TNO innovation for life

Breaking free from fossil dependence

How the Trilateral Chemical Region can deliver sustainable products



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How the Trilateral Chemical Region can deliver sustainable products

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Samenvatting

De Trilaterale Chemische Regio (Nederland, Vlaanderen, Noordrijn-Westfalen) is een belangrijk centrum voor de Europese chemische industrie. Dit werk stelt dat de Regio een levensvatbare en duurzame industriële toekomst kan veiligstellen door haar bestaande infrastructuur te benutten, de koolstof instroompunten te verschuiven van fossiele naar circulaire bronnen en levenscyclus gebaseerd productbeleid te hanteren. Dit versterkt de veerkracht tegen geopolitieke risico's, vermindert emissies over de volledige levenscyclus en behoudt de industriële ruggengraat waar Europa's strategische autonomie op steunt. Dit werk is parallel aan het 3CVaCS project uitgevoerd, en staat op zichzelf. TNO rapporteert hiermee direct aan het Nederlandse ministerie van Economische Zaken en Klimaat.

Het 3C VaCS project is een initiatief van de Trilaterale Chemische Regio (TCR) en wordt uitgevoerd in samenwerking met DECHEMA, VITO en TNO. Het project onderzoekt de uitdagingen voor het verdienvermogen van de chemische industrie in de regio, brengt huidige productiemiddelen in kaart en verkent strategische conversie routes voor niet-fossiele grondstoffen die overheden kunnen ondersteunen. Binnen de 3CVaCS samenwerking levert TNO een waardeketen en systeemperspectief, met bijzondere aandacht voor niet fossiele grondstoffen en circulaire koolstofgrondstoffen, en voor alternatieve chemische routes om olefinen en aromaten te produceren uit niet fossiele bronnen.

De chemische industrie in de Trilaterale Chemische Regio bevindt zich op het snijvlak van ingrijpende economische, ecologische en geopolitieke verschuivingen. Haar historische kracht is een sterk geïntegreerd industrieel ecosysteem: procesinstallaties in clusters, grensoverschrijdende ethyleen- en propeenpijpleidingen, gedeelde nutsvoorzieningen en productiemiddelen die grotendeels boekhoudkundig zijn afgeschreven, waardoor productie voor een belangrijk deel tegen marginale kosten plaatsvindt. Dit systeem maakte daarom decennialang betrouwbare en wereldwijd concurrerende productie mogelijk. Juist die onderlinge verwevenheid maakt het systeem echter ook kwetsbaar: wanneer kerninstallaties niet meer competitief worden door mondiale verschuivingen in grondstoffen of wanneer energieprijzen pieken, plant de schok zich voort door het hele cluster.

Tegelijkertijd verandert het kader rond de industrie ingrijpend. Decarbonisatiebeleid heeft CO_2-emissies van een voorheen niet-beprijsde externaliteit tot een essentiële kostenfactor gemaakt, terwijl energieprijzen, die ooit waren verankerd in goedkoop regionaal aardgas, nu een nieuwe mondiale realiteit weerspiegelen. De mondiale chemische markten verschuiven nog sneller: grootschalige capaciteitsuitbreidingen in China en goedkope grondstoffen in de Verenigde Staten en het Midden-Oosten verkleinen de prijsbepalende positie van de Trilaterale Chemische Regio en bemoeilijken herinvesteringsbeslissingen bij elk onderhoudsmoment van assets. Deze dynamiek vergroot het risico op weglek van industrie, waarbij productie migreert naar regio's met lagere grondstofprijzen en een gunstiger vestigingsklimaat. Deze verplaatsing van productie en het risico op koolstof-lekkage zijn rationele uitkomsten van een reguleringskader dat productie-emissies geïsoleerd adresseert in plaats van de duurzaamheid van het product zelf.

Ondanks deze uitdagingen heeft de regio een doorslaggevend voordeel: de route naar duurzame chemie vereist geen volledige herbouw van het systeem. Het grootste deel van de downstream-productie kan worden verduurzaamd via elektrificatie met hernieuwbare energie,

terwijl de upstream-opgave om fossiele koolstof te vervangen kan worden aangepakt via chemische routes gebaseerd op methanol, ethanol en paraffinen uit afval en biomassa. Deze drie ‘precursor intermediates’ vormen de belangrijkste schaalbare brug van het huidige fossiele grondstoffenplatform naar een duurzaam, op olefinen en aromaten gebaseerd systeem. Ze stellen de TCR in staat haar industriële weefsel te behouden, terwijl de koolstof die de toeleveringsketens binnenkomt wordt afgebogen van primaire fossiele bronnen. Wat nu nodig is, is dat het regelgevend kader naast het beprijzen van CO_2-emissies uit productie ook het belang van defossilisatie op productniveau erkent.

Een centraal inzicht dient zich aan: de duurzaamheid van chemische producten is primair een levenscyclusvraagstuk, niet louter een vraagstuk van productie. Voor koolstofgebaseerde materialen vinden de meeste CO_2-emissies vandaag plaats aan het einde van de levensduur, waar verbranding de moleculaire waarde definitief vernietigt. Regulering van productieprocessen, bijvoorbeeld via CO_2-beprijzing en energiemandaten, pakt deze structurele inefficiëntie niet aan. Duurzaamheidsnormen op productniveau kunnen de verantwoordelijkheid verschuiven richting het punt van consumptie, door te borgen dat materialen die op de markt worden gebracht geen fossiele koolstof bevatten, ongeacht waar ze zijn geproduceerd. Deze aanpak brengt beleid in lijn met de systeemlogica en neemt druk weg bij lokale producenten terwijl zij de concurrentie aangaan met andere producenten op wereldmarkten.

Afval, biomassa en hernieuwbare elektriciteit zijn echter niet zo overvloedig als fossiele hulpbronnen. België, Nederland en Duitsland, de landen waarin het de Trilaterale Chemische Regio zich bevindt, genereren circa 3 Mt C aan recyclebare koolstof uit plasticafval en 30–50 Mt C aan koolstof uit lignocellulose- biomassa. De chemische sector in deze landen produceert ongeveer 18 Mt C in producten. Dit betekent dat deze chemicaliën in principe met niet-fossiele lokale koolstof kunnen worden geproduceerd.

De mogelijkheden voor circulariteit van plastic zijn begrensd: plastic accumuleert in het gebruik en een groot deel van de regionale kunststoffen wordt als product geëxporteerd, waardoor volledige binnenlandse recyclestromen onmogelijk zijn zonder her-import van afval of pyrolyse-oliën. Louter mechanische recycling kan de kloof niet dichten door verontreiniging, polymeerafbraak en kwaliteitseisen; chemische recycling via vergassing en pyrolyse wordt essentieel om koolstof terug te winnen, maar heeft geen volledige koolstof efficiëntie.

Daarbij blijft het volume aan koolstof dat nodig is in alle producten inclusief brandstof (nu in de orde van 250 Mt C voor de drie landen) een veelvoud van dat in chemicaliën. Hoewel dit volume in brandstoffen door elektrificatie zal afnemen, blijft het zeer significant. Daarom zal er ook import nodig zijn van koolstofhoudende grondstoffen. De lokale koolstofbronnen worden daarom het beste zo strategisch en effectief mogelijk aan de belanghebbende sectoren toegewezen, daarbij rekening houdend met de mogelijkheid van import van precursors en beschikbaarheid van hernieuwbare energie voor verwerking.

Voor de industrie rust de transitie op drie randvoorwaarden: toegang tot betrouwbare, koolstofarme energie en grondstoffen; de mogelijkheid om winstgevend te opereren met duurdere, duurzame routes; en de aanwezigheid van duidelijke, verifieerbare productnormen die de markt in staat stellen ingesloten duurzaamheid te herkennen en te belonen, een vorm van waarde die in het product zelf onzichtbaar is maar essentieel om klimaatdoelen te halen.

Voor beleidsmakers is precisie de opgave: interventies moeten worden onderbouwd met heldere data over toeleveringsketens, grondstoffenbeschikbaarheid en technologische routes. Vandaag belemmeren datalacunes en gefragmenteerd zicht effectieve actie. Een geharmoniseerde gegevensbank die aanbodopties op product- en marktniveau in kaart brengt, stelt overheden in staat risico's te voorzien, scenario's te vergelijken en gerichte interventies te sturen.

Duurzaamheid en leveringszekerheid (beschikbaarheid) leveren duidelijke maatschappelijke waarde op, maar brengen aanzienlijke kosten mee voor producenten in de vroege schakels van de keten. Deze kosten moeten voorspelbaar en transparant worden doorberekend langs de waardeketen naar de eindmarkten. Omdat duurzaamheid fundamenteel is, moet zij niet worden behandeld als een producteigenschap maar als een productnorm. Naleving behoort daarom geen basis te zijn voor concurrentie; bij voorkeur definiëren deze normen het mondiale gelijke speelveld voor industriële productie. De industrie floreert bij heldere, verifieerbare en breed erkende normen.

Door deze waarde via standaarden te formaliseren, kunnen markten producten herkennen en belonen die echte voordelen op systeemniveau leveren. Dit creëert transparantie voor regelgevers, consumenten en de industrie, en biedt een geloofwaardige basis voor het opschalen van circulaire en bio-gebaseerde productie van chemicaliën en brandstoffen.

Deze analyse beargumenteert dat de transitie geen ontmanteling van het bestaande systeem vergt, maar een gerichte heroriëntatie en erkenning van de waarde die de transformatie oplevert. Door de geïntegreerde industriële structuur te behouden, de koolstofinstroom systematisch te verschuiven van fossiele naar circulaire en hernieuwbare bronnen, en beleid te baseren op levenscyclus-gebaseerde productprestaties, kan de Trilaterale Chemische Regio concurrerend én relevant blijven in een veranderend mondiaal landschap.

Dit vereist consistentie tussen industriestrategie en reguleringsontwerp: het belonen van duurzaamheid op productniveau, het mogelijk maken van toegang tot niet-fossiele koolstof en het borgen van de randvoorwaarden voor aanhoudende investeringen. Als dit wordt gerealiseerd, vermindert dit pad niet alleen het risico op industriële neergang, maar verankert het ook een veerkrachtig en toekomstbestendig systeem voor chemische productie in Europa.

Summary

The Trilateral Chemical Region (the Netherlands, Flanders, North Rhine–Westphalia) is a key hub for the European chemical industry. This work argues that the Region can secure a viable and sustainable industrial future by leveraging its existing infrastructure, shifting carbon feedstock inputs from fossil to circular sources, and adopting life cycle based product policies. This enhances resilience to geopolitical risks, reduces emissions across the full life cycle, and preserves the industrial backbone on which Europe's strategic autonomy depends. This work was carried out in parallel with the 3CVaCS project, and stands independently. TNO hereby reports directly to the Dutch Ministry of Economic affairs and Climate.

The 3C VaCS project is an initiative of the Trilateral Chemical Region (TCR) and is being carried out in collaboration with DECHEMA, VITO and TNO. The project examines the challenges to the earning capacity of the region's chemical industry, maps current production assets and explores strategic conversion routes for non fossil feedstocks that governments can support. Within the 3CVaCS collaboration, TNO provides a value chain and systems perspective, with particular attention to non fossil feedstocks and circular carbon resources, as well as alternative chemical pathways to produce olefins and aromatics from non fossil sources.

The chemical industry in the Trilateral Chemical Region is at the intersection of profound economic, ecological and geopolitical shifts. Its historical strength lies in a highly integrated industrial ecosystem: process installations in clusters, cross-border ethylene and propylene pipelines, shared utilities and production assets that have largely been amortized, allowing a significant share of production to take place at marginal cost. For decades, this system therefore enabled reliable and globally competitive production. Yet it is precisely this interconnectedness that also makes the system vulnerable: when core installations become uncompetitive due to global shifts in feedstocks or when energy prices spike, the shock propagates throughout the entire cluster.

At the same time, the framework surrounding the industry is undergoing profound change. Decarbonization policy has transformed CO_2 emissions from a previously unpriced externality into a key cost factor, while energy prices, once anchored in inexpensive regional natural gas, now reflect a new global reality. Global chemical markets are shifting even faster: large-scale capacity expansions in China and low-cost feedstocks in the United States and the Middle East are eroding the price-setting position of the Trilateral Chemical Region and complicating reinvestment decisions at every maintenance cycle of assets. This dynamic increases the risk of industrial relocation, with production migrating to regions with lower feedstock prices and a more favorable business environment. Such relocation of production and the associated risk of carbon leakage are rational outcomes of a regulatory framework that addresses production-phase emissions in isolation, rather than the sustainability of the product itself.

Despite these challenges, the region has a decisive advantage: the pathway to sustainable chemistry does not require a complete rebuilding of the system. Most downstream production can be made sustainable through electrification using renewable energy, while the upstream challenge of replacing fossil carbon can be addressed through chemical pathways based on methanol, ethanol and paraffins derived from waste and

biomass. These three ‘precursor intermediates’ form the most important scalable bridge from the current fossil feedstock platform to a sustainable system based on olefins and aromatics. They enable the TCR to preserve its industrial fabric while diverting the carbon entering supply chains away from primary fossil sources. What is now needed is for the regulatory framework, in addition to pricing production-phase CO_2 emissions, to recognize the importance of product-level defossilization.

A central insight emerges: the sustainability of chemical products is primarily a life-cycle issue, not merely a production issue. For carbon-based materials, most CO_2 emissions today occur at the end of life, where incineration destroys the molecular value permanently. Regulation of production processes, for example through CO_2 pricing and energy mandates, does not address this structural inefficiency. Product-level sustainability standards can shift responsibility towards the point of consumption by ensuring that materials placed on the market contain no fossil carbon, regardless of where they were produced. This approach aligns policy with system logic and eases pressure on local producers as they compete with other manufacturers in global markets.

