Fossil-free energy system and the chemical industry in the Netherlands

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Summary

Context and approach

In line with EU climate goals, the Netherlands has committed to achieving a climate-neutral energy system by 2050 – a legally binding target under the European Climate Law. While this target is legally binding, the government aims to minimize the use of fossil carbon carriers, such as natural gas and crude oil, by 2050 and is exploring what is needed to achieve a fossil-free society. Thus, a complete phase-out of fossil fuels—particularly for industrial feedstocks—remains a long-term ambition and requires further exploration and validation. In 2023, industry accounted for 46% of the Netherlands' total final consumption, with almost half of its fossil fuel use being non-energetic (CBS, 2025). This industry sector contributed to around 30% of total GHG emissions. Transitioning to a fossil-free industry means addressing not only energy use but also feedstock transformations, infrastructure adaptations, and related costs and cost savings.

This study, conducted for the Ministry of Climate Policy and Green Growth, assesses the feasibility of a fossil-free energy system and industry in the Netherlands by 2050. It evaluates the transition from a climate-neutral to a fossil-free system by comparing system-wide impacts, total system cost differences, and key challenges. It is assumed that same ambitions will be followed up to 2040, with 90% GHG emission reduction, compared to 1990. Beyond, a climate-neutral energy system is compared with a fossil-free energy system and industry. Special attention is given to the transformation of the Dutch chemical industry.

The energy system model OPERA is used to analyse different scenarios. The analysis builds on earlier modelling and compares a climate-neutral reference scenario (POLICY) with two fossil-free scenarios that differ in assumptions on renewable fuel and intermediate import potentials in costs. All scenarios are based on the same reference input parameters, such as the projected industrial activity and energy use, fuel demand for international aviation and maritime sectors, and the domestic resource potentials. In this study, climate neutrality is defined within the boundaries of the national energy system. Emissions from international maritime and aviation bunkering are addressed in line with the EU Regulations. The FuelEU Maritime Regulation (Regulation (EU)2023/1805) sets GHG intensity reduction requirements for the energy used on voyages. Under this framework, all energy used on voyages within the EU is covered, while half of energy used on voyages between EU and non-EU ports is included. The ReFuelEU Aviation Regulation (Regulation (EU) 2023/2405) introduces sustainable aviation fuel (SAF) target, reaching to 70% by 2050 Consequently, the reference policy scenario is set accordingly and does not target full CO_2 neutrality for all bunkering emissions.

The OPERA model identifies the lowest-cost energy system from a societal perspective, calculating *total system costs* as the sum of annual capital, O&M, transport, and import costs, minus export revenues. We present *cost differences*—as *additional system costs*—relative to the reference POLICY scenario to highlight the incremental impacts of fossil-free choices. While the analysis is based on scenario modelling, which allows for a system-level comparison, the complexity of the chemical sector and its transition pathways cannot be fully captured by scenarios alone. Therefore, the study also explores promising novel value chains for plastic production, such as Poly Lactic Acid (PLA) and Polyethylene Furanoate (PEF). These are discussed qualitatively, with follow-up work planned to further develop and assess their viability and impact to the modelling results.

It should be noted that all scenario outcomes are dependent on the underlying modelling framework (OPERA), which applies a system cost-optimization approach. The results are not predictions, but rather explorations under a given set of assumptions regarding technology deployment, imports, and energy demand.

Results

A fossil-free energy system in 2050 demands earlier action, full use of domestic renewables, and strategic imports of renewable fuels and intermediate energy carriers

The findings show that under the climate-neutral reference scenario (POLICY), fossil fuel use in the Netherlands declines steadily, reaching a 70% reduction by 2050, compared to 2030. However, fossil fuel use remains significant—nearly 700 PJ—primarily in the petrochemical industry and for international bunkering, which are outside current regulatory requirements. Achieving a fully fossil-free energy system (including bunkering) and industry requires going beyond current climate neutrality ambitions. This involves earlier and more aggressive action, including full deployment of all available renewable resource potentials (including 100% of the technically feasible offshore wind potential and a major expansion of solar PV and nuclear deployment), but also imports of renewable fuels and intermediate energy carriers.

The industry sector—especially petrochemicals—will carry the highest costs, and requires major scale-up of clean electricity and hydrogen

Industry is the most impacted sector in the fossil-free transition, bearing nearly all of the additional system costs. In the carbon-neutral energy system there is still use of fossil fuels for bunkering and feedstocks for the chemical industry. In the fossil-free system, these are supplied by renewable and circular fuels and feedstocks, resulting in additional costs. Scenario analysis suggests that moving from a climate-neutral to a fossil-free energy system and industry sector could increase total system costs by approximately 6–10%. In absolute terms, the total system cost difference (also referred to as the additional system costs) is calculated to be €7.7 to €12.8 billion[1] by 2050, for the two fossil-free scenarios compared with the POLICY reference scenario. This additional system costs consist of additional capital expenditures and maintenance costs and costs of importing renewable fuels. It also includes cost savings related to avoided fossil fuel imports and other revenues. These cost differences should be interpreted as indicative ranges. They are sensitive to assumptions on fuel prices, technology learning rates, and international supply chains, which may evolve differently than assumed. To put this into perspective, to reach the levels of renewable energy deployment and CO_2 reduction options outlined in the Climate and Energy Outlook (PBL, 2022) — and assuming these options qualify for SDE++ support — approximately €3.2 billion in annual SDE++ subsidy expenditures were allocated.

The additional total capital and operational expenditures of the fossil-free scenarios are in the range of €12.8 to €16.8 billion annually by 2050, for the high import and low import scenarios, respectively. Of this, 42–39% of the investment goes directly into industrial transformation, while 32–41% is related to expanding renewable electricity generation—mainly to meet the industry's rising demand for electrification and hydrogen for the high and low import scenarios, respectively. The remaining additional expenditures mainly relate to heating and energy savings in buildings and additional fleet adaptations in road transport (shifting more to electric vehicles).

[1] All monetary values are corrected for 2023.

While the electrification of industry is already a major driver of decarbonisation in the climate-neutral pathway, shifting to a fossil-free system demands even greater electricity and hydrogen use, particularly in sectors like chemicals, steel, and fertilizers. Study results suggest that under the climate-neutral reference scenario, electricity demand in the Netherlands will quadruple by 2050 compared to 2024, reaching levels that will create immense pressure on both domestic renewable generation and grid infrastructure. In the fossil-free scenario with low imports, electricity demand is 31% higher than in the reference, requiring even more aggressive expansion of offshore wind, solar PV, and nuclear capacities. In the high import scenario this expansion need is approximately 20%. These shifts require, by 2050, annual additional investments and operational costs in renewable power generation ranging from €6.9 to €4.1 billion annually, for the low import and high import scenarios, respectively.

One of the main drivers behind this electricity demand increase is the need for renewable hydrogen. The study projects a need for approximately 16 GW of electrolyser capacity by 2050 under the reference scenario, and as high as 26 GW under the low import fossil-free scenario and 22 GW under the high import scenario—implying additional capital investments of €1.8 to €1.2 billion annually. However current project realisation is limited: as of 2023, only one project had reached final investment decision (200 MW),while others are delayed due to regulatory and market uncertainties. The current figures represent potential capacities under favourable conditions, not guaranteed developments. Their development will depend on cost developments of electrolysers, renewable electricity availability, and supportive policy frameworks.

Fossil-free industry depends on aggressive scale up of renewable fuels and circular feedstocks—requiring new refineries, significant amounts of sustainable biomass, and secure global supply chains

Within industry, the chemical sector is the largest contributor to these additional system costs—accounting for up to half of the total increase—primarily due to its heavy reliance on fossil-based feedstocks and the high capital and operational expenses required to substitute them with alternatives like biomass, plastic waste, and renewable fuels and feedstocks. Methanol-to-olefins and pyrolysis oil offer promising pathways to reduce fossil dependence, while aromatics production remains a key challenge, requiring further R&D due to the lower maturity of biobased alternatives.

Similarly, the deployment of bio-based and synthetic fuels for transport sector must scale up drastically. Renewable fuel supply for transport is projected to increase 3.4 times between 2030 and 2040, and a further 1.7-fold by 2050 within the climate-neutral reference scenario[2]. This is even greater in the fossil-free scenarios, with a further 2.5-fold increase between 2040 and 2050. The viability of this expansion is dependent on the deployment of many new renewable fuel refineries, substantial amounts of sustainable biomass supply and international trade logistics.

Within the chemical sector, replacing fossil feedstocks such as naphtha and aromatics with renewable and circular alternatives demands an equally ambitious transition. This study projects a sharp increase in renewable and circular naphtha supply. The circular naphtha supply, particularly bio and synthetic based, is driven by the developments in renewable refineries. Thus, defossilisation of this sector within this study is very much dependent on the successfully commissioning of such refineries and availability of renewable naphtha as a by-product.

2 Based on energy content. Based on volumes the increase is much steeper.

The transition of the chemical industry assessed in this study focuses on large-volume, drop-in value chains. While production processes for novel materials have been briefly described, they are not included in the scenario modelling. Qualitatively, these novel materials offer the potential for better properties, improved environmental footprints and increased efficiency (i.e. reduced biomass demand).This topic requires further research and development.

Conclusions

In conclusion, the results of this study show that a fossil-free energy system and industry is technically feasible, but will require an ambitious and coordinated roadmap for industrial transformation. The move from climate-neutral to fossil-free industry will challenge the infrastructure development, and technology scale-up. While the cost estimates presented provide a robust indication of trends and investment needs, it should be noted that electricity infrastructure costs may be partially underestimated due to modelling limitations. The success in this transition will depend not only on domestic policies and capabilities, but also on the collaboration across borders and supply chains in Europe and beyond. In addition, the modelling framework has inherent limitations. For instance, electricity infrastructure costs and potential technological breakthroughs are only partially captured. The behavioural aspects of technology adoption is challenging and not fully incorporated into the model. As such, outcomes should be seen as indicative pathways, not exact forecasts.

Recommendations

Based on this research we propose the following policy recommendations to reach a fossil free industry in the Netherlands by 2050:

- **Maximise the domestic renewable resource use:** Utilising all available domestic resources such as wind, solar, sustainable biomass, and recyclates, is essential, especially in the fossil-free scenario, where near-full deployment is required. This is complemented by nuclear energy and international imports.
- **Secure access to renewable and circular energy carriers through international supply chains**: The transition to fossil-free industry requires imports of biomass, renewable and circular fuels and feedstocks. Even in the low-import scenario, imports of renewable kerosene, methanol, and other synthetic oil products become necessary beyond 2040. Key actions include:
  - Expanding diplomatic and trade instruments to establish long-term supply agreements with countries rich in renewable energy resources
  - Support international certification systems and sustainability frameworks for renewable fuels and create these for the chemical feedstocks
  - Accelerate infrastructure investment for these imports
  - Coordinate biomass sourcing strategies across transport and chemical sectors to minimise competition and maximise synergies
- **Accelerate grid and hydrogen infrastructure expansion**: Electricity and hydrogen demand is projected to grow significantly, especially within industry clusters. This is confirmed by previous studies (i.e. PBL,TKVN 2025, TNO, 2024 and others). Supplying these demand will require further acceleration and expansion of infrastructure.
- **Accelerate deployment of electrolysers and fuel production facilities**: Meeting both climate-neutral and fossil-free targets demands rapid scale-up, but most projects are still in planning phases.
  - Provide targeted investment support, and risk guarantees for projects that are not yet fully commercial

  - Promote industrial offtake agreements to reduce market uncertainty and further stimulate demand, particularly for the chemical products
- **Advance low-TRL technologies through R&D and targeted policy support**: Many key technologies—e.g., electrified crackers and (novel) biobased polymers—are still in early stages. Key actions are:
  - Accelerate R&D and demonstration of high-impact industrial decarbonisation technologies, recognising long lead times for commercialisation.
- **Strengthen cross-sectoral coordination and establish a long-term transformation pathway for sustainable and circular chemicals, including interim targets and early demand signals**.
  - Define a technology roadmap for bio-based and CO_2-based chemicals with intermediate targets.
  - Support integrated biorefineries with dual output (fuels + chemical feedstocks).
  - Promote cross-sectoral innovation platforms linking electricity, hydrogen, carbon, and biomass supply chains
- **Develop an integrated carbon management strategy**: A balanced mix of CCS, CCU, and DAC is necessary to close the carbon cycle, especially post-2040.
  - Develop a national DAC roadmap and explore industrial clustering for shared infrastructure.
  - Reassess biogenic CO_2 availability and co-locate biofuel production with capture capacity. Incorporate CDR pathways into a trading system and design policy to facilitate early investments in BECCS and DACCS, with a view to monetizing surplus removals.

Contents

1 Introduction

1.1 Context

The EU has set the goal to become climate-neutral by 2050. Accordingly, the Dutch government established the National Energy System Plan (NPE), which outlines how the Netherlands is developing an energy system that aligns with a climate-neutral society. In the NPE, next to climate-neutrality, the ambitions to become fossil-free and circular are also articulated (NPE, 2023). Additionally, the Dutch government initiated the National Program Sustainable Industry (NPVI) with the ultimate goal of achieving a clean and sustainable industry while ensuring companies remain within the country and continue to contribute to the GDP at the same level.

The Dutch ambition to achieve a carbon-neutral energy system by 2050 is legally binding, while a fully fossil-free system remains aspirational and requires further exploration. Carbon neutrality involves balancing GHG emissions through reductions, efficiency, cleaner technologies, and offsets such as carbon capture and storage (CCS). Yet, achieving carbon neutrality does not inherently mean industries will be entirely fossil-free.

The base industry in the Netherlands heavily relies on fossil fuels for both energy and non-energy purposes, including feedstocks like petrochemicals. In 2023, industry accounted for 46% of the Netherlands' total final consumption, with almost half of its fossil fuel use being non-energetic (CBS, 2025). This sector contributed to around 30% of total GHG emissions, with the chemical industry being the largest emitter, followed by oil refineries and base metals.

Efforts to transition away from fossil fuel use, including non-energetic use, particularly in heavy industry involves exploring alternative feedstocks, adopting circular economy principles, and investing in innovative technologies. These depend on, among others, the availability and supply of sustainable and renewable resources, and market readiness, the timely scale up of innovations and the financing of these innovations.

In summary, while achieving a carbon-neutral energy system is a critical goal, a fossil-free energy system and industry needs to be researched extensively, where many different aspects are taken into consideration.

1.2 Objectives/research questions

This study aims to support the Ministry of Climate and Green Growth (KGG) in exploring the feasibility of a transition to a fossil-free energy system and industry in the Netherlands. It offers insights into the possible trade-offs and synergies between achieving carbon neutrality and establishing a fossil-free industry. The project is designed to address the below questions:

- What are the overall impacts of a transition to a fossil-free energy system and industry by 2050, compared to a climate-neutral reference energy system in the Netherlands with limited or no transition away from fossil feedstock by 2050?
- What are the possible renewable energy and feedstock mixes to attain a fossil-free system in the Netherlands?

- What are the total system cost differences of a climate-neutral and fossil-free energy systems and industry? The total system cost considers the national cost perspective, and refers to the cost balance including, among other things, investment costs (whether or not annualized over the economic life of the investments), energy costs, operational costs and cost savings, and revenues resulting from the measure (e.g. through savings on energy use or sales of energy).
- What are the main obstacles along the path achieving fossil-free production?

This study focuses on specific aspects of transitioning to a carbon-neutral and fossil-free energy system, but does not cover all related topics. The competitive position of Dutch industry and the economic competitiveness of innovations compared to other regions are outside its scope. While circularity is considered, a comprehensive analysis—such as evaluating product design, material substitution, and recycling systems—is beyond the scope and requires a separate study. Circularity is addressed in this study only within scenario definitions, incorporating simplified assumptions like improved waste stream management and efficiency.

1.3 Report outline

This report is structured as follows:

- Chapter 2 outlines the methodological framework and key scenario parameters, including projections for industry and international bunkering, as well as the availability of renewable and sustainable resources.
- Chapter 3 describes the scenario setup, detailing the climate-neutral reference scenario and the alternative fossil-free scenarios.
- Chapter 4 presents the modelling results, focusing on energy demand and supply across the overall system, industry, bunkering, and the chemical sector.
- Chapter 5 quantifies the additional system costs required to move from climate neutrality to fully fossil-free energy system and industry by 2050, with a breakdown by sector.
- Chapter 6 explores key sensitivities, such as variations in aromatics production and bunkering demand.
- Chapter 7 discusses critical success factors and methodological limitations, with a focus on the chemical industry and assumptions around imports and renewable value chains.
- Chapter 8 provides the main conclusions and recommendations for policy and future analysis.

2 Approach/Methodology

This study uses a structured, scenario-based methodology to assess the transition to a fossil-free energy system and industry in the Netherlands. The approach consists of three key components: defining relevant long-term scenarios, conducting detailed scenario modelling, and analysing the results extensively.

To capture the full system aspects of de-fossilizing the energy system and the industry, scenario modelling was conducted using OPERA (Option Portfolio for Emissions Reduction Assessment) model. The OPERA model is a tool that simulates the Dutch energy system, ensuring that energy demand across all sectors in the economy can be met and industrial production can be realized while at the same time certain preconditions such as GHG emission reductions and/or renewable targets, can be met. The model optimizes the selection of technologies and energy sources, aiming for the lowest cost energy system from a societal perspective. **Figure 2.1** provides the schematic presentation of the model.

It should be noted that all scenario outcomes are dependent on the underlying modelling framework (OPERA), which applies a system cost-optimization approach. The results are not predictions, but rather explorations under a given set of assumptions regarding technology deployment, imports, and energy demand.

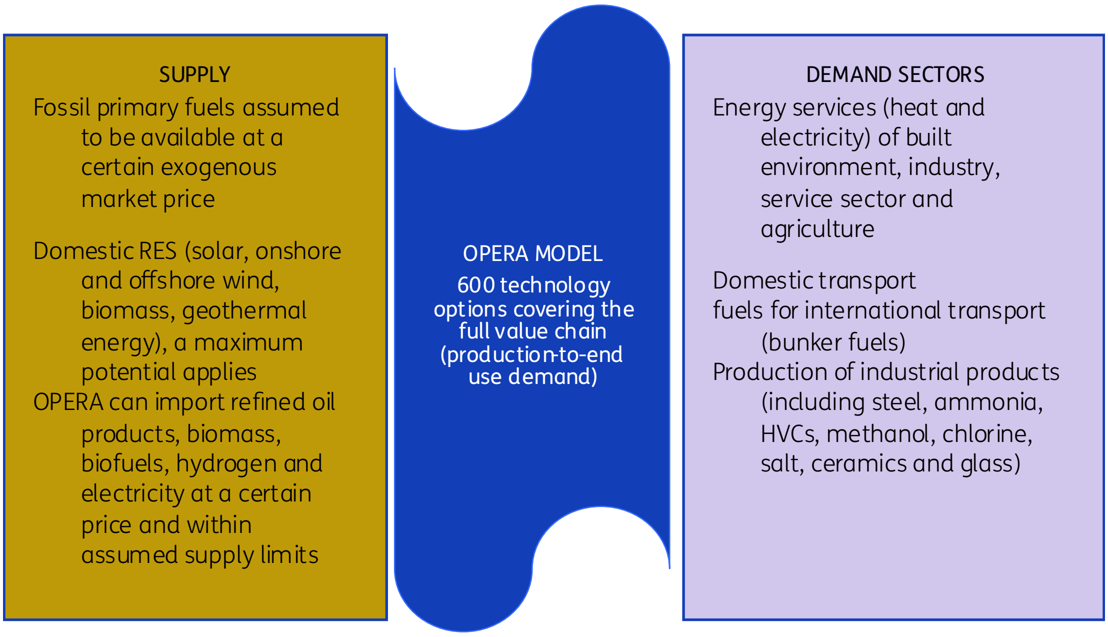


Figure 2.1: Simplified schematic presentation of OPERA model

Industry is one of the sectors in the model and both process energy demand and the fossil fuel non-energy demand such as fossil feedstocks like naphtha are covered in this model to produce industrial products such as steel, ammonia, chlorine and salt, etc..

The organic chemical industry is represented in the model by the production of olefins and aromatics, and the demand for methanol for conventional applications. Olefins, such as ethylene, propylene and butadiene, are commonly used to produce plastics, resins, and synthetic fibers. Aromatics, including benzene, toluene, and xylene, are used in the manufacture of dyes, detergents, and various plastics. The model includes conventional steam cracking using fossil naphtha for olefins production and the production of aromatics from refinery co-product reformates. The remaining part of the organic chemical industry, including the downstream conversion of olefins to polymers, is represented by a fixed fuel demand and final heat and electricity demand, derived from the Climate and Energy Outlook.

Decarbonisation of the chemical industry consists of substituting fossil energy and heat use with renewable supply options, electrification of steam crackers and Carbon Capture and Storage (CCS). In addition, reducing emissions by replacing fossil feedstocks with renewable alternatives, thereby re-carbonising the bulk chemicals is included in the model. The alternative de-fossilisation options included in the model consists of:

- Co-feed to existing steam crackers and future electrified cracker: These options enable the use of existing infrastructure.
  - Any suitable by-product from the biofuel or e-fuel refineries, namely renewable naphtha, can be co-feed to the existing conventional steam crackers or possibly future electrified crackers.
  - Plastic waste pyrolysis oil can be co-feed.
- New drop-in options for olefins and aromatics: These are all alternative stand-alone value chains,
  - Biomass-to-methanol-to olefins (Bio-MTO).
  - Biomass-to-methanol-to aromatics (Bio-MTA).
  - Biomass-to-direct thermochemical liquefaction (DTL)-to aromatics (Bio-DTLA).
  - Synthetic methanol-to-olefins.
  - Biomass-to-ethanol-to-ethylene (lignocellulosic only) (Bio-ethylene).
  - Plastic waste-to-methanol-to-olefins (PW-MTO).

Table 2.1 illustrates the organic chemical industry, decarbonisation and re-fossilisation alternatives included in the modelling.

Table 2.1: Decarbonisation and de-fossilisation alternatives for the organic chemical industry

Resources	Current illustration (feedstock replacement)		GHG emission reduction options (scope 1)
Fossil (oil, gas)-reference	Naphtha crackers		Use of renewable electricity and heat options Electrification and CCS
	As input to crackers	New routes	
Plastic Waste	Chemical recycling • pyrolysis co-feed	Chemical recycling • gasification followed by methanol synthesis-to-olefins and aromatics (PW-MTO /MTA)	Circularity
Biomass (2nd generation, focus on annex IX, list A and B of Renewable Energy Directive)	Bio-naphtha co-feed, biomass pyrolysis co-feed	Biomass to olefins & aromatics • gasification followed by methanol synthesis-to-olefins and aromatics (Bio-MTO & Bio-MTA) • ethanol to ethylene (Bio-ethylene) • direct thermochemical liquefaction to aromatics (Bio-DTLA)	Bio-CCS
Renewable energy + CO_2 (flue gas or Direct Air Capture)	E-naphtha co-feed	E-methanol synthesis to olefins	Bio-CCS

To address specific aspects of the chemical industry's transformation—particularly those challenging to capture through the main scenario modelling with OPERA—a separate assessment was carried out. This focused on evaluating potential options for novel plastics production, offering additional insights into industry-specific transition pathways (see Appendix B).

2.1 Key scenario parameters

In order to construct a scenario that achieves climate neutrality by 2050 in the Netherlands the sector demand and the renewable resources potentials need to be determined. This study builds up on the previous scenario modelling and builds up on the scenario parameters of OPERA and TRANSFORM "Towards a sustainable energy system for the Netherlands in 2050 – Scenario update and scenario variants for industry" (Scheepers et al. 2024).

The key scenario parameters relevant for industry and also parameters that are implemented differently than the previous study are introduced below. All other parameters that are unchanged can be found in Scheepers et al. (2024).

2.1.1 Industry sector projections

Table 2.2 shows the production volume projections for specific industries up to 2050. These are based on the Climate and Energy Outlook (KEV, 2022) projections up to 2040 and extrapolated thereafter. The exemptions to KEV projections and also to previous scenario modelling projections from Scheepers et al, (2024), are mentioned below.

- Olefins and aromatics production are updated based on the shutdown of one of the naphtha crackers[3] and the production amounts are kept constant.
- Waste incineration capacity is reduced by 50% in 2050, compared to current capacity to represent the possible effects of the Single Use Plastics (SUP) Directive and the Waste Framework Directive.
- Methanol and ammonia production in this table represents the current industrial demand. Further demand increase for these due to demand from transport sector, mainly maritime shipping, and from the chemical industry as alternative feedstock intermediate are not covered here as these are results of the scenario modelling and will be presented in the results chapter.

Table 2.2: Industry sector projections (derived from the ADAPT scenario (Scheepers et al., 2024))

Sector	Uni	Reference scenario			Comparison with ADAPT
		2030	2040	2050	
Steel production	Mtonne	7.2	7.2	7.2	Same
Ammonia production	Mtonne	2.83	3.01	3.2	Same
Olefine production	Mtonne	4.21	4.21	4.21	Updated due to unit shut down in SABIC and kept constant
Aromatics production	Mtonne	3.34	3.34	3.34	Updated due to unit shut down in SABIC and kept constant
Methanol demand conventional*	Mtonne*	0.51	0.55	0.59	Same
Chlorine production	Mtonne	1.14	1.27	1.41	Same
Salt production	Mtonne	8.22	9.09	10.11	Same
Glass production	Mtonne	0.97	1.02	1.07	Same
Ceramic production	Mtonne	3.04	3.05	3.06	Same
Non-energetic use other industries	PJ	19.00	19.75	20.57	Same
Waste incineration	PJ	31.24	31.24	31.24	50% low

* This is methanol demand for conventional applications.

[3] Sabic closes OIefins-3 cracker Geleen after maintenance shutdown – Industrylinqs

2.1.2 International bunkering projections

Maritime bunkering

The maritime bunkering projections are implemented differently than the previous scenario modelling and the ADAPT and TRANSFORM scenarios. The maritime bunkering is maintained to 2019 level and considered as a sensitivity parameter in this study. This assumption is due to significant uncertainties surrounding the transition to alternative fuels and its impact on port competitiveness. While there are some discussions that the shift to renewable fuels could reduce the competitiveness of major bunkering ports like Rotterdam[4], research suggests both scenarios are possible - either a decline in bunkering due to higher fuel costs or continued dominance as transportation costs for alternative fuels may not be a major limiting factor. Looking at the current initiatives, for instance, the efforts to establish green shipping corridors[5], secure alternative fuel supply options[6] different conclusions may be drawn up. While low cost production of alternative fuels may happen in regions with abundant resources, this does not mean their bunkering will also shift to those regions as these are tradable commodities. Given the uncertainty, the assumption to maintain the bunkering level constant ensures a neutral baseline for scenario modelling, allowing sensitivity analyses to explore potential variations.

Aviation bunkering

Same assumption is applied for the aviation bunkering; thus, the fuel demand will remain at 2019 levels and stay stable thereafter. This is due to uncertainties in fuel price developments, the impact of European emission Trading System (EU ETS) and International Civil Aviation Organization's (ICAO's) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) regulations, and the high costs of renewable fuel substitution. The ICAO net-zero 2050 goal adds further uncertainty, making it challenging to predict how fuel demand will evolve.

Table 2.3 presents, in addition to aviation, also the maritime bunkering assumptions, distinguishing fuel use based on voyage type. It highlights the share of fuels used for intra-EEA voyages (within the European Economic Area) and extra-EEA voyages (trips that either originate from or arrive at the EEA). Additionally, inland bunkering is shown separately. This breakdown is essential for determining the portion of fuel consumption subject to the EU ETS and Fuel EU Maritime Regulations. This table also presents the aviation bunkering demand broken down to flights within EEA and to or from non-EEA countries.

[4] The Port of Rotterdam, part of the so-called ARA region (Amsterdam-Rotterdam-Antwerp), is currently Europe's largest bunkering port and the second largest in the world , following Singapore. Energy and materials transition will impact the bunkering ports significantly. The transition from heavy fuel oil and marine diesel oil to alternative renewable fuel options will influence the competitiveness of the bunkering ports. Among others, port infrastructure, port costs, including bunker fuel costs, and geographical location are the most important drivers of port competition (Lirn et al., 2004; Notteboom et al., 2022; Parola et al., 2017; Tongzon, 2007).

[5] According to Hendriksen (2023), there are 24 different projects that are classified as green shipping corridors (Global Maritime Forum & Getting to Zero Coalition; Hervas, 2023). Among these initiatives, the Rotterdam-Singapore green shipping corridor is the only corridor that spans between Asia-Europe and one of the most active initiatives.

[6] Among the majority of ports involved in green shipping corridors port of Singapore, Rotterdam and Antwerp are the only three that enables bunkering methanol, biofuels and hydrogen. Both Port of Rotterdam and Singapore actively seek strategies to secure alternative fuels. For instance Rotterdam has signed several MoU to secure hydrogen imports from other geographical locations. Singapore signed a MoU with Indonesia to import renewable energy such as hydrogen (Hendriksen, 2023)

Table 2.3: Demand assumptions for the Dutch maritime and aviation bunkering (PJ)

	2019	2030	2040	2050	Comparison with ADAPT
Maritime bunkering	478.4	478.4	478.4	478.4	This is slightly different than ADAPT (469.1 PJ in ADAPT in 2050)
... of which intra-EEA	86	86	86	86	This differentiation was not done in ADAPT
... of which extra-EEA	393	393	393	393	This differentiation was not done in ADAPT
Inland bunkering	36.4	36.4	36.4	36.4	
Maritime bunkering that falls under FuelEU Maritime/ETS	246.1	246.1	246.1	246.1	This differentiation was not done in ADAPT
Aviation bunkering	166.3	166.3	166.3	166.3	This is lower than ADAPT (194.2 PJ in ADAPT)
... of which intra EEA	31.7	31.7	31.7	31.7	This differentiation was not done in ADAPT
... of which extra EEA	134.6	134.6	134.6	134.6	This differentiation was not done in ADAPT
Aviation covered by ETS (intra-EEA)	31.7	31.7	31.7	31.7	This differentiation was not done in ADAPT

2.2 Renewable and sustainable resource potentials

This study uses the maximum renewable energy supply potentials in the Netherlands. This is due to the inclusion of the policies with stringent renewable energy and GHG emission reduction targets; the ReFuelEU Aviation and FuelEU Maritime Regulations and the EU ETS1. The maximum renewable energy potentials are derived from the previous scenario modelling and correspond to the TRANSFORM scenario. The core difference relates to the CO_2 capture potential. In discussion with the ministry the capture potential is set to 20 Mt. This is lower than the ADAPT and higher than the TRANSFORM scenario. The table below presents the renewable supply potential assumptions.

