-8	1.5 ML/y	Forest residues	Operational
Altaca Energy	Turkey	Catalytic HTL	TRL 7	8.7 ML/y	Various biomass sources	Operational
Biogas Energy Ltd	USA	Fast pyrolysis	TRL 6-7	500 kg/h	Wood waste, forest residues and orchards grindings	Operational
Annelotech	USA	Fast pyrolysis	TRL 6-7	-	Wood, corn stover, bagasse	Operational
RTI International	USA	Catalytic pyrolysis	TRL 6	1 t/day	Lignocellulosic biomass	Operational
Frontline BioEnergy and Stine	USA	Autothermal pyrolysis	TRL 6-7	50 t/day	Corn stover	Near completion

Financial parameters used in biomass pyrolysis value chain calculations.
SGAB follows a simplified methodology by estimating the production cost from a capital cost contribution, an OPEX contribution and the feedstock contribution. CAPEX is seen as equal to the overnight investment cost for building the plant and no cost for interest during construction or working capital has been added. The capital recovery charge is composed of an annual cost estimated as an annuity based on the CAPEX using a real interest of 10% for 15 years. Elements of a fully elaborated project economic model such as level of grant support, debt-to-equity ratio, loan repayment grace and amortization periods, etc. have been ignored (SGAB, 2019).

TNO calculations follows the SDE++ methodology (see SDE++ calculation tool from RVO[32]), in which a 22 MW output reference installation, with a 61% energy efficiency, is considered.

[32] Rekentool SDE++ 2023.xls (live.com)

Table D.2: Financial parameters used in different studies

	SGAB 2019	Yanez et al., 2020	TNO
Full load hrs	8000	8000	7500
Life time	15		15
Interest rate	10%	12%	
Inflation	-		1.5%
Equity/debt ratio	-		30%/70%
Required return on equity			15%

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