Waste, biomass and renewable electricity, however, are not as abundant as fossil resources. Belgium, the Netherlands and Germany, the countries in which the Trilateral Chemical Region is located, generate roughly 3 Mt C of recyclable carbon from plastic waste and 30–50 Mt C of carbon from lignocellulosic biomass. The chemical sector in these countries produces approximately 18 Mt C in products. This means that these chemicals could in principle be produced using non-fossil local carbon.

The possibilities for plastics circularity are limited: plastics accumulate in use, and a large share of produced plastics leave the region as products, making full domestic recycling streams impossible without re-importing waste or pyrolysis oils. Mechanical recycling alone cannot close the gap due to contamination, polymer degradation and quality requirements; chemical recycling via gasification and pyrolysis is essential to recover carbon, but does not achieve full carbon efficiency.

Moreover, the total volume of carbon needed in all products including fuels (currently on the order of 250 Mt C for the three countries) is many times larger than that used in chemicals. Although this fuel-related volume will decline with electrification, it will remain very significant. Imports of carbon-containing feedstocks will therefore also be necessary. Local carbon sources are thus best allocated to sectors as strategically and effectively as possible, taking into account the possibility of imports and the availability of renewable energy for processing.

For industry, the transition rests on three preconditions: access to reliable, low-carbon energy and feedstocks; the ability to operate profitably with more expensive, sustainable pathways; and the presence of clear, verifiable product standards that allow the market to recognize and reward embedded sustainability: a form of value that is invisible in the product itself but essential for achieving climate goals.

For policymakers, precision is the task: interventions must be supported by clear data on supply chains, feedstock availability and technological pathways. Today, data gaps and fragmented visibility hinder effective action. A harmonized database that maps supply options at the product and market level enables governments to anticipate risks, compare scenarios and steer targeted interventions.

Sustainability and security of supply (availability) deliver clear societal value, but they impose significant costs on producers in the early stages of the value chain. These costs must be passed on in a predictable and transparent manner along the value chain towards end markets. Because sustainability is fundamental, it should not be treated as a product feature but as a product standard. Compliance should therefore not be a basis for competition; ideally, such standards define the global level playing field for industrial production. Industry thrives on clear, verifiable and widely recognized standards.

By formalizing this value through standards, markets can recognize and reward products that carry real system-level benefits, creating transparency for regulators, consumers, and industry alike, and providing a credible foundation for the scaling of circular and bio-based chemical and fuel production.

This analysis argues that the transition does not require dismantling the existing system, but rather a targeted reorientation and recognition of the value generated by the transformation. By preserving the integrated industrial structure, systematically shifting carbon inflows from fossil to circular and renewable sources, and grounding policy in life-cycle-based product performance, the Trilateral Chemical Region can remain both competitive and relevant in a changing global landscape.

This requires consistency between industrial strategy and regulatory design: rewarding sustainability at the product level, enabling access to non-fossil carbon, and safeguarding the conditions for sustained investment. If achieved, this pathway not only reduces the risk of industrial decline but also anchors a resilient and future-proof system for chemical production in Europe.

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Glossary

Asset	The resource- and capability-oriented part of a value chain, owned and controlled by a business, that provides the physical, technical, or natural basis for production and value creation.
Basic chemicals	High-volume chemicals with low molecular complexity that serve as primary building blocks for the chemical industry. In this work specifically: the olefins (ethylene, propylene, butene, butadiene) and aromatics (benzene, toluene, xylene). These are also referred to as High Value Chemicals (HVC).
Bio-based	A material or product that is wholly or partly derived from biomass, meaning biodegradable fractions of products, waste and residues from biological origin (excluding fossil carbon).
Bio-derived	A material or product produced from bio-based feedstock fraction through chemical, biochemical, or thermochemical modification processes.
Business	The product- and market-oriented part of a value chain, owned and governed by a corporate entity, responsible for customer value creation and accountable to shareholders for financial performance.
Chemical products	Substances, mixtures, or formulations manufactured by the chemical industry and placed on the market for industrial, professional, or consumer use.
Circular carbon	Carbon-based materials recovered from products that have lost their consumer value and are reintroduced into the economy as secondary resources.
Complex feedstock	Feedstocks consisting of heterogeneous mixtures with variable composition, requiring pre-treatment, separation, or upgrading before chemical use. In this work, specifically, waste and biomass.
Compounds	A chemical substance composed of two or more elements chemically bonded or mixed in fixed proportions.
Functional chemicals	Chemicals designed to provide a specific technical or performance function in a product or process.
Intermediates	Substances that are manufactured for and consumed in chemical processing to produce other substances. In this work specifically those derived from basic chemicals: ethylene oxide, propylene oxide.
Paraffins	Mixed hydrocarbons, with the general form C_nH_{2n+2}, consisting essentially of carbon backbones in linear or branched form. For the purpose of this work, the denomination spans a wider range e.g. pyrolysis oils, HEFA, HVO, FTL, in untreated or upgraded state depending on industry standards.
Platform chemicals	Platform chemicals are versatile chemical substances that can be converted into a wide range of downstream chemicals, materials, or products, thereby serving as strategic nodes in chemical value networks.

Precursor	A chemical precursor is a substance that comes before another chemical in a reaction pathway. It's the starting material (or one of them) that gets transformed into a target compound through chemical reactions.
Renewable carbon	Carbon embodied in biomass or in materials derived from biomass that is replenished through biological growth cycles.
Supply chain	The network of organizations and flows that deliver a product from raw materials to the customer.
Synthetic chemistry	The creation of complex carbon molecules from simple feedstocks like syngas, enabling the reuse of carbon from renewable or recovered sources.
Value chain	The sequence of activities that creates and captures value for customers and business profitability.

1 Introduction to the project

1.1 The Trilateral Chemical Region

The Trilateral Chemical Region forms the heart of North Western Europe's key industrial cluster in the Antwerp Rotterdam Rhine Ruhr Area – the ARRRA cluster. The Trilateral Chemical Region consists of North Rhine-Westphalia, the Netherlands and Flanders, which agreed on a joint vision on the future development of their flagship chemical industry[1].

In a rapidly changing, globally competitive environment, the trilateral chemical industry faces fundamental economic, environmental and technological challenges. To prepare for the future, capture the benefits of a growing chemical industry and remove existing bottlenecks for this development, an important strategic process was launched in 2017.

1.2 Motivation for the 3C-VaCS study

The chemical industry in the Trilateral Chemical Region is undergoing a profound restructuring driven by decarbonization imperatives, changing energy and feedstock economics, and increasing regulatory pressure. Traditional fossil-based value chains are becoming less competitive, while new low-carbon pathways based on alternative feedstocks, electrification, and circularity are emerging. This transition is occurring unevenly across technologies, sites, and value chains, creating uncertainty about future investment priorities, infrastructure needs, and regional competitiveness.

The ambition shared by society and industry alike is to create a future that is simultaneously sustainable, competitive, and resilient. From an environmental perspective, sustainability primarily concerns meeting climate-related goals, which can be achieved by replacing fossil-based resources with renewable energy, recovered materials, and biomass, while also minimizing emissions and resource depletion across the value chain.

Resilience refers to the capacity to remain a relevant and autonomous actor in a complex geopolitical landscape, by maintaining strategic options, securing access to critical resources, and retaining the ability to adapt and trade essential elements under changing conditions.

Competitiveness emphasizes the economic dimension, focusing on creating and capturing value in ways that generate robust business profits, ensure long-term growth, and maintain market relevance in a rapidly evolving global economy. Together, these three dimensions form a guiding framework for aligning industrial strategy with societal expectations, environmental limits, and economic imperatives.

A value chain study is therefore essential to understand how upstream feedstock choices, intermediate chemical precursors, and downstream product markets interact under these changing conditions, and to identify robust transition pathways that could preserve industrial activity in the region while aligning with climate and sustainability objectives.

[1] https://www.trilateral-chemical-region.eu/

1.3 The project stakeholders and partners

The governments of the Netherlands, Flanders, and North Rhine–Westphalia act as the primary stakeholders and sponsors of this project, reflecting the strategic importance of the chemical industry for the Trilateral Chemical Region. Supported by the respective national industry associations (VNCI, ESSENSCIA, and VCI-NRW), the public partners seek to develop a shared, evidence-based understanding of the current state of chemical production in the region, as well as the options and trade-offs for its future development under changing economic, regulatory, and sustainability conditions. Their central interest lies in identifying transition pathways that safeguard industrial competitiveness, employment, and strategic autonomy while aligning with climate and circularity objectives.

The research institutes contribute complementary technical and system-level expertise to the project. In this project the centre of DECHEMA expertise pertains to the current production infrastructure, the VITO expertise to modelling of industry & infrastructure and policy, and the TNO expertise to resources and conversion processes. Together, they bring in-depth knowledge of chemical production processes, the organization and interdependencies of industrial supply chains, and the availability of resources and technologies relevant to the sector's transition. Their role is to translate this technical understanding into coherent value-chain analyses, assessing feasible pathways, infrastructure implications, and innovation needs that can inform both policy decisions and industrial strategy across the region.

DECHEMA and VITO have presented their findings together in a joint report, while TNO has published its results in this stand-alone report.

1.4 The TNO share and research question

The main objective of TNO's contribution to the 3C-VaCS project is to **identify how non-fossil feedstocks and conversion pathways can enable supply chains for the production of sustainable consumer products in the Trilateral Chemical Region**, while making those supply chains more resilient against geopolitical tensions, and building on the existing production infrastructure of the chemical sector.

To achieve this objective, we need to clarify the essence of the chemical conversion pathways that underpin the industry today. We aim to analyse how the supply of chemicals in the TCR is foreseen through production and imports, and how demand is generated from exports and conversion in the TCR. We aim to identify non-fossil pathways to produce the same chemicals and indicate how they intersect with the current supply chains.

Hence, our main research question is:

> **How can chemical conversion pathways in the Trilateral Chemical Region be reconfigured to enable resilient, non-fossil supply chains for sustainable consumer products, while building on existing chemical production infrastructure and reducing exposure to geopolitical risks?**

To answer this question, TNO's work covers:

(1) The analysis of conversion pathways to chemicals that start from non-fossil feedstocks: waste and biomass
(2) The study of public data on installed production capacities and realised production, import and export of key feedstocks and chemicals in the trilateral chemical region

1.4.1 Chemical product scope

Especially the chemicals that are highly energy-intensive to produce can create significant competitiveness challenges for the industrial operations that manufacture them. The energy intensity arises primarily from the ‘activation’ of chemically inert molecules, transforming them into small but reactive ‘basic chemicals’. These basic chemicals then undergo a thermo-catalytic cascade of chemical reactions that ultimately yield the target products. Among the most critical activation steps are the conversion of nitrogen (N_2) into ammonia (NH_3), chloride ions (Cl^-) into elemental chlorine (Cl_2), and carbon-based feedstocks into key building blocks such as olefins and aromatics. These activations represent the chemical and energetic bottlenecks of industrial production, often defining both the cost and environmental footprint of the resulting products.

The production of chlorine (Cl_2) from chloride (Cl^-) is fundamentally an electrochemical process, meaning that the carbon footprint of chlorine is almost entirely determined by the CO_2 intensity of the electricity used. As power systems continue to decarbonize and the share of renewable electricity grows, the carbon intensity of chlorine production is expected to decline correspondingly, making it a highly electrifiable and potentially low-carbon chemical.

Ammonia production, by contrast, is more complex. Converting nitrogen (N_2) into ammonia (NH_3) requires hydrogen, which today is predominantly derived from natural gas through steam methane reforming - a process with significant CO_2 emissions. However, the electrochemical (or “green”) production of hydrogen through water electrolysis has reached a level of technological maturity that enables it to increasingly serve as a low-carbon alternative, but economically it is not attractive. The direct electrochemical nitrogen reduction to ammonia is actively researched, but not yet industrially mature[2]. Like chlorine, the CO_2 footprint of electrochemical hydrogen - and consequently of ammonia production will directly reflect the carbon intensity of the electricity used. This highlights the central role of renewable electricity not only in decarbonizing heat and power but also in enabling low-carbon industrial chemistry.

The production of activated carbon compounds, such as olefins and aromatics, remains, however, far more challenging. Conventional steam crackers, which transform hydrocarbon feedstocks into these high-value products, operate at high temperatures generated by the direct combustion of fossil fuels. While several innovative pathways are under development, including electrically heated crackers, mechanical generation of high temperatures, and electrochemical reduction of hydrocarbons, these approaches are not yet commercially scalable. For the purposes of near- to medium-term materials transition strategies, large-scale electrification of decarbonization of carbon activation processes must therefore be considered technologically out of reach.

This distinction underscores critical asymmetries in techno-economic maturity of electrifying the production of these chemicals: while for chlorine production, electrolysis is the techno-economical industry standard[3], electrochemical hydrogen production is technically mature but not yet an industry standard for economic reasons. Hence, although nitrogen activation with hydrogen is the industry standard, using electrochemical ‘green’ hydrogen for now remains economically challenging. Alternative technologies for carbon activation are not yet mature

[2] Muhammad Yasir, Zhiliang Zhao, Min Zeng, Sangaraju Shanmugam, Xinyi Zhang, Recent progress and prospects in electroreduction of nitrogen to ammonia in non-aqueous electrolytes, Current Opinion in Electrochemistry, Volume 45, 2024,101487, ISSN 2451-9103, https://doi.org/10.1016/j.coelec.2024.101487.

[3] https://en.wikipedia.org/wiki/Chloralkali_process

enough for industry-wide deployment and, for now remains the domain of research, industrial development and life cycle analysis[4].

Unlike N_2 and Cl_2, carbon-based products carry inherent climate risk. When eventually oxidized or degraded, they form CO_2 or methane, both potent and persistent greenhouse gases. The impact mainly follows from the sheer scale of carbon embedded in these products across global production volumes.