Table 2.4: Renewable energy supply potentials as input to the reference scenario (derived from Scheepers et al., 2024)

	Reference scenario [2050]
Wind offshore	70GW
Wind onshore	12 GW
Solar energy	132 GW
Nuclear energy	8.3 GW
Geothermal	200 PJ
Biomass – domestic	184 PJ
Biomass (woody) – import	650 PJ
Biomass (UCO&AF)	67 PJ

	Reference scenario [2050]
Plastic Waste*	3879 kt (136 PJ)
CO_2 storage potential (Mt)**	20 Mt

* Plastic waste potential is adapted.

** ADAPT scenario set this to 40 Mt and TRANFORM to 15Mt. This is adapted in discussion with the ministry.

Biomass and plastic waste availability

Biomass resource types are restricted to feedstock categories deemed eligible under the Renewable Energy Directive (REDIII). Other biomass feedstocks, such as sugar and oil crops, are excluded despite being the primary sources for many current chemical production processes. This exclusion relates to concerns about sustainability and the potential unintended consequences of using land-based food and feedstocks from agriculture, such as direct and indirect land-use changes. These has been a core reason for limiting biofuels produced from food and feed crops.

There is currently no consensus on whether food and feed crops should be considered ineligible for use in the chemical industry. In this study, the overall biomass potential is limited to non-food and feed crops across all sectors, including chemical industry.

Further details on how the biomass import potential is defined are provided in Appendix A. The plastic waste potential includes estimates of both domestic plastic waste generation and imports from other European countries to the Netherlands. The underlying methodology used to determine plastic waste potential and import volumes is also described in Appendix A, along with an explanation of how plastic waste is allocated between mechanical and chemical recycling.

Additional information on the characteristics of recycling technologies and the relative contributions of mechanical and chemical recycling is also available in Appendix A.

3 Scenario set up

This study aims comparing a climate-neutral energy system with a fossil-free energy system and industry by 2050. In order to do that, the key parameters such as the renewable resource potentials, including import of plastic wastes, the overall energy demand and the industry sector production volumes are kept the same. While only biomass and plastic waste import is considered in both scenarios, to become fossil free import of renewable resources are allowed in the fossil-free scenarios. The policies that have been adapted by end of 2024 are introduces below and implemented in all scenarios.

3.1 Climate-neutral reference scenario

The climate-neutral energy system for the Netherlands has been previously studied by Scheepers et al (2024) using two distinct scenarios, called ADAPT and TRANSFORM. While building up on these, this study redefines a reference scenario.

The climate-neutral reference scenario sketches a future where the policies adapted by the end of 2024 are implemented. This scenario also considers the Communication from the Commission on 90% overall emission reduction by 2040, compared to 1990. In the rest of the document the climate-neutral reference is referred to as POLICY scenario. Below section introduces the key policy objectives included in the POLICY scenario.

3.1.1 Key policy consideration

Renewable Energy Directive (REDIII)

RED III sets specific targets for various sectors, including transport, buildings, and industry. In the industrial sector, RED III seeks to increase the share of renewable energy for both end-use and non-energy purposes by an average of 1.6% annually between 2021-2025 and 2026-2030. Additionally, RED III introduces targets for renewable fuels from non-biogenic fuels (RFNBO) for industry, requiring that by 2030, at least 42% of hydrogen used in the industry comes from renewable sources, rising to 60% by 2035.

For the transport sector, RED III provides two compliance options by 2030: either achieving a minimum of 29% renewable energy use or reducing greenhouse gas intensity by 14.5%, compared to a refence value of 95 g CO_2eq/MJ. In the Netherlands, the latter will be followed.

The Communication on 2040 targets

The Commission has published a Communication which starts the process of preparing the 2040 climate target. In this communication, the Commission recommends a 90% reduction in net GHG emissions by 2040, compared to 1990. The 2040 climate target for the EU is currently under the political debate and the final legislative proposal to include the 2040 target in the European Climate Law will take some years.

ReFuelEU Aviation Regulation
On 9 October 2023, the European Council formally approved the ReFuelEU Aviation Regulation. This regulation introduces a set of harmonized rules across the EU. This means that member states are not allowed to put in place national mandates that supersede ReFuelEU. Therefore, the sustainable aviation fuel (SAF) targets introduced in this regulation are set as the targets for the climate-neutral reference scenario. Shares of SAF referred to in Article 4 of this regulation are introduced in Table 3.1. This table also introduces the contribution of renewable fuels of non-biologic origin (RFNBO) that shall at least be supplied up to 2050.

Table 3.1: SAF targets introduced in the climate-neutral reference scenario

Year	Volume shares (% of aviation fuel to EU airports)	
	Overall SAF	Minimum RFNBO
2025	2%	-
2030	6%	0.7%
2031		1.2%
2032		1.2%
2033		
2034		2%
2035	20%	5%
2040	34% [7]	10%
2045	42%	15%
2050	70%	35%

Note[8]: From 1 January 2025 until 31 December 2034, aviation fuel suppliers have the flexibility to average supplies of SAF to Union airports for compliance with the minimum shares. This means that fuel suppliers can choose to supply all their SAF at one or more of the airports they supply, if that is logistically more attractive. Since fuel suppliers located in one member state often supply aviation fuel across borders, this could also mean that the average share of SAF in some countries will be higher or lower compared to the minimum shares in ReFuelEU.

The eligible sustainable aviation fuels within this Regulation includes certified biofuels (excluding biofuels from food and feed crops), renewable fuels of non-biological origin (including renewable hydrogen) (RFNBO) and recycled carbon aviation fuels, as well as low-carbon aviation fuels (including low-carbon hydrogen) all complying with the Renewable Energy Directive (RED) sustainability and emissions saving criteria. Eligible SAF under this regulation are listed in Table 3.2. It is also highlighted which options are implemented in this scenario modelling.

[7] This target may not necessarily be inline with the recent communication from the Commission on 90% GHG emission reduction by 2040. This number was based on the 80% GHG emission reduction.
[8] Disentangling ReFuelEU: How will it shape the SAF market? – SkyNRG

Table 3.2: SAF types eligible under the ReFuelEU Aviation Regulation

	Eligible	Implemented in this study
Biofuels	Advanced biofuels made from feedstocks in REDII, Annex IX A list.	Yes
Biofuels	Biofuels made from feedstocks in REDII Annex IX B list. These are used cooking oil (UCO) and animal fats (cat. I and II)	Yes
Renewable fuels of non-biological origin (RFNBO)	Hydrogen or liquid fuels complying with REDIII RFNBO criteria, the energy content of which is derived from renewable resources	Yes
Synthetic low-carbon aviation fuels	Hydrogen or fuels made from low-carbon hydrogen, the energy content of which is non-fossil and non-renewable, i.e. nuclear	No
Recycled carbon fuels (RCF)	Fuels of which the energy content is from waste fossil energy, i.e. steel mill or refinery waste gases. Shall comply with the REDII GHG methodology for RFNBO and RCF.	No

FuelEU Maritime Regulation

This regulation introduces GHG intensity reduction targets to the ship owners with voyages between the EU ports and the voyages to and from the EU ports. The GHG intensity relates to the life cycle GHG emissions and the required a percentage reductions are relative to a reference value of 91.16 gCO_2e/MJ.

A recap of this regulation is introduced below.

Table 3.3: Main elements of the FuelEU Maritime Regulations

<table>
<tr><th></th><th colspan="3">FuelEU Maritime Regulation</th></tr>
<tr><td>Type of target/obligation</td><td colspan="3">A GHG intensity reduction target on energy used on board by a ship</td></tr>
<tr><td>Obliged parties and sector coverage</td><td colspan="3"><u>All ship owners above 5000 gross tonnage</u>
100% of energy on voyages between EU ports and to 50% of energy used on voyages where the arrival or departure port are outside the EU or the EU's outermost regions[9]</td></tr>
<tr><td rowspan="7">Targets/obligations</td><td rowspan="7">GHG intensity reduction of
All GHG cuts are relative to a defined GHG intensity level of 91.16 gCO_2eq per MJ.</td><td>Reduction</td><td>Required GHG intensity (gCO_2eq/MJ) [10]</td></tr>
<tr><td>2% from 2025</td><td>89.3</td></tr>
<tr><td>6% from 2030,</td><td>85.7</td></tr>
<tr><td>14.5% from 2035</td><td>77.9</td></tr>
<tr><td>31% from 2040,</td><td>62.9</td></tr>
<tr><td>62% from 2045,</td><td>34.6</td></tr>
<tr><td>80% in 2050</td><td>18.2</td></tr>
<tr><td>Sub-target for RFNBO/H_2</td><td colspan="3">No sub target, but, if the Commission reports that the share of RFNBO/H_2 accounts for less than 1% of the shipping sector fuel mix in 2031, a <u>2% RFNBOs fuel use target will be set from 2034</u>.
From 1 January 2025 to 31 December 2033, a multiplier of "2" can be used to reward the ship for the use of RFNBO.</td></tr>
<tr><td>Renewable and sustainable fuel coverage</td><td colspan="3">All low carbon fuels both renewable and fossil</td></tr>
</table>

9 Ports in the nine EU outermost regions are Açores, Madeira, Canarias, Guadeloupe, French Guyana, Martinique, Mayotte, Saint Martin and Reunion.

10 The EU agrees on well-to-wake GHG limits to energy used on board ships from 2025 (dnv.com)

	FuelEU Maritime Regulation
Role of biofuels from Annex IXB	No cap is set on fuel suppliers meeting targets with animal fats and UCO.
Role of 1G biofuels	Food and feed crop based biofuels shall be considered to have the least favourable fossil fuel type emission factor, thus, not contribute to any reduction

Below table introduces the average GHG intensities implemented in this scenario modelling.

Table 3.4: The average GHG intensity reduction of renewable fuels and better fossil for maritime shipping compared to reference emission for this sector

	Now -2030	2030-2045	2045-2050
GHG intensity reduction of renewable fuels	• 75% for all biofuels (incl BioLNG) • 75% for RFNBO	• 85% for all biofuels (Annex A and B), except BioLNG • 85% for RFNBO • 78% for BioLNG	• 78% for BioLNG • 98% for RFNBO • 90% for Biofuels(Annex A and B)
GHG intensity of fossil LNG	15% reduction (77.43 gCO_2eq/MJ (Transport & Environment, 2023)		

The International Maritime Organization (IMO) has adopted a revised strategy aiming for net-zero greenhouse gas (GHG) emissions from international shipping by or around 2050. In April 2025, the IMO approved the *Net-Zero Framework* that introduces the first global, sector-wide combination of mandatory GHG intensity standards and an emissions pricing mechanism for international shipping. These measures target large ocean-going vessels and are scheduled for formal adoption in October 2025, with entry into force expected in 2027. The current study does not incorporate these developments. This is due to the timing of the study's, and the current uncertainty regarding its precise design, implementation timeline, and enforcement. As such, the implications of this framework—though potentially significant for future maritime fuel use and emissions—fall outside the scope of this analysis.

EU ETS1

EU ETS covers next to energy sector, manufacturing industry and intra-EEA aviation, also maritime emissions since 2024.

- From 2024 onwards, cargo and passenger ships of or above 5000 gross tonnage (GT) is covered in EU ETS[11]. Offshore ships will not be included.
- From 2027 onwards, also offshore ships larger than 5000GT will be included in ETS.

The OPERA model covers only the Dutch energy system, whereas EU ETS is an EU-wide emission trading system. In the previous scenario modelling ETS targets were set only to the sectors in the Netherlands. Thus, the emission trading was limited within the Netherlands.

In this study, we introduce a CO_2 price that is based on the European Commission impact assessment study (EC, 2040) (See Table 3.5). Thus, a CO_2 tax is introduced, indicating that the shadow CO_2 prices to reduce emissions will be compared with the CO_2 price and technologies with higher shadow prices will assume to offset their emissions with certificates.

[11] These are already covered in MRV

Table 3.5: CO_2 price estimates according to the European Commission

€2023/ton	2025	2030	2035	2040	2045	2050	
This study	95	95	140	290	430	490	EC recommendations for climate-neutral energy system

Policies around circularity

The EU has been amending its packaging and packaging waste regulations (PPWR). In its latest amendment (February 2025), among others, the Commission introduced specific targets for recycling. These are introduced below.

	PET	PO Contact Sensitive	PO Non Contact sensitive
PCR content	2030: >30% 2040: >50%	2030: >10% 2040: >50% (exemption possible)	2030: >35% 2040: >65%
Approved recycling technology	Mechanical recycling with 95% PET content as input waste Chemical recycling (reduced carbon footprint) rPET price > vPET> import rPET (both technology)	Collected via controlled loop, or Novel technology Pyrolysis (higher carbon footprint than vPO) rPO price > vPO (both technology) > import vPO	No regulation, mechanical recycling is fine, quality is low with the biggest challenge is sealing. rPO price = vPO (import)

Figure 3.1: Recycling targets according to PPWR

Single use plastics (SUP) Directive aims, whenever possible, to stop single use plastics for cotton bud sticks, cutlery, plates, straws, stirrers, and sticks for balloons. It also applies to cups, food and beverage containers made of expanded polystyrene , and on all products made of oxo-degradable plastics. For other single use plastics, the aim is to limit their use.

The specific targets introduced in this Directive are:

- A 77% separate collection targets for plastic bottles by 2025, increasing this to 90% by 2029.
- Incorporating 25% of recycled plastic in PET beverage bottles from 2025, and 30% in all plastic beverage bottles from 2030.

According to Plastics Europea, approximately 5% of fossil based plastics production relate to PET in 2022.

Unfortunately, this scenario modelling does not allow implementation of these specific regulations and directive. Instead, plastic recycling is pre-determined (see Appendix A).

3.2 Fossil-free scenarios

Two scenarios for a fossil-free future are explored, focusing on the main uncertainties: future global demand for renewable resources and how market prices for renewable energy (or feedstock) will be determined. Table 3.6 outlines the key narratives for these two scenarios.

Table 3.6: The fossil-free scenario narratives

Name	Features
FossilFREE_Low Imports (FosFREE_LowImp)	Climate neutrality by 2050 is a shared goal for all nations, with many prioritizing the use of domestic renewable resources. However, not all countries have sufficient renewable energy, or feedstock supplies to meet their needs entirely on their own. As a result, countries with limited domestic resources must compete globally to secure the remaining available renewable energy and feedstock. This competition drives up market prices for these resources. The Netherlands maximizes the use of its domestic renewable resources but imports when necessary.
FossilFREE_High Import (FosFREE_HighImp)	While climate neutrality is the common narrative, renewable resource mobilisation is much larger, and a global market economy is followed with significant trade flows. The Netherlands can achieve fossil-free targets with the possibility of full import of remaining fossil fuel use, compared to climate-neutral scenario (POLICY).

As described in Table 3.6 import prices for FosFREE_LowImp and FosFREE_HighImp are respectively high and low. The prices are determined based on the following steps:

- In the low import scenario, 50% of the remaining fossil fuel use from the POLICY scenario is allowed to be substituted with imports of renewable energy carriers—specifically renewable kerosene, methanol, and other oil products.
- The prices in this scenario have been derived from a reference run with 50% lower fossil fuels.
- In the high import scenario, a more optimistic approach is taken. Here, 100% of the remaining fossil fuel use from the POLICY scenario could be replaced by imported renewable energy carriers.
- The import prices are directly based on the shadow prices of the corresponding fuels in the POLICY scenario.

The import prices used can be found in Table 3.7 together with other key scenario parameters. As can be seen all three scenarios carry the same ambition up to 2040 and deviate thereafter.

Table 3.7: Key scenario parameters

	Reference climate-neutral	Fossil-free	
Scenario names	POLICY	FosFREE_LowImp	FosFREE_HighImp.
2030 and 2040 targets	55% reduction 2030; 90% reduction in 2040		
2050 target	Climate-neutrality	Fossi-free energy system and industry	
Specific policy implementation	REDIII, ReFuelEU Aviation & FuelEU Maritime Regulations, EU-ETS1	Same as POLICY, with the policy aspiration to be fully fossil-free	Same as POLICY, with the policy aspiration to be fully fossil-free
Primary resource import	Biomass and plastic waste Fossil fuels import	Biomass and plastic waste	Biomass and plastic waste
Renewable fuel & intermediate imports	No	Only when domestic resources and the primary import assumptions are not sufficient to close the gap	Yes

	Reference climate-neutral	Fossil-free	
Import prices [€2023/GJ]		Renewable kerosene: 44.7 Renewable methanol: 40.9 Renewable other oil products: 60.1	Renewable kerosene: 34.1 Renewable methanol: 32.0 Renewable other oil products: 34.4

4 Modelling results-From climate-neutral to fossil-free

4.1 Overall energy system

4.1.1 Primary energy supply

Total primary energy supply reflects the total amount of energy available from primary energy sources before undergoing any conversion or transformation process. It includes raw energy forms such as crude oil, natural gas, coal, uranium and renewable sources (e.g. wind and solar energy) along with imported energy in its various forms.

Figure 4.1 illustrates the projected use of fossil fuels under the climate-neutral reference scenario, labelled POLICY. The modelling results indicate a substantial decline in fossil fuel use over time. However, despite the influence of EU-ETS CO_2 pricing, fossil fuels retain a role in the energy mix.

The reduction in fossil fuel consumption is estimated at 18% between 2030-2035, 26% between 2035-2040, 27% between 2040-2045, and 29% between 2045-2050. Over the entire period from 2030 to 2050, the cumulative reduction reaches 70%, highlighting a steady but incomplete phase-out of fossil fuels within the modelled scenario. Above 55% of this remaining fossil fuel is supplied to industry and 42% to bunkering.

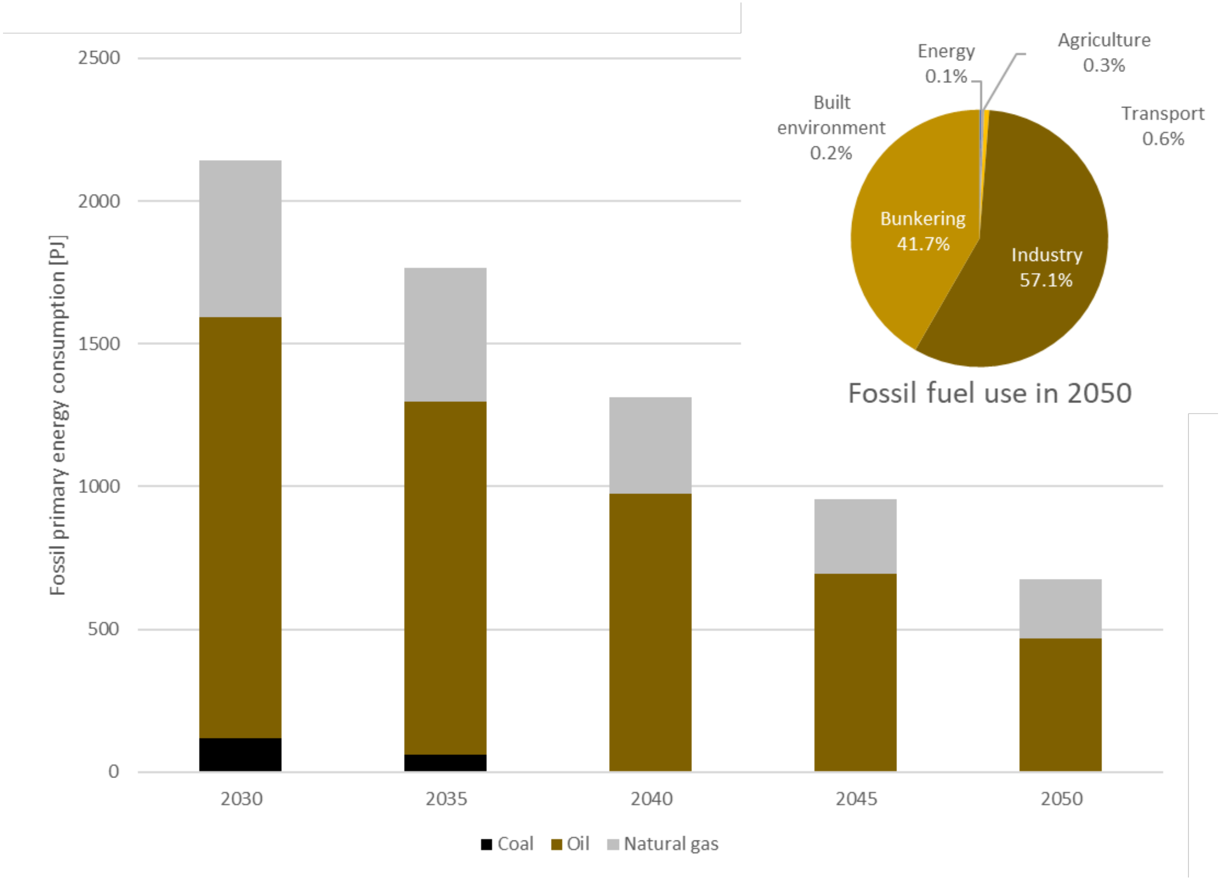


Figure 4.1: Fossil fuel use according to the climate-neutral reference scenario (POLICY)

A comparison of the reference POLICY scenario with the two fossil-free scenarios is presented in Figure 4.2. All three scenarios aim for a 90% reduction in GHG emissions by 2040, with a fully fossil-free energy system and industry targeted beyond that. The fossil-free scenarios achieve a much faster phase-out of fossil fuels compared to the POLICY scenario. By 2045, fossil fuel use in the fossil-free scenarios is already as low as in 2050 under POLICY, meaning fossil fuel use is cut nearly in half between 2040 and 2045.

This highlights that achieving a fossil-free system sooner—rather than gradually—requires more aggressive measures before 2045. These aggressive measures relate to further utilisation of available sustainable resources, that are relatively more expensive and import of renewable commodities. Almost all of the fossil fuel use in the reference POLICY scenario relates to international bunkering and industry. Therefore, the import will mainly consist of renewable kerosene for aviation, renewable methanol for shipping and chemical industry and other renewable oil products for the part of the chemical industry that is not explicitly modelled via products. No distinction is made regarding whether these imports are based on bio and synthetic based value chains with the assumption that beyond 2040 the two markets will merge.

Table 4.1 shows the utilisation rates of available potentials in the Netherlands. Both the figure and table show that already in the climate-neutral reference POLICY scenario above 80% of the available biomass and plastic wastes (including imports), wind (both onshore and offshore) and geothermal energy potentials are deployed to achieve a climate-neutral energy system in the Netherlands in 2050. Among the resources, offshore wind energy, followed by biomass plays the most significant role. The fossil-free scenario that aims maximum use of (domestically) available potential pushes further use of nuclear energy and solar PV, compared to the high import scenario.

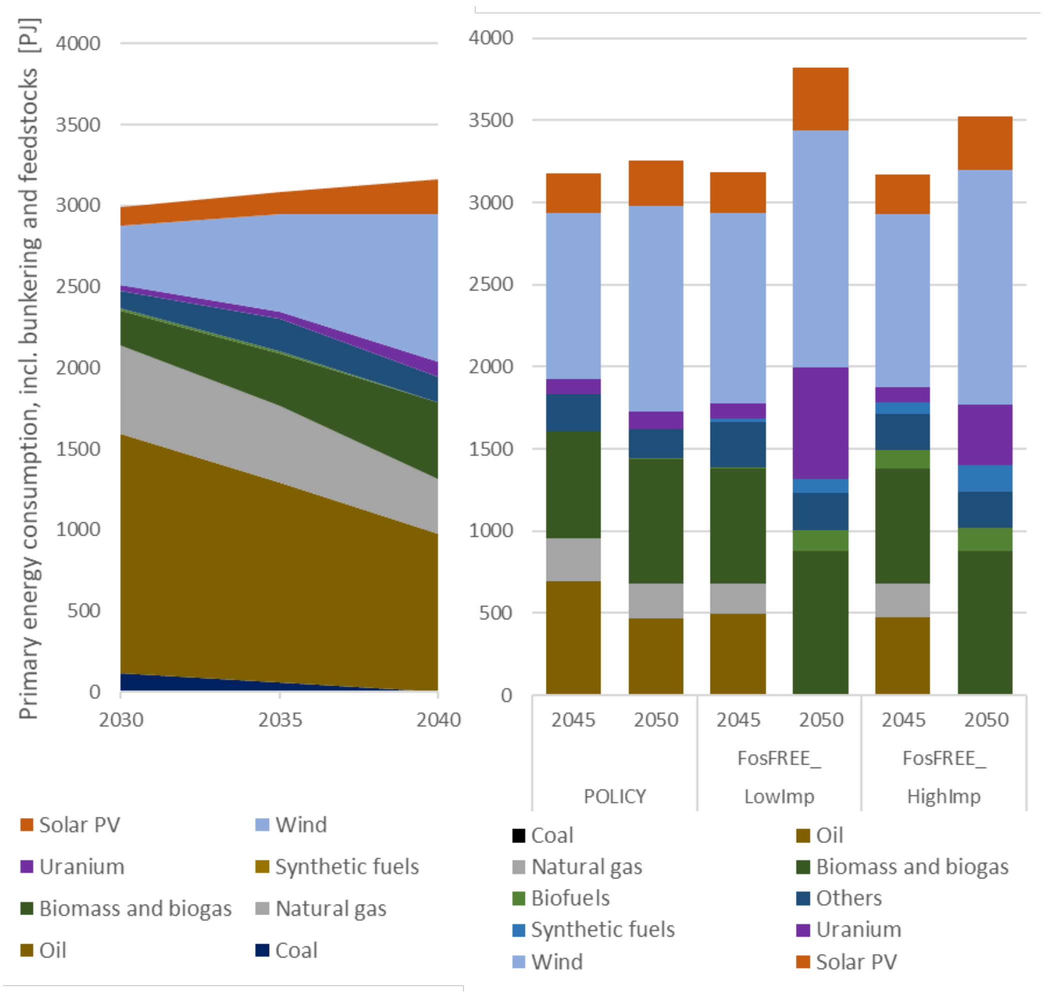


Figure 4.2: Primary energy consumption, including bunkering and feedstocks, according to the three scenarios

Table 4.1: Utilisation rate of technically available renewable resource potentials according to the three scenarios

	POLICY	FossFREE_LowImp	FossFREE_HighImp
Solar PV	58%	82%	68%
Wind offshore	85%	100%	100%
Wind onshore	100%	100%	100%
Nuclear	12%	90%	48%
Biomass	85%	97%	97%
Waste	100%	100%	100%
Geothermal	88%	88%	88%

4.1.2 Total final consumption

Final consumption represents the energy used by end-users in the built environment, industry, agriculture and transportation (domestic and international) and non-energy use. This amount is the total primary energy supply, minus losses from transmission, distribution, and conversion.

Figure 4.3 presents the final consumption, including bunker fuels and feedstocks in the Netherlands according to the scenarios that aim at achieving climate neutrality by 2050 and become fossil-free and maintain the same production and consumption levels.

In absolute terms, direct electricity consumption comprises the largest share, 13% of the total final consumption, including bunkering and feedstocks in 2022 (CBS, 2024). This increases to approximately 30% of the final energy consumption across all scenarios in 2050. The second largest consumption relates to biomass, as feedstock for the olefins and aromatics production, biogas and biofuels for transport sector.

Remaining fossil fuel in the reference POLICY scenario by 2050 is replaced by larger use of biomass and synthetic fuels, and imported renewable fuels and oil products, according to the two fossil-free scenarios.

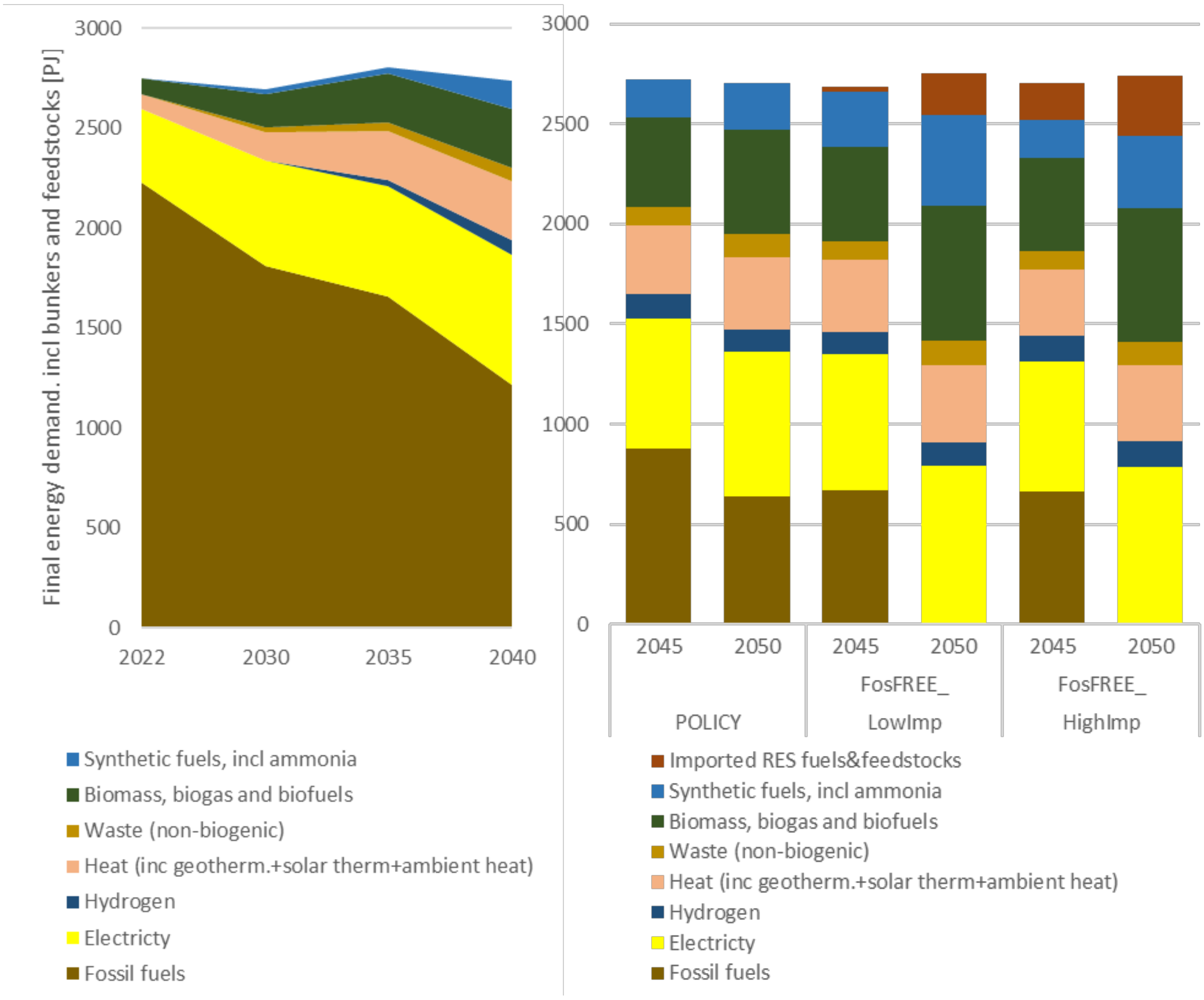


Figure 4.3: Total final energy demand, including bunker fuels and feedstocks according to POLICY and two fossil-free scenarios

As highlighted previously, the fossil-free scenarios are built up on the reference POLICY scenario and aimed at substituting the remaining fossil fuels in the system. Figure 4.4 shows the potential renewable fuel imports to achieve a complete fossil-free energy system and industry. Within the low import scenario, available (domestic) renewable resources are further utilised to the maximum, therefore, import of renewable fuels is much lower in this scenario. In 2045, the additional import needed for the low import scenario relates to renewable kerosene only. However beyond, next to renewable kerosene renewable methanol and other oil product imports become inevitable. The amount of other oil products and methanol appears very comparable in both scenario variants.

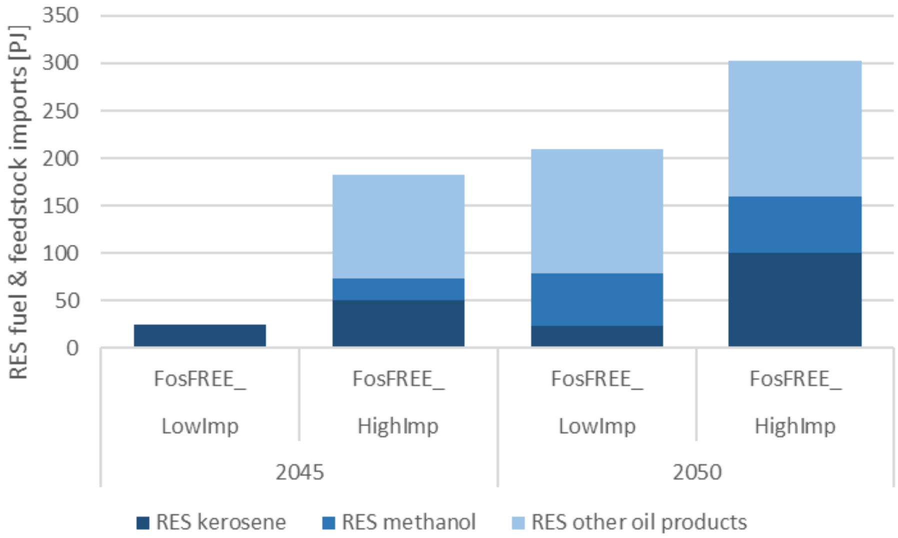


Figure 4.4: Breakdown of RES fuel imports according to the two fossil-free scenarios

4.2 Final energy consumption in industry

Industry category covers all industry sectors in the Netherlands, most notably basic chemical industry including fertilisers, basic metals including both ferro and non-ferro, food and beverage industry, waste processing industry and the rest of the industry in the Netherlands. While refineries are part of the overall Dutch energy system analysis, they are not part of the final energy consumption in this section.

Final energy consumption in industry including feedstock use comprises approximately 39% of the total final energy consumption, including bunkering and feedstock use in the Netherlands in 2030. This share gradually increases over the years to approximately 42% in 2040 and between 43-44% in 2050, across the different scenarios.

Figure 4.5 shows the final energy and feedstock consumption in industry across the three scenarios. Electrification emerges as a key decarbonisation strategy for industry, already contributing significantly by 2030 and maintaining a comparable share across all scenarios beyond that point. Among the sectors, chemical industry demands the largest share of electricity supply to industry, followed by food and beverage industry. In 2050, almost 47% of the total electricity supply in industry relates to the chemical industry across all scenarios.

The second largest contribution comes from the use of biomass, biogas, and bio-intermediates derived from biofuel refineries. Biomass demand increases steadily until 2040. To achieve climate neutrality, a 1.8-fold increase in demand is required between 2040 and

2050. In the fossil-free scenarios, the demand grows even more substantially—by 2050, it needs to be around 3.9 times higher than in 2040 to fully replace natural gas and oil.

Hydrogen and ammonia[12] demand relates mainly to the two sectors, namely fertilisers and the iron and steel industries. This study shows that H_2 use becomes an important decarbonisation option for the iron and steel industry by 2040, comprising 25PJ and continues to increase up to approximately 30PJ in 2050 in the reference POLICY scenario. In fossil-free scenarios, the demand for green H_2 is even larger, above 40 PJ in both scenarios.

The demand for synthetic feedstocks is primarily related to the chemical industry and is discussed in more detail in the corresponding chapter. Similarly, the use of waste shown in this graph refers to its role as a feedstock for the chemical sector, which is also further elaborated in the chemical industry chapter.

Imported renewable fuels within industry refers to renewable oil products and methanol used for the chemical industry.

The increase in final demand in the fossil-free scenarios is mainly driven by the chemical sector, particularly by the need for dedicated aromatics production. In the reference POLICY scenario, aromatics are obtained as by-products from refineries, naphtha crackers, or imported, meaning associated conversion losses occur outside the Dutch chemical sector and are not reflected as final demand. In contrast, the fossil-free scenarios require domestic production of aromatics (e.g. via HTL), with significant conversion losses attributed to the chemical industry.

[12] For the production of fertilizers it was assumed that part of the ammonia is from imported ammonia. This was to comply with the RFNBO obligation for industry in 2030. After that 2030 the share of imported ammonia for fertilizer production has been kept constant.

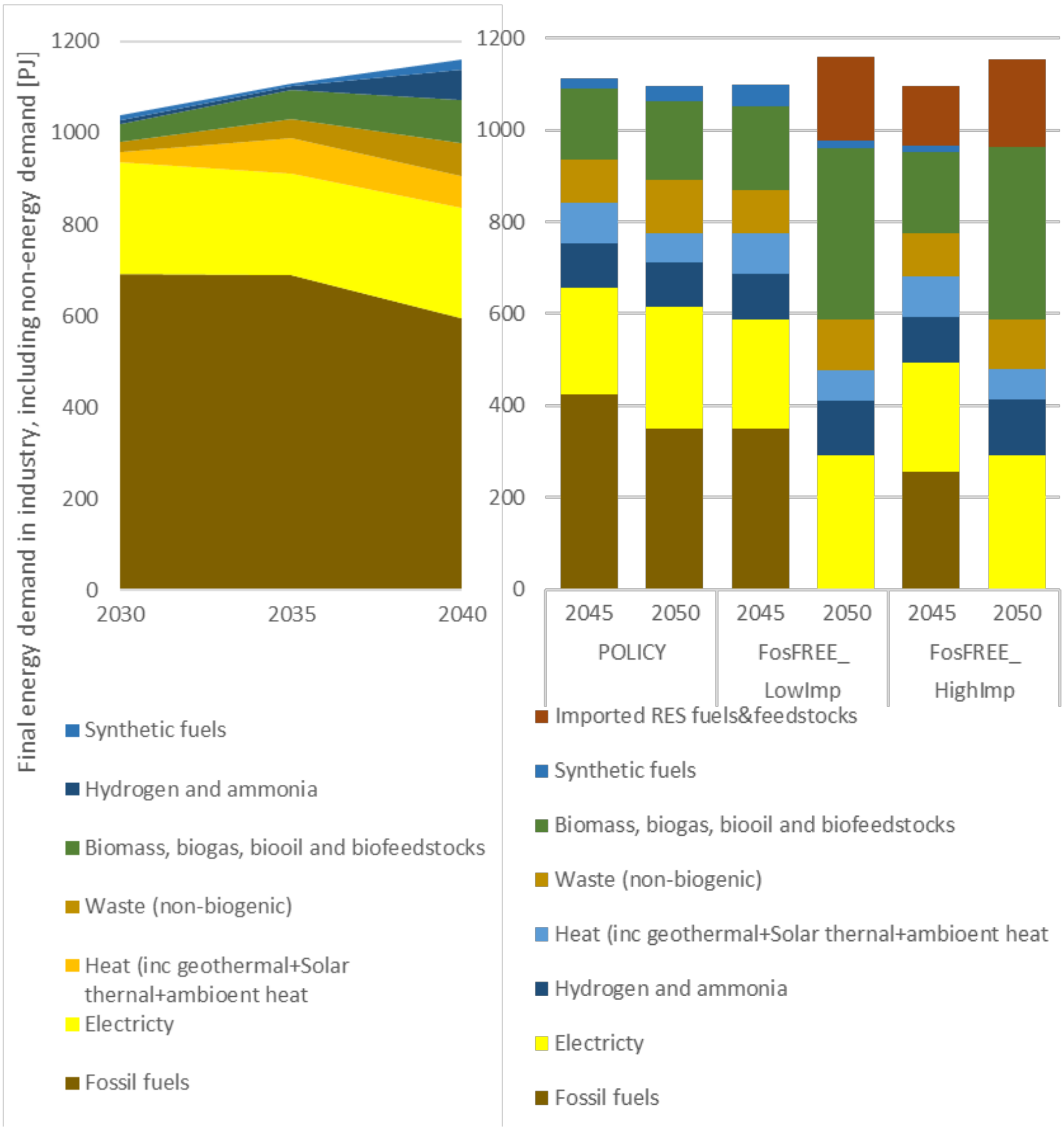


Figure 4.5: Final energy consumption in industry according to the different scenarios

4.3 Bunker fuels

Figure 4.6 and Figure 4.7 illustrate the future scenario projections for the bunker fuels and compare them with the 2022 bunkering supply in the Netherlands. It is assumed that this sector will recover from the impact of COVID-19 and stabilize at 2019 level, with total fuel demand remaining constant beyond 2030 both for aviation and maritime sectors.

As the RefuelEU Aviation Regulation sets sustainable aviation fuel targets, including sub-targets for RFNBO, the POLICY scenario modelling results align with these targets through 2050. Thus, by 2050, 70% of the aviation fuel bunkering is sustainable aviation fuel (SAF), of which 35% is from RFNBO.

In the fossil-free scenarios all fuels are SAF. In the low import scenario, where the domestic resources are utilised to the maximum, synthetic kerosene plays a much larger role when compared with the reference POLICY scenario both in 2045 and 2050. In addition, almost

14% of the SAF is imported in this scenario. Within the high import scenario 60% of the SAF bunkering is from imports.

In this scenario modelling, the primary value chains for SAF production in 2030 is hydroprocessed esters and fatty acids (HEFA). In 2050, the contribution of HEFA to total biokerosene is approximately 25%. Alcohol-to-jet value chain plays a minor role according to this modelling results, contribution to 2% of the total biokerosene. The majority of biokerosene is via gasification, followed by Fischer-Tropsch synthesis in POLICY scenario.

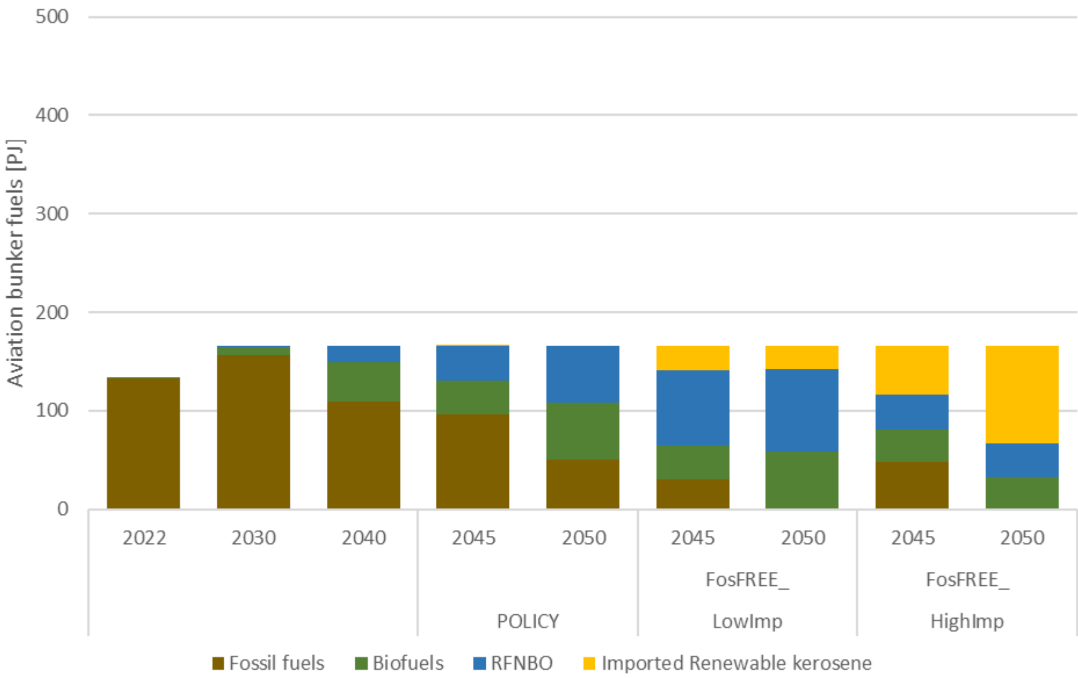


Figure 4.6: Historical (2022) and future projections for aviation bunkering based on the scenarios

The FuelEU Maritime Regulation establishes targets to reduce the sector's GHG intensity. Under this regulation, GHG intensity shall gradually decline from 2025 to 2040, achieving a 31% reduction over 15 years, followed by a steeper decline after 2040. Specifically, there shall be a 45% reduction between 2040 and 2045 and a 47% reduction between 2045 and 2050. Additionally, the regulation applies to a specific portion of total bunkering, covering all voyages within the European Economic Area (EEA) and 50% of voyages to and from third countries.

Figure 4.7 shows the fuel mix that is sufficient to achieve the targets set by the regulation within the reference POLICY scenario. As can be seen, while a limited supply of biofuels is sufficient to meet the GHG intensity reduction target in 2030, achieving 2040 targets requires a significantly larger volume of renewable fuels. Between 2030 and 2040 the supply of renewable fuels (thus both bio and synthetic) shall increase almost 12-fold. The share of renewable fuels corresponds to 46% of the total bunker fuel supply in 2040 and 51% in 2050 in the reference POLICY scenario.

Although the FuelEU Maritime Regulation sets an ambitious target of reducing GHG intensity by 80% by 2050, results indicate that nearly half of the bunker fuel supply remains fossil-based. This is due to the Regulation’s scope—covering all voyages within the EEA and only

50% of those to or from third countries—while a substantial portion of the fuels and CO_2 emissions from Dutch maritime bunkering comes from extra-EU voyages.

Shifting from the climate-neutral POLICY scenario to the fossil-free scenarios indicate the need for large volumes of renewable fuels. While the demand for biofuels is 20-26% larger in the fossil-free scenarios, the RFNBO demand growth is significant when compared with the reference scenario results. The modest growth in biofuels can be explained by the limited availability of raw biomass. The RFNBO demand in the fossil-free scenarios is almost 3 times the RFNBO demand in the POLICY scenario in 2050. In addition, a limited amount of import is considered in the high import scenario.

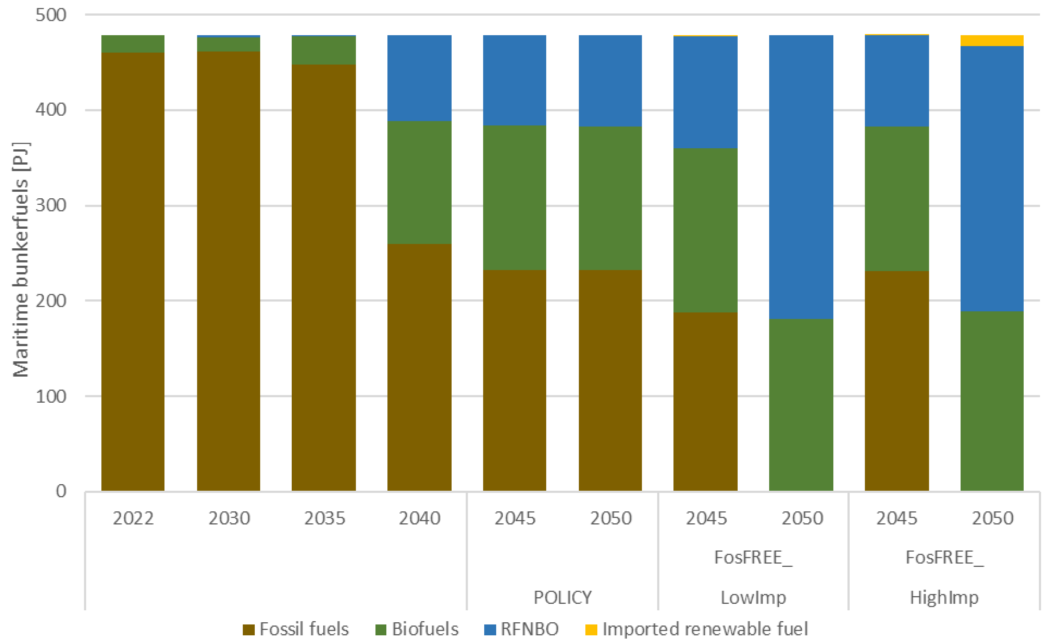


Figure 4.7: Maritime bunkering results according to the different scenarios

4.4 Chemical industry results

4.4.1 Final energy demand, including feedstocks in chemical industry

Chemical industry in this chapter covers base chemicals sector (steam crackers) that produce olefins and aromatics, methanol production, salt and chlorine production and the production of fertilisers. All other chemical industries, including downstream process, where polymers and plastics are produced, are grouped under “rest of the chemical industry” and their energy demand is included. There is also the other oil products category[13] which covers remaining oils that are used for different purposes such as the downstream processing in the chemical industry, lubricants in the mobility sector and other non-energy use of oils.

In 2022, the chemical industry made up about 25% of total final energy and feedstock demand in the Netherlands. Figure 4.8 shows future projections across three scenarios.

[13] This category is derived from the CBS and MONIT energy balance and not well defined and it includes turpentine and special petrol, lubricants, bitumen, mineral waxes, petroleum coke, and other residual petroleum products

While fossil fuel use gradually reduces in the reference POLICY scenario, it continues to play a role. By 2050, fossil fuel use drops from 67% in 2030 to 36% in 2050 in this sector. Of the remaining fossil fuel, approximately 57% relates to non-energetic use, thus use as primarily feedstock. By 2050, the chemical sector accounts for 83% of all fossil fuel use (excluding bunkering), or 46% if bunkering is included.

In the fossil-free scenarios, fossil fuel use drops more sharply between 2040 and 2045 to ensure a complete phase-out by 2050, when compared with the reference POLICY scenario.

Across all scenarios, direct electricity use appears to contribute to 12% of the total final energy consumption, including feedstocks by 2045. This corresponds to 93-99 PJ (25.8-27.5 TWh) in absolute terms. This increases to 124-137 PJ in 2050. The high end of the ranges relate to the fossil-free scenarios. Thus, fossil-free scenarios indicate larger electrification compared to reference POLICY scenario.

Oil use in this sector is substituted by recycling plastic waste, using bio and synthetic naphtha, use of biomass and imported renewable fuels, including other renewable oil products.

Waste use appears similar across all scenarios. Waste is either converted to waste oil via pyrolysis and co-feed into steam crackers, or gasified to methanol and further processed to olefins. The contribution of plastic waste recycling depends on the availability of plastic waste. In this study, plastic waste availability for the Dutch market is presented in Appendix A.

While waste use appears as one of the key circular production value chain, biomass and biobased feedstocks appear to play a larger role beyond 2040. The supply of biobased feedstock (bionaphtha) is closely linked to the expansion of biofuel refineries for the transport sector. Bionaphtha can be co-fed into existing steam crackers, partially replacing fossil naphtha. Similarly, synthetic refineries producing SAF via Fischer-Tropsch synthesis can also generate synthetic naphtha.

In the POLICY scenario, biomass is mainly used for methanol-to-olefins. The larger demand for biomass in the fossil-free scenarios relates to the production of aromatics from biomass resources as all of the products need to be fossil-free. This also explains why final energy demand in the two fossil-free scenarios is larger than the reference POLICY scenario in 2050. A large share of the aromatics are produced within the integrated refineries in the Netherlands, therefore the oil demand for these are allocated to the refineries. Within the fossil-free scenarios, however, aromatics are produced at stand-alone chemical production facilities using biomass.

Hydrogen and ammonia demand in this figure exclusively relate to the fertilisers industry decarbonisation beyond 2035.

The fossil-free scenarios clearly highlight that given the renewable resources available in the Netherlands, including the sustainable biomass and plastic waste imports to the Netherlands, a fossil-free industry cannot be realised without additional imports of renewable intermediates for industry, particularly for the chemical industry.

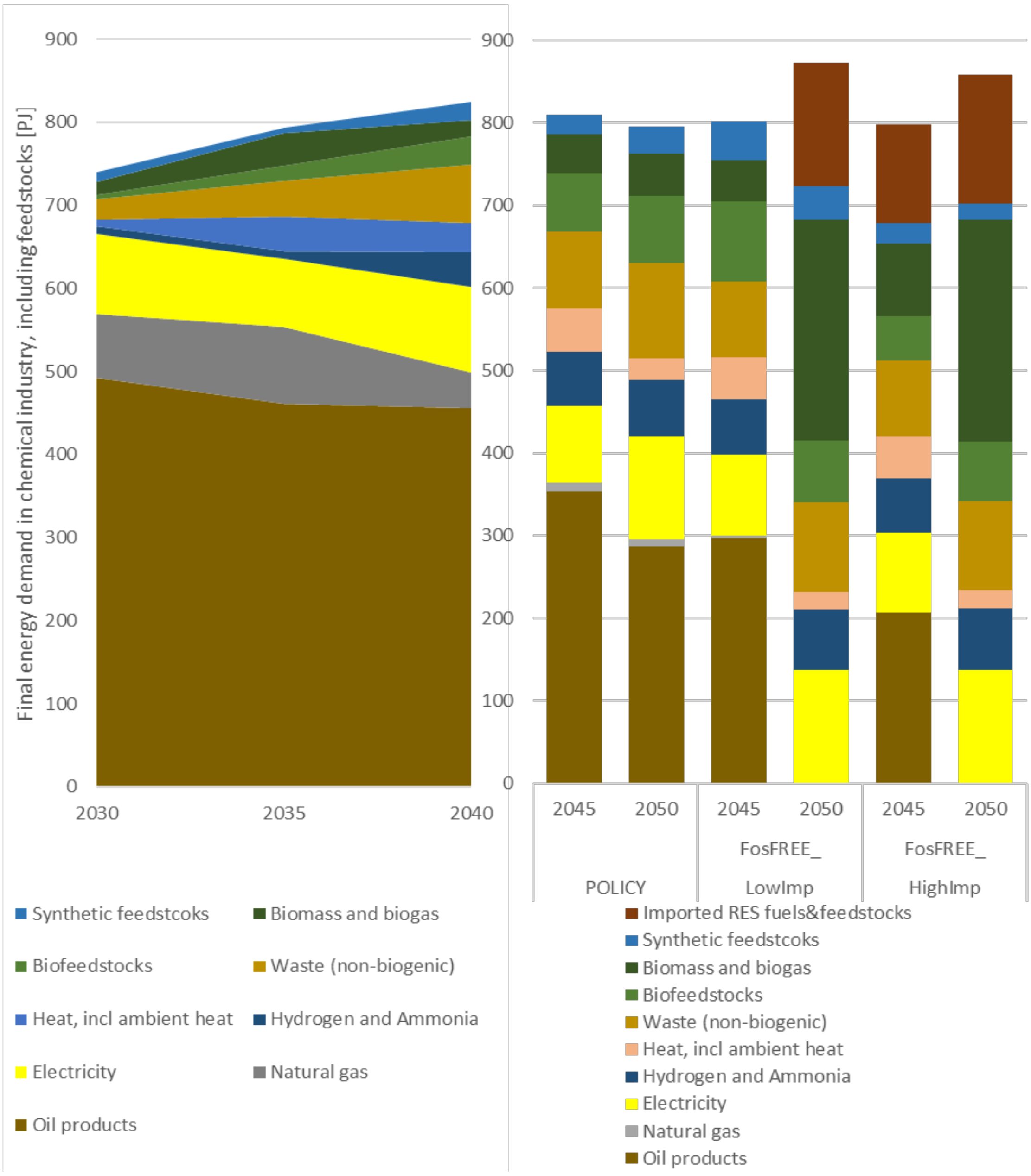


Figure 4.8: Final energy demand in chemical industry, including feedstocks, according to the three scenarios

4.4.2 Olefins production

Figure 4.9 illustrates the transformation of the organic chemical industry to produce olefins within a climate-neutral energy system and compares this scenario with the two fossil-free scenarios for 2045 and 2050.

The scenario framework highlights how mechanical recycling of plastics into recycled polymers can reduce the need for virgin polymers, which are typically derived from olefins such as ethylene and propylene. According to this study, by 2030, mechanical recycling substitutes almost 11% of total olefin production, increasing to 36% by 2050 across all scenarios. To put this number into perspective Lange et al (2024) indicates the conventional mechanical recycling to have the potential to displace nearly 40% of naphtha.

Methanol-to-olefins (MTO) emerge by 2035 and meet approximately 2.4% of the olefins production in 2040. This value chain increases to contribute 7.4% of the total olefins production in the reference POLICY scenario in 2050. In the fossil-free scenario with relatively lower import it reaches to 13% of the production and in the high import scenario 16% of the total production.

While reduced over time, naphtha steam cracking stays to play an important role in producing olefins. In 2040, almost 74% of the production relates to steam cracking and in the reference scenario almost 57%. The contribution of steam cracking reduces to 47-51% in the fossil-free scenarios by 2050.

Ethanol-to-ethylene, often considered as a promising alternative for ethylene production, barely appear in this scenario modelling for two reasons:

1. Feedstock constraints – Biomass eligible for industrial use is limited to waste and residues from agriculture and forestry, and ethanol production from lignocellulosic feedstocks is costly and the less efficient (~37% to 41%).
2. Product yield limitations – The MTO pathway produces multiple valuable olefins (ethylene, propylene, and butadiene), whereas ethanol-to-ethylene yields only ethylene, making it less attractive.