While natural processes such as photosynthesis and carbonate formation can re-assimilate some of this carbon, the effect is overwhelmingly outweighed by the continuous output of fossil-derived carbon through fuels combustion and chemicals incineration. Consequently, a central goal of the materials transition is to replace fossil carbon with alternative sources - primarily recycled carbon from waste streams and biomass-derived carbon. By shifting the feedstock basis of industrial chemistry away from fossil inputs, the transition addresses both climate impact and resource availability, creating pathways for a more circular, low-carbon and resilient chemical industry.

While feedstocks for nitrogen- and chlorine-based chemicals are locally abundant and they can follow low-carbon trajectories through electrification and green hydrogen, the greatest challenge and opportunity lie in the carbon-intensive building blocks, where local feedstocks and innovative processing strategies can decouple industrial growth from fossil carbon and support a resilient, locally anchored chemical industry.

Accordingly, the materials and process scope of this work is focused on:

> **The conversion of complex carbon-based waste and biomass into high-value, carbon-based chemicals through the olefins and aromatics platform.**

Intentionally kept out of scope are oxygenates and other bio-derived chemicals, processing though mechanical recycling, and the recovery of polymers or monomers. From a systems perspective, these pathways should generally be preferred whenever their resulting products can meet the required functional demand, as they typically deliver higher carbon efficiency and lower energy requirements. This work instead focuses on the challenge of producing sustainable products via the olefins and aromatics pathways of the conventional large-scale chemical industry, where existing assets, scale, and market structures dominate and where decarbonisation poses fundamentally different system, energy, and investment challenges.

1.4.2 Technology scope

This report deliberately avoids to evaluate or discuss technologies, even though the Appendices D and E do reflect the capabilities of solutions that enable new pathways.

These solutions generally exhibit a high level of technical maturity: the core technologies face no remaining fundamental bottlenecks that would prevent them from passing a technical due-diligence assessment. The remaining learning curve lies primarily in integrating these solutions effectively into real supply chains through robust standardization, harmonized specifications, and reliable long-term offtake agreements. In practice, the challenge is no

[4] Oleksii Mynko, Mike Bonheure, Ismaël Amghizar, David J. Brown, Lin Chen, Guy B. Marin, Rodrigo Freitas de Alvarenga, Didem Civancik Uslu, Jo Dewulf, Kevin M. Van Geem, Electrification of steam cracking as a pathway to reduce the impact of the petrochemical industry on climate change, Journal of Cleaner Production, Volume 427, 2023, 139208, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2023.139208.

longer whether the technologies work, but how to scale them consistently, predictably, and in alignment with market and infrastructure realities.

1.5 Outline of this report

Chapter 2 (Background to the transformation of the chemical industry) provides several perspectives that we believe are relevant to understand the current situation of the chemicals industry and what may shape its recovery.

- How multiple transitions deteriorate the profitability of the chemical industry in the Trilateral Chemicals Region.
- The pivotal role of syngas chemistry in producing non-fossil fuels and chemicals.
- Why the olefins and aromatics platform may be most likely to deliver the bulk of sustainable industrial chemicals.
- Why the production of some industrial chemicals is co-located, and others can be produced in a distributed network.

Chapter 3 (Results of the TNO deep-dives in 3C-VaCS) presents publicly available data on current chemical industry supply chains, as well as on the supply chains for waste- and biomass-based pathways.

- Presentation and discussion of public data about products and feedstock of the Trilateral Chemical Region chemical industry.
- Analysis of pathways for producing olefins and aromatics from waste and biomass.
- Analysis of the availability of waste and biomass in the Trilateral Chemical Region.

Chapter 4 (Discussion and conclusions) concludes that methanol, ethanol and paraffins are key commodities for both sustainable fuels and chemicals that can be produced locally and traded globally.

- Sustainable consumer products are the ultimate goal, not the reduction of CO_2 emissions from production.
- Non-fossil carbon is to displace fossil carbon for chemicals and for fuels.
- The existing infrastructure is a strategic asset for industry as well as for society.
- Industry needs to be reconfigured based on product standards.
- Industry and its products define our advanced society, and therefore, its disappearance is a geopolitical risk.

Chapter 5 (Recommendations)

- A business-oriented framework can leverage the industry’s nature to compete and excel.
- Effective framework interventions require structured public information.

2 Background to the transformation of the chemical industry

The Trilateral Chemical Region faces mounting structural pressures that erode competitiveness: carbon pricing makes CO_2 emission a constrained resource, energy costs are normalizing upwards as the system transitions, ethylene production from natural gas liquids has scaled and geopolitical fragmentation is reshaping global value chains. Together, these and other forces raise production costs and intensify global exposure of the European chemical industry.

The ambition of reducing the CO_2 footprint of chemicals requires a serious shift from fossil inputs to renewable electricity, circular carbon from waste and sustainably sourced biomass. The production of the desired functional products will always require carbon based chemicals. To unlock these resources it is unavoidable that syngas chemistry plays a bigger role and in particular the olefins-and-aromatics platform will remain central to producing sustainable materials at scale. Yet waste and biomass are limited resources, and their availability will increasingly set feedstock prices.

Industrial geography adds further complexity. The TCR's current structure emerges from the physics and boundary conditions of molecule transport: co-location-forced toxics, regionally transportable intermediates, and system feedstock pipelines of high-value chemicals form a tightly integrated corridor. While highly efficient, this system is path-dependent and vulnerable to anchor-asset loss. In the globally tradable chemicals market, even modest structural disadvantages can shift industry's reinvestment decisions, making coordinated transition strategies essential for the Trilateral Chemical Region.

2.1 Multiple transitions deteriorate profitability of industry operations in the TCR

Structural forces are reshaping the space for chemical industry operations in the Trilateral Chemical Region:

- Carbon pricing and sustainable energy mandates for industrial production
- Normalization of energy prices and increasing energy-system costs
- The production boom of Natural Gas Liquids and new Crude-Oil-To-Chemicals complexes
- Strategic fragmentation of global supply chains driven by geopolitical actors.

2.1.1 Carbon pricing and sustainable energy mandates

Society has recognized climate change as a defining challenge, making the reduction of CO_2 emissions a top priority for policymakers. While the energy transition focuses on lowering emissions from final energy use, the materials transition targets the life-cycle CO_2 emissions associated with the synthetic chemical products that underpin and enrich modern life.

While much of the final energy demand for heat and power can be met through electrification, carbon-based products will require careful carbon management throughout their life cycle. Apart from demand-side behavioural changes, such as shifts in consumption patterns to satisfy demand, the main carbon management levers that contribute to climate goals are storing CO_2 and reducing fossil feedstock inputs by keeping synthetic carbon in a loop and using bio-based feedstock to make up for the loop's carbon-inefficiencies.

Governments are deploying an increasingly broad set of policy instruments to address global warming, with sector-specific regulations that all ultimately aim to reduce CO_2 emissions. In the industrial sector, and particularly in energy- and materials-intensive industries, the main regulatory levers are: requirements for improved energy efficiency, mandates or incentives to use renewable electricity (either directly or indirectly via green hydrogen), and the monitoring, registration, and pricing of greenhouse-gas emissions through mechanisms such as emissions trading schemes or carbon taxes.

Over recent decades, materials science and engineering have enabled major progress in clean energy. Renewable power has seen remarkable success: solar costs have plummeted, storage technologies have rapidly improved, and wind turbines have matured into a large-scale, reliable power source. Carbon capture and storage has also advanced from concept to pilot projects, demonstrating technical feasibility across sectors.

Yet despite the advances of energy and CCS, the adoption by the chemical industry of circular carbon processing has proven far from straightforward. The transition to more sustainable production routes almost invariably requires substantial upfront capital investments, often combined with higher operating complexity or increased energy input. These investments must ultimately be recovered through the economics of the business. In a 'natural' or unconstrained market setting, this recovery typically occurs either through lower production costs via efficiency gains, cheaper inputs or through higher product prices that reflect added value of new functionality.

The limited pace of investment in low-carbon chemical production, therefore, points to a structural mismatch between technological performance and economic viability. In many cases, sustainable production routes do not yet offer sufficiently lower costs to justify investment on their own merits. At the same time, chemical products are largely traded in highly competitive, global commodity markets, which severely restrict the ability of sustainable producers to pass additional costs on to customers. As a result, those first movers risk losing competitiveness without a clear mechanism for cost recovery.

Carbon pricing and mandates for clean energy inputs imposed by governments further accentuate this tension. While these instruments are essential to internalize environmental externalities, they directly increase operating costs for incumbent production assets. Unless accompanied by credible pathways for value recovery through protected markets, demand-side pull, border adjustment mechanisms, or long-term policy certainty, such measures tend to compress operating margins rather than unlock large-scale investment. The consequence is a growing gap between regulatory ambition, technological potential, and the investment logic that governs the reality of industrial decision-making.

2.1.2 Normalization of energy prices and increasing energy-system costs

The long-standing availability of abundant and relatively low-cost natural gas in the Trilateral Chemical Region has come to an end. The closure of the Groningen gas field has removed a cornerstone of domestic supply, while geopolitical developments have made the import of Russian pipeline gas politically and strategically undesirable for Europe. As a consequence, natural gas can no longer be assumed to provide a stable, low-cost backbone for energy-intensive industries, fundamentally altering the cost structure, investment assumptions, and risk profile of chemical production in the region.

In parallel, the energy system must undergo a profound transformation to accommodate high shares of renewable electricity and to enable new energy carriers and carbon management solutions. This requires large-scale investments in electricity grid reinforcement, hydrogen production and transport infrastructure, and CO_2 transport and storage. These developments represent systemic shifts rather than incremental adjustments and will directly influence the location, design, and operation of chemical plants, as well as the degree to which industrial sites can be integrated into regional and European energy and carbon networks.

As a result, industrial operations in Europe, and in the Trilateral Chemical Region in particular, are increasingly exposed to global energy prices and to the costs of system transformation. This upward pressure on production costs challenges the international competitiveness of the regional chemical industry and increases uncertainty around future investments, reinforcing the need for coordinated, value-chain-oriented transition strategies.

2.1.3 The production boom of Natural Gas Liquids and new Crude-Oil-To-Chemicals complexes

U.S. natural gas liquids (NGLs), containing large amounts of ethane, have surged on the back of the shale gas expansion, with U.S. ethane production averaging a record ~2.8 mb/d in 2024 and exports at record highs; this expanding, low-cost ethane stream feeds a large fleet of U.S. ethane crackers and growing export capacity [5]. The U.S. now exports not only ethane, but also shown in **Figure 2.1** the produced ethylene and ethylene derivatives.

The ethane crackers produce predominantly ethylene, which is different from the olefins mix produced by naphtha crackers that produce also propylene, butadienes and aromatics. The introduction of ethane based ethylene this also affects the price setting of the other olefins, as relatively their supply decreases.

[5] U.S. Energy Information Administration (EIA), U.S. ethane production, consumption, and exports set new records in 2024, Today in Energy, March 20, 2025. https://www.eia.gov/todayinenergy/detail.php?id=64785

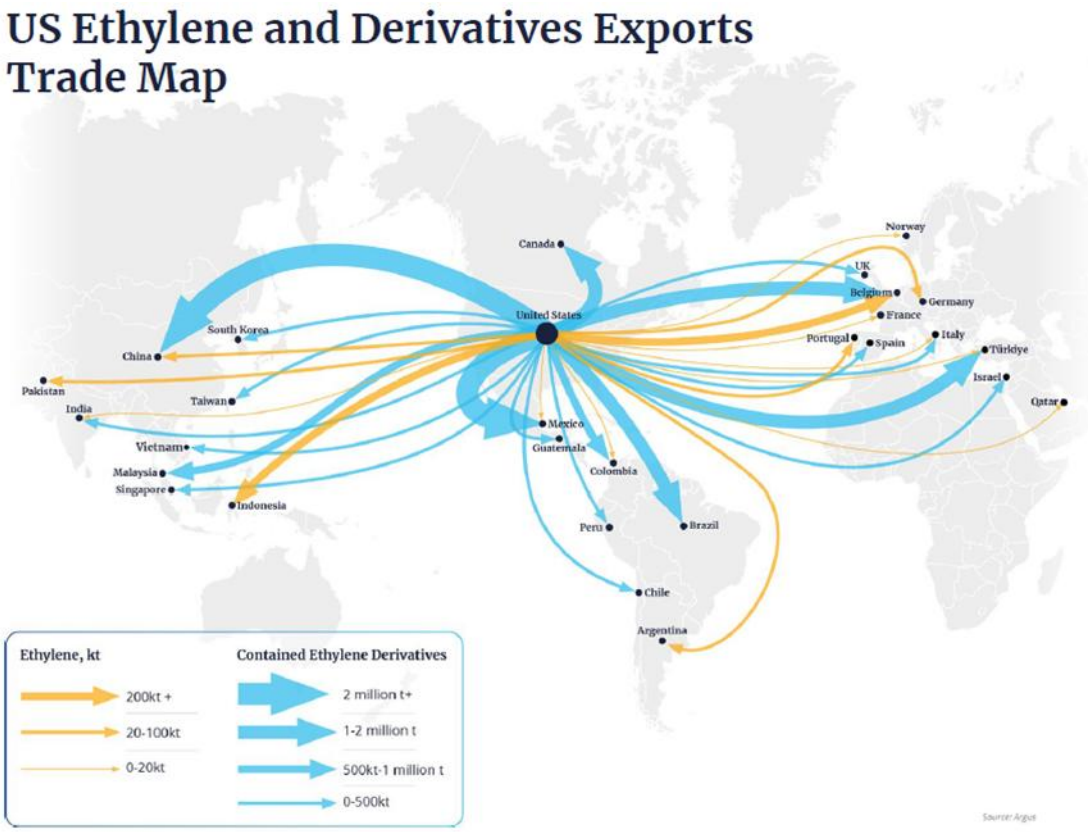


Figure 2.1: US ethylene and ethylene derivatives exports trade map, Argus, March 2026. (For reference: the production of ethylene by the countries of the Trilateral Chemical Region in 2019 was around 10 million tonnes).

In parallel, Middle Eastern supply is scaling: Qatar's multi-phase North Field expansion targets 142 mtpa of LNG by 2030 and will yield substantial co-products, including ethane, LPG and condensate, bolstering regional ethane availability for petrochemicals.

Together, these advantaged NGL streams give U.S. and Middle East ethylene producers a structural cost edge over Europe's largely naphtha-based crackers, with analyses showing gas-based (ethane) steam cracking as the lowest-cost route and widening ethane - naphtha differentials in recent years, eroding the competitiveness of olefins production in the Netherlands, Germany and Flanders [6], traditionally based on steam cracking naphtha.

New-build crude-oil-to-chemicals (COTC) complexes especially in China are configured to convert 40% or more of crude directly into chemicals, far above the 15 to 20% typical of conventional refinery-to-naphtha routes [7]. China's Zhejiang Petrochemical (ZPC) Zhoushan megacomplex exemplifies the model, pairing very large refining with aromatics and olefins capacity (~11.8 Mt/y aromatics and ~4.2 Mt/y olefins), which improves unit costs via scale and deep integration. This COTC build-out is intensifying global overcapacity and pressuring high-cost, naphtha-based olefins and aromatics producers in Northwest Europe including the

[6] Boston Consulting Group (BCG), Opportunities in Global Ethylene Economics, White Paper, May 2023. https://media-publications.bcg.com/opportunities-in-global-ethylene-economics.pdf

[7] Alexander H. Tullo, "China's aromatics building boom rattles the petrochemical industry," Chemical & Engineering News, Mar. 12, 2024 https://cen.acs.org/business/petrochemicals/China-aromatics-building-boom-rattles-the-petrochemical-industry/102/i8

Trilateral Chemical Region, where operating rates and therefore margin have already been under strain, accelerating rationalisation [8].

2.1.4 Strategic fragmentation of global supply chains driven by geopolitical actors

Strategic fragmentation refers to the deliberate reshaping of global value chains by governments and geopolitical actors to reduce dependencies on perceived strategic rivals.

We must recognize that the production of advanced chemical products is no longer the exclusive domain of the geopolitical West. Two major forces are driving this shift. First, the commoditization of basic chemical technologies and plant designs has lowered barriers to entry: any actor with sufficient capital and market access can now replicate or license industrial processes that were once the preserve of Western incumbents [9,10]. Second, global businesses are pursuing shareholder value by strategically locating production where resources, costs, and regulatory conditions are most favourable. This has led to the rapid expansion of chemical manufacturing in Asia-Pacific, particularly in China and ASEAN countries, which now capture increasing shares of both basic and higher-value chemical production [11,12].

The consequences of this global reallocation extend beyond mere production metrics. Regions that lose industrial presence may experience strategic disadvantages, as the presence of chemical industry contributes not only to infrastructure and economic output, but also to social cohesion, innovation ecosystems, technical expertise, and a strong position in global supply chains [13,9]. Evidence of this dynamic is visible in Europe, where rising energy costs, regulatory pressures, and global competition have led to investment slowdowns, plant closures, and growing dependency on imports for critical chemical products[13,11].

Figure 2.2 illustrates this clearly: virtually all net new ethylene capacity, the foundational building block of the petrochemical value chain, is being added outside Europe. Recent investment waves in China, the US Gulf Coast, and the Middle East dwarf European additions. The combined scale of these projects exceeds not only incremental European capacity, but in many cases rivals or surpasses the entire installed ethylene base of the Trilateral Chemical Region.

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8 ICIS feature, “Cracker closures: facing the inevitable,” 2024. https://www.icis.com/explore/resources/cracker-closures-europe/

9 https://en.wikipedia.org/wiki/Global_Value_Chains_and_Development

10 https://www.chemengconsulting.com/blog/2025/02/20/asia-pacific-chemical-market-leadership-analysis/1044/

11 https://www.mckinsey.com/industries/chemicals/our-insights/chemicals-and-capital-markets-regional-differentiation

12 Muhammad Mohiuddin, Mohammad Nurul Huda Mazumder, Elie Chrysostome, Zhan Su, Relocating high-tech industries to emerging markets: case of pharmaceutical industry outsourcing to India, Transnational Corporations Review, Volume 9, Issue 3, 2017, Pages 201-217, ISSN 1925-2099, https://doi.org/10.1080/19186444.2017.1370808.

13 https://www.ft.com/content/6d7dee96-4d6f-431c-a229-b78f9298f1ef

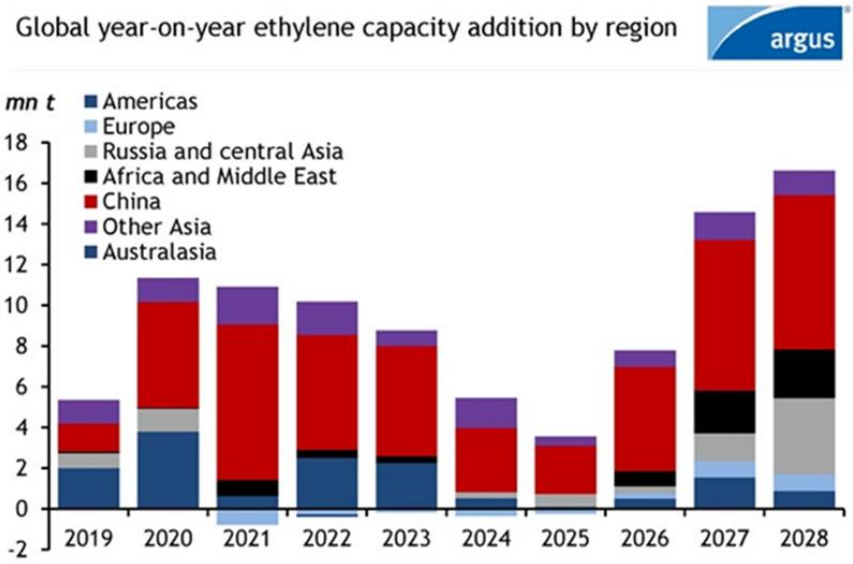


Figure 2.2: Ethylene production capacity additions by region (source: Argus)

The implication is straightforward yet profound. Even if regional demand for chemical products remains stable or grows moderately, the projected global overcapacity is likely to outnumber current TCR ethylene capacity several times over. When a region's local assets become a marginal fraction of global supply, price-setting power shifts decisively to the low-cost regions. For Europe, and the TCR in particular, this increases competitive pressure on existing assets, erodes contribution margins, and heightens the risk that structurally disadvantaged crackers lose their place in global cost curves. With such capacity additions, while assets in Europe are struggling and even closing, it seems plausible that these are also driven by strategic investments beyond a free-market rationale.

In such a market, the TCR's role can no longer be taken for granted. Without strategic positioning in sustainable production pathways, and without leveraging its unique cluster synergies, the region risks being structurally displaced by new capacity built closer to both advantaged feedstocks and growing demand centres.

The European share of the global chemicals market is indeed declining, as illustrated in **Figure 2.3** by the steadily falling orange line. This relative decline, however, must be understood in the context of absolute performance: EU27 chemical sales have continued to grow over the long term, shown by the rising blue bars. Europe is not shrinking, rather it is being outgrown. The centre of gravity of chemical production and demand has shifted toward regions experiencing rapid industrialisation, urbanisation, and population growth, particularly in Asia and the Middle East. Part of this growth is also captured by global corporate businesses (BASF, Shell) that have their industrial roots in Europe.

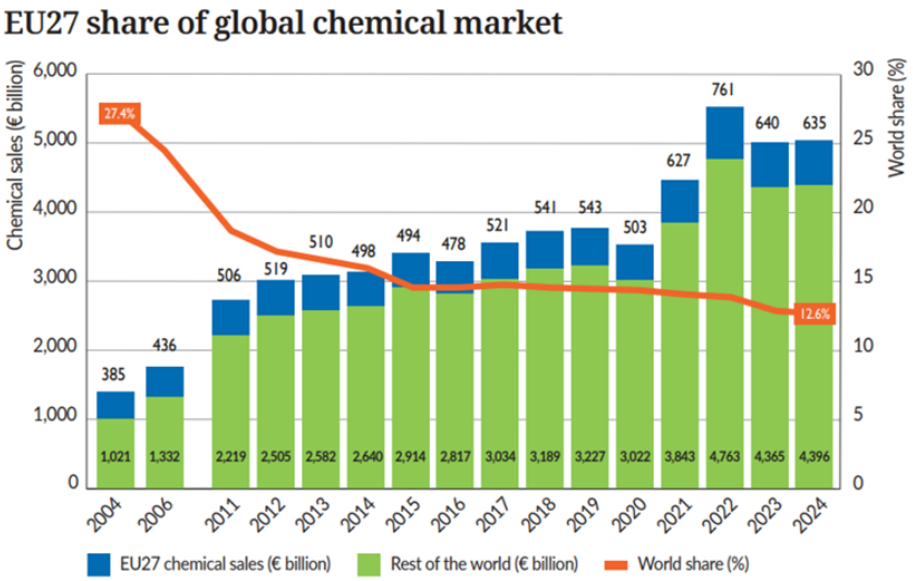


Figure 2.3: The EU27 share of global chemical market (Source: CEFIC)

For Europe, the consequence is a gradual loss of global market share: not because demand is falling, but because relative global growth is taking place elsewhere and at lower cost levels. This shift represents a structural, long-term rebalancing of the global chemical industry, with implications for competitiveness, asset utilisation, and future investment decisions in the Trilateral Chemical Region.

Strategic fragmentation thus means that instead of maximizing efficiency through market-led global integration, countries provide businesses with 'advantaged resources' to tip the balance of industrial investments to prioritize security of supply, political control, and resilience. This leads to the regionalization of production, selective reshoring or 'friend-shoring', trade restrictions, and the duplication of critical industrial capacity. For the chemical industry, this means that access to feedstocks, energy, technologies, and markets is increasingly shaped by geopolitical considerations rather than purely economic ones, resulting in higher costs, reduced scale advantages, and structurally different supply-chain configurations.

2.2 The life cycle emission of carbon products

The production of carbon-based chemicals and materials is inherently energy-intensive, with the dominant contribution arising from the steam cracking of naphtha. In conventional crackers, this energy demand is largely met by the combustion of by-products, primarily methane and other light hydrocarbons. As a consequence, today's production of carbon-based chemicals is associated with substantial CO_2 emissions. On average, the production phase alone results in approximately 1 to 2,5 kg of CO_2 emissions per kg of polymer [14], while other petrochemicals are in the range of 1 to 5 kg of CO_2 per kg of chemical [15].

[14] Manufacturing Energy and Greenhouse Gas Emissions Associated with United States Consumption of Organic Petrochemicals, Scott R. Nicholson, Nicholas A. Rorrer, Taylor Uekert, Greg Avery, Alberta C. Carpenter, and Gregg T. Beckham, ACS Sustainable Chemistry & Engineering 2023 11 (6), 2198-2208, DOI:10.1021/acssuschemeng.2c05417

[15] Manufacturing energy and greenhouse gas emissions associated with plastics consumption, Scott R. Nicholson, Nicholas A. Rorrer, Alberta C. Carpenter, Gregg T. Beckham, Joule, Volume 5, Issue 3, 2021,Pages 673-686, ISSN 2542-4351,https://doi.org/10.1016/j.joule.2020.12.027.

At the end of a product's life, the carbon embedded in these materials is ultimately released back into the atmosphere, either as CO_2 or methane. This occurs through decomposition processes in landfills or through combustion during incineration. The associated CO_2 emissions of embedded carbon typically exceed those of the production phase. From a stoichiometric perspective, the full oxidation of carbon-based products corresponds to typically 3 kg of CO_2 per kg of product [16], underscoring that end-of-life emissions are a very significant contributor to the overall carbon footprint.

In the production phase CO_2 emissions from energy generation in the supply chain may in cases be eliminated through electrification with renewable electricity, although combustion may be necessary when byproducts need to be incinerated or when high temperature is required. Steam cracking is an example where a high temperature is required, which is still difficult to electrify. Of steam cracking also the byproducts of steam cracking are nowadays combusted and provide the energy for the cracking process. If the byproducts are not combusted in the cracking process, for example when the heating can eventually be electrified, the carbon will eventually still find its way to the atmosphere.

An alternative route involves the use of bio-based feedstocks, such as bio-naphtha. In steam crackers this approach effectively shifts fossil-based fuel combustion to the firing of furnaces with bio-based byproducts, thereby reducing net fossil CO_2 emissions. Similarly, alternative production pathways to cracker products, such as methanol-to-olefins or ethanol-to-ethylene, exhibit climate impacts that are strongly dependent on both the origin of the carbon feedstock and the degree of electrification across the conversion steps.

Some oxidation is unavoidable
In the end-of-life phase, the central objective should be to retain carbon within a closed loop for as long as possible, minimizing decomposition and combustion. Closing this loop should be driven predominantly by renewable electricity, and avoid chemical oxidation of the carbon backbone in the molecules. For certain complex material waste streams, however, some oxidation may be technically or economically unavoidable. In such cases, partial oxidation via gasification represents the preferred option. Gasification converts carbon-containing waste streams into synthesis gas (a mixture of carbon monoxide and hydrogen) which, from a chemical perspective, constitutes a foundational building block of synthetic chemicals. From syngas, carbon-based molecules can be reconstructed 'from the ground up', enabling circular carbon pathways rather than irreversible carbon loss through the formation of CO_2.

As waste recycling technologies are unable to convert all their input into product, there is a need for gasification. Partial oxidation gasification produces syngas, which is the basis of syngas-based chemistry.