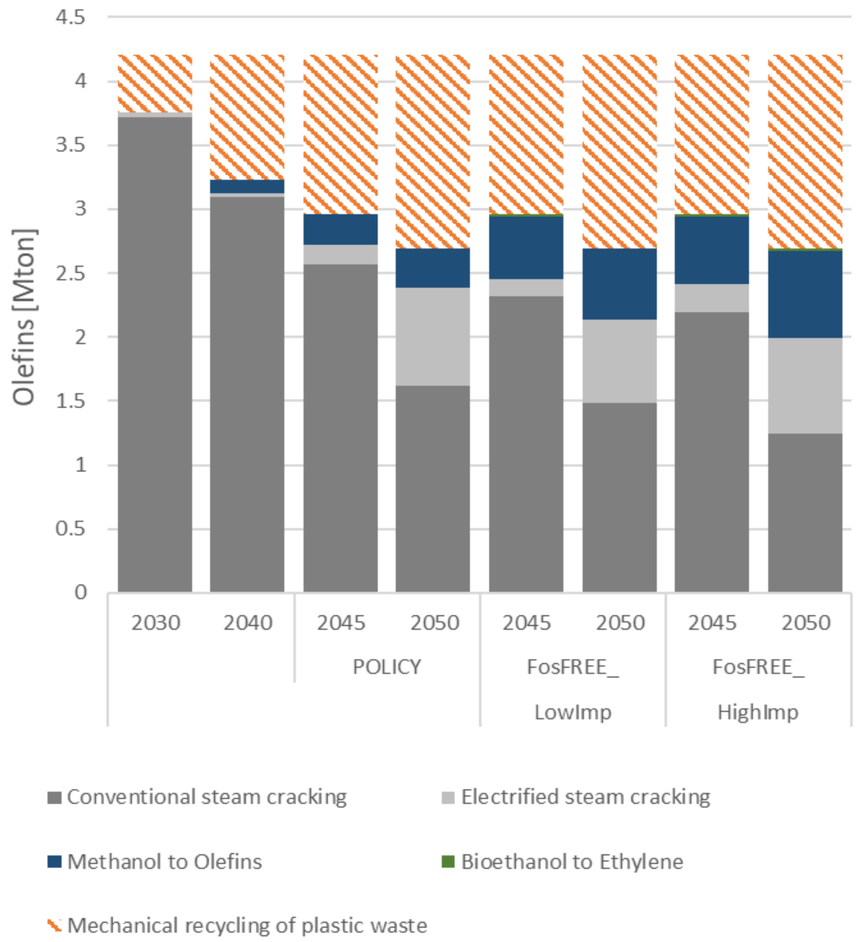


Figure 4.9: Breakdown of olefins production according to the scenario runs

Feedstock mix in naphtha steam crackers

While naphtha crackers continue to play a significant role, the feedstock input to crackers shifts from fossil naphtha to a mix of bio-and synthetic naphtha, along with plastic pyrolysis oil. This transformation is closely linked to the renewable fuel demand from the transport sector, particularly aviation and the maritime shipping. As the renewable refineries expand, one of their byproducts, renewable naphtha, is expected to become sufficiently available to meet the feedstock needs of the naphtha crackers, replacing almost 72% of the fossil naphtha by 2050 in the climate-neutral scenario. In fossil-free scenarios, naphtha cracking is further reduced by 10% in the low-import case and 16% in the high-import case compared to the reference POLICY scenario by 2050. The remaining naphtha used for cracking is entirely renewable and circular.

The demand for naphtha cracking steadily declines due to increased mechanical recycling and the growth of methanol-to-olefins value chains. Consequently, this transformation is highly dependent on developments within the transport sector and systems that enable mechanical recycling. By 2050, the key value chains supplying renewable naphtha as a by product include biomass gasification followed by Fischer-Tropsch synthesis towards kerosene production, biomass hydrothermal liquefaction towards diesel production, synthetic Fischer-Tropsch synthesis towards kerosene production and HVO production from used cooking oils and animal fats. Unfortunately, none of these value chains other than HVO, are currently commercially available in large scales and these results are highly dependent on the successful implementation of set targets in transport. An important aspect is that this renewable naphtha will have a competing market: road transport, as it can be blended with gasoline and help meeting the existing mandates for road transport.

Chemical recycling in this study consists of pyrolysis of plastic waste and gasification of waste to methanol followed by the methanol-to-olefins processes. The contribution of plastic waste based pyrolysis oil to olefins production appears to be 2% in 2030 and 2040. This increases to almost 13% in the reference POLICY scenario. In the fossil-free scenarios, the share of olefins produced from pyrolysis oil increases to almost 21% in 2050 (See Figure 4.10)

The relatively larger import of renewable methanol in the Fossil-free high import scenario shows that the methanol to olefins production increases and renewable naphtha cracking somewhat reduces. This has to do with the fact that available methanol serves both to shipping sector and the chemical industry.

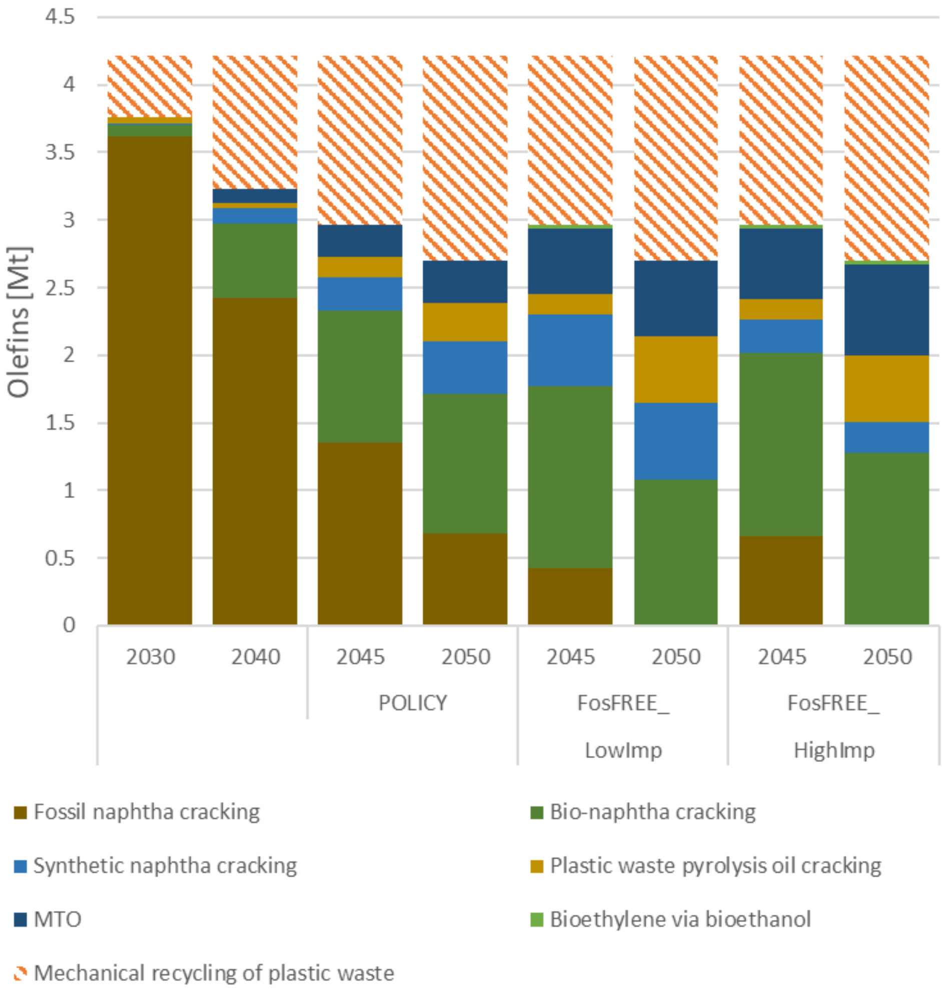


Figure 4.10: breakdown of feedstock use to produce olefins according to the scenarios

4.4.3 Aromatics production

While naphtha crackers currently produce some aromatics next to olefins, the majority of aromatics production is linked to oil refineries with chemicals integration. One of the by-products of refineries, reformates, is presently converted into aromatics. However, the future of the aromatics sector remains uncertain if oil refineries shrink due to a significantly decline in fuels demand from the transport sector.

In this study, we assume that the demand for aromatics will remain at current levels and any production losses due to refinery shrinks will be offset by increased fossil aromatics imports in the POLICY scenario. This assumption is based on the fact that there is currently no policy driven demand for renewable aromatics. In the fossil-free scenarios aromatics is selected to be produced from renewable resources.

Figure 4.11 shows the aromatics supply to the Dutch market according to the scenario modelling. Already in 2030, approximately 10% of the domestic supply relates to import of fossil aromatics. This increases to 36% in 2040 and 70% in 2050 in the POLICY scenario. As stated previously, this relates to the shrink in oil refineries and the loss of reformates compensated by imports.

While no specific sustainability goal has been introduced in the POLICY scenario a part of the aromatics is based on circular carbon, namely biobased, synthetic based and recycled plastic waste based. Their contribution is approximately 0.7% in 2030, increasing to almost 4% in 2050 and approximately 11% in 2050, in the reference POLICY scenario. These contributions relate to the aromatics produced in steam crackers and the contribution of circular naphtha replacing fossil naphtha.

Within the fossil-free scenarios the majority of the aromatics are produced from biomass resources. Aromatics from synthetic resources and plastic recycling relate to larger use of synthetic naphtha and plastic waste pyrolysis oil at the steam crackers. Results indicate that approximately 87% of the aromatics to be from biomass to aromatics and the remaining from circular naphtha in steam crackers. This modelling included methanol-to-aromatics (MTA) and direct thermochemical liquefaction (DTL) -to-aromatics value chains and the results indicate a selection of hydrothermal liquefaction (HTL) value chain. It is necessary to highlight that this value chain is relatively at a lower technology readiness level(TRL) than for instance MTO.

The potential impact of a decline in fossil refineries on the aromatics sector in the Netherlands remains uncertain. Therefore, we explored the possible implications of significantly reduced aromatics production as a sensitivity analysis in Chapter 6.

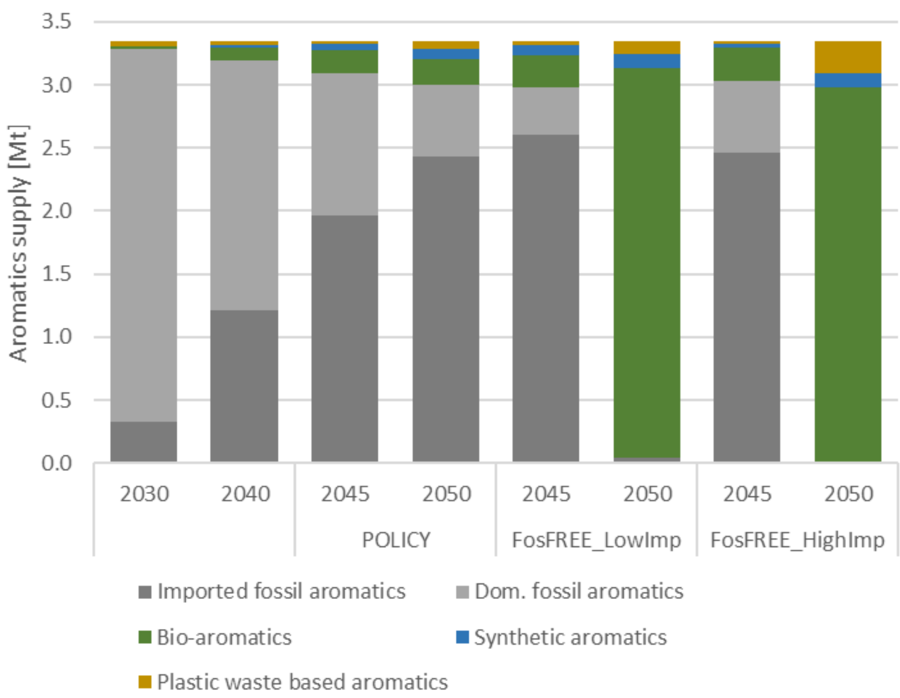


Figure 4.11: Aromatics supply according to three scenarios

5 Additional system costs - from climate-neutral to fossil-free by 2050

This chapter introduces the total system cost differences of shifting from climate -neutral to fossil-free for the overall energy system, also called as additional system costs. Additional system costs related to industrial transformation and the chemical industry transformation are also presented in this chapter.

The OPERA model calculates an energy system with the lowest societal costs. For this the annual total system costs are calculated. The total system costs are the sum of the annual capital costs, the annual operation and maintenance costs, energy transport costs and imported energy costs minus the revenues from exported energy. The annual capital costs per technology is determined from the investment costs, the economic lifetime and the discount rate. Because optimization is based on social costs, a discount rate of 2.25% is used (Werkgroep Disconteringsvoet, 202), it is important to highlight that this provides a cost figure for the Netherlands as a whole. Taxes, financial and innovation levers, and norms are deemed to be 'internal transactions' - and are hence not reflected by this number. The ETS levy is included since this is not an internal transaction but a European mechanism. The 2.25% WACC does not account for profits that financiers expect in turn for the risks that they take by allocating the money. This is also deemed to be an 'internal transaction'. In reality, people who will invest will face a market conform WACC - dependent on the risks of the investment. Consequently, it cannot be used to assess what the consequences of specific stakeholders - such as the competitiveness of the industry - is.

The OPERA model determines which investments need to be made for each year for which an energy system is calculated. In principle, this concerns all assets of the system (greenfield investments). By determining for each technology option what capacity expansion has taken place compared to the previous year and examining whether new options replace existing options, it can be determined what additional investments are required. The absolute value of investment costs are only meaningful within this analysis framework. For example, within the model framework, investments in domestic car fleet are fully included, while for homes only investments in indoor installations and insulation are considered. This leads to substantial differences in investment levels per sector, not all of which (e.g. complete passenger cars) can be attributed to the transition costs of the energy system.

Consequentially, in this study, the primary focus is on the difference in cost between the various scenario's, where the reference serves as the base cost level.

It is important to note that while the analysis presents additional system costs with sectoral detail, some underlying infrastructure costs—particularly for electricity grid expansion—may be underestimated due to model limitations and the actual grid costs may be significantly higher due to recent market developments. Nonetheless, these figures provide a robust indication of the relative magnitude and distribution of costs associated with a fossil-free transition and can be used to inform strategic decision-making and policy design.

5.1 Total additional system costs

Figure 5.1 illustrates the total additional system costs of the fossil-free low import and high import scenarios, compared to the climate-neutral reference scenario (POLICY). It also shows the breakdown of these cost differences. The annual additional system cost increases between €7.7-12.8 billion for the low import and high import fossil-free scenarios, respectively by 2050. The fossil-free alternative scenarios cost 6%-10% more than the climate-neutral reference under the conditions indicated in the previous chapters. To put these cost, which are in the several billion range into perspective: to reach the levels of renewable energy deployment and CO_2 reduction options outlined in the Climate and Energy Outlook — and assuming these options qualify for SDE++ support — approximately €3.2 billion in annual SDE++ subsidy expenditures were shown as available (See letter to the cabinet (2024). The increased investments and operational costs to compensate the remaining fossil fuels in the system and accommodate new renewable fuels and feedstocks drive these cost increases. According to the results the allowances from the EU ETS can generate a net benefit for the system. The reduced fossil fuel import volumes also mean that, although the renewable alternatives are more expensive per unit, the net cost for imported goods is lower than in the reference scenario.

It is important to note that, as stated previously, the absolute system cost are entirely dependent on the scope, which is why the focus is on the relative cost increase.

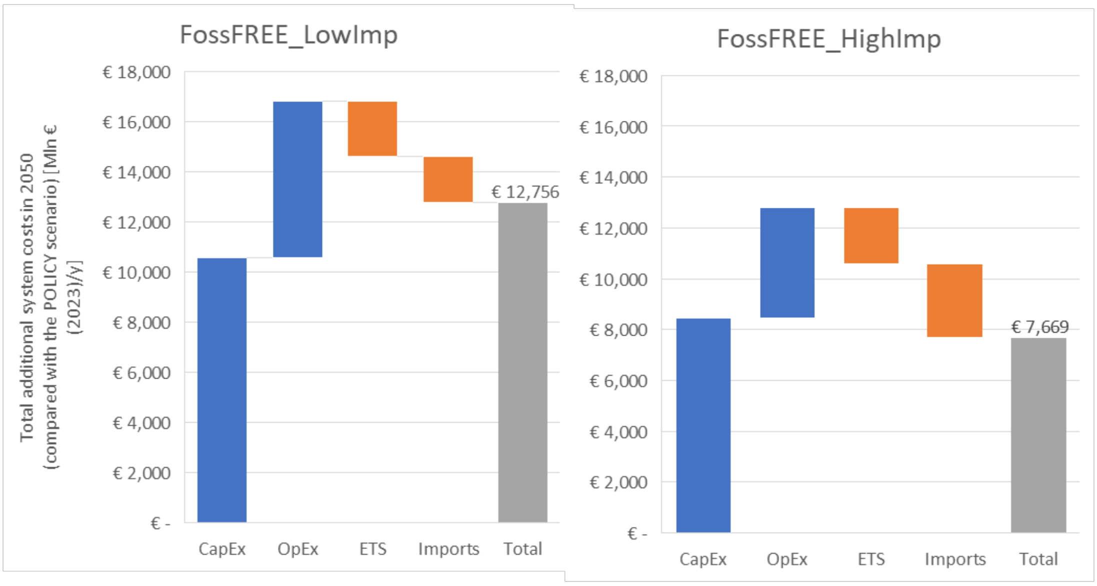


Figure 5.1: Total system cost difference between the reference climate-neutral POLICY scenario and the two fossil-free scenarios for 2050

5.1.1 Additional total CAPEX & OPEX

Capital investment and operational costs increase between €12.8-16.8 billion per year, for the high import and low import scenarios, respectively Figure 5.2 shows the cost breakdown of the total additional CAPEX and OPEX. Overall, the main contributors to the cost increase with respect to the reference climate-neutral POLICY scenario are related to investments in energy generation and infrastructure, industrial transformation, and the electrification of residential heating and road transport. Because there is no longer access to, relatively cheap, fossil fuel imports, the optimal balance shifts more towards increased electrification and renewable production value chains.

Industrial transformation is the dominant driver for the capital investment and operational cost increases, especially considering the lion's share of investments in electricity generation technologies are a result of increased demand in industry. The total annualized CAPEX and OPEX attributed to industry also includes investments in carbon management. These include the cost of generalized post combustion storage technologies, the CO_2 network, and Direct Air Capture (DAC). The carbon management costs in this figure are almost entirely for DAC, with small cost increases for the CO_2 network since the fossil-free scenarios are compared with the reference scenario. However, because the industrial transformation is the focus of this report, it will be examined separately at a later stage.

Further details of the capital investment and operational costs for the industrial transformation are discussed in chapters 0 and 5.3.

The investment in electricity generation in particular rises significantly in the fossil-free low import scenario. This is because this scenario aimed at maximum use of the renewable energy potentials that are defined available for the Netherlands. As a consequence, more expensive renewable energy technologies are deployed in this scenario. This goes for solar PV and offshore wind generation, which combined comprises 18 to 16% of the total CAPEX and OPEX for the fossil-free low import and high import scenarios, respectively. Within the total renewable energy generation, including infrastructure and storage, the two technologies combined comprise 43 to 51% of the total CAPEX and OPEX increase. Nuclear in particular sees large additional investments in the low import scenario, comprising approximately 21% of the total CAPEX and OPEX in 2050.

The built environment has two main cost components, being heating alternatives and energy savings. The overwhelming majority of the additional investment costs in these scenarios are for additional heating, which comprise around 94% of the total additional investments in this sector in both scenarios. An important note is that OPERA has a limit to installing insulation for houses[14]. Retrofitting homes with the lowest energy labels happens in all scenarios, because it is the most cost effective way to decarbonise the built environment.

As mentioned prior, OPERA includes investments in the car fleet in its costs. In all scenarios, the electrification of passenger cars and vans is invested to the fullest extent possible. This means there is no difference with respect to the reference POLICY scenario for both of the fossil-free scenarios. However, the electrification of trucks and motorized machinery is relatively higher in the fossil-free scenarios, consequently adding up to the additional costs.

[14] Start label GFE can be upgraded at most to label B. Start label DC and B can be upgraded at most to label A. Start label A can be upgraded to A+.

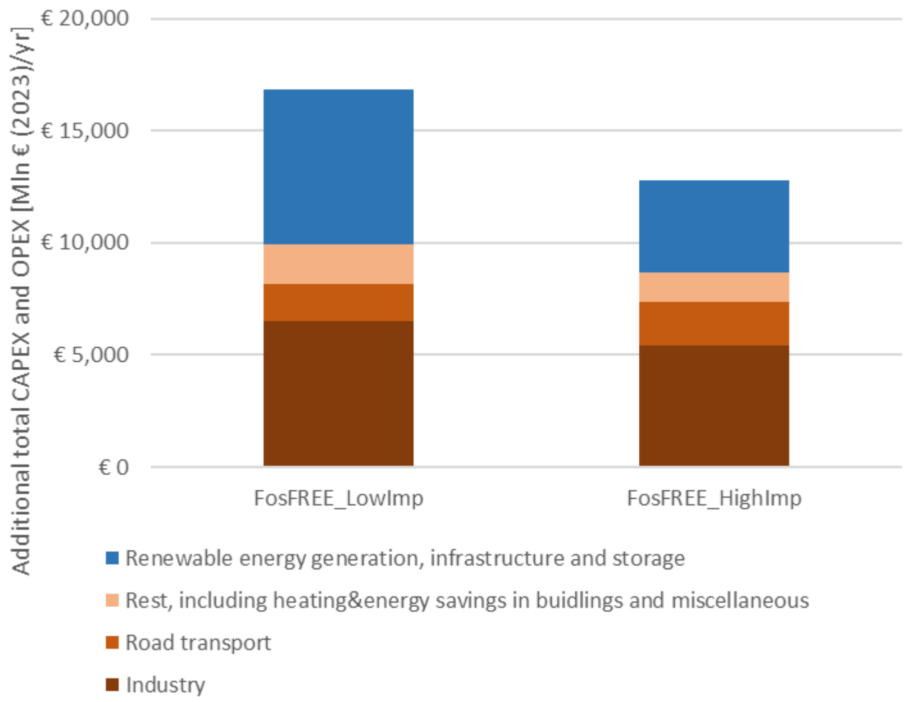


Figure 5.2: Additional costs related to annualised CAPEX and OPEX , compared to reference POLICY scenario

5.1.2 Import costs

Import costs refer to cost differences of importing additional renewable fuels, including renewable other oil products, wood pellets and electricity minus import cost saving related to avoided fossil fuels (oil and natural gas) and feedstocks (imported fossil aromatics).

Figure 5.3 shows the cost breakdown within this category. Surprisingly, the net import costs appear negative, meaning that they become savings. This can be explained by the high cost savings related to fossil fuels and feedstocks. As the fossil-free scenarios are compared with the reference climate-neutral scenario, the imports of fossil fuels and feedstocks in the reference scenario turns into relative annual savings for the fossil-free scenarios. These fossil fuels consist, mainly, of importing crude oil, other oil product and fossil aromatics. The costs savings related to imports does not mean that fossil fuel prices are higher than renewable fuel prices. While fossil fuels are cheaper per gigajoule (GJ), their total import costs appear larger than the total import costs of renewable fuels in this figure. This can be explained by two factors: the total volume of fossil fuel import has been larger in the reference scenario than the total amount of renewable fuel imports in the fossil free scenarios. Second, in the fossil free scenarios more domestic resources are used, thus not all fossil fuels are substituted with renewable fuel &feedstock imports. In other words, a share of the costs related to renewable fuels and feedstocks, for instance biomass-to-aromatics conversion, are allocated to the capital and operational expenditures. The import prices used in each scenario are detailed in Appendix C.

Wood import cost relates to the additional woody biomass use in the fossil-free scenarios and related costs, compared with the climate-neutral reference scenario. It is necessary to highlight that this additional wood use is within the limits of the total biomass import potential assumed in this study.

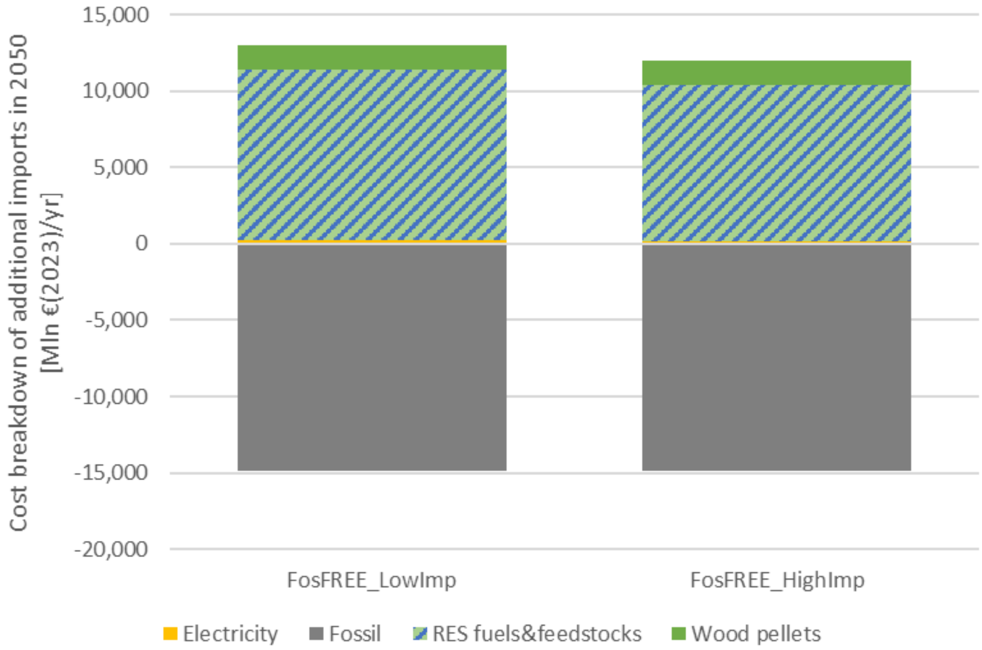


Figure 5.3: Break down of additional import costs, compared to POLICY reference scenario

The relatively lower RESfuel import costs in the high import scenario may appear contradicting. However, even though the total import of renewable fuels, including renewable other oil products is higher in the high import scenario, the total cost of these renewable imports is lower. This relates to the renewable fuel import price assumptions.

Fossil-free low import scenario considers a future, where domestic use of renewable resources are maximized. As a consequence, the renewable fuels that are available for export to other regions are relatively more expensive. In the high import scenario, the assumption is set as there will be more available renewable fuel imports with relatively lower market prices (see for further clarification Paragraph 3.2). The low import scenario considers the renewable import prices 22%, 24% and 43% high for renewable methanol, kerosene and other oil products, compared to high import scenario. Figure 5.4 shows the renewable fuel import values in PJ and the corresponding monetary values. The renewable other oil products in particular are one of the primary drivers of the cost of renewable alternatives.

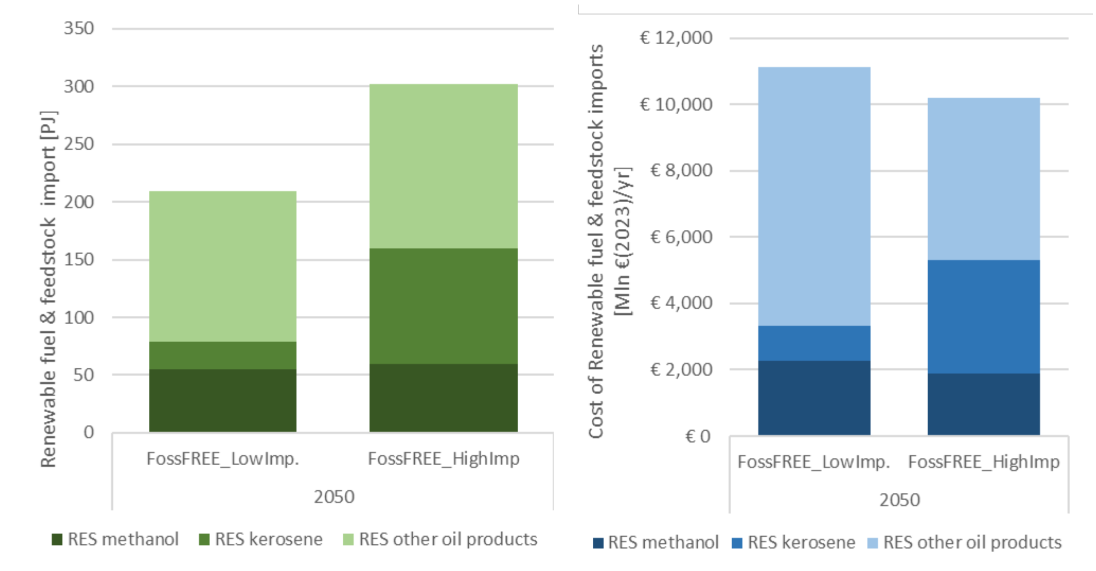


Figure 5.4: Total renewable fuel imports and corresponding costs according to the two fossil-free scenarios for 2050

5.1.3 ETS allowances

From 2045 onwards ETS costs turn into allowances for the Netherlands for both scenarios. The ETS price, adapted from the European Commission's recommendation (430 €/tonne in 2045 and 490 €/tonne in 2050), appears to be higher than the marginal cost of carbon removal technologies for 2045 and 2050, which motivates large utilization of DAC within this scenario modelling. This study assumes that carbon dioxide removals (CDR) (or negative emissions) are integrated into the EU ETS and there will be a carbon market, where these negative CO_2 removal rights can be traded. However, it should be noted that it has not been determined if, and if so how, CDR will be integrated into the ETS. The Dutch government has taken a cautious position in the Roadmap CDR and related EU discussions, emphasizing the need for safeguards to ensure that the incentive to reduce emissions is not weakened by CDR crediting.

5.2 Additional costs related to industry

Figure 5.5 presents the additional system costs attributed to the industry sector. The industry holds for almost all additional costs of the energy system where the ambition is raised from climate-neutral to fossil-free. In case of low import scenario, the total additional system costs of industry are even larger than the total energy system costs as the additional energy costs of this sectors, particularly the electricity costs are higher.

The main drivers behind these increased system costs are higher CAPEX and OPEX, along with increased energy and net import costs.

All EU-ETS related cost savings are assigned to the industry sector, and relates to the relatively high EU-ETS price and the lower cost of DAC and storage options, as discussed in the previous chapter.