2.3 Chemical synthesis plays a pivotal role in producing non-fossil fuels and chemicals

The transition away from fossil resources implies that chemical synthesis will play an essential and increasingly central role in the production of functional chemicals, materials, and energy carriers. Unlike fossil feedstocks, alternative carbon sources such as biomass and waste are chemically complex, heterogeneous, and rich in heteroatoms. As a result, target products can no longer be obtained through simple physical separation or the relatively

[16] Multiplication of mass by 44/14 = 3,14 (the mass ratio of CO_2 / CH_2).

“mild” rearrangement of carbon chains that has traditionally been used to refine crude oil into fuels and chemical intermediates.

In the geological past, crude oil and natural gas were formed through the deposition and burial of organic matter in sedimentary environments. Over geological time scales, spanning millions of years, this organic matter was exposed to increasing temperatures and pressures as it was buried deeper within sedimentary basins. Under these conditions, a sequence of thermochemical transformations occurred in which large, highly functionalized biomolecules were progressively broken down and reorganized into simpler, hydrocarbon-rich molecules. Temperature, time, and the geochemical environment (including the presence of water and minerals) were the dominant drivers of this transformation, favouring the formation of hydrocarbons that are thermodynamically more stable than the original complex biomolecules. The result was crude oil and natural gas: energy-dense feedstocks with a substantially reduced content of heteroatoms such as oxygen, nitrogen, and sulphur.

Biomass has not undergone this long-term geological ‘maturation’. Consequently, when biomass-derived carbon or complex waste streams are used as feedstocks for conventional chemical products, the chemical industry must actively perform (within industrial time scales and reactors) the transformations that geology previously provided over millions of years. This represents an intrinsic additional burden in terms of process severity, energy input, and chemical complexity.

From a circularity perspective, waste streams are ideally separated into fractions that can be routed back into similar product categories with minimal intervention. However, a substantial fraction of waste consists of complex, mixed, or contaminated materials that cannot be directly linked to specific product pathways. Re-using the carbon contained in these molecules requires particularly intensive treatment to break down their chemical structure.

For the production of crude oil-based chemicals from biomass and complex waste, high-severity conversion routes such as pyrolysis and gasification become essential. These processes decompose complex molecules into smaller fragments such as syngas, light hydrocarbons, or oxygenated intermediates that no longer resemble the original feedstock.

The value creation therefore shifts to targeted synthetic chemistry, in which these fragments are selectively recombined through multi-step reaction pathways into functional chemicals, materials, and fuels. This synthesis from molecular fragments to end products typically proceeds through several intermediate stages, each requiring precise control over reaction conditions, catalysts, and energy input.

In this sense, synthetic chemistry becomes the central enabling discipline of the non-fossil chemical industry: it replaces geological time with engineered processes and converts chemically disordered carbon into the structured molecules required by modern society.

2.4 The olefins and aromatics platform delivers the bulk of sustainable industrial chemicals

Olefins and aromatics are among the most essential platform chemicals in the global chemical industry, underpinning a vast array of polymers, resins, fibres, coatings, and other functional materials. Their industrial scale, versatility, and integration into existing supply

chains make them foundational to modern chemical production. As such, sustainable production of olefins and aromatics represents a critical stepping stone toward decarbonizing the chemical sector and enabling the broader use of renewable carbon feedstocks [17].

At the same time, it is important to recognize that the functional requirements of end-use applications, rather than the chemical lineage alone, ultimately define material performance. In many cases, molecules derived from biomass, CO_2, or other alternative feedstocks can deliver equivalent chemical functionality and material properties to those traditionally obtained from olefins and aromatics. Examples include bio-based polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA)[18], as well as functionalized bio-aromatics for resins, adhesives, or coatings. These alternatives can replicate mechanical strength, chemical resistance, or other critical attributes, although often at smaller scale or with additional process complexity.

Taken together, this implies a dual strategy for sustainable chemical production: olefins and aromatics remain indispensable as high-volume, foundational platforms, forming the ‘gateway’ to a sustainable materials economy, while functional equivalents from renewable sources can complement them in applications where scale, cost, or performance requirements permit. Sustainable olefins and aromatics thus provide the structural backbone for the chemical industry’s transition, while the development of alternative molecules broadens the toolbox for functional, low-carbon products.

A critical balance must be struck to avoid overcommitting to sustainable olefins and aromatics if alternative chemical platforms, such as oxygenates, could ultimately deliver superior environmental or functional performance. Lock-in to a particular pathway may occur if these alternatives do not mature rapidly enough or remain under-invested, potentially leaving the industry reliant on a platform that is suboptimal in terms of carbon efficiency, energy use, or material functionality. To safeguard both competitiveness and sustainability, it is therefore essential to monitor emerging chemistries and maintain flexibility in the development and deployment of chemical building blocks.

[17] A global analysis of the rise, reign, and retreat of topics in research toward sustainable platform chemicals, Paul Tautorat et al., Green Chem., 2025, 27, 12985–13003

[18] https://publications.tno.nl/publication/34643657/nscrew0P/ruiter-2025-pathways.pdf

2.4.1 Chemical pathways based on olefins and aromatics

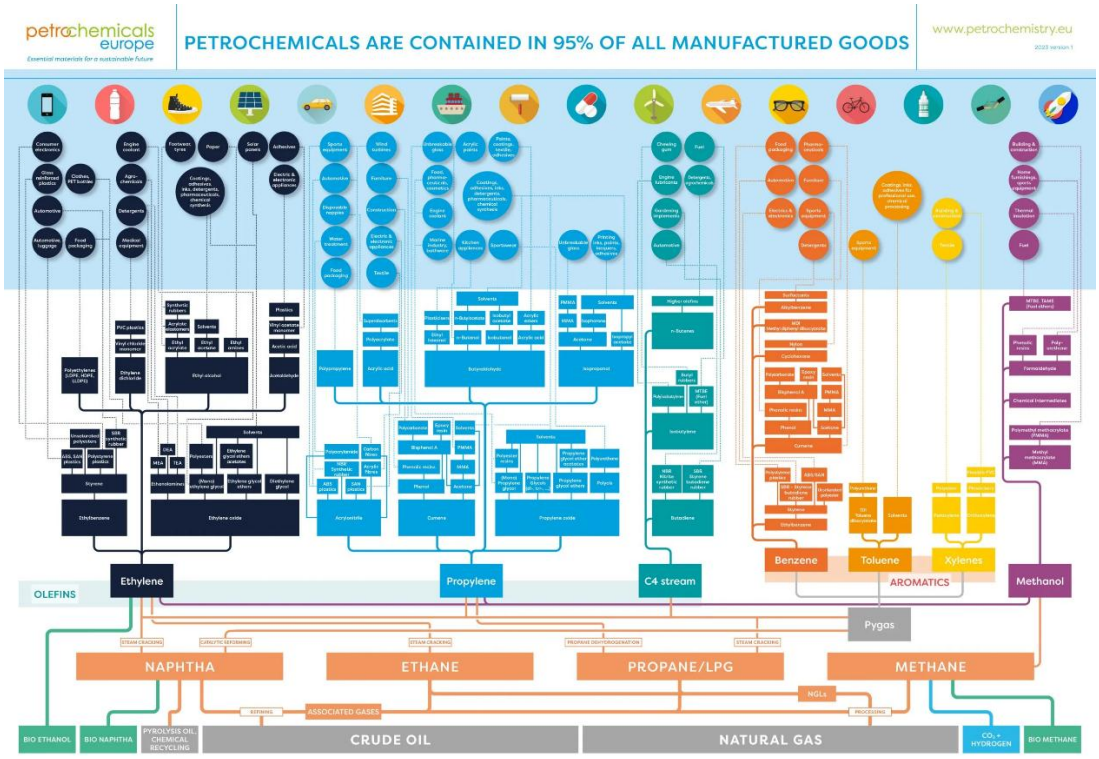


Figure 2.4: The petrochemical pathways: a map of how dependencies of chemicals production evolves from olefins and aromatics. https://cefic.org/news/the-journey-of-petrochemicals-explained-from-raw-materials-to-95-of-all-manufactured-goods/. Olefins and Aromatics are key entry points to the synthesis of a large number of chemicals.

Figure 2.4 illustrates the “petrochemical pathways” – a schematic showing how fractions of crude oil and natural gas (primarily naphtha, ethane, propane/LPG, and methane) are transformed into the fundamental platform molecules of the chemical industry. Through steam cracking and related processes, these feedstocks are converted into olefins (ethylene, propylene, ‘C4’: butenes/butadiene) and aromatics (benzene, toluene, xylenes). These molecules are in a chemically high-energy, unsaturated or ‘activated’ state, which makes them highly reactive and suitable as building blocks for downstream synthesis.

Producing this activated state requires substantial energy input. In conventional naphtha steam crackers, this energy is delivered almost entirely through the combustion of carbon-based fuels, typically methane and other light hydrocarbons produced within the cracker itself. This fuel combustion is the dominant source of CO_2 emissions associated with the production of olefins and aromatics. Within the entire chain from fossil feedstock to finished chemical products, the steam-cracking step is by far the most energy-intensive process, and thus the primary driver of operational CO_2 emissions.

Alternatively, the olefins and aromatics may be produced from methanol, ethanol and paraffins (HEFA, HVO, FTL, Pyrolysis oils). These may in turn be derived from waste and biomass. Hence waste and biomass as feedstock reduce the need of fossil carbon for chemicals. At the same time these are also suitable to be used as fuel. This dual use of methanol, ethanol, and paraffins can contribute to scale and enhance global availability.

Although this work has explored the pathways from the perspective of converting waste and biomass to chemicals, some parts of the supply chains are already operational for the production of fuels, e.g. the blending of ethanol in petrol and the blending of HVO/HEFA in diesel.

2.4.2 Sustainability considerations

At the end of their useful life, most chemical products are either incinerated or gradually decompose in the environment. In both cases, the carbon they contain is ultimately released to the atmosphere and ultimately forms CO_2. When these products are derived from fossil feedstocks, this release represents a net transfer of carbon from geological storage to the atmosphere.

Producing olefins and aromatics from waste streams or biomass instead of all virgin fossil resources both reduces the input of new fossil carbon into the system. In these pathways, carbon that has already been mobilised, either within the technosphere (waste) or the biosphere (biomass), is reused for an additional product life before eventual release.

Conversion of waste into chemical products avoids the immediate release of CO_2 that would otherwise occur through direct incineration. A fraction of the carbon in the waste is therefore retained within the product system, while the remainder is typically converted into low-molecular-weight by-products that are combusted to supply process energy.

Biomass-based feedstocks introduce carbon into the chemical system that originates from the biosphere rather than from fossil reservoirs. The resulting CO_2 emissions therefore represent a transfer of carbon from the biosphere to the atmosphere, rather than an addition of fossil carbon to the atmospheric system. The assessment of climate impact then depends on the chosen system boundaries and carbon accounting conventions, rather than on assumptions about instantaneous neutrality.

The carbon efficiency of biomass conversion pathways can be increased through the use of hydrogen, which enables oxygen removal from biomass in the form of water rather than CO_2. This increases the fraction of biogenic carbon retained in chemical products and reduces process-related CO_2 formation.

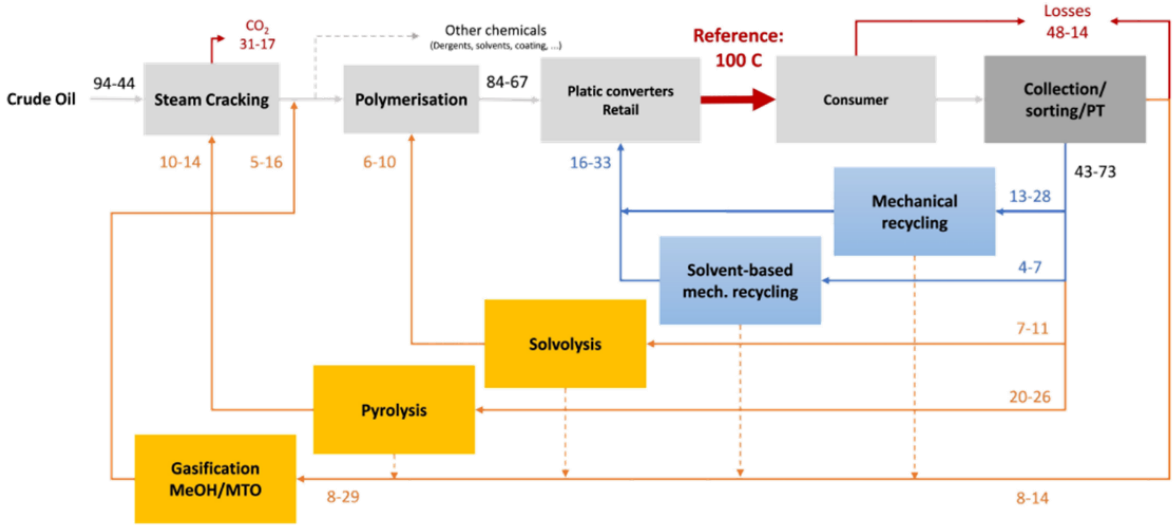
2.4.3 Olefins and aromatics from mixed plastic waste

Plastic waste primarily consists of synthetic chemicals based on the olefin and aromatic platforms. Because these molecules were originally created for these platforms, they are already carbon-rich and relatively low in oxygen, making them an attractive starting point for producing olefins and aromatics.

While incineration is largely indifferent to the chemical nature of waste, circular pathways will gain efficiency from first separating waste into fractions. Each fraction then follows the best pathway back to chemical products. Especially some plastic types, the poly-olefins, may be readily converted back to olefins or olefin-derived monomers. Other plastic types, the poly-condensates, should best not be converted to olefins and follow different routes back to their monomers.