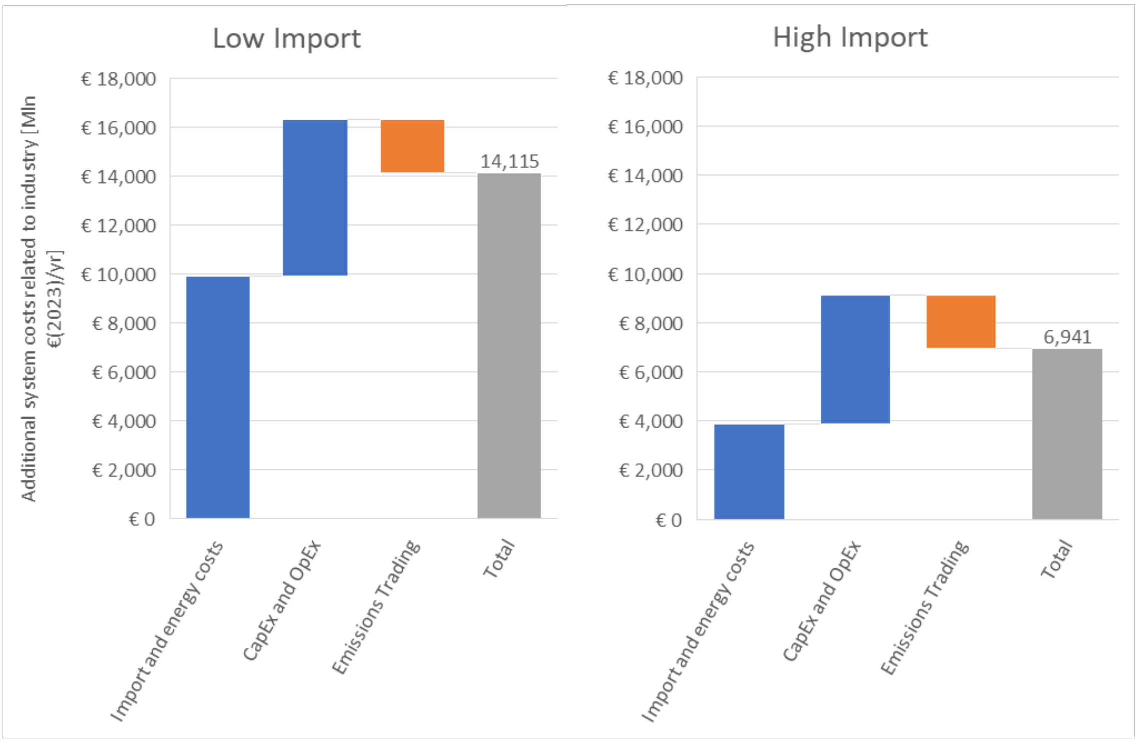


Figure 5.5: Additional system costs attributed to industry

5.2.1 Additional CAPEX and OPEX in industry

Figure 5.6 shows the additional CAPEX and OPEX for industry broken down to specific industry sectors. The largest additional costs relate to the petrochemical industry, followed by the costs for electrolysers and the costs related to DAC. The additional CAPEX related to electrolysers refer to hydrogen supply for particularly the production of synthetic bunker fuels.

Industrial heating is largely electrified across all scenarios, including the POLICY scenario. This includes the electrification of boilers for steam and salt and the use of heat pumps for medium-temperature processes and for upgrading waste heat streams. However, as this electrification does not differ between scenarios, it is not visualised in the figures.

Some additional investments are needed in specific industrial-sub sectors, though these represent relatively minor costs compared to the petrochemical industry (chemicals and refineries). Firstly, hydrogen-based direct reduction in steel making needs more investment to further decarbonise steelmaking. Electrification of kilns and smelters in glass making and ceramics manufacturing also increases.

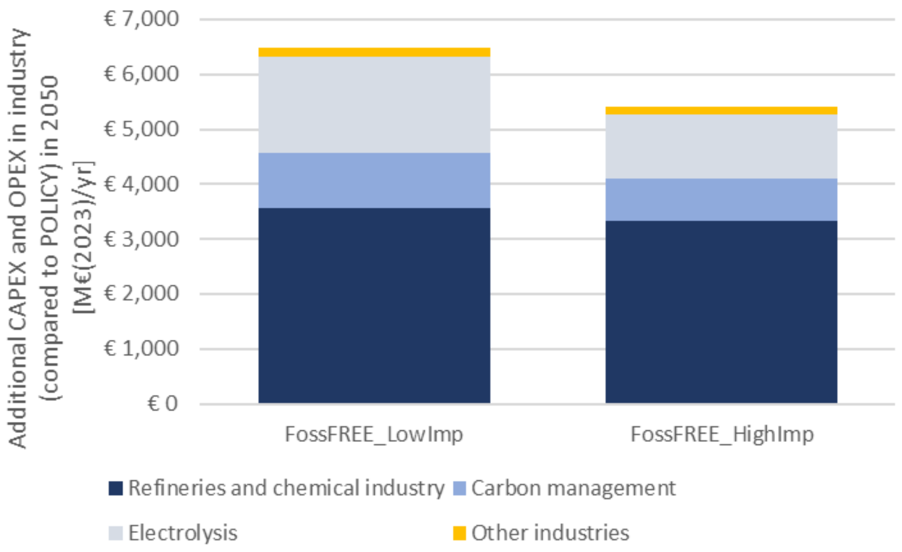


Figure 5.6: Industry related additional CAPEX and OPEX costs for the two fossil-free scenarios when compared with the reference scenario

5.2.2 Additional net energy and import costs in industry

Figure 5.7 presents the additional costs related to the net energy consumption of the industry and the breakdown of the imports and import savings.

Additional electricity demand of industry and related costs appear as the largest cost component, next to the additional costs related to importing renewable fuels and other renewable oil products. Additional wood pellet imports is also one of the cost component but compared to the other two it is relatively small.

The additional costs savings relate to avoided crude oil imports and avoided import of fossil aromatics. Net hydrogen savings in this graph refer to benefits from production of ammonia that is used by ships. Since in the fossil-free scenario's a significant amount of additional ammonia is used for international shipping, the production of ammonia results in additional benefits for industry.

While the overall energy system shows a reduction in additional import costs (**Figure 5.7**), the industry faces higher additional energy and import costs. First , the cost savings from avoided fossil fuel imports are smaller, as savings related to fuel production for bunkering are not included here. At the same time, Renewable fuels and other oil products are substantial.

Unlike the overall system, a key a key additional energy cost for industry is electricity. While for the energy system as a whole these are not visible (because of demand and supply), the industry sector is a net consumer of electricity. Since electricity is mainly generated in the power sector, it must be transferred to the industry sector, adding to its energy costs.

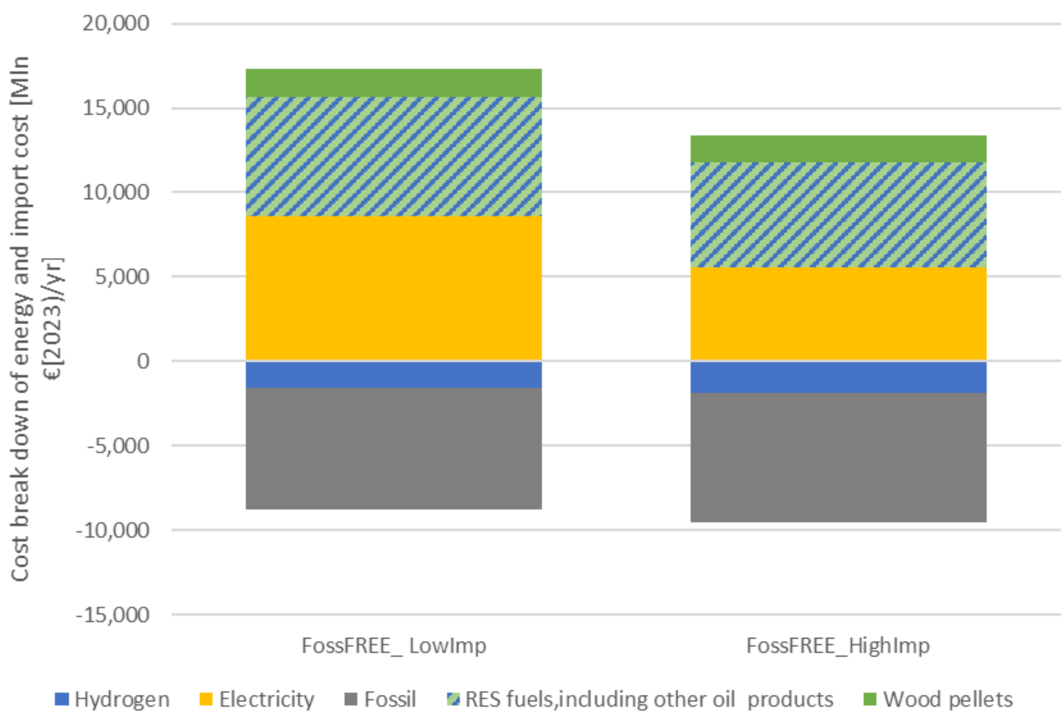


Figure 5.7: Cost breakdown of additional energy and import costs

5.3 Additional costs in the chemical sector

The chemical sector is a significant contributor to the total system cost increase, at 37% and 48% of the total net annual cost increase, for the fossil-free high import and low import scenarios, respectively.

Figure 5.8 illustrates the additional system costs for the chemical industry, broken down to cost component. In line with the additional system costs for the overall energy system, the fossil-free high import scenario provides the lower total additional system costs for the chemical industry.

The annualised total CAPEX and OPEX cost difference in fossil-free high import scenario is slightly lower than the low import scenario. This relates to the slight shift to imported methanol to olefins, instead of having stand-alone renewable methanol processes, followed by methanol to aromatics production. Nevertheless, the difference between the two fossil-free scenarios is minor.

The main difference relates to the net import costs. As illustrated in the figure the net import costs of high import scenario is almost 80% lower than the low import scenario. This may sound strange, however, the import figure in this graph relates to net imports where fossil fuel related saving are also taken into consideration. For further explanation see the section on imports below. In addition, net import costs presented in this study are a comparison of the total imports in the fossil-free scenarios with the reference climate-neutral scenario. It includes both the additional costs needed and the benefits related to avoiding fossil fuels and feedstock imports.

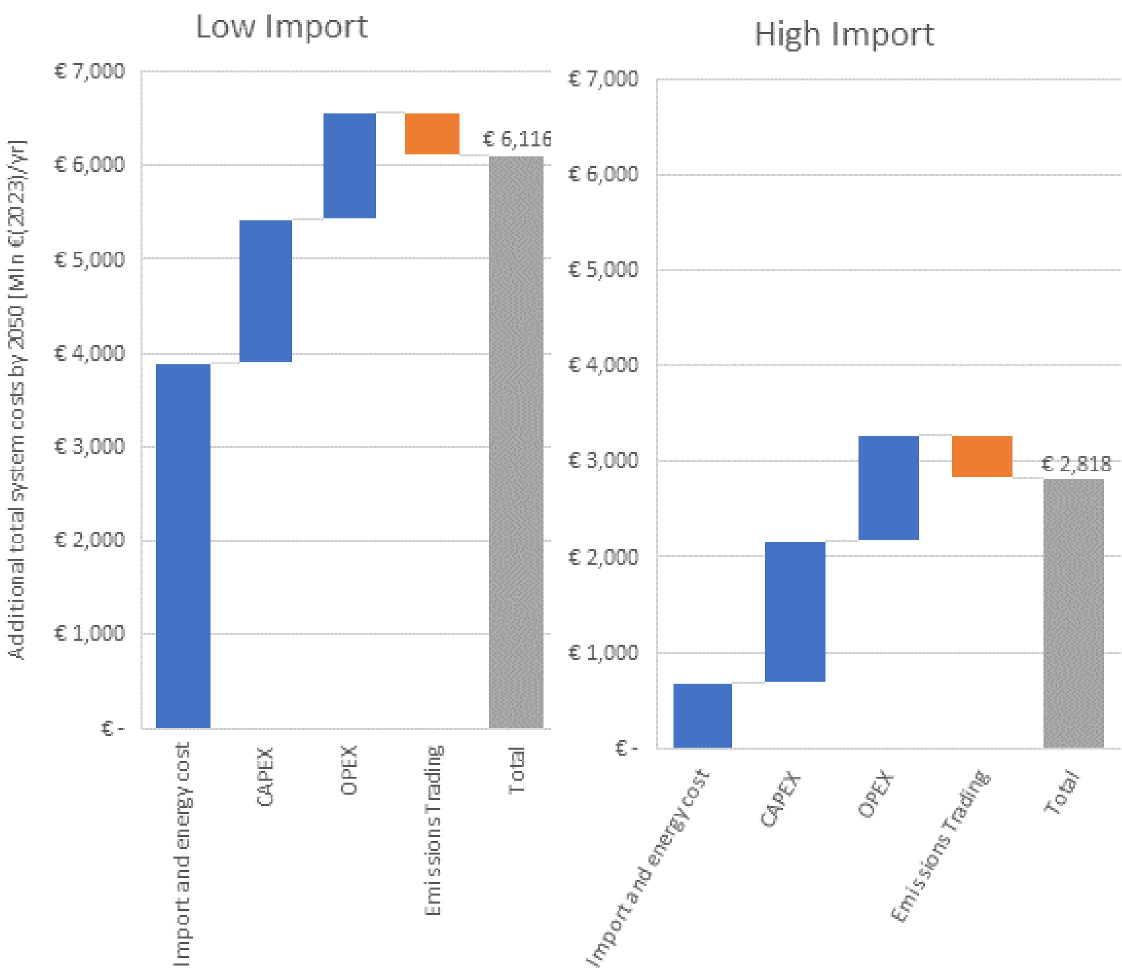


Figure 5.8: Additional total system costs of the two fossil-free scenarios attributed to the chemical industry (compared to the POLICY scenario)

5.3.1 Additional CAPEX and OPEX costs related to chemical industry

Figure 5.9 shows the annualised total CAPEX and OPEX cost difference for the chemical industry. Between the low and high import scenarios there appear to be limited differences, with the capital investment and operational cost increasing slightly for the low import scenario.

The major cost difference component relates to the stand-alone production of aromatics. As stated earlier in the report, a significant amount of aromatics production relates to the chemically integrated oil refineries in the Netherlands. A fossil-free industry would mean that those oil refineries will be replaced by renewable fuel refineries with the product slates quite different from that of conventional oil refineries. That is why, stand-alone biomass-to-aromatics value chains appear in the fossil-free scenarios and related costs play a major role, when compared with the reference climate-neutral scenario.

This is followed by the additional costs related to pyrolysis oil production that can substitute fossil naphtha in naphtha crackers to produce olefins. Compared to the reference POLICY scenario, the CAPEX and OPEX costs of plastic waste oil processes are approximately 74% higher in the two fossil-free scenarios by 2050.

The savings highlighted in this graph as negative values relate to reduced methanol production from lignocellulosic feedstocks for the olefins production. This can be clarified with the fact that import of renewable methanol reduces the CAPEX and OPEX needs for the production of renewable methanol.

Other costs differences relate to additional use of alternative industrial heat pumps and the downstream methanol to olefins production.

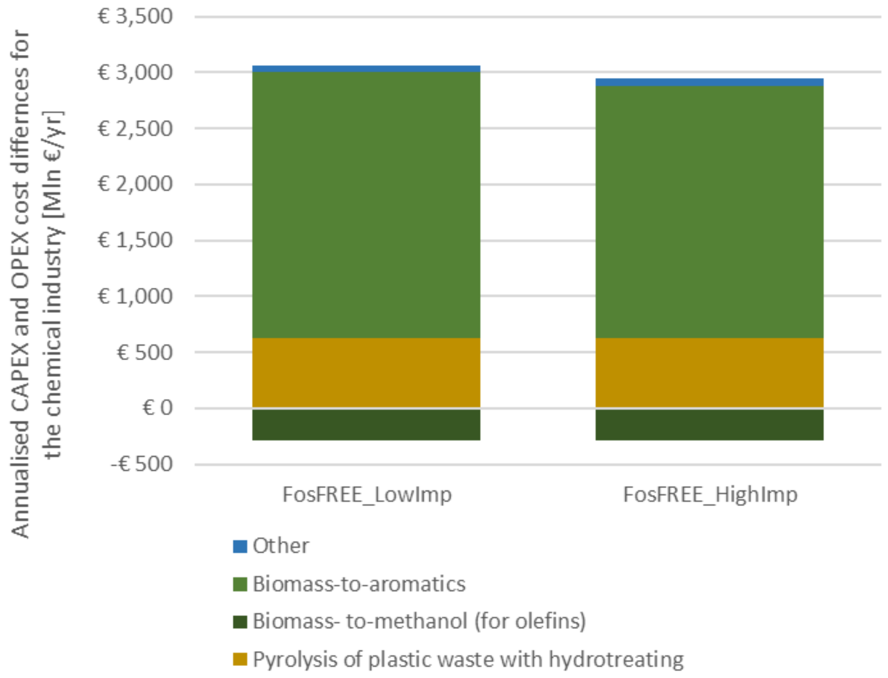


Figure 5.9: Aggregated additional CAPEX and OPEX cost differences (compared to reference POLICY scenario)

5.3.2 Additional energy costs and imports

Figure 5.10 shows the breakdown of additional energy and import costs and savings compared to the reference climate-neutral scenario. To achieve fossil-free chemical industry, the use of wood pellets[15] increases. As a result, wood pellet import costs also rise.

The main difference between the two scenarios lies in the cost of importing renewable other oil product imports and renewable methanol. While the import volumes for these fuels are relatively similar between the high and low import scenarios, the prices in the low import scenario are significantly higher—especially for other bio-oil products. This is due to the underlying scenario assumptions: it reflects a future where renewable product availability for imports is more limited and prices are higher. As a result, the total import costs for renewable fuels and products are greater than in the high import scenario.

[15] These relate to the higher utilization of the available import potentials set in the modelling.

In terms of savings, both fossil-free scenarios achieve same savings as they compensate the same amount of fossil fuel imports.

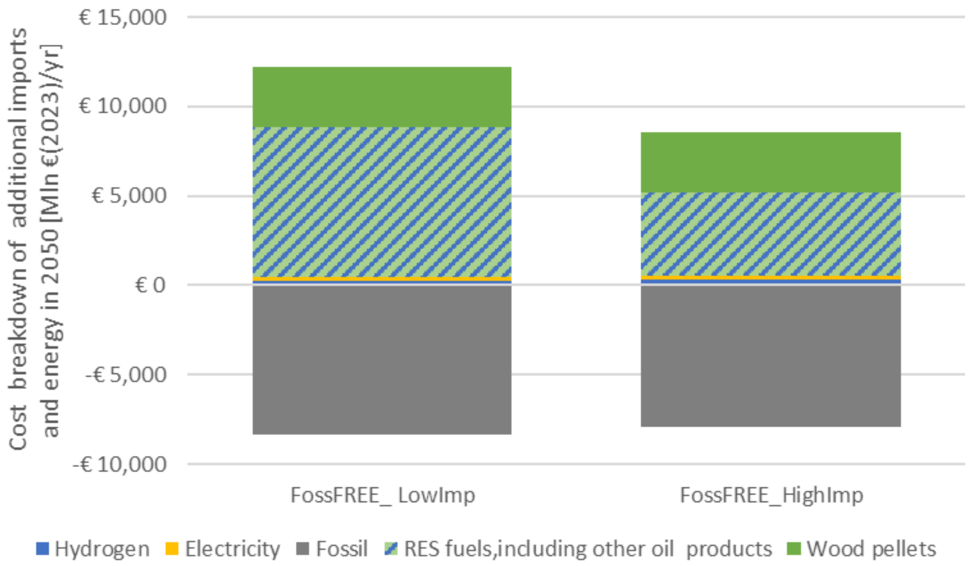


Figure 5.10: Cost breakdown of imports

6 Sensitivities

6.1 Low aromatics supply

A significant portion of aromatics such as benzene, toluene, and xylene (BTX) is currently produced as by-products of oil refining, specifically during catalytic reforming of naphtha. By 2022, almost 90% of the total aromatics production in the Netherlands was from refineries. (CBS,2025b).

Oil based refinery outputs are projected to be shrinking within the climate-neutral energy system and industry scenario. Within the fossil-free scenarios there will be no oil based refineries in the Netherlands. This raises the question of what will happen to the production of aromatics in the Netherlands.

We assumed that they will be substituted by imports in the reference climate-neutral scenario (POLICY). In the fossil-free scenarios the current production level is kept and decarbonised, meaning produced using renewable resources, mainly biomass.

In this sensitivity case , we study what if aromatics production is reduced gradually starting from 2035. The reduction is set to 37.5% by 2045 and 50% by 2050. These reductions are implemented to all three scenarios.

Reduction of aromatics production by 50% in 2050 does not create any significant systemic changes within the overall energy system other than the total final energy demand (including bunker fuels and feedstocks) being reduced by 3 to 4% in 2050 across all scenarios. Within the fossil-free scenarios, reduction of aromatics production enables the biomass used for aromatics production shift to production of biofuels for the transport sector.

Figure 6.1 shows the comparison of the sensitivity case for the energy demand of the chemical industry, including feedstocks. The total energy demand including feedstocks reduces by 8.5% in the POLICY scenario sensitivity, and 13 to 14% in the fossil-free scenarios, low import and high import respectively.

The lower demand for biomass to produce aromatics can be clearly seen in this graph, when the sensitivity cases are compared with the reference POLICY scenarios. In the high import scenario, the lower use of biomass for aromatics results in larger demand for renewable fuel imports, particularly renewable other oil products. This has to do with the loss of valuable by-products of the biomass to aromatics[16] value chain.

[16] The biomass -to-aromatics value chains provide by-products that could substitute other oil products that are produced from fossil fuels.

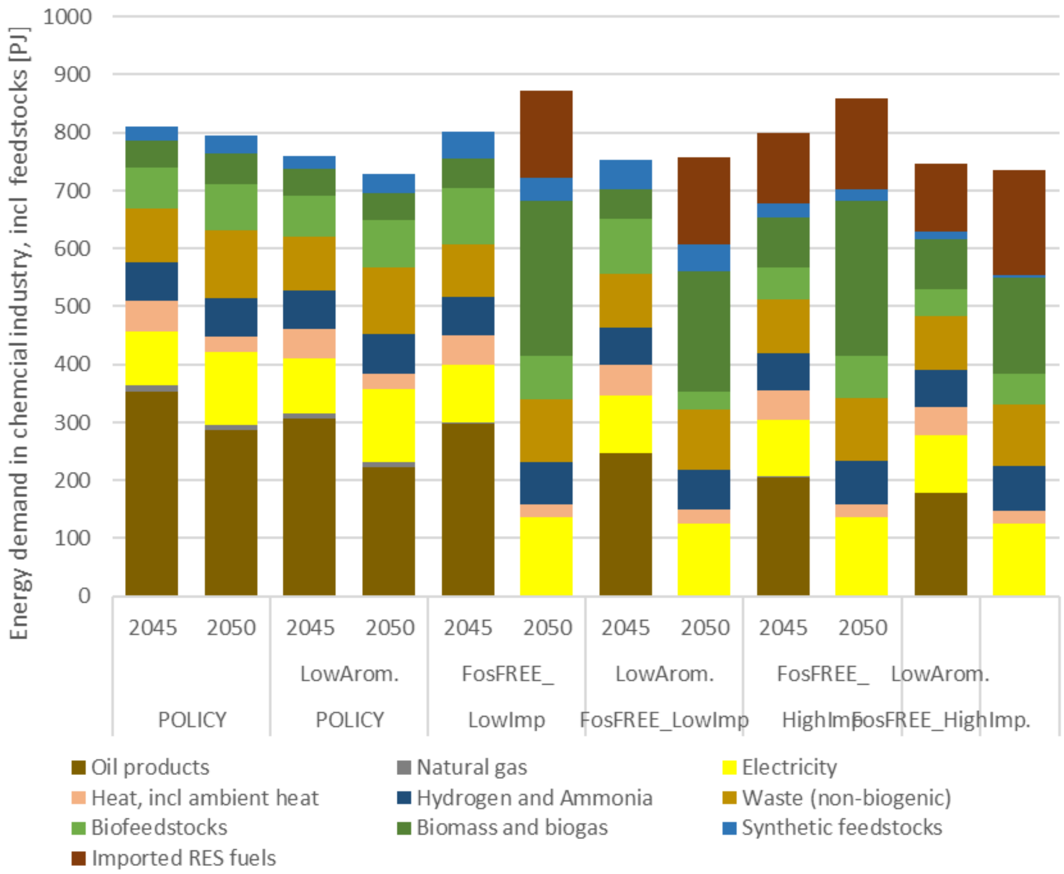


Figure 6.1: Effects of reduction in aromatics production on the energy demand of the chemical industry (including feedstocks)

Figure 6.2 shows the costs impacts of reducing the aromatics production by 50% in 2050. This results in approximately 16% less additional total system costs for the low import scenario. For the high import scenario, the additional system cost reduction is higher in relative terms, of approximately 31%.

The real cost impacts relate to the chemical industry and **Figure 6.3** shows the additional system cost differences for this sector. Within the low import scenario, the total system cost difference reduces by 58%. The main cost category that contributed to this total system cost reduction is the reduced CAPEX and OPEX needs.

In the high import scenario, cutting aromatics production by 50% leads to a significant decrease in both CAPEX and OPEX, resulting in an overall system cost reduction of nearly 98%. This demonstrates the high cost sensitivity associated with aromatics production.

It’s also important to note that a substantial share of olefins is produced by replacing fossil naphtha with renewable naphtha. This renewable naphtha is a by-product of renewable fuel refineries, and its associated costs are fully allocated to the total system costs of these refineries.

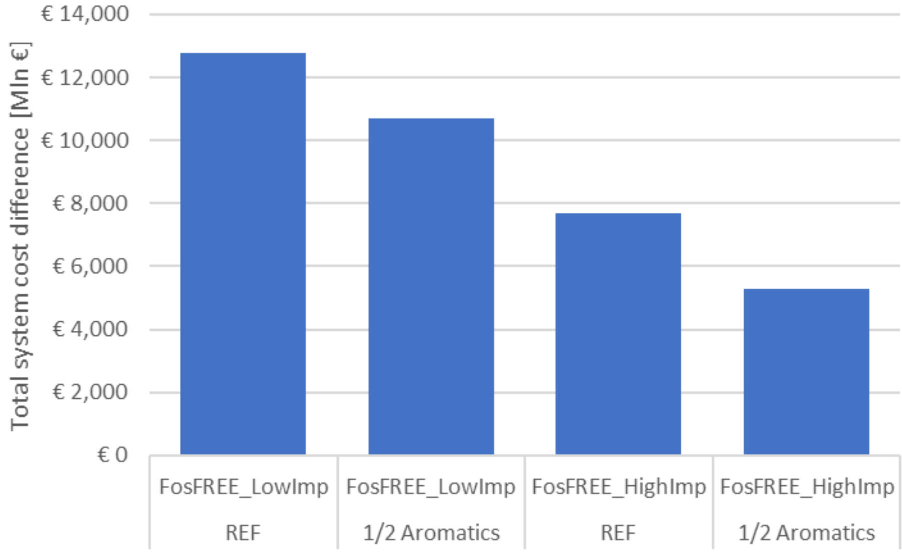


Figure 6.2: Comparison of the total system cost differences of the energy system and industry

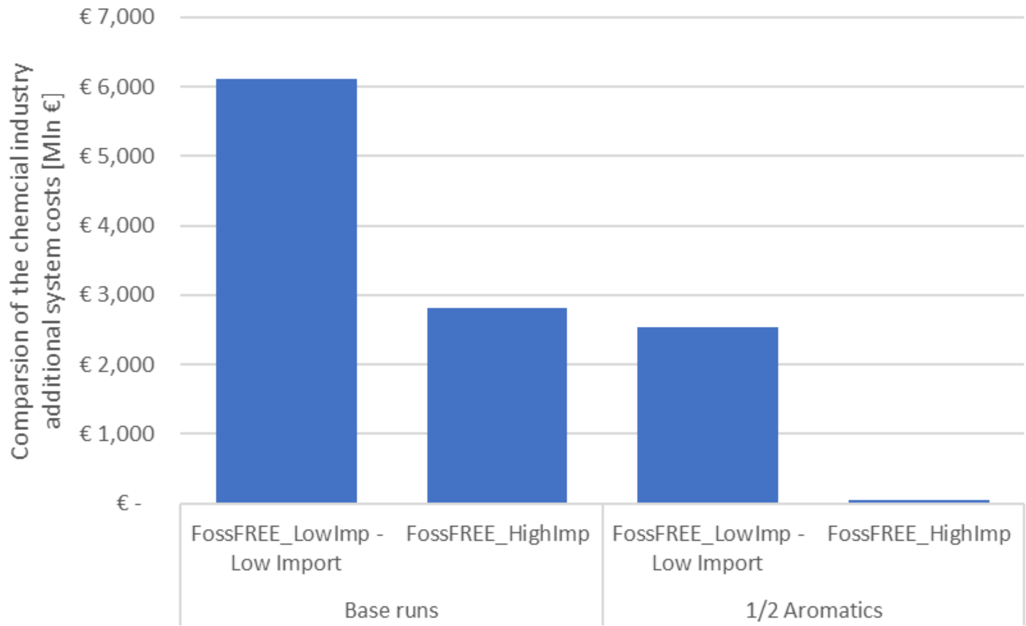


Figure 6.3: Comparison of the chemical industry additional system cost differences

6.2 Lower bunkering demand

This sensitivity analysis looks at the uncertainty around maritime bunkering in the Netherlands. It explores what happens to the energy system if bunkering is lower, reaching a 37.5% drop in 2045 and a 50% drop in 2050, compared to the main scenarios where bunkering remains constant.

Figure 6.4 shows how final energy demand changes under this assumption, compared to the main scenario results. Obviously, the total final energy demand reduces across all scenarios, when compared with the base scenario runs.

In the POLICY scenario, lower demand for bunkering results in lower synthetic fuels demand for the maritime shipping to achieve the GHG intensity reduction targets of the FuelEU Maritime Regulation. In addition, the total fossil fuel demand reduces in line with the bunkering demand reduction.