A system of waste recycling technologies was studies by Jean-Paul Lange c.s.[19] and a graph is shown in **Figure 2.5**. This graph shows categories of plastic waste recycling technologies and the carbon flows through such a system. Mild processing technologies are preferred because they maintain the structure of molecules and consume less (renewable) energy. Where the capabilities of milder technologies fall short, the study indicates that pyrolysis and gasification are the end of the line. These technologies, certainly gasification, are not as demanding on the quality of the feedstock, although the capability to process materials such as PVC will remain very limited due to the presence of Chlorine, which causes severe corrosion in equipment.

The olefins and aromatics, in this graph, are produced by steam-cracking the light pyrolysis products and producing olefins from gasification, methanol (MeOH) production and subsequent Methanol-To-Olefins (MTO) conversion.



Normalized carbon flow of a cascade of recycling technologies based on mechanical recycling (blue) and chemical recycling (Orange) technologies. The numbers represent normalized C-flows, based on a realistic (2030) -futuristic (2050) sorting scenario. (The naphtha intake is scaled to deliver 100 unit of C plastics on the market, excl. the additional non-plastics chemicals).

Figure 2.5: Waste processing options and estimates of fossil-naphtha input displacement.

According to the study to produce a reference 100 units of carbon-based product in 2030 requires 94 units of Crude Oil (naphtha). Combining and optimizing waste collection and applying the recycling technologies to the separated streams could reduce this to 44 units of Crude Oil input in 2050 to fulfil the same 100 reference units of demand. Further the study estimates that, while the carbon efficiency may be further improved by using renewable energy, displacing more than 70% of the naphtha would consume a disproportionate amount of renewable energy. Naphtha displacement beyond 70% should therefore come from another non-fossil carbon source: biomass – more specific lignocellulose.

2.4.4 Bio-based olefins and aromatics

Bio-based olefins and aromatics represent the renewable-carbon drop-ins of the high-volume platform chemicals that underpin modern materials and chemical production. While starches, sugars, and lipids have historically been the most accessible renewable feedstocks for

[19] Plastic recycling stripped naked – from circular product to circular industry with recycling cascade, Jean-Paul Lange,* Sascha R. A. Kersten, Steven De Meester, Marcel C. P. van Eijk, and Kim Ragaert, ChemSusChem (2024), doi.org/10.1002/cssc.202301320

chemical production, lignocellulosic biomass offers far greater potential for large-scale, sustainable chemical synthesis. This type of biomass, which includes agricultural residues, forestry waste, and dedicated energy crops is abundant, non-food competing, and structurally rich in carbon, making it ideal for producing high-volume platform chemicals such as olefins and aromatics.

In contrast, starches and sugars, though easier to process via fermentation, are limited in supply and often compete with food production, restricting their scalability for industrial chemical production. Lipids are already converted on industrial scale into fuels and specialty chemicals, but their chemical functionality is narrower, and large-scale deployment is constrained by agricultural and ecological limits.

Lignocellulosic biomass contains a complex matrix of cellulose, hemicellulose, and lignin, each of which can be valorised through appropriate chemical or thermochemical processes. Cellulose and hemicellulose are sources of sugars for fermentation or catalytic conversion to intermediates such as ethanol, methanol, or syngas, while lignin, the most abundant natural source of aromatics, provides a direct route to renewable aromatic chemicals, which are otherwise difficult to produce from sugars or lipids. By leveraging all three fractions, lignocellulosic biomass enables the full utilization of carbon and the production of a broader spectrum of functional chemicals, making it the preferred feedstock for a circular, low-carbon chemical industry.

The carbon-efficiency of processing biomass to olefins and aromatics was investigated by Arts, W et.al.[20] and a key graphic from this paper is shown in **Figure 2.6**. The study illustrates that the basic process for the conversion of lignocellulosic biomass to olefins and aromatics through gasification, Fischer-Tropsch and cracking has a typical 28% carbon efficiency, that can be improved to 64% by gasification in the presence of hydrogen. Naturally this hydrogen should be generated from renewable electricity. In both cases the gasification produces CO_2, at relatively high concentrations, which may be stored to maintain carbon neutrality of the cycle.

[20] Feasibility of wood as a renewable carbon feedstock for the production of chemicals in Europe, Arts, W et.al. DOI: 10.1002/bbb.2575; Biofuels, Bioprod. Bioref. (2024)

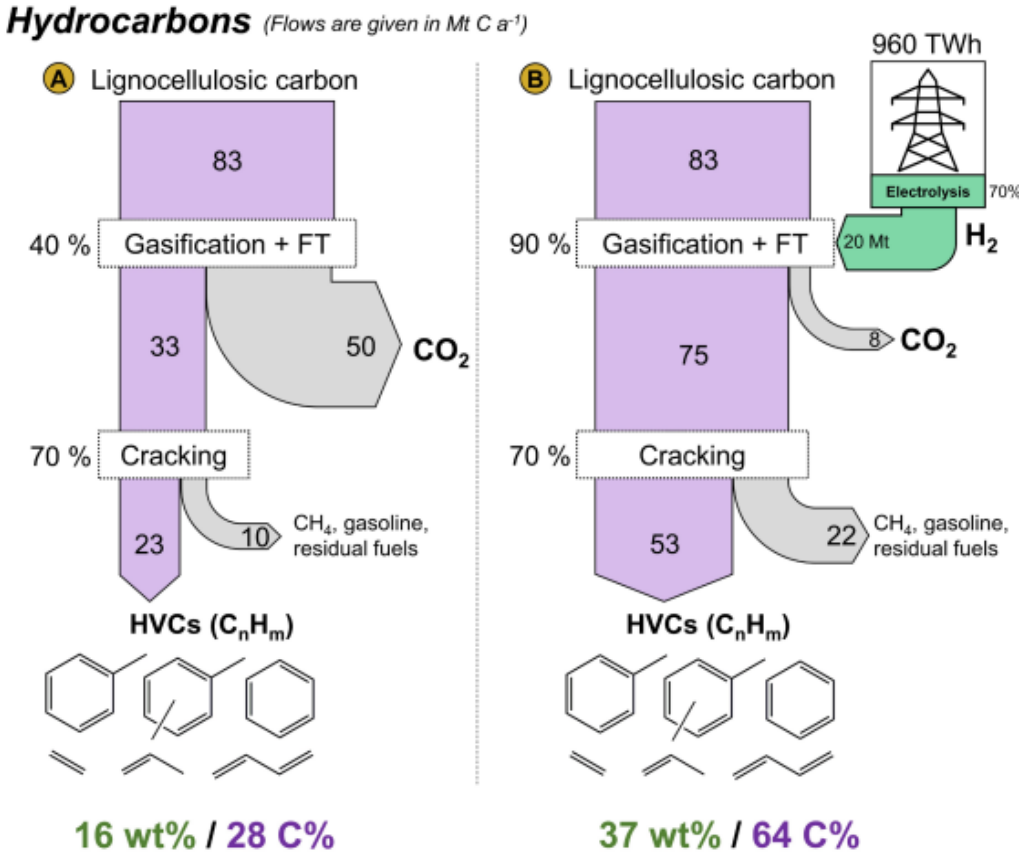


Figure 2.6: The carbon efficiencies for the production of HVC (High-Value Chemicals = olefins and aromatics) from lignocellulosic biomass. Flows are given in Mt carbon per year. Figure clipped from a figure in [20].

In both cases the cracking produces olefins and aromatics as well as other carbon-based compounds ('CH_4, gasoline, residual fuels' in **Figure 2.6**) that can be added to the blendstock and end up in formulated fuels. Although the carbon-efficiency to olefins and aromatics is estimated in the order of 28% and 64%, the carbon efficiency of lignocellulosic biomass to carbon-based fuels and chemicals can be as high as 40% and 90%.

The authors [20] make a point that the separation of biomass in fractions should be preferred. And oxygenates have a potential for more optimal carbon efficiency and energy demand. This would, however, demand re-development of many, if not most, applications of chemicals in products today, which at this moment seems not feasible to achieve before climate action needs to be taken, and this can only be achieved at considerable cost.

2.4.5 Waste and biomass as resources are different from fossil

Fossil resources and renewable carbon sources differ fundamentally in their physical, ecological, and system characteristics. Fossil resources such as crude oil and natural gas are available as large, concentrated point sources, accumulated over geological timescales and accessible in volumes that support highly centralized, large-scale industrial processing. Their high carbon and energy density, together with mature extraction and transport infrastructure, have enabled the chemical industry to operate with exceptional economies of scale.

By contrast, biomass and waste are inherently dispersed, heterogeneous, and structurally limited resources. Biomass availability is constrained by photosynthetic productivity, land use, and the need to preserve ecosystem functions and biodiversity. Importantly, there is no broad scientific or policy consensus on how much biomass can be responsibly mobilized without undermining nature's vital role in ecosystems[21], leading to significant uncertainty regarding long-term sustainable supply.

Waste streams are fragmented across many sources and subject to substantial carbon inefficiencies: during use and end-of-life, a large share of carbon is dissipated and cannot be recovered. Many chemical products do not end up in durable materials but are discharged through wastewater systems (e.g. detergents), released to the atmosphere (e.g. solvents), or destroyed through incineration (e.g. paints and coatings), because recovery is technically or economically infeasible. Also, plastics do not simply flow through the economy and dissipate; instead, a substantial and growing portion accumulates in societal stock. Durable applications, including building materials, automotive components, textiles, and infrastructure, retain plastic carbon for years to decades. Material flow analyses indicate[22] that total historical plastic production far exceeds annual disposal, with a significant mass remaining in products in use or stored in landfills, creating a continuously increasing societal reservoir of plastic carbon. As a result, maintaining and expanding the plastic stock in use requires a continuous input of new material that exceeds the amount recoverable from waste streams.

From the perspective of feedstock demand, this means that waste and biomass must be regarded as limited resources, a reality that has direct consequences for competition, pricing, and prioritization in renewable carbon markets.

This fundamental asymmetry explains why replacing fossil feedstocks with biomass and waste is not a simple one-to-one substitution, but a systemic transformation that requires careful resource allocation, high carbon efficiency, and strategic choices about where renewable carbon delivers the greatest societal value.

Through the global commodities methanol, ethanol and paraffins, the centralized large scale character of the current chemical industry may be retained. These three can either be produced in or around the TCR from waste and biomass, or be imported from production elsewhere.

2.5 How molecules' properties shape industry location and co-location

The Trilateral Chemical Region (or wider ARRRA) did not emerge because it is "centrally located" in an abstract geographic sense. It has evolved from the coal and steel industry [23] and it emerged in its current shape because it is one of the few places in Europe where three distinct transport envelopes overlap at scale: of co-location-forced molecules, of regionally transportable toxic intermediates, and of high-value system feedstocks. Each envelope imposes a different spatial logic on industrial organization. Together, they produce a geography that cannot be explained by cost, labour, or policy alone.

[21] Bioenergy and climate change mitigation: an assessment, Felix Creutzig et al, Bioenergy, Volume7, Issue5, September 2015, Pages 916-944
[22] Production, use, and fate of all plastics ever made, Geyer, Jambeck, Law Sci. Adv. 2017;3: e1700782
[23] The dynamic development of organic chemistry in North-West Europe, J. Meijering, J. van Leeuwen, CIEP paper 2021-1 (project 'cracking the clean molecule')

2.5.1 Acutely toxic and hence co-location-forced molecules

Acutely toxic intermediates such as carbon monoxide, chlorine, phosgene, and closely related substances are produced and consumed within the same sites or on immediately adjacent sites in Antwerp, Rotterdam–Moerdijk, and the Ruhr. Chlorine electrolysis units are directly coupled to downstream PVC, epoxy, and isocyanate value chains. CO and phosgene circulate inside fenced industrial estates or through very short, dedicated pipelines.

Public safety constraints, permitting regimes, and social risk make inter-hub transport of these acutely toxic substances politically and practically prohibitive. As a consequence, off-takers must co-locate with these highly toxic intermediate chemicals.

2.5.2 Toxic but transportable intermediate molecules

A second layer consists of toxic or pressurized bulk intermediates such as ammonia, vinyl chloride monomer, and similar substances. These chemicals can be transported safely, but only under strict conditions and still with non-trivial societal risk. Their movement is therefore feasible at regional scale, but preferably not freely across populated areas.

The Rhine river system enables barge-based integration from Rotterdam deep into the Ruhr. Pipelines connect nearby hubs such as Antwerp and Rotterdam and provide dense internal connectivity within the Ruhr. Rail and short-sea shipping extend reach further, but with rising cost, complexity, and risk.

This transport envelope creates a corridor-shaped chemical region, rather than a point cluster. Ports specialize in imports, cracking, and storage, while inland sites specialize in transformation and downstream manufacturing. Toxic-but-transportable intermediates define the meso-scale system: larger than any single port complex, yet far more integrated than a Europe-wide dispersion of plants.

2.5.3 High-value system feedstock molecules

At the widest spatial scale sit high-value, capital-intensive system feedstocks most notably ethylene and propylene, alongside hydrogen and liquid carriers such as methanol. Among these, ethylene and propylene pipelines form the backbone of ARRRA’s physical integration. They are the molecules through which the region quite literally operates as one system, with co-location forced molecules and regional transport where necessary.

Ethylene and propylene are produced in a limited number of large steam crackers, whose economics demand extreme scale, high utilization, and long asset lifetimes. As a result, these crackers are not replicated at every site. Instead, they are connected to multiple downstream plants through dense, cross-border ‘ARG’ pipeline networks that link Antwerp, Rotterdam–Moerdijk, the Rhine–Ruhr, and adjacent clusters deeper inland. While propylene can be transported in pressurised containers (18 bar), ethylene requires refrigeration below its atmospheric boiling point of -104°C because of its low critical temperature (9,5°C). Apparently the added cost of refrigeration are not prohibitive for its global distribution see section 2.1.3, and the pipeline thus loses part of its advantage.

These pipelines allow a cracker in one country to supply polymer, rubber, and chemical intermediates plants in another, independent of national borders or ownership structures.

Downstream investments are therefore made based on access to the olefin grid, not proximity to a specific cracker.

The olefin pipeline system therefore transforms ARRRA from a set of adjacent hubs into a single, integrated production space. Crackers, import terminals, and energy-intensive upstream units are placed where infrastructure, port access, and energy supply are optimal. Downstream units plug into the olefin network wherever it intersects with co-location-forced toxic chemistry or specialized manufacturing capabilities.

2.5.4 Cluster Dynamics: Efficiency, Dependence, and Exposure

Co-location of chemical production facilities within industrial clusters creates important synergies that can significantly improve competitiveness. Shared infrastructure for energy, utilities, feedstocks, logistics, and waste management reduces capital and operating costs, while physical proximity enables the efficient exchange of intermediates, by-products, and heat. In addition, co-location supports higher asset utilisation, greater operational flexibility, and faster innovation through knowledge spillovers and a shared skilled workforce. These synergies can materially lower production costs and risk, making clustered facilities more resilient in globally competitive markets.

At the same time, the strong interdependencies created by co-location also introduce systemic vulnerabilities. When a key player within a cluster reduces operations or exits entirely, shared infrastructure may become underutilised, by-product and intermediate flows can be disrupted, and the cost advantages of scale may rapidly erode for the remaining participants. This can trigger a cascading effect in which the loss of one anchor facility undermines the economic viability of others, potentially leading to accelerated decline of the cluster as a whole. Such path dependency makes clusters highly efficient when stable, but fragile when confronted with sustained structural disadvantages or abrupt investment withdrawal.

2.6 Chemicals production is exposed to global markets

The chemical industry is characterised by the extreme complexity and breadth of its supply chains, driven by the large number of intermediates and end products that are produced and traded. With the exception of a limited number of substances that are too hazardous to transport over long distances from a societal risk perspective, most chemical intermediates and products can be transported efficiently over large distances without loss of quality or quantity.

The high transportability of chemical products enables a truly global-for-global production and trade system [24]. Consequently, virtually every chemical production facility worldwide is exposed to global competition. The production facilities represented in the petrochemical pathways shown in **Figure 2.4** are distributed across all major industrial regions and together

[24] This sharply contrasts with electricity and ‘e-‘energy carriers. Electricity - whether transported directly through transmission lines or indirectly via hydrogen, ammonia, or liquefied synthetic natural gas (s/e-LNG) - suffers from substantial losses during conversion, storage, and transport. As a result, electricity and electricity-derived energy carriers are predominantly traded on a local-for-local or regional basis. While transport distances may be considerable, they are fundamentally constrained economically and certainly do not seem to support fully global trade.

form a complex, interdependent global network. This network is continuously optimised by globally operating companies seeking competitiveness in international commodity markets.

For each individual chemical plant, the cost of production is the primary determinant of its global competitiveness. Actual production costs depend on a wide range of factors, including feedstock and energy prices, the technical performance and age of assets, capital and labour costs, and the synergies achieved through co-location in industrial clusters. These costs are highly sensitive to local conditions and operational strategies and are therefore considered commercially confidential. Production cost data are typically well-guarded secrets of the companies operating the facilities, because of their strategic relevance to a business.

Companies may accept operating a chemicals plant in their asset portfolio at a loss for extended periods if these losses are offset by profits elsewhere in the portfolio and the asset is considered strategically important. Similarly, lower profit margins may be acceptable when a facility benefits from long-term offtake agreements, provides access to key markets, supports downstream integration, or forms part of a broader knowledge–industrial complex.

Although exact production costs are proprietary businesses information, specialised market analysts such as ICIS, Wood Mackenzie, Platts, and Argus maintain detailed databases of major chemical production assets worldwide and develop best-estimate cost curves for key products. These datasets are widely used by companies to benchmark the performance of their assets against global competitors. While such data can be purchased for internal use, it cannot be republished.

Figure 2.7 shows an example of an Argus-modelled cost curve for ethylene production via steam cracking, differentiated by region. The Middle East and North America exhibit the lowest production costs, primarily due to access to low-cost feedstocks in the form of natural gas liquids co-produced with natural gas. European steam crackers occupy the mid-range of the cost curve, while Asian crackers generally appear at the higher end of the cost spectrum.

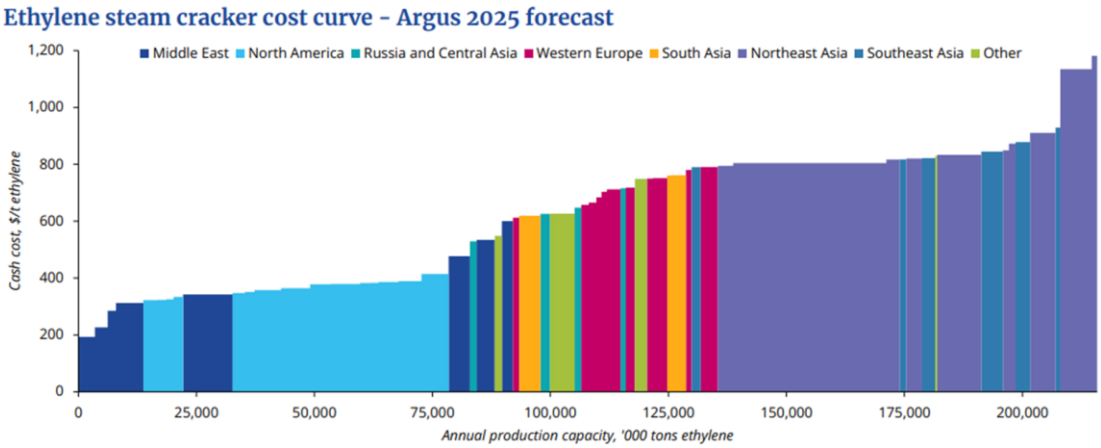


Figure 2.7: Argus-modelled 2025 forecast cost curve as of May 2025, Argus insight paper May 2025, https://www.argusmedia.com/en/news-and-insights/market-insight-papers/global-ethylene-market-costs-tariffs-volatility.

Besides these steam cracker routes olefins can be produced from coal, and therefore these are not shown in **Figure 2.7**. This 'CTMTO' route (Coal-To-Methanol-To-Olefins) has a very high CO_2 emission and capital cost, but very low marginal cost because coal is very inexpensive. The levelized cost of olefins from CTMTO is therefore similar to the levelized

cost of olefins based on naphtha, yest the marginal cost is very low. Hence coal-based olefins (or methanol for that matter) can be very cost-competitive in global markets if the producer has no more capex to finance.

The additional cost burden for European crackers resulting from CO_2 emission pricing can be estimated by combining the carbon footprint of steam cracking with the prevailing CO_2 price. Assuming a footprint of approximately 1 tonne of CO_2 per tonne of carbon-based product and a CO_2 price of € 100,= per tonne, European crackers would experience a substantial rightward shift on the global cost curve. If these additional costs cannot be passed on to customers, production margins are likely to erode rapidly, making plant closures economically unavoidable from a business perspective.

While CBAM might protect local markets from carbon leaking-in, it works only one-way and will make export from European facilities uncompetitive. Industry points out that for the chemicals CBAM is very difficult (if not impossible) to implement. Therefore, their argument is that the responsibility for sustainability should lie as close to the consumer as possible. For chemicals this may be the new level playing field that the current CO_2 pricing of emissions aims to achieve.

2.6.1 Some chemicals are critical for security and autonomy of the European Union

Eight EU Member States have proposed a European Critical Chemicals Act to safeguard essential upstream chemical production and protect the industry from further decline. The Act targets strategic ‘building-block’ molecules - including ethylene, propylene, ammonia, methanol, benzene, toluene, xylene, chlorine, and sodium hydroxide - that underpin Europe’s defence, health, agri-food, construction, and clean-tech value chains. Loss of domestic capacity in these chemicals is considered a direct risk to European industrial resilience and strategic autonomy.

To counter this trend, the Act would relax state-aid rules, enable funding for decarbonisation and modernization, and provide protection against structurally lower-cost imports from outside the EU. It is designed to complement the EU’s broader industrial strategy - including the Clean Industrial Deal and the European Chemicals Industry Action Plan, which aim to strengthen resilience and secure critical production within the Union.

Without intervention, up to 20 European steam crackers could close by 2035, removing major upstream capacity and deepening reliance on non-EU suppliers. The Critical Chemicals Act thus marks a strategic shift: maintaining domestic production of essential chemicals is no longer seen solely as a competitiveness issue, but as a matter of economic security, sovereignty, and long-term decarbonisation.

2.6.2 The type of feedstock determines steam cracker exposure to carbon pricing

While some steam crackers in the TCR are currently under-utilized or idle, and others are undergoing restructuring through closures or takeovers, there are also notable new-build projects, such as INEOS’s Project One. Understanding this apparent paradox requires looking at the economics of CO_2 emissions pricing. Project One is designed to use natural gas liquids (NGLs), primarily ethane, as its feedstock. Cracking ethane into ethylene is largely a dehydrogenation process, producing hydrogen as a co-product. This hydrogen can then be

used as an on-site fuel to fire the cracker furnaces, similar to the way methane is used in LPG or naphtha cracking. Thus an ethane cracker significantly reduces its direct CO_2 emissions, thereby mitigating exposure to the expected carbon pricing.

Because the feedstock itself remains fossil-derived, the overall carbon footprint of the resulting ethylene and downstream products is still substantial. However, from the perspective of EU emissions accounting and CO_2 costs, this design provides a competitive advantage. Today the same advantage applies to other crackers worldwide, particularly in the USA and Middel East that use NGL feedstocks: when their products are imported into the EU, they benefit from lower operational CO_2 emissions and therefore face a smaller carbon price burden. This dynamic helps explain why new-build investments in NGL-based crackers remain attractive despite broader market closures and restructuring across Europe.

Especially Natural Gas Liquids (NGLs) sourced from the United States carry a disproportionately high Scope-3 upstream greenhouse-gas footprint. This is largely because NGLs - particularly ethane - are predominantly produced as co-products of shale gas extraction, where fracking and associated gas handling often exhibit elevated methane leakage rates. methane leakage across U.S. gas basins is a well-documented upstream emissions source, with leakage occurring during fracking, gathering, processing, and pipeline transport. Methane (CH_4) is a potent greenhouse gas, with a global warming effect roughly 28 times stronger than CO_2, meaning even small leakage rates materially amplify the upstream climate impact of NGL supply chains. Upstream emissions of ethane adds approximately 0,4 ton CO_2-eq per ton of ethylene to the footprint [25].

As a result, although ethane cracking itself is relatively carbon-efficient, requiring less fuel combustion and generating fewer direct (Scope-1) CO_2 emissions compared to naphtha cracking - the full life-cycle warming impact of U.S. NGL-based feedstocks is significantly higher once upstream extraction, processing, and methane leakage are accounted for. In essence, low operational emissions do not equate to a low carbon footprint when the upstream supply chain is methane-intensive. The upstream emissions associated with U.S. shale-derived feedstocks therefore represent a substantial Scope-3 contribution that must be acknowledged when assessing the climate impact of ethylene derived from NGL cracking.

Electrification of steam cracking eliminates the need to combust methane - or other fuels - in the cracker furnaces, thereby sharply reducing direct CO_2 emissions from energy use. However, electrification does not prevent the formation of methane as a by-product of the cracking process itself. If the feedstock remains fossil-based, the methane produced is also fossil-derived and must either be sold or combusted, which ultimately generates CO_2. If the feedstock is bio-based, however, the methane can serve as a carbon-neutral source of heat or as a feedstock for further chemical production, therefore, contributes to closing the carbon loop while reducing reliance on fossil resources.

2.6.3 Market Exposure: Spot Trading and Long-Term Contracts

Chemical businesses operate in a dual market environment, balancing spot-market transactions with long-term contracts. Spot markets enable producers to respond rapidly to

[25] Decarbonization approaches for ethylene production: comparative techno-economic and life-cycle analysis, Woojae Shin, Bosong Lin , Haoxiang Lai , Gasim Ibrahim and Guiyan Zang, Green Chem., 2025, 27, 3655-3675, DOI: 10.1039/D4GC04538F – conversion of 8.2 kg CO_2e per GJ-LHV ethane → g CO_2e per g ethane with 47.206 MJ/kg ethane.

short-term fluctuations in global supply and demand, seizing opportunities when prices temporarily exceed production costs or offloading surplus output during tight market conditions. However, reliance on spot trading also introduces volatility and exposes producers to price swings and broader market risk. By contrast, long-term contracts provide revenue stability and predictable offtake, often underpinned by downstream integration, strategic partnerships, or customer guarantees. Companies typically manage their portfolios by combining both approaches using contracts to secure baseline volumes and mitigate risk, while participating in spot markets to optimize margins and adapt to shifting global conditions. This balance is particularly crucial in a globally exposed industry, where production costs and competitiveness differ significantly across regions.

From a business perspective, this duality adds another layer of complexity to the already intricate supply chains of the chemical industry.

2.6.4 Business investment decisions in their global production asset portfolio

This global exposure directly translates into a sequence of recurring investment decisions at every major maintenance, revamp, or reinvestment cycle of a chemical production asset. At each such decision point, operators reassess whether continued operation and reinvestment at a given location remain economically justified relative to alternative uses of capital elsewhere in their global portfolio. Because chemical assets are long-lived but modular, incremental investments - such as furnace revamps, efficiency upgrades, debottlenecking, or life-extension maintenance - effectively constitute repeated “go/no-go” decisions. In a globally competitive market, even relatively small and structurally persistent cost disadvantages, such as higher energy prices or carbon costs, can tilt these decisions away from reinvestment and towards gradual capacity erosion, relocation, or closure, well before a plant reaches the end of its technical lifetime.

2.7 Sustainable consumption as a societal objective

Sustainable consumption refers to satisfying legitimate human needs and desires in ways that ensure others, both in the current generation and in the future, can enjoy the same opportunities. It is not merely about reducing consumption or restricting lifestyles, but about aligning the provision and use of goods and services with ecological limits, social equity, and long-term resilience. Sustainable consumption is thus both a personal and societal responsibility, bridging the choices of individuals with the structural capabilities of industries and governance systems.

From a systems perspective, the sustainability of fulfilling society’s demand for industrial goods is not determined by any single production process or technological innovation. Instead, it emerges from the cumulative effects across the entire life cycle of a product, spanning raw material extraction, production, distribution, use, and end-of-life treatment. Each stage contributes in distinct ways to resource consumption, greenhouse gas emissions, water and energy use, and the creation or destruction of economic and social value. For example, efficient manufacturing may be offset by resource-intensive raw materials, or low-impact use may be undermined by poor end-of-life recycling practices.

Only by considering the full life cycle of products can the true contribution of industrial systems to sustainable consumption be evaluated. Life-cycle thinking enables the identification of trade-offs, the prioritization of interventions, and the recognition of systemic synergies. It also emphasizes that sustainability is not an isolated attribute of a product, but an emergent property of complex industrial and societal interactions. In this way, sustainable consumption becomes a guiding principle that informs industrial strategy, policy design, and consumer behaviour alike, ensuring that economic activity can coexist with ecological limits and intergenerational equity.

2.7.1 The value of sustainability

Most important of all, society needs to recognize and value the embedded sustainability in products - a form of value that is largely intangible because it does not alter the technical performance or functionality of the product itself. A plastic bottle, a chemical intermediate, or a fuel molecule produced sustainably would behave identically to its conventional counterpart, yet its lifecycle carries significantly lower environmental impact, preserved molecular carbon value, and reduced climate risk. This value is hidden in the supply chain, in the choice of feedstocks, in the integration of circular processes, and in the avoidance of emissions or resource depletion.

From a systems perspective, this embedded sustainability represents a premium on responsible design, production, and end-of-life management. It is the outcome of aligning industrial operations with ecological limits and societal expectations, often through investment in advanced chemical processes, renewable energy, and carbon-efficient supply chains. The benefit to society is real: fewer emissions, lower dependency on fossil resources, and long-term resilience of industrial ecosystems - but it does not manifest as an immediately visible or functional improvement in the product itself.

For this value to be fully realized, society - including consumers, regulators, and investors - must internalize sustainability as a measurable asset, much like energy efficiency or safety standards. Only then can markets reward producers for circular, low-carbon products rather than purely commoditized goods, creating incentives for innovation and investment in low-impact industrial systems. In essence, embedded sustainability transforms the invisible advantages of system-conscious production into tangible societal benefits, even when the product's outward form and function remain unchanged.

2.7.2 Locus of responsibility for sustainability

Desirable industrial supply chains are circular rather than linear, designed to retain value, minimise waste, and close material loops across production, use, and end-of-life stages. True sustainability cannot be achieved by regulating isolated, linear actors, such as waste incinerators, landfills, or upstream raw material suppliers, because these measures target only isolated processes rather than the systemic patterns of resource use and impact. Circular economy research emphasises that sustainable supply chains must embed circular principles throughout the value chain, including product design for durability, reuse, remanufacturing, and recycling, to realise environmental, economic, and societal benefits[26].

In a globalised economy, industrial supply chains span multiple countries and jurisdictions, each with differing environmental standards, resource availability, and enforcement practices. To deliver meaningful sustainable outcomes without creating competitive distortions,

[26] Almelhem, M., Buics, L. & Süle, E. Comparison of sustainability and circularity indicators: downstream vs. upstream supply chain strategies. Discov Sustain 6, 302 (2025). https://doi.org/10.1007/s43621-025-01158-0

responsibility should be assigned as close to the consumer as possible, where it can influence product design, functionality, and end-of-life management such as embodied in Extended Producer Responsibility[27]. This aligns with the concept of product stewardship, which recognises that environmental impacts must be managed not just upstream but throughout the life cycle of the product itself. Regulatory focus should therefore establish a level playing field at the level of consumer products, rather than attempting to standardise upstream inputs, which are often subject to heterogeneous conditions and different national contexts.

Only when sustainability is embodied in the product itself, through verified low-impact materials, circular design principles, and measurable environmental performance, can consumers make informed choices. Tools such as environmental product declarations (EPDs) and similar life-cycle transparency mechanisms quantify a product's environmental footprint in a consistent and comparable way, enabling decision-making by consumers, market actors, and policymakers alike. These mechanisms rely on life-cycle assessment (LCA) to capture impacts from raw material extraction through disposal, and are increasingly referenced in sustainability policy and reporting frameworks to support transparent product evaluation.

By concentrating accountability at the product level and requiring consistent measurement, monitoring, and verification (MMV), sustainability becomes measurable, verifiable, and enforceable across diverse markets and jurisdictions, allowing products to be compared fairly regardless of origin. A product-focused regulatory approach, as exemplified by the Ecodesign for Sustainable Products Regulation (ESPR) in the European Union[28], seeks to embed circularity requirements, such as durability, reparability, and recyclability, into product design and information disclosure obligations, thereby supporting a competitive market where sustainable products compete on equal terms.

This downstream focus also creates systemic incentives for circular design, responsible materials selection, and resource-efficient production processes throughout the value chain, because upstream and midstream actors are indirectly held accountable through the product's verified environmental performance. Ultimately, this ensures that circularity and sustainability are tangible in the products society consumes, rather than in isolated nodes of a fragmented, linear system.

[27] https://www.oecd.org/content/dam/oecd/en/publications/reports/2024/04/extended-producer-responsibility_4274765d/67587b0b-en.pdf
[28] https://oneclicklca.com/en/resources/articles/ecodesign-sustainable-products-regulation-guide

3 Results of the TNO deep-dives in 3C-VaCS

TNO has performed a background analysis and three deep-dives. Combined with the background analysis these deep-dives should allow us to answer the research question in the discussion and conclusions in chapter 4.

Section 3.1	Deep-dive 1 Key molecules for producing sustainable carbon chemicals
Section 3.2	Deep-dive 2 on TCR supply chains for the chemical industry
Section 3.3	Deep-dive 3 on the availability of waste and biomass for chemical production

3.1 Deep dive 1 – Key molecules for producing sustainable carbon chemicals

As outlined in Section 1.4 the scope chosen for the TNO studies in the 3C-VaCS project is **the conversion of complex carbon-based waste- and biomass into high-value, carbon-based chemicals through the olefins and aromatics platform.**

In Appendix D (production from waste) and Appendix E (production from biomass) we have investigated pathways to produce olefins and aromatics from non-fossil resources.

Our deep-dive analysis shows that the key chemical precursors for producing non-fossil olefins and aromatics are **methanol**, **ethanol**, and mixed hydrocarbons (referred to in this study as **paraffins**). These same precursors are also highlighted in expert guidance on the future of sustainable carbon chemistry in the Netherlands [29].

For the Trilateral Chemical Region, the strategic significance is substantial: these precursors can be produced from a wide range of locally available complex feedstocks, including waste and biomass, supporting low-carbon and circular production pathways. At the same time, they can be imported at scale from other regions, reinforcing the region's ability to reposition itself within global value chains for sustainable chemicals.

The pathways to convert waste and biomass into methanol, ethanol, and paraffins have been extensively researched and developed, making them well understood within both academic and industrial communities. The technologies along these pathways exhibit varying levels of readiness, ranging from established industrial practice to pilot- or demonstration-scale deployment, reflecting differences in feedstock, process complexity, and product targets. This breadth of experience provides a strong foundation for scaling low-carbon and circular production routes while leveraging existing chemical and energy infrastructure.

[29] De toekomst van duurzame koolstof-chemie in Nederland, Sanne Akerboom, Gert Jan Kramer, Yvonne van der Meer, Arnold Stokking, Bart Strengers, Jacqueline Vaessen, Expertadvies, 31 maart 2025. https://www.rijksoverheid.nl/documenten/rapporten/2025/10/31/berenschot-de-toekomst-van-duurzame-koolstofchemie-in-nederland-expertadvies

3.1.1 Methanol, ethanol and paraffins are the bridge to sustainable chemicals production

Methanol, ethanol, and paraffins produced from waste streams and sustainable biomass can play a central role in displacing fossil-based feedstocks in chemical production. These molecules are fully compatible with large parts of the existing petrochemical value chain and can be converted into key building blocks such as olefins and aromatics through established processes, including methanol-to-olefins, ethanol-to-ethylene, and steam cracking of paraffinic feeds. As such, they offer a pragmatic transition pathway that leverages existing assets while reducing reliance on fossil carbon. How the three key precursors can form the new basis for the current pathways for chemicals production is shown in **Figure 3.1**.

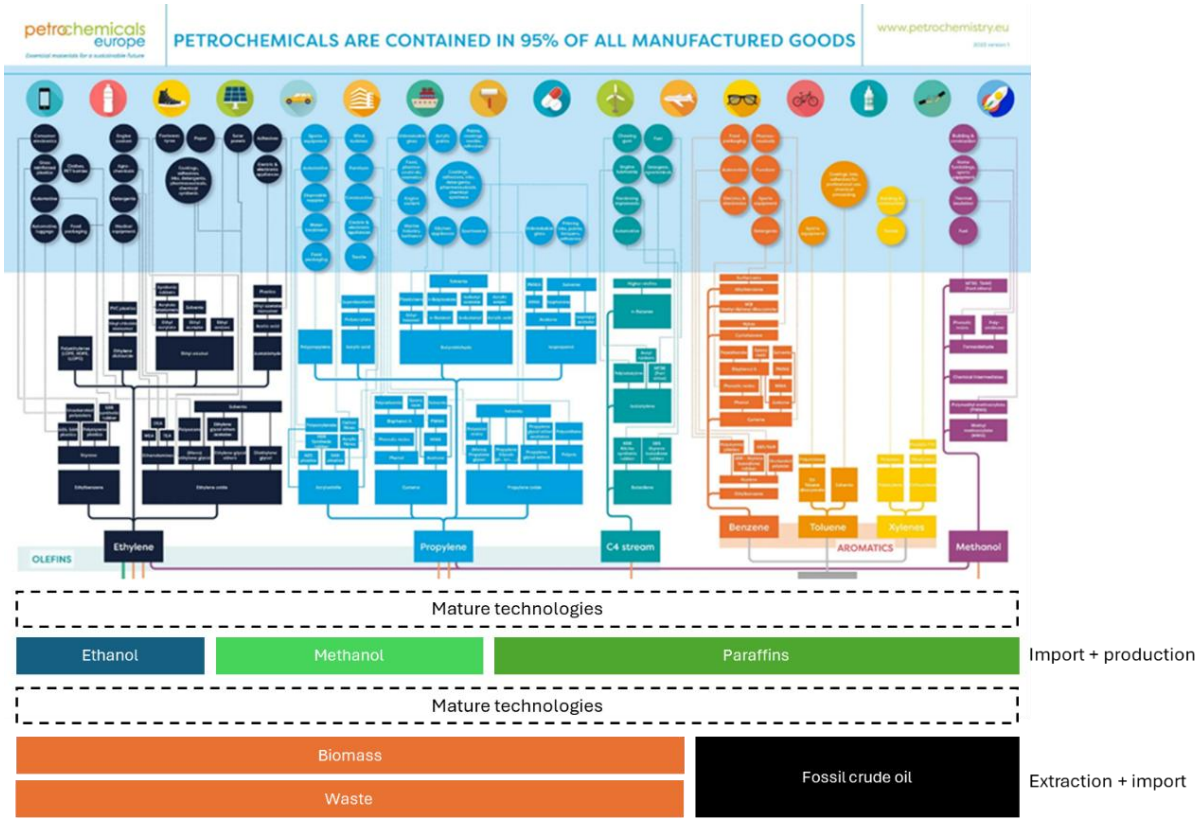


Figure 3.1: Ethanol, methanol and paraffins represent the extended feedstock platform for the chemical industry. This platform forms the bridge between waste, biomass and fossil resources.

When derived from waste or sustainably sourced biomass, these feedstocks introduce biogenic or recycled carbon into the chemical system, effectively substituting fossil inputs at the point of entry. Their use directly lowers the fossil carbon intensity of chemical production without fundamentally altering downstream process chemistry or product specifications. Over time, increasing shares of bio-based and waste-derived methanol, ethanol, and paraffins can progressively decouple chemical production from fossil feedstocks, particularly when combined with electrified conversion processes and renewable energy inputs. In this way, they act as scalable bridge molecules that enable a gradual yet structurally significant shift towards circular and low-fossil carbon feedstock systems.

When sustainability has become a standard for products rather than a feature, local waste and biomass will be the new strategic carbon resources. Combined with renewable electricity they are the basis to remain strategically relevant.

3.1.2 The current use of the key precursors

Methanol is primarily used as a feedstock for chemicals such as formaldehyde, acetic acid, plastics, and solvents, representing the largest share of global methanol consumption. Methanol is also a serious option as sustainable feedstock for producing olefins and aromatics, where so far China leads the way in development and deployment [30]. In addition, methanol is gaining attention as a fuel, particularly in shipping and industrial applications, due to its clean-burning properties and ease of handling.

Ethanol is one of the few large-volume chemicals where biological production is the norm rather than the exception. Around 75 % of global ethanol production is currently used as a fuel or fuel blend component, primarily in road transport. As electrification of mobility reduces fuel demand, existing ethanol production infrastructure could increasingly supply chemical and material value chains.

Paraffins are mixtures of (saturated) hydrocarbons, widely obtained as fractions from crude oil refining and lipid processing. These fractions find direct use in fuels, lubricants, and waxes, depending on chain length and branching. Among them, the naphtha fraction is particularly