For the fossil-free scenarios, reduction in bunkering demand results in much lower demand for ammonia for bunkering. In addition, total import of renewable fuels is also reduced.

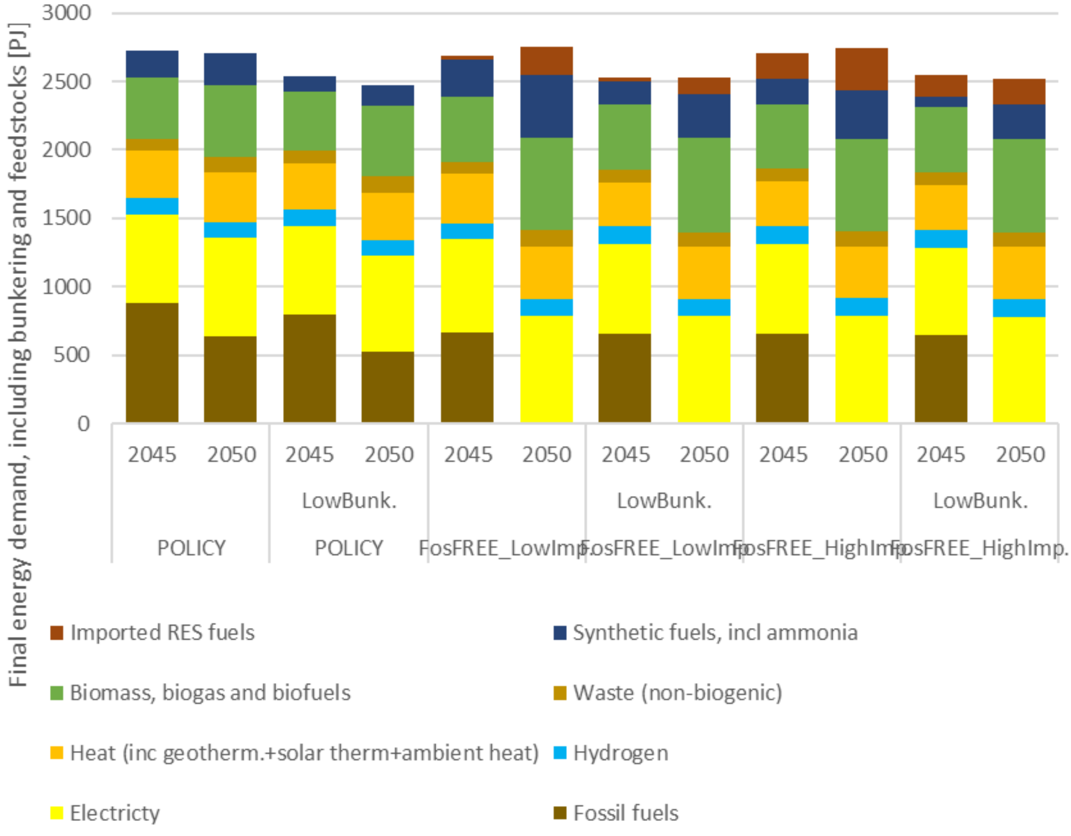


Figure 6.4: Comparison of the final energy demand (including bunker fuel and feedstocks) for the low bunkering cases

Figure 6.5 shows the impacts of lower bunkering on the additional total system costs (compared to POLICY). Such a reduction enables almost a 36% reduction in the additional costs within the low import scenario and 42% reduction within the high import scenario. These costs reductions can be explained by the lower demand for synthetic fuels for the maritime sector.

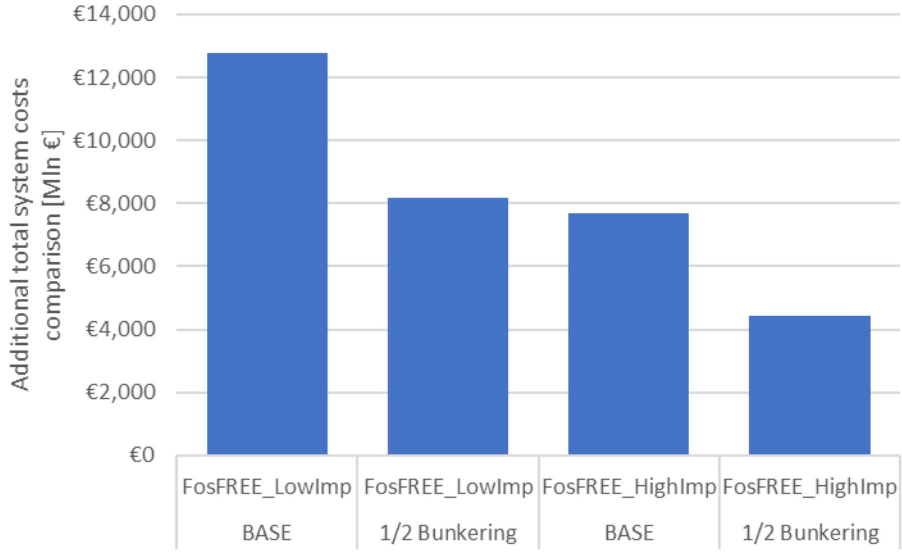


Figure 6.5: Additional system costs comparison of bunkering sensitivity

7 Critical success factors and discussions

7.1 Overall energy system

Achieving climate-neutrality by 2050 is a major challenge, let alone becoming fully fossil-free.

The pace of scaling up electricity and electrification is a key success factor. It is already essential for climate neutrality and becomes even more critical under fossil-free ambitions. One of the corner stones of this is the immense demand for renewable electricity. Figure 7.1 shows the electricity demand up to 2050, according to the three scenarios. This figure also introduces the breakdown of the renewable electricity supply options needed to meet the demand.

Already in the climate-neutral reference POLICY scenario electricity demand in 2050 appears to be 4 times the electricity supply in the Netherlands in 2024. Within the fossil-free scenarios the electricity demand beyond 2040 is even higher. This relates to larger electricity demand in industry and the significantly higher renewable hydrogen supply for the production of synthetic fuels, including ammonia for shipping.

The fossil-free scenario with low imports show the largest electricity demand. Compared to the reference, approximately 30% higher electricity is needed by 2050. This relates to the scenario assumption that the available renewable resources in the Netherlands will be used to the maximum and the imports will be needed to close the gap to become fully fossil-free. In the high import scenario, the electricity demand is approximately 20% higher than the reference in 2050.

Among the renewable electricity supply options, wind offshore grows significantly, meeting almost 67% of the total electricity demand in 2040 and increasing further in 2050. Within the fossil-free scenario, where the use of domestically available resources are prioritised, larger use of solar PV, wind offshore and nuclear energy can be observed.

Next to the challenge of deploying these large amounts of wind and solar energy and installing generation capacities, the needed infrastructure scale up will be massive. Next to increased HVDC grid, there will be a need for massive offshore hydrogen production facilities and supply of this hydrogen to onshore. In addition, there will be a need for massive upgrades to high voltage AC transmission lines to avoid congestion.

These challenges can be balanced and the steep pressure, particularly beyond 2040 can be relieved by increased reliance on imports of renewable energy carriers. However, such a strategy will introduce a new set of uncertainties and dependencies. The viability and cost-effectiveness of large imports will depend on multiple external factors, including global supply and demand dynamics for hydrogen and its derivates, geopolitical developments and trade relations with exporting countries, competition with other importing regions, which may drive up prices or limit availability.

The modelling of electricity infrastructure costs in this study includes inherent uncertainties. Recent insights suggest that the unit cost of grid expansion are higher than expected a few years ago, which is not fully captured in this study (PWC, 2024). Moreover, the model allows for several degrees of freedom, potentially underestimating the scale of grid expansion required and therefore investments, especially in scenarios with extensive electrification. As a result, the reported additional costs for renewable electricity integration may not fully reflect the system-wide infrastructure investments needed. Since the study presents additional rather than total system costs, this underestimation is partially mitigated. Nevertheless, it remains an important limitation to consider when interpreting infrastructure-related results.

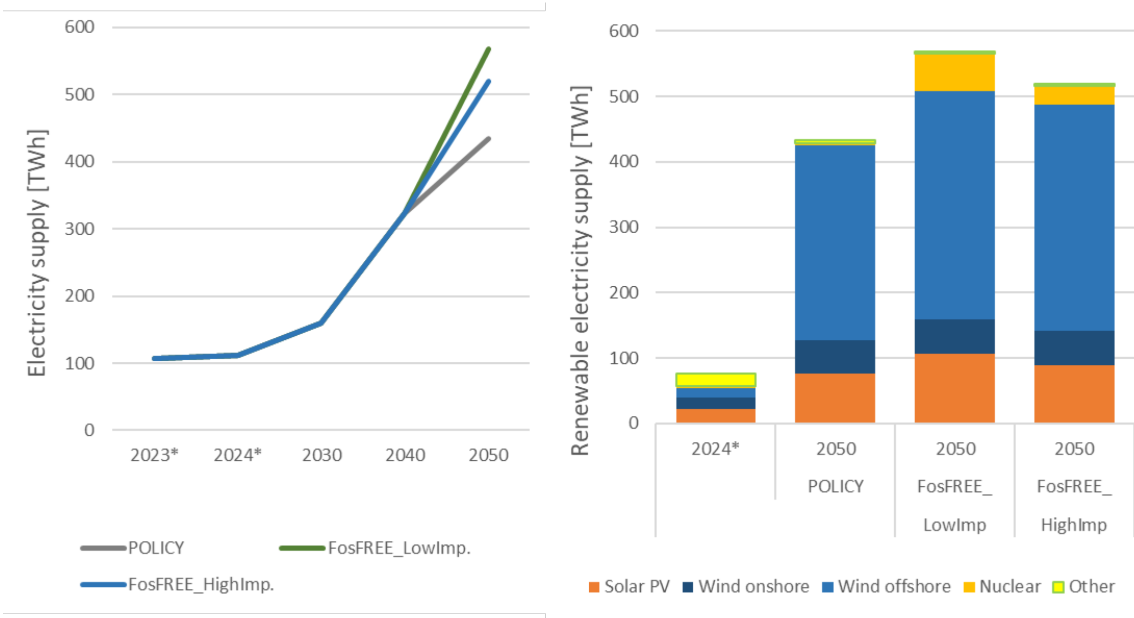


Figure 7.1: Electricity demand and renewable electricity supply options according to the scenarios

Meeting future hydrogen demand depends critically on the timely scale-up of electrolyser capacity. While medium-term targets appear feasible with supportive policies and infrastructure, the longer-term ambition—particularly in fossil-free scenarios—poses a significant implementation challenge

Another challenge relates to the significant demand for renewable hydrogen and the needed electrolysers capacity to generate this hydrogen from renewable electricity and water. In fact, the electricity demand increase is mainly driven by the hydrogen demand. Figure 7.2 shows the electrolysers capacity needed to supply the hydrogen demand over the period up to 2050. Already in 2030 approximately 2 GW electrolysers capacity will be needed. This shall be increased to almost 9 GW in 2040 and almost 15.5 GW in 2050 in the reference POLICY scenario. The fossil-free scenarios foresee even larger installed capacity. Low import scenario projects the installed capacity need of 65% higher than the reference in 2050, and the high import scenario 40% higher.

The medium-term capacity increase from 2 to 9 GW increase between 2030 and 2040 appears realistic/reasonable, provided that there is stronger policy coordination, timely expansion of hydrogen-ready infrastructure and better market incentives for industrial offtakes to switch to green hydrogen.

In the long-term, the results appear technically feasible for the reference POLICY scenario, if the Netherlands continues to position itself as an EU hydrogen hub. This, however, will require a holistic energy system integration (electricity, hydrogen, CO_2 infrastructure) and cross-border cooperation with countries like Germany, Denmark will be essential for import/export balancing. The needed expansion for the fossil-free scenarios are also technically feasible (based on the resource availability) but capacity increase of 2.5 to 3 time, within 10 years' time may prove to be very difficult.

From technical feasibility to real implementation many barriers will need to be overcome. The total installed electrolysers capacity in Europe was only 216 MW in 2023. There has been 52 electrolysers under construction in Europe with a total capacity of 1.8 GW, and are expected to be deployed by the end of 2026 (ACER, 2024). In the Netherlands, there has been a large interest, with a number of projects adding up to 10.3 GW (Elzenga et al, 2025). Among the projects, however, only Holland Hydrogen (Phase 1) with 200 MW has taken the final investment decision by the end of 2024. The rest of the projects were at the feasibility stage and some of them announced that they postponed their investment decisions. The key reasons referred to by the market parties were increased grid tariffs, lack of certainty for green hydrogen demand and the limited availability of renewable electricity (PBL, 2025).

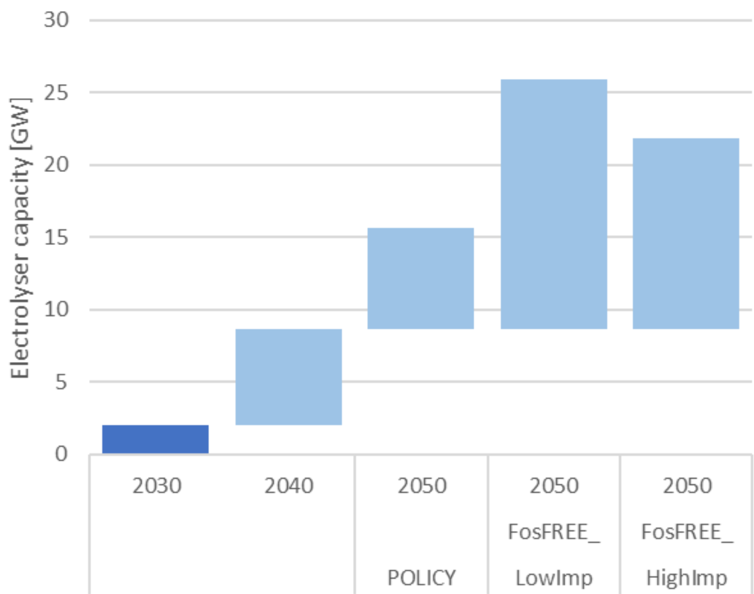


Figure 7.2: Electrolyser capacity needs according to the three scenarios

Unlike conventional oil refining, renewable fuel supply will rely on a larger number of smaller-scale bio- and e-fuel facilities. Planning for this distributed infrastructure—both domestically and across Europe—will be a key implementation challenge
The climate-neutral reference scenario already assumes that large volumes of biomass will be imported into the Netherlands. These estimates are based on a 2024 study for the European Commission, which assessed European sustainable biomass availability in line with RED II sustainability criteria and the feedstock list in Annex IX (EC, 2024).

Table 7.1 introduces the biomass potential assumptions and the use of biomass according to the three scenarios.

According to CBS, the solid biomass use in the Netherlands was approximately 104 PJ[17] in 2022. This corresponds to approximately 65% of the solid biomass potential (including

[17] This excludes liquid biomass use for instance used cooking oil and animal fats.

imports) considered for the Netherlands in 2030 in the scenario modelling. This indicates that the 2030 assumptions are within a plausible range.

Looking beyond 2030, the scenario foresees a significant increase in available biomass potential, particularly through imports. between 2030 and 2040, biomass imports are projected to more than triple, followed by an additional 1.6-fold increase beyond 2040.

Estimates from PBL and CE Delft (Strengers and Elzenga, 2020; CE Delft, 2020) provide further context, suggesting a global sustainable biomass potential of 85-120 EJ by 2050. For the EU 27, potential supply is estimated at 15-30 EJ in 2030 and around 17 EJ by 2050. The biomass availability assumed in this study for 2050 corresponds to 0.7–1% of the global projections and about 5% of the EU28 estimate for 2050.

While the assumed potential appear reasonable, achieving these volumes will be demanding. It will require the mobilisation of sustainable biomass resources through the development of efficient supply chains. This includes robust systems for collection, pre-treatment, upgrading, storage, and transport, as well as procedures to ensure timely and reliable delivery.

Table 7.1: Biomass potential and use according to the three scenarios

			POLICY	FossFREE_ LowImp	FossFREE_ HighImp
Year/PJ	**2030**	**2040**	**2050**	**2050**	**2050**
Biomass domestic	95	126	158	158	158
Biomass imports	129	423	716	716	716
Total biomass	224	549	874	874	874
Utilisation rates	94%	86%	87%	100%	100%

This study results highlight that achieving climate neutrality and moving further to fossil-free energy system and industry will require significant amounts of bio-based and synthetic fuels and related facilities to produce these.

Figure 7.3 illustrates the total amounts and volumes of renewable fuels needed according to the scenario modelling.

Between 2030 and 2040, renewable fuel supply in the Netherlands will increase by a factor of 3.4, followed by a further 1.7-fold rise by 2050 to reach a climate-neutral energy system. Achieving a fully fossil-free system will require an even greater increase in renewable fuel supply between 2040 and 2050.

The current supply of renewable fuels in the Netherlands mainly consists of small volumes of biofuels. Most existing production facilities in Europe and globally focus on first-generation biofuels made from food crops, as well as biofuels from used cooking oil and animal fats—both limited under the Renewable Energy Directive (RED). Demand for advanced biofuels made from agricultural and forestry residues is expected to grow, but these supply chains are not yet operating at scale. Production of renewable fuels of non-biological origin (RFNBOs), is still very limited, with almost no use in transport today.

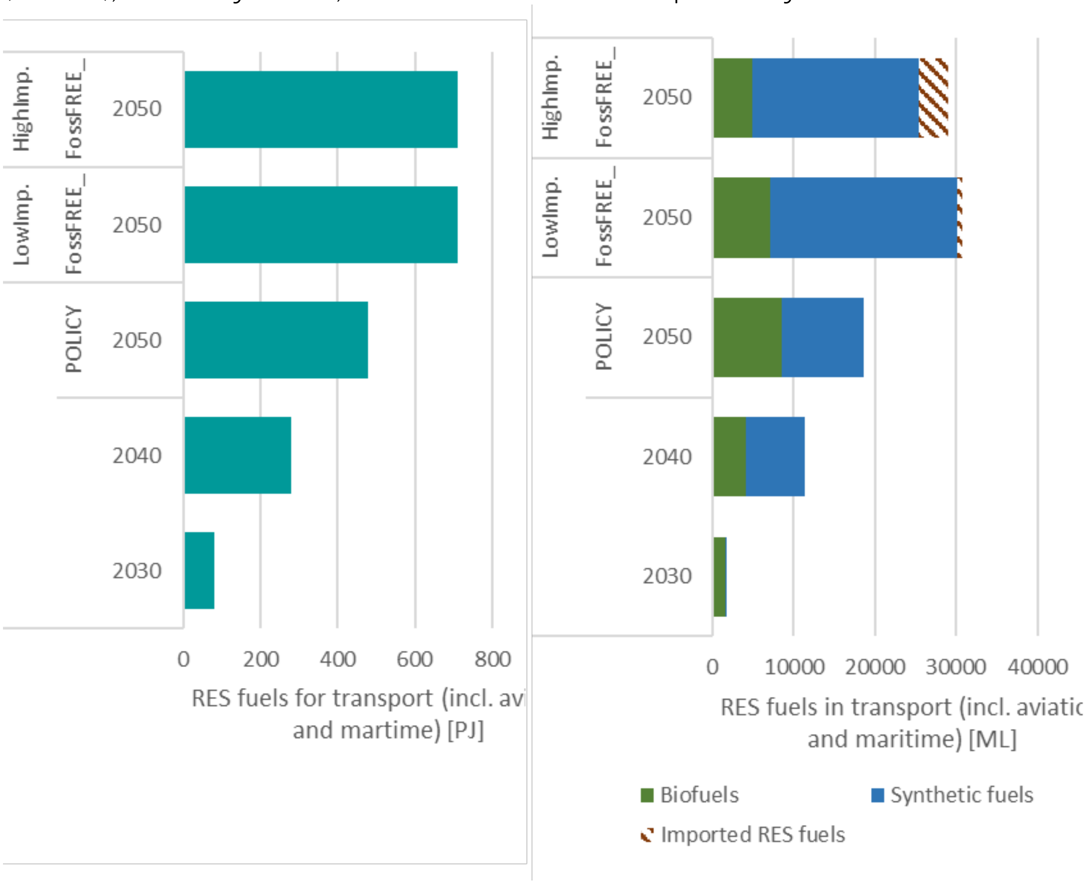
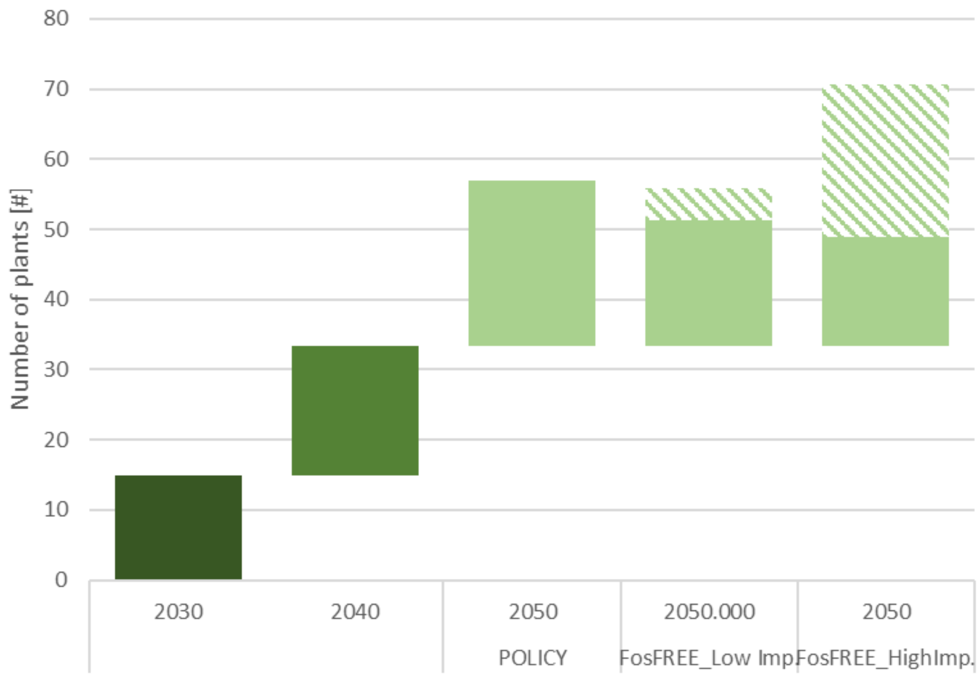


Figure 7.3: Total amount (PJ) and volumes (ML) of renewable fuels demanded, according to the three scenarios

Meeting these volumes will require a major expansion of renewable fuel refineries. To illustrate the scale, we estimate the number of required facilities based on an average biofuel refinery with a 6 PJ output capacity. Figure 7.4 shows the results. While this study does not distinguish between bio-based or synthetic fuel imports, we included them as biofuels for illustrative purposes and estimate the additional number of biofuel refineries needed, regardless they are built in the Netherlands or elsewhere. The numbers are significant.

This estimate is based on the average scale typical for planned biomass gasification projects. For comparison, the Neste HVO biorefinery in the Netherlands has nearly ten times this size. Although larger refineries could reduce the total number needed, they also pose challenges such as securing a steady biomass supply and requiring substantial capital investment.



*Pattern fill relates to imports. Included here with the assumption that they are all biofuel, while they could also be RFNBO.

Figure 7.4: Number of biofuel refineries to meet the biofuel demand in the Netherlands

7.2 Deep dive organic chemical industry

Figure 7.5 recaps the role of various decarbonization options projected for the organic chemical industry, more specifically for the production of olefins and aromatics in the Netherlands.

In this study, mechanical recycling is assumed to reduce the need for virgin plastic production and, consequently, the demand for olefins[18]. It is important to note that the amount of plastic waste allocated to mechanical recycling is predefined in this analysis, as are the related yields. These remain constant across all scenarios. This results in an overall plastic waste-to-mechanical recycling efficiency of 39% in 2030, increasing to 45% in 2040 and 2050 (see Table 7.2). The energy demand of mechanical recycling is included in the analysis; however, the costs and the material and energy flows related to collection, sorting, and transport are not accounted in the modelling.

The extent to which mechanical recycling can replace virgin materials depends on the availability and suitability of plastic waste for recycling. It is assumed that part of the post-consumer plastic waste can be imported from other European countries, with imports gradually increasing from 2035 to 2050. Mechanical recycling faces inherent limitations, such as reduced product quality, contamination issues, and its unsuitability for certain plastic types—factors that cannot be captured within this scenario analysis. As such, the findings related to plastic recycling should be interpreted with these limitations in mind.

[18] It is assumed that 1.54 Mtonne plastics will be needed to reduce the demand for 1 Mtonne Olefins

Table 7.2: Mechanical recycling related assumptions

	2030	2040	2050
Share of total plastic waste sent to mechanical recycling	60%	75%	75%
Mechanical recycling efficiency	65%	70%	70%
Net efficiency (plastic waste -to-mechanical recycling)	39%	45%	45%

Results show a limited electrification of steam crackers up to 2040. Beyond, electrification takes up and more than 30% of the steam cracking relates to electrified steam cracker in both the reference POLICY and fossil-free scenarios. This technology is currently in the research and development phase. According to IEA, the technology readiness level is at 5; indicating large prototype developments (IEA, 2025)[19]. In Germany, BASF, SABIC and Linde have initiated a demonstration plant to test material behaviour and process on an industrial scale. In the Netherlands, Shell, Dow, TNO and ISPT have been researching the possibility of electrifying existing gas-fired crackers.

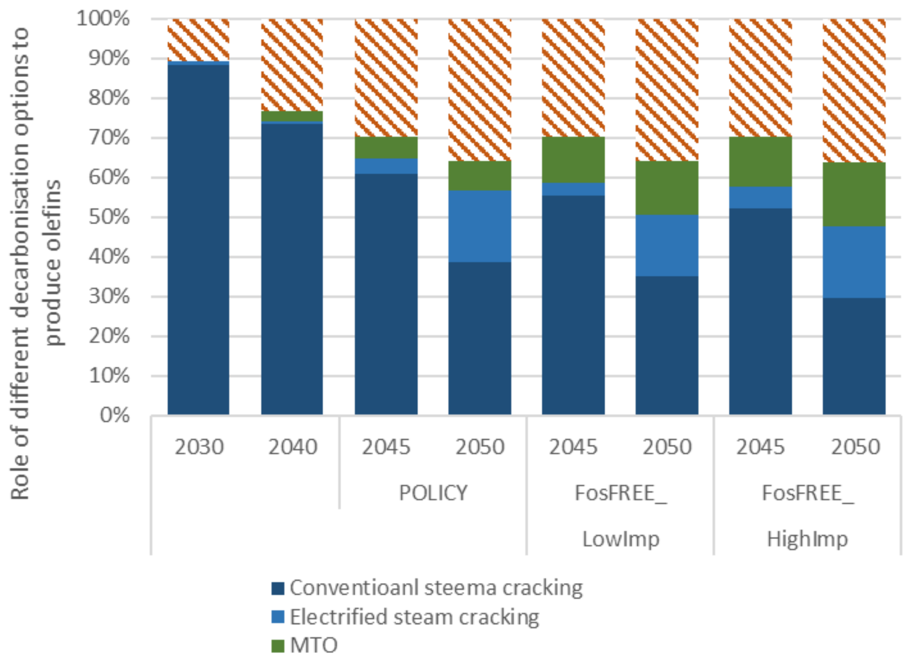


Figure 7.5: Role of various decarbonisation options in olefins production

The continued use of naphtha steam cracking in this scenario model is closely linked to the potential synergy between renewable fuel production for the transport sector and the chemical industry. Figure 7.6 details the renewable and circular naphtha supply potentials according to the three scenarios. As previously discussed, the demand for renewable fuels and the associated developments will have a direct impact on this sector. Consequently, the transformation of the organic chemical industry is strongly tied to advancements in both bio-based and synthetic refinery technologies. Therefore, the successful substitution of fossil-based naphtha with renewable alternatives depends heavily on the development and scale-up of these renewable refineries.

[19] ETP Clean Energy Technology Guide – Data Tools - IEA

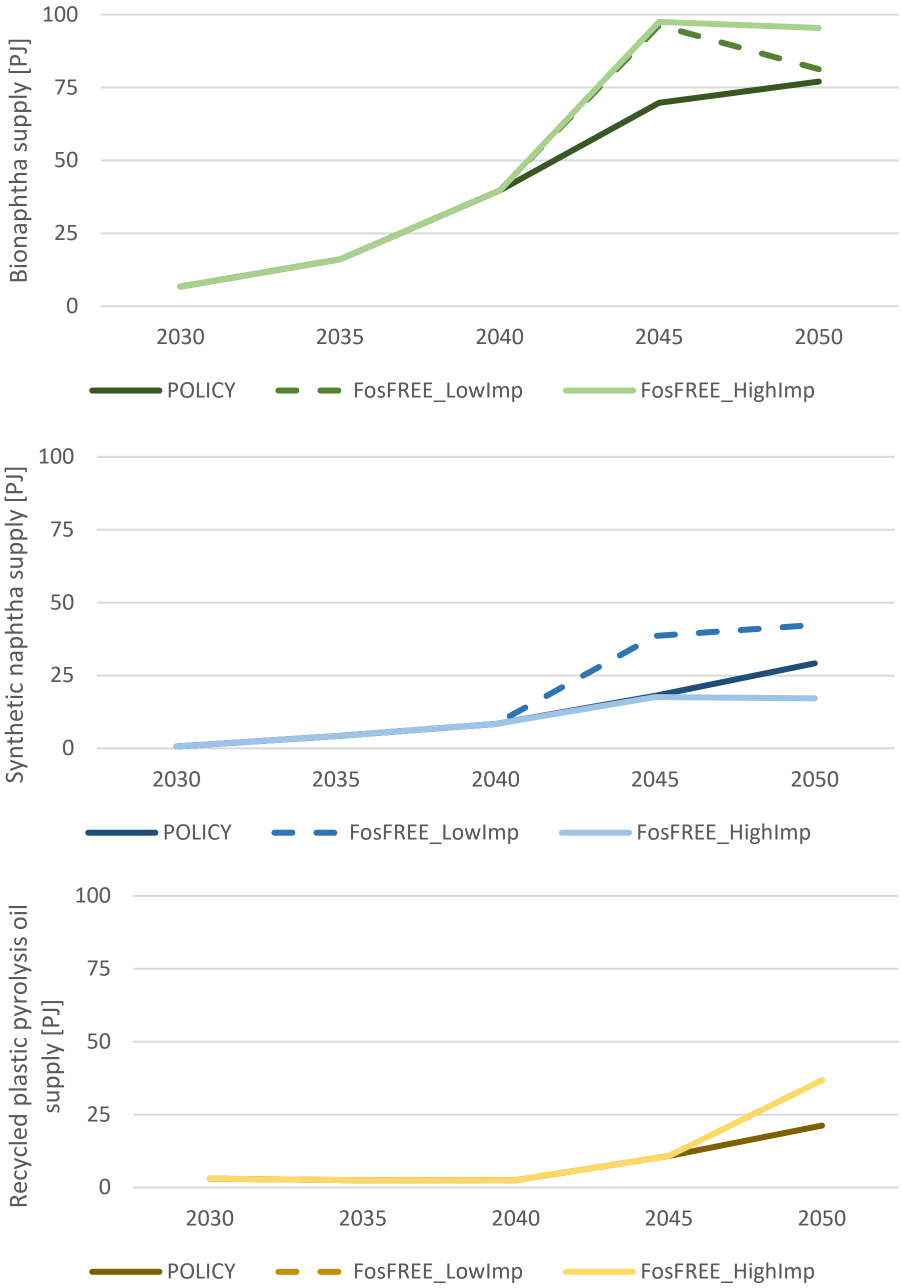


Figure 7.6: Renewable and circular naphtha supply to the naphtha crackers according to the scenarios

The reference POLICY scenario indicates a relatively small transformation of fossil aromatics with renewable and circular aromatics. This mainly relates to the substitution of fossil naphtha with circular naphtha and some aromatics production from these naphtha crackers. Moving to fully fossil-free industry results in a significant shift from fossil to bio-based aromatics production between 2045 and 2050. Such a sharp increase in just 5 years' time appear unrealistic. Figure 7.7 shows the scenario modelling results for the renewable and circular aromatics production. Almost 90% of the circular aromatics relate to bio-based aromatics production in 2050 in the fossil-free scenarios.

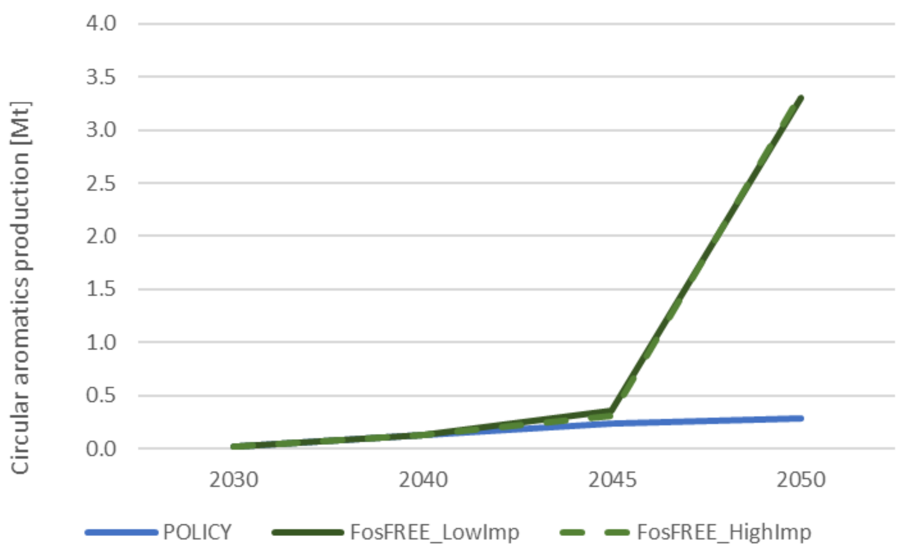


Figure 7.7:Circular aromatics production according to three scenarios

Current analysis included two alternative pathways for the stand alone aromatics production. These are biomass- to- methanol, followed by methanol-to-aromatics and biomass hydrothermal liquefaction (HTL)- to-bio-crude, followed by bio-crude-to-aromatics. Due to relatively higher conversion efficiency, biomass hydrothermal liquefaction followed by aromatic extraction is chosen as the preferred value chains. However, the technology readiness of this value chain is lower, therefore, the plausibility of this result will depend on the research and development and scale up of this technology.

A comparison of the TRL levels of various bio-based olefin and aromatic value chains are introduced in below table. While higher TRL value chains may be considered as more likely, what will happen in the next 15 to 20 years will determine the successful value chains.

Table 7.3: TRLs of various value chains

Value chain	Technology Readiness Level (TRL)
Biomass to methanol	7-8
Methanol-to-olefins	8-9
Methanol-to -aromatics[20]	6-8
Lignocellulosic biomass-to-ethanol	7-8
Ethanol-to-ethylene	8-9
Biomass-to bio-crude (HTL) [21]	7-8
Bio-crude-to aromatics	5-6
Biomass-to-pyrolysis oil	8-9
Pyrolysis oil to aromatics	5-6

[20] In contrast with the industrially implemented methanol-to-olefin (MTO) process, most MTA studies are still in the laboratory-scale stage. Recently, a few demonstration plants of MTA have been successfully launched (Li et al,.2021)

[21] While a dedicated study from IEA on direct thermochemical liquefaction commercialization report refers to TRL 7-8 for this technology, a recent JRC report on advanced biofuels indicate the TRL of HTL to be at 5-6

7.2.1 Discussions-drop-in versus novel value chains

An important limitation relevant for the transformation of the chemical industry is the representation of defossilisation options for the production of chemicals for plastics. This study includes the drop-in alternative value chains to produce olefins and aromatics. The novel alternative value chains have not been included to the scenario modelling but identified and assessed separately. These are (Ruiter et al.,2025):

- Poly lactic acid (PLA) as the novel alternative to high density polyethylene (HDPE) in plastic bags.
- Polyethylene furanoate (PEF) novel alternative to PET in bottles.
- A novel copolymer of furan dicarboxylic acid(FDCA), fumaric acid, and butanediol-abbreviated as PBFFu, as alterative to poly propylene (PP) in automative parts.
- Novel copolymer of FDCA and 1,3-propanediol abbreviated as PPF as alternative to PA in clothing.

Simplified flow diagrams of these novel value chains are presented in Figure 7.8. The assessment methodology and the results can be found in Appendix B. While these processes are assessed and compared with the alternative drop-in value chains using a set of key performance indicators, their potential contribution to the transformation of the Dutch chemical industry pen requires further analysis. This would involve, among other things, exploring the potential for expanding biomass feedstock categories from feedstocks listed in REDII to including other feedstock types that may be feasible for Dutch industry.

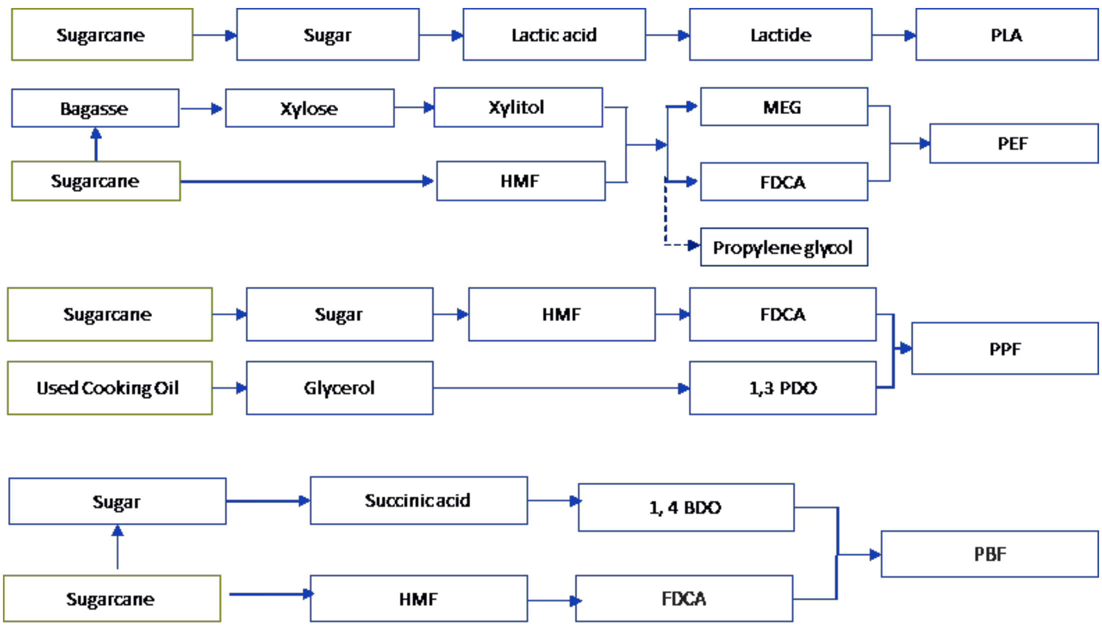


Figure 7.8: Simplified flow diagram of biobased novel value chains

In this study, biomass availability and import potential are limited with the sustainability criteria and the eligible feedstock list defined in the Renewable Energy Directive (REDII). This list mainly consists of wastes and residues from agriculture and forestry. Biofuel produced from food crops has been capped to 2020 levels; therefore, cereals, sugar and oil crops are not included as available resources. Currently, the chemical industry relies heavily on food and feed crops, such as starch, sugar and vegetable oils (See Figure 7.9). Also, the alternative value chains listed above are mostly based on sugars and oil.

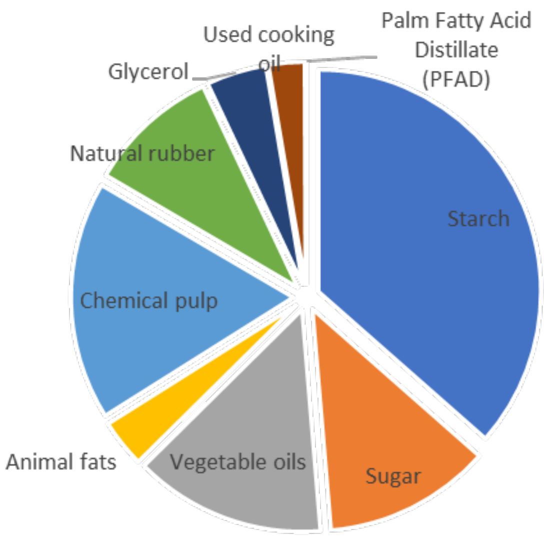


Figure 7.9: Overview of estimated use of the most important feedstocks in chemical and derived materials industry in EU for 2022-2023 (Carus et al. 2025).

A recent study from Nova institute (Carus et al. 2025) estimates that by 2050, the chemical industry's biomass feedstock mix will include both food and feed crops and lignocellulosic feedstocks (such as wood & straw and biowaste). In their future scenarios, lignocellulosic biomass is projected to make up 14% to 26% of the feedstock mix by dry weight, or 10% to 20% of the biogenic carbon content. Food and feed crops are still expected to dominate, accounting for 55%–69% of biomass use globally and 42%–53% within the EU.

In addition, a better understanding of drop-in versus novel alternatives is essential. Figure 7.10 illustrates the transformation options included in this scenario modelling (coloured in green and blue). It also shows some of the alternative/novel production routes within the downstream process of the chemical industry (coloured in yellow) that are not covered in this the scenario analysis. It is important to note that transforming some of the downstream processes and products may prove to be more efficient than upstream transformation using biomass. However, many upstream transformation options are at a higher technology readiness levels and are also driven by policies targeting GHG emissions reduction in the transport sector.

Increasing the TRL of innovations typically require long lead times, and therefore, value chains that are already more advanced may be considered as more realistic in the near term. Nevertheless, the role of novel value chains will need further analysis and will be part addressed in a follow-up update to this study on the chemical industry.

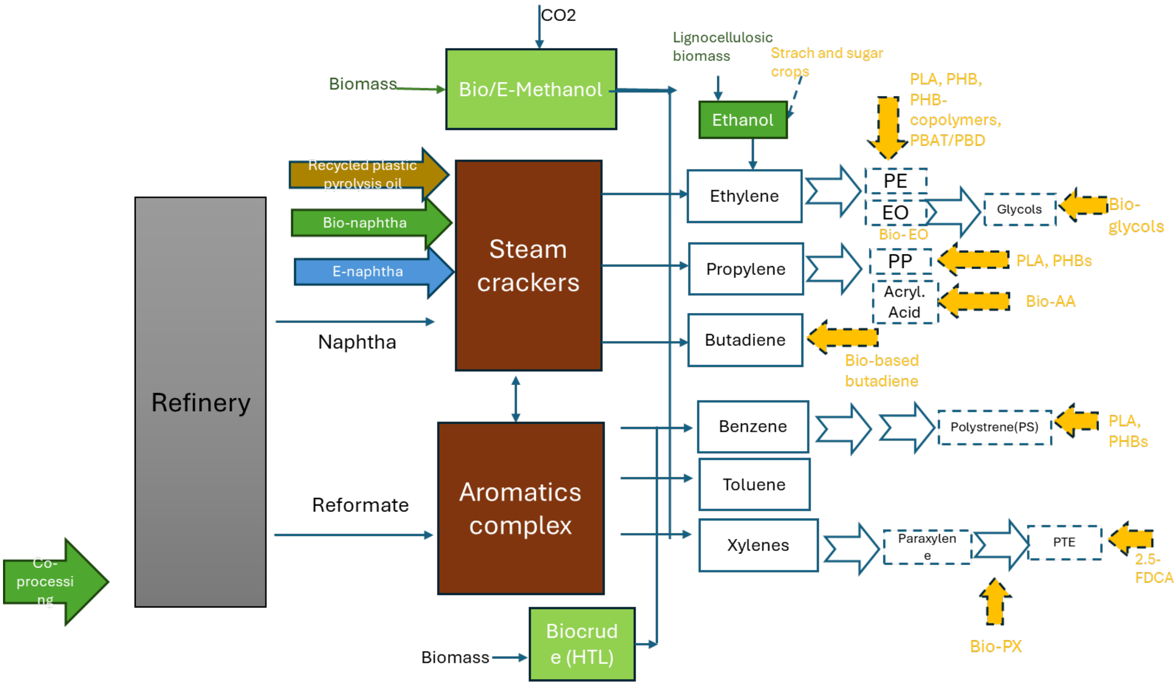


Figure 7.10: Simplified presentation of alternative pathways included in the model (in green, blue) and potential downstream transformation options that are not covered in this modelling(yellow)

7.3 Representation of the chemical industry and other oil products

The organic chemical industry representation in OPERA model consists of upstream production of olefins, aromatics, the demand of methanol representing current consumption in the chemical industry and non-energetic use and conversion of other oil products.

This category other oil products includes turpentine and special petrol, lubricants, bitumen, mineral waxes, petroleum coke, and other residual petroleum products. These products, although representing a small share of the overall energy and material balance, pose specific analytical challenges due to the lack of clearly defined product types. Given this constraint, and their relatively minor contribution to total energy use, these products were partially assumed to be imported in the fossil-free scenarios. While this solution is not ideal, it provides a pragmatic approach that allows the overall scenario analysis while acknowledging the limitations in substituting certain specialized fossil-based products.

Chemical sector requires complex oil derivatives that are difficult to model, and further research is required to improve the estimates of viability and costs of renewable alternatives.

7.4 Methodological considerations - Defining import volumes and prices

The POLICY scenario presented in this study is constructed on the assumption that climate neutrality in the Netherlands can be achieved primarily through the use of domestic resources, and imports of biomass and plastic wastes. As such, determining the potential trade flows of renewable energy and energy carriers (e.g. renewable hydrogen, renewable fuels, renewable methanol, etc.) is not explicitly included in the modelling framework. This exclusion should not be interpreted as an indication that international trade in renewable intermediates or end products will not occur. On the contrary, such trade is expected to play an important role in future decarbonisation pathways. However, due to high uncertainties regarding future market prices, commodity types, availability, and geopolitical dynamics, incorporating these trade flows into the scenario framework would have introduced a level of uncertainty/speculation that could compromise the objectivity and robustness of the analysis.

To the extent possible, the same assumptions are implemented for the fossil-free scenarios to enable a robust and fair comparison. However, a fully fossil-free energy system and industry under the same input parameters used in the POLICY scenario was not technically feasible. This study already integrates the technically feasible domestic renewable potential; expanding beyond this would imply assumptions that are unsubstantiated. Therefore, for a fair and systematic comparison, additional assumptions were introduced in the development of the alternative fossil-free scenarios.

In the fossil-free low import scenario, half of the remaining fossil fuel use from the POLICY scenario was allowed to be met by renewable imports, specifically by imports of renewable kerosene, methanol and other oil products. The import prices of these three renewable fuels were derived from a test run of the POLICY scenario in which the total allowed fossil consumption was halved, while not allowing for renewable fuel import. The resulting shadow prices is an indication of the willingness to pay for such imports by the Netherlands.

In the high import scenario, a more optimistic pricing approach was adopted, with import prices derived from the shadow prices of renewable kerosene, methanol and other oil products of the POLICY scenario. For this scenario, 100% of the remaining fossil fuel use from the POLICY scenario was allowed to be met by import of renewable fuels. For both fossil-free scenarios, the values assumed for the import prices are mostly intended to explore the sensitivity of the outcomes to these input parameters, and the resulting range of outputs.

7.5 Carbon Capture and Storage/Use (CCS & CCU), CDR and EU-ETS

Figure 7.11 shows the origin of the carbon capture and whether this carbon is used for the production of fuels and chemicals or is stored in 2050, according to the three scenarios.

In 2050, the total volume of CO_2 captured in the model is distributed between Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU). As shown in Figure 7.11, in the reference POLICY scenario, CCS accounts for 67%, while CCU represents 33% of the captured carbon. CCS remains unchanged across all three scenarios, making full use of the assumed CO_2 storage capacity of 20 Mt/year.

The share and absolute volume of CCU increase significantly in the fossil-free scenarios, as more renewable and circular carbon based products are needed to achieve a fully fossil free energy system and industry. The figure also shows that carbon captured from fossil and non-biogenic waste contributes approximately 15% of total captured carbon in the reference scenario. This share decreases in the fossil-free scenarios; to non-biogenic waste related CO_2 capture.

Figure 7.11 also shows a high reliance on DAC. In the POLICY scenario, DAC accounts for approximately 27% of total CO_2 capture. In the fossil-free scenarios, its role nearly triples, comprising over 63% of the total captured carbon.

The balance between DAC and biogenic CO_2 capture is influences by the available biogenic CO_2 in the energy system. The more biogenic CO_2 is available, the less DAC is requirements, as the former is a lower-cost option.

Compared to previous TNO studies using the OPERA model – such as the ADAPT and TRANSFORM scenarios (Scheepers et al., 2024 and 2025) – this study shows a larger role for DAC. This difference relates to a key assumption made in this analysis: the limited availability of biogenic CO_2 for capture. The model assumes that only 50% of the biogenic CO_2 from biofuel production is available domestically for capture and use. This assumption is key and directly impacts the split between DAC and biogenic sources of CO_2, as seen in below figure. This conservative assumption is based on two main considerations:

- **Uncertainty regarding biorefinery location:** Stakeholders expressed doubts about whether all the required biorefinery capacity—especially for bunkering—will be built in the Netherlands. If a significant portion is built abroad, the domestic availability of biogenic CO_2 would be significantly reduced.
- **Plausible cost estimation:** Assuming full domestic use of biogenic CO_2 would underestimate system costs. Limiting its availability allows the model to reflect more robust system dynamics.

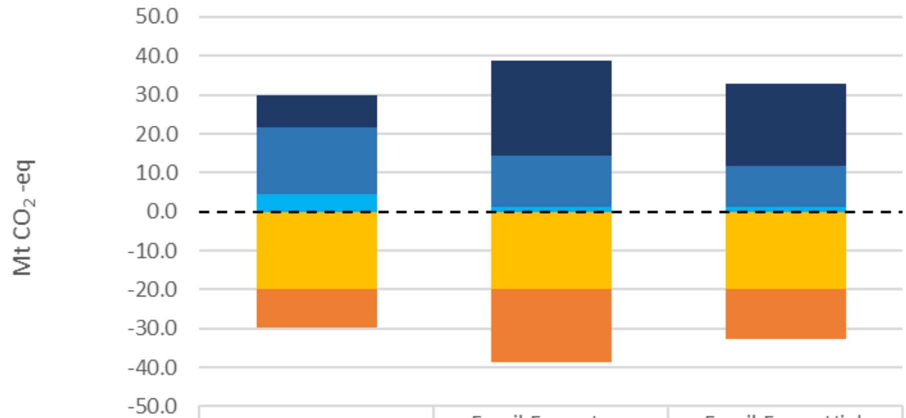
In previous scenarios, greater reliance on BECCS and lower use of DAC are observed. However, sensitivity analyses in Scheepers et al. (2025) show that when BECCS costs are increased or biomass availability is constrained, DAC use also increases—supporting the logic of this study's assumptions.

In this study, CDR from BECCS and DACCS are evaluated under the EU ETS framework. From 2040 onwards, the model results show that the total cost of generating CDR becomes lower than the projected ETS carbon price. This implies that, if integrated into the ETS, CDR could generate revenues (by earning allowances), thereby reducing overall system costs. These findings highlight the trade potential and strategic role of CDR in cost-effective decarbonization pathways. In fact, the total amount of CDR in the reference scenario is larger than the residual GHG emissions. This is also the case for the fossil free scenarios. Thus, not only are residual emissions from sectors like agriculture and LULUCF offset to achieve a climate-neutral energy system, but also the system benefits from additional revenues through surplus CO_2 removals.

Currently, CDR is not included in the EU Emissions Trading System (EU ETS), which limits its integration into cost-optimization strategies and market-based incentives. However, the European Commission has acknowledged the importance of CDR in its 2050 long-term climate strategy and has initiated a policy development process to explore how these technologies could be integrated into the EU climate architecture.

In 2021, the Commission launched the Carbon Removal Certification Framework (CRCF) proposal, aiming to create an EU-wide certification system for carbon removals. While the CRCF is not a market instrument like the EU ETS, it represents a critical step toward standardizing and validating CDR. Discussions are ongoing whether and how certified removals could be used in compliance markets in the future (European Commission, 2022).

It is important to note that it has not been determined if, and if so how, CDR will be integrated into the ETS. The Netherlands has taken a cautious position in the Roadmap CDR (Routekaart Koolstofverwijdering) and related EU discussions, emphasizing the need for safeguards to ensure that the incentive to reduce emissions is not weakened by CDR crediting. This uncertainty regarding ETS integration could influence the interpretation of model outcomes and the role of CDR in future compliance frameworks.



	Reference	Fossil Free - Low Import	Fossil Free - High Import
Atmospheric capture	8.1	24.5	20.9
Biogenic capture	17.2	13.1	10.7
Fossil and non-biogenic waste capture	4.4	1.2	1.2
Use (CCU)	-9.7	-18.8	-12.7
Storage (CCS)	-20.0	-20.0	-20.0

Figure 7.11: Origin and direction of captured CO2 in 2050 according to three scenarios

This study assumes a CO_2 storage capacity of 20 Mt, which is fully utilised across all scenarios. This aligns with other major studies (e.g. PBL's TKVN (Trajecten naar een klimaatneutrale samenleving voor Nederland in 2050)(PBL,2024), TNO's ADAPT and TRANSFORM(TNO,2024), II3050), where storage volume assumptions typically range between 15–40 Mt.

The storage is used to compensate remaining fossil CO_2 emissions and non-CO_2 emissions (e.g. methane from agriculture and land use), and also to generate surplus reductions for trading in future carbon markets. If a lower CO_2 storage capacity would have been assumed, the system would face higher costs, fewer options for offsetting hard-to-abate emissions, and limited potential for CDR. If more storage were available, flexibility would increase, along with options to trade surplus reductions and reduce reliance on imports.
While 20 Mt/year is a reasonable estimate based on current Dutch capacity (e.g. North Sea sites), real-world deployment depends on regulatory, geological, and societal factors. Thus, CO_2 storage capacity is not just a modelling input—it is a critical variable shaping the feasibility and cost of climate neutrality.

8 Conclusions & recommendations

This study shows that a fossil-free energy system and industry in the Netherlands by 2050 is technically feasible—but significantly more challenging and costly than achieving climate neutrality alone. It requires much earlier action, stronger policy alignment, full utilisation of domestic renewables, and strategic imports of biomass, renewable fuels and feedstocks. Thus, the shift from climate-neutral to fossil-free systems brings higher system costs, greater resource demands, and increased interdependencies across sectors and borders—but also strategic opportunities for innovation.

Key Conclusions
While the climate-neutral energy system significantly reduces domestic GHG emissions, it does not achieve full fossil phase-out. Sectors such as international aviation and maritime, and the petrochemical industry continue to rely on fossil resources. This reflects current regulatory boundaries (e.g. Regulations for aviation and maritime sectors) and a lack of dedicated policy instruments to re-carbonise feedstock use in industry. The results show that under a climate-neutral energy system and industry, embedded carbon in products can still originate from fossil sources.

While achieving climate neutrality already requires major changes across the energy system, moving to a fully fossil-free system would demand even greater transformation in industry. This would lead to higher costs and added complexity, due to more electrification, wider use of renewable and circular feedstocks, and growing dependence on global supply chains that still need to be built. Making this shift will require long-term policy coordination and joint investments across sectors and countries.

The industrial sector—especially petrochemicals—will be among the most difficult to defossilise due to its dependence on fossil feedstocks and complex production processes. Transitioning to fossil-free production will require the scale-up of emerging technologies such as green hydrogen and bio-based and other circular feedstocks, many of which are not yet commercially mature. This demands targeted innovation support, investment in infrastructure, and secure access to sustainable raw materials. Decarbonising key feedstocks like aromatics and olefins will also require long lead times and close coordination across the energy and materials systems. Since sustainable biomass and recycled plastic wastes are limited resources, their optimal use across fuels and materials sectors—and across world regions—must be carefully coordinated and prioritised within strong governance frameworks.

Mutually reinforcing transition pathways can enhance efficiency and impact; for example, multiproduct renewable refineries that produce transport fuels alongside by-products like renewable naphtha, or products like methanol that can serve to several markets can simultaneously support decarbonisation in both energy and chemical value chains.

Infrastructure readiness will play a decisive role in determining the speed and efficiency of the transition. Electricity grid expansion, hydrogen transport networks, and renewable fuel logistics must be developed in parallel with industrial transformation.

Maximising the use of domestic renewable resources is a key priority. However, even with strong domestic efforts, imports of renewable fuels and intermediates will remain an important complement—especially to meet the needs of hard-to-abate sectors. This highlights the need for coordinated international supply chains and trade frameworks to support the transition.

Carbon management in both climate-neutral and fossil-free scenarios remain necessary. A balanced mix of carbon capture, use and removal will be necessary to close the carbon cycle and meet long-term sustainability goals in a cots-effective manner.

Finanly, strong coordination between industrial development, infrastructure planning, and feedstock supply can provide significant efficiencies and synergies. By aligning these elements, projects can maximise impact and accelerate the transition away from fossil use.

Based on these insights, we recommend the following priority actions.

Strategic recommendations

- **Maximise the domestic renewable resource use:** Utilising all available domestic resources such as wind, solar, sustainable biomass, and recyclates, is essential, especially in the fossil-free scenario, where near-full deployment is required. This is complemented by nuclear energy and international imports.
- **Secure access to renewable and circular energy carriers through international supply chains**: The transition to fossil-free industry requires imports of biomass, renewable and circular fuels and feedstocks. Even in the low-import scenario, imports of renewable kerosene, methanol, and other synthetic oil products become inevitable beyond 2040. Key actions include:
  - Expanding diplomatic and trade instruments to establish long-term supply agreements with countries rich in renewable energy resources
  - Support international certification systems and sustainability frameworks for renewable fuels and create these for the chemical feedstocks
  - Accelerate infrastructure investment for these imports
  - Coordinate biomass sourcing strategies across transport and chemical sectors to minimise competition and maximise synergies
- **Accelerate grid and hydrogen infrastructure expansion**: Electricity and hydrogen demand is projected to grow significantly, especially within industry clusters. This is confirmed by previous studies (i.e. PBL,TKVN 2025, TNO, 2024 and others). Supplying these demand will require further acceleration and expansion of infrastructure.
- **Accelerate deployment of electrolysers and fuel production facilities**: Meeting both climate-neutral and fossil-free targets demands rapid scale-up, but most projects are still in planning phases.
  - Provide targeted investment support, and risk guarantees for projects that are not yet fully commercial
  - Promote industrial offtake agreements to reduce market uncertainty and further stimulate demand, particularly for the chemical products
- **Advance low-TRL technologies through R&D and targeted policy support**: Many key technologies—e.g., electrified crackers and (novel) biobased polymers—are still in early stages. Key actions are:
  - Accelerate R&D and demonstration of high-impact industrial decarbonisation technologies, recognising long lead times for commercialisation.

- **Strengthen cross-sectoral coordination and establish a long-term transformation pathway for sustainable and circular chemicals, including interim targets and early demand signals**.
  - Define a technology roadmap for bio-based and CO_2-based chemicals with intermediate targets.
  - Support integrated biorefineries with dual output (fuels + chemical feedstocks).
  - Promote cross-sectoral innovation platforms linking electricity, hydrogen, carbon, and biomass supply chains
- **Develop an integrated carbon management strategy**: A balanced mix of CCS, CCU, and DAC is necessary to close the carbon cycle, especially post-2040.
  - Develop a national DAC roadmap and explore industrial clustering for shared infrastructure.
  - Reassess biogenic CO_2 availability and co-locate biofuel production with capture capacity.
  - Incorporate CDR pathways into a trading system and design policy to facilitate early investments in BECCS and DACCS, with a view to monetizing surplus removals.

Reaching a fossil-free future will require an integrated strategy across sectors, strong domestic policy, and international cooperation. The Netherlands has already laid important groundwork through the *National Energy System Plan (NPE)*, *National Programme for Industrial Sustainability (NPVI)*, *National Circular Economy Programme (NPCE)*, the *National Vision on Sustainable Carbon Chemistry* (Draft, 2025), the *Routekaart Koolstofverwijdering* (2025), and the *National Hydrogen Programme*. What is needed is aligning national efforts with broader EU strategies, increasing international cooperation and more importantly accelerated action in all energy carriers (electricity, hydrogen, CO_2, biomass).

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Appendix A
Biomass and plastic waste import potentials

Biomass import potential

Import of biomass to the Netherlands is one of the major uncertainties and there are various studies providing a wide range for sustainable biomass potential in Europe and globally. A recent study has analysed the sustainable biomass potential or the European Commission with a focus on the feedstock types listed in the Annex IX of the Renewable Energy Directive[22] (EC, 2024-Task2). The import potential within Europe is derived from this study.

This study updated the biomass resources potential that can be designated for generating drop-in advanced biofuels in the EU, the UK, and Associated Third Countries by 2030 and 2050. While this study builds upon existing studies of biomass potential, for most of the biomass potentials, new and more up-to-date baseline data, methodologies, and scenario assumptions were used in this study.

- The biomass assessments in S2BIOM, Biomass Policies, ENPRESO, and CONCAWE use 2015 baseline data to generate future biomass potentials.
- In this study, latest CAPRI baseline run data for 2030 and 2050 published in the 2022 report were utilized providing new agricultural land use baseline scenarios. (CAPRI, 2022).
- Waste assessments for 2030 and 2050 projections considered the most recent regional EUROSTAT waste statistics as a starting point. •
- For forest biomass potential, the study leverages S2BIOM data, as no more updated EFISCEN model runs are available. Specific scenarios from S2BIOM are selected to align with the drop-in fuel low, medium, and high mobilization scenarios, accommodating variations in competing use levels and sustainability requirements.
- New quantification approaches were developed for the proposed new types of Annex IX Part A and B biomass, not previously assessed, involving extensive data collection.
- Data were processed at NUTS 2/3 regional level, necessitating several disaggregation and data processing steps.
- Cost assessments for all biomass types are updated with new data and revised to reflect 2020 cost levels, taking into account inflation developments up to that year.

Competing uses for instance for forestry biomass such as for textile, wood working in construction, carpentry, building materials, board and some of the chemical intermediates (such as succinic acid) resins, for forestry biomass are excluded from the total technical potential. For agricultural feedstocks possible competing uses such as animal bedding, horticulture protection, again fiber based building materials etc are counted in and excluded from the technical potential. As such, this study provides somewhat more conservative biomass potential. Nevertheless, this is the most recent dataset, and we will use this data for the reference "climate-neutral energy system" and conduct sensitivity analysis.

[22] For biofuels to be eligible for the renewable energy targets they need to be from this list.

The following approach is followed to determine the biomass potential for his study:
- *Import within Europe:* The import potential is based on datasets including lignocellulosic crops, primary forest biomass (including stem wood and primary residues), solid waste (including secondary agricultural & forestry residues). It is assumed that these selected biomass categories can be available for trade and 10% is considered for the Dutch market. This corresponds to 551 PJ woody biomass and 34 PJ non-agricultural oils, such as used cooking oil (UCO) and animal fats (AF). This 10% aligns with the current refinery contribution to the European market.
- Other biomass categories, such as agricultural primary residues, all gaseous biomass resources, such as manure, sewage sludge, are excluded from consideration. Additionally, the possibility to import black liquor is not considered. The excluded categories collectively represent more than 50% of the total biomass potential. Thus, the 10% import potential to the Netherlands relates to less than 5% of the total EU biomass potential.
- *Import potential from outside EU:* Woody biomass can also be imported from outside the EU. In fact, wood pellet net imports to the Netherlands have been highest in 2020, reaching to almost 2.1 Mtonne (around 45 PJ[23]) of which 20% was from the US.[24] For this study, we used the import potential data included in (Panoutsou & Maniatis, 2021) (which was derived from a BioTrade2020 plus and Biomass Policies). The import potential estimate for the Netherlands is based on the wood pellet import potential, where approximately 10% was assumed to be export to the Netherlands. This corresponds to 98.6 PJ. Same approach is implemented for the UCO & AF import potentials, corresponding to 48 PJ.

Plastic waste potential

Starting from the current plastic data of Plastics Europe (Plastics Europe, 2022), the growth rates from Stegmann are implemented (Stegmann, Daioglou, Londo & Junginger, 2022). These are based on the historic relationship of chemical and plastic production and GDP and population development. The GDP and population projections were derived from the second shared socioeconomic pathway (SSP2) (O'Neill, et al., 2017). These project a plastic demand growth of 46% and plastic waste growth of 41% until 2050 for Europe.

For the Netherlands, the slightly lower growth of Western Europe was assumed (for further information on included countries in Western and Central Europe regions, see (PBL, 2018)). For comparison, the OECD plastics demand projections estimate a growth of 64% for OECD EU countries until 2050 (OECD, 2022).

Plastic waste imports to the NL: it is assumed that plastic waste can be imported from other European countries to the Netherlands. To determine the import potential, the following was considered:
- Only packaging plastic waste is considered (e.g. based on polyethylene, polypropylene, polystyrene and PET. This is to allow more feedstock for recycling in the Netherlands. This scenario modelling includes mechanical recycling, pyrolysis and gasification and packaging waste appears to be the most suitable waste category for these technologies.
- In 2020, around 61% of the plastic waste collected was composed by packaging waste (most recent data from Plastics Europe, 2022). The EU aims to recycle 55% of plastic packaging waste by 2030, and these targets could further drive improvements in collection and recycling rates. If these targets are met, the share of packaging waste within the plastic waste stream could increase significantly, potentially approaching 70%

[23] Applied 18 GJ.t
[24] DownloadReportByFileName (usda.gov)

or more of the total plastic waste collected, depending on the progress in other areas of plastic recycling. In this reference scenario, it is assumed that this share (70%) in terms of composition of plastic waste collected in the EU will be kept constant towards 2050.

- Import of plastic waste from the EU is assumed to start from 2035, mainly due to the limited capacity of chemical recycling available in the NL.
- From the total waste generated in the EU, 10% is assumed to be imported to the Netherlands by 2050. This 10% relates to the Dutch market share of organic chemicals industry in Europe Between 2035 and 2050, the imported volumes are assumed to increase linearly.

Table A.1: Plastic waste availability

	Unit	2020	2030	2040	2050
Domestic plastic waste availability in the NL	kt	1058	1161	1302	1437
Plastic waste import to the NL	kt	0	1939	2203	2442
Total	kt				
Total	PJ	37.0	108.5	122.7	135.8
PBL	PJ				160-260

Energy content assumed for plastic waste is 35 (GJ/t) (Stegmann, Daioglou, Londo & Junginger, 2022)

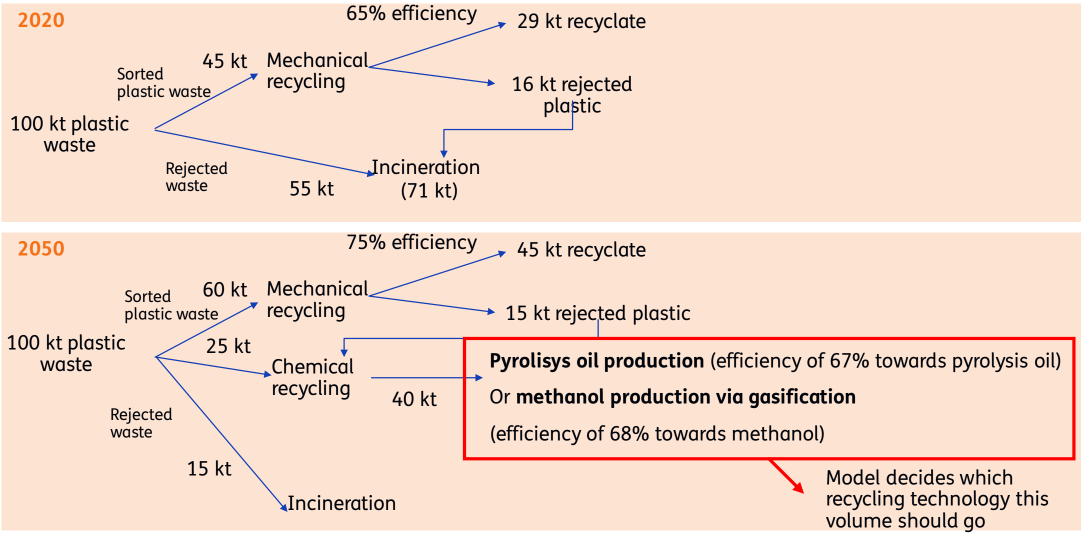
Table A.2 presents the main assumptions recycling flows and efficiencies.

Table A.2 - Summary of scenario data input in ktonne

	2020	2030	2040	2050
Domestic plastic waste availability	1058	1161	1302	1437
Plastic waste import	0	0	1221	2442
Total plastic waste available	1058	1161	2523	3879
Plastic waste sent to mechanical recycling	476	697	1512	2327
Mechanical recycling rejected waste	167	244	454	582
Plastic waste sent to chemical recycling	0	150	851	1551
Mechanical recycling efficiency	65%	65%	75%	75%
Plastic waste pyrolysis efficiency	67%	67%	67%	67%
Gasification pyrolysis efficiency	68%	68%	68%	68%
% Plastic waste incinerated	55%	48%	21%	15%
% Plastic mechanically recycled	29%	39%	45%	45%
% Plastic sent to chemical recycling*	0%	13%	34%	40%

The percentages consider both the share of plastic waste sent from the total amount available sent to chemical recycling (25% in 2050) and the rejects of mechanical recycling.

An example of the proposed plastic flows is as following:



Additional information on the availability of plastic waste in the Netherlands and the EU can be found in the following studies:

- "Navigating Volumes and Value Chains Towards Circularity - Total - Circular Plastics NL, and
- the *KPMG study on chemical recycling*, presented via the Versnellingstafel Chemische Recycling (PowerPoint Presentation).

Appendix B
Alternative plastic production routes

Introduction and Approach
So far the scenario modelling analysed the potential transformation of the chemical industry. This chapter provides the main conclusions of the exploration conducted to identify novel production routes, with a focus on the biobased plastics production.

TNO has developed a 3-step framework to analyse pathways to sustainable plastics. A brief summary of this framework is presented below. Further details of this framework can be found in de Ruiter et al., 2025.

Derived from "Pathways to sustainable plastics" by **Ellen de Ruiter, Jan-Harm Urbanus, Anna Schwarz, Milad Golkaram and Pieter Imhof**

Step 1: The first step in the framework involves mapping out the potential value chains for a certain polymer, various options exist for each polymer, such as producing biobased HDPE via corn-based ethanol or from forest residues via pyrolysis, replacing HDPE with a biobased alternative such as PLA, or producing a CO2-based HDPE via the methanol to olefins process.

To determine viable biobased alternatives for an existing (fossil) polymer in a certain product application, a comparison method is developed by TNO to compare polymer properties like modulus, tensile strength, elongation at break, oxygen transmission rate (OTR), and impact strength. A weighting factor is included to prioritizes key properties depending on the application (e.g., OTR for food packaging, impact strength for automotive parts). If a biobased polymer meets at least 90% of the required properties of a fossil-based polymer, it is considered a potential alternative. A database with >1000 biobased polymers is analysed, showing that many alternatives could replace existing plastics. Some products may currently use over-engineered polymers, suggesting the 90% threshold might sometimes be too strict, and for some products a perfect property match may be needed. The 90% threshold can be adjusted depending on the specific product/polymer.

STEP 2: the next step is to evaluate environmental sustainability impact and economic feasibility for each product-pathway combination. The key performance indicators selected for the environmental sustainability are global warming potential, cumulative energy demand, land use, water depletion, and feedstock input. These were assessed using a sustainability impact assessment tool combining Life Cycle Analyse and Material Flow Analysis.

For economic feasibility, cost components related to feedstocks, utilities, and investment costs are taken into consideration. For investment costs a rough CAPEX estimate based on processing complexity is set (more production steps increase investment needs).

STEP3: in this step most suitable pathways for a product can be identified. This will be based on constraints and scenario assessments, such as the availability of biomass.

Screening and selected value chains

To demonstrate the application of the three-step framework, a set of illustrative use cases was developed using global-average input data. These examples serve to show how the framework can be used to identify and evaluate potential biobased polymer alternatives.

The initial analysis within step one resulted in at least one novel biobased polymer alternatives with a 90% match for the polymers in applications highlighted by the icon in the matrix below. **Figure B.1** illustrates the bio-based alternatives identified in an initial analysis.

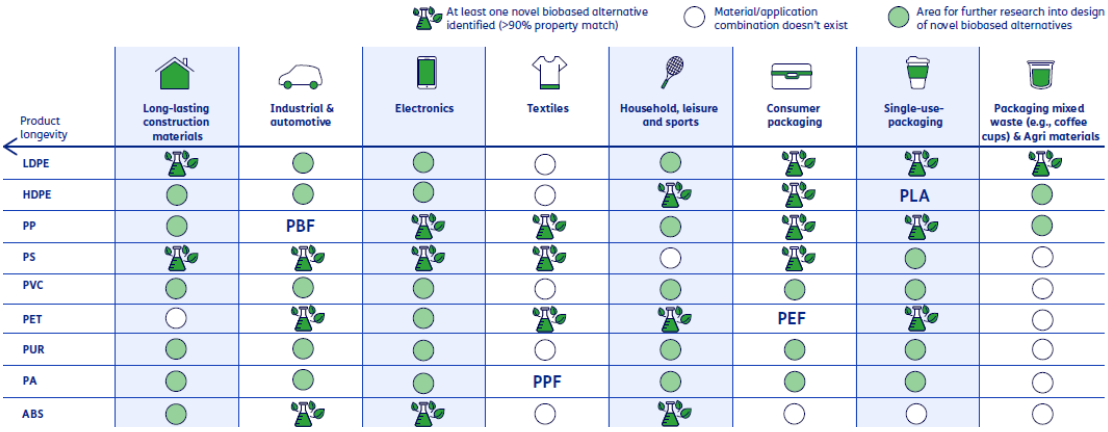


Figure B.1: Initial analysis found at least one novel biobased polymer alternative with a 90% property match for most applications (de Ruiter et al., 2025)

The novel bio-based alternatives selected for an initial analysis are:

- Poly lactic acid (PLA) as the novel alternative to high density polyethylene (HDPE) in plastic bags.
- PEF novel alternative to PET in bottles.
- A novel copolymer of FDCA, fumaric acid, and butanediol-abbreviated as PBFFu, as alterative to poly propylene (PP) in automative parts.
- Novel copolymer of FDCA and 1,3-propanediol abbreviated as PPF as alternative to PA in clothing.

PLA (Poly Lactic Acid)

PLA is a biobased polymer already applied in multiple single-use packaging products and medical and healthcare applications. Its production can occur from various sugar rich crops, including sugarcane, sugar beet, corn and cassava. At this moment, most PLA is produced from either sugarcane (Corbion) or Corn (NatureWorks).

For this study, the sugarcane production route is taken, where the corn route is relatively similar, where corn is dry or wet milled, and the sugar (mostly fructose) that is obtained from this process is fermented to lactic acid.

Figure B.2: Simplified flow diagram of PLA production

Polyethylene furanoate (PEF)

PEF is a bio-based polyester made from 2,5-furandicarboxylic acid (FDCA) and mono ethylene glycol (MEG), both of which can be derived from renewable sources like sugarcane, corn, or lignocellulosic biomass. At production level, the synthesis process for PEF is similar to the PET production process, but it substitutes terephthalic acid with 2,5-furan dicarboxylic acid (FDCA) Europlats, 2025.[25]

Current largest producers of PEF are Avantium in the Netherlands, through its YXY technology platform aiming for commercial-scale production. Toyo Seika in Japan is partnering with Avantium to commercialize PEF-based packaging solutions. In addition, Carlsberg Group in Denmark develops PEF-based beer bottles through partnerships. This value chain is in pilot and pre-commercial stage (TRL 7-8).

Figure B.3 illustrates the simplified flow diagram of PEF production from biomass resources. FDCA and MEG are the to key intermediate products for PEF production. As can be seen Sugarcane is considered as the key feedstocks.

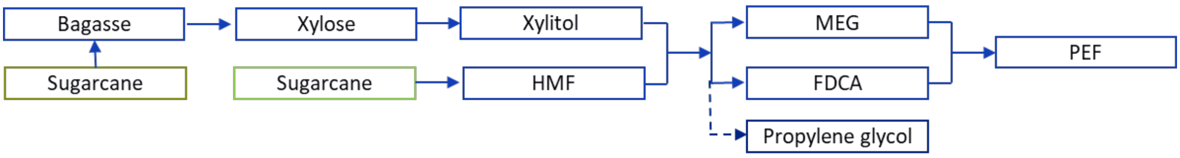


Figure B.3: Flow diagram of bio-based PEF production route

PBF (Polybutylene Furanoate)

PBF is a polyester derived from bio-based monomers. It is typically produced from FDCA, which is derived from sugars(fructose or glucose) via catalytic or enzymatic oxidation, and butanedial (BDO), that can be produced via bio-based fermentation of sugars. The polymerisation process involves polycondensation of FDCA and BDO, similar to PEF production. PBFF u is in early stage of development. Similar to FDCA relates players, Avantium, is researching this product. This product has some potential to replace fossil aromatics such as PET, PBT. As it is based on FDCA it can serve as a bio-aromatic alternative in certain applications.

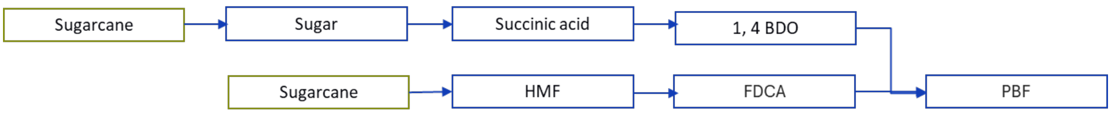


Figure B.4: Schematic illustration of PBFFu production

Bio-Based PPF (Polypropylene Furanoate)

PPF can be derived from FDCA and bio-based propylene glycol. This is thus a member of the polyfuranoae family, similar to PEF. As such PPF can be derived from sugar-based biomass, such as corn, sugarcane, lignocellulosic feedstocks. PPF is in early-stage of development. Companies that work of bio-based furanoate polymers are Avantium, BASF, Corbion, and DuPont.

Figure B.5 illustrates the schematic flow diagram of PPF production.

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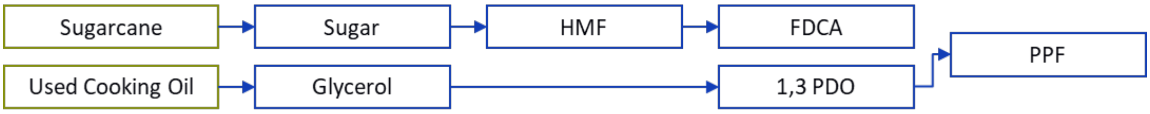

Figure B.5: Schematic illustration of bio-based PPF production value chain

Assessment results

Above introduced value chains are compared with the drop-in biobased alternatives and also the CO_2 based drop in alternatives in terms of sustainability KPIs and economic indicators.

Reference fossil product	Novel value chains	Bio-based drop-in alternative	CO2- based drop-in alternative
HDPE in plastic bags	PLA from sugarcane	HDPE from corn to-ethanol to ethylene	Point source CO_2+H_2 to methanol to ethylene to HDPE
PP in automative parts	Sugarcane to PBF	Forest residue to pyrolysis to PP	Point source CO_2+H_2 to methanol to propylene to PP
PET in bottle packaging	Sugarcane and Miscanthus to PEF	Corn to ethanol-to ethylene to MEG+ Forest residue to pyrolysis oil to Xylene to PTA >> PET	Point source CO2+H2 to methanol to ethylene to MEG + Methanol to Xylene to PTA >>PET
PA in clothing textile	Sugarcane and used cooking oil to PPF	Forest residue to pyrolysis oil to benzene to PA6	Point source CO_2+H_2 to methanol to benzene to PA6

The assessment results show the impact patterns of various alternative value chains that produces same product (see below figures).

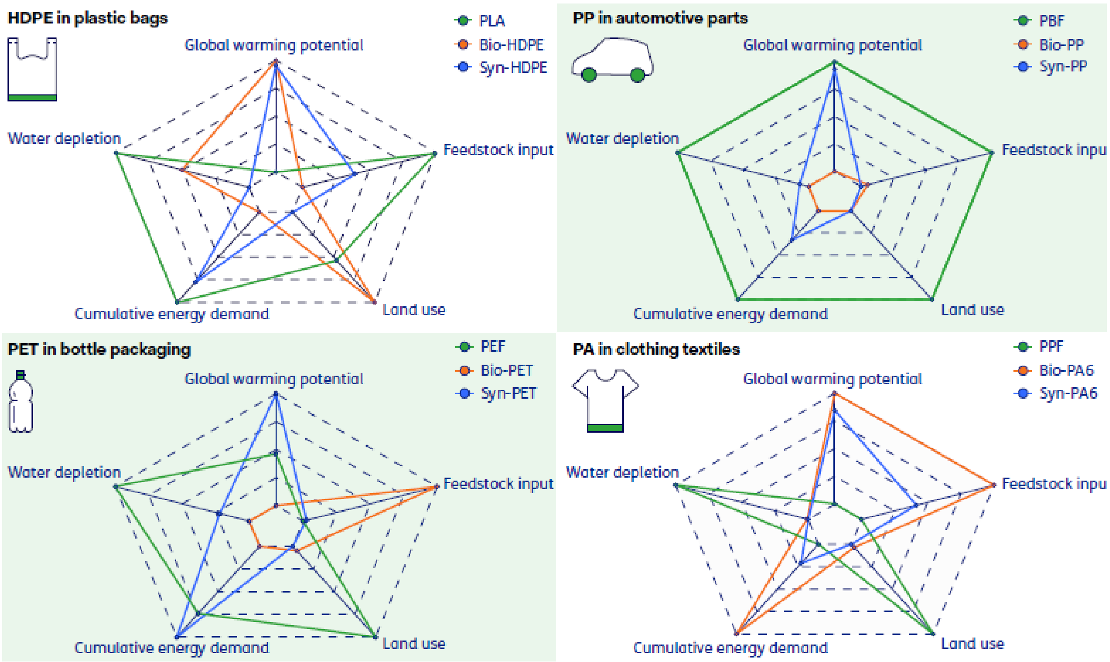

Figure B.6: Sustainability impact results (de Ruiter et al., 2025)

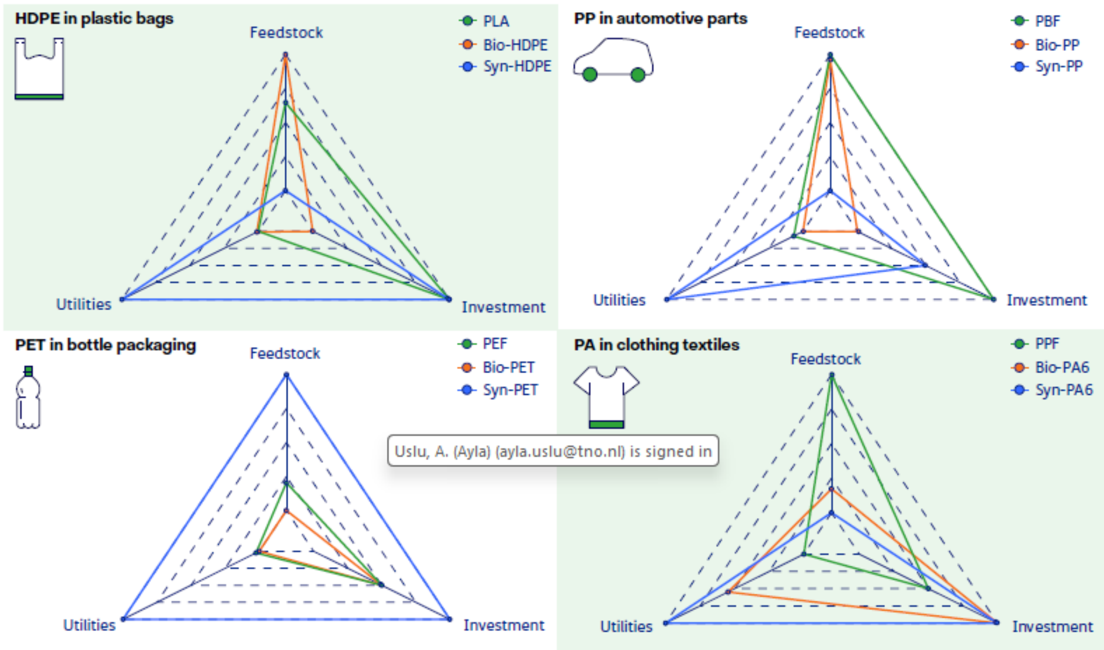

Figure B.7: Economic feasibility of alternative value chains (de Ruiter et al., 2025)

The environmental sustainability impact results depend on both process yield and type of biomass used, which is resembled in the amount of feedstock input required, land use and water depletion that are all related to biomass growth. For first-generation feedstock (e.g., sugarcane, corn) these impacts are highest, whereas production routes using second-generation feedstocks (e.g., used cooking oil, forest residues) show lower (better) scores on these indicators.

For condensation polymers, the opposite pattern is observed. Here the novel biobased alternatives already generally perform better compared to drop-in polymers on feedstock input required and sustainability impact. This is in line with the principle of 'oxygen efficiency'; conversion of biomass into hydrocarbon drop-in building blocks requires the full removal of oxygen in biomass (presenting yield losses since CO_2 or CO are being formed in this process) while some novel biobased alternatives can be produced with improved atom efficiency from biomass to monomer (maintaining the oxygen).

The economic feasibility assessment highlights Novel biobased alternatives usually have a more complex production process and thereby a relatively higher costs for utilities and CAPEX. Since the focus in this project is on (novel) biobased alternatives. Some of the key results are summarised below.

- In terms of cumulative energy and feedstock demand bio-based drop-in HDPE scores best. However, this value chain scores worst on land requirements. This relates to the high demand for corn to produce ethanol.
- PLA appears to score best in global warming potential. This relates to the energy recovery during this process, where baggage is used to meet the process heat demand. Not surprisingly CO_2 base HDPE scores best in terms of water depletion, land use and feedstock input. However, the global warming potential appears high, and this relates to the cumulative energy demand.
- Biobased drop-in PP scores best on all indicators. This relates to using used cooking oil. Novel biobased alternative PBF scores worst in most indicators driven by high feedstock input required and corresponding land use and water depletion combined with a relatively high cumulative energy demand for production.
- Biobased drop-in PET has a high feedstock input required, but aside from that seems to be environmentally favourable compared to PEF and the synthetic route because of the lower cumulative energy demand.
- PPF scores best on feedstock input required, cumulative energy demand, and global warming potential.

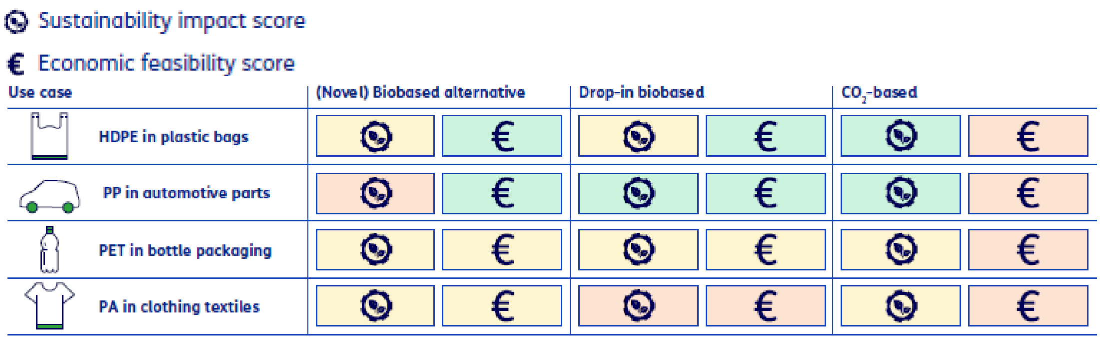

Figure B.8: Results comparison matrix (de Ruiter et al, 2025)

Appendix C
Import prices of fossil and renewable fuels

Year 2050	POLICY	FossFREE	FossFREE
€2023/GJ	Ref	Low import	High Import
Kerosine	29		
Olie	24		
Other oil products	29		
Naphtha	31		
HFO	29		
Aromatics	24		
LPG, benzine, diesel	24		
Natural gas	14		
Renewable kerosine	-	45	34
Renewable methanol	-	41	32
Renewable other products		60	34
Biomass, woody, domestic	7		
Biomass, woody, import, cheap	12		
Biomass, woody, import, expensive	16		
Biomass, UCO	21		

Energy & Materials Transition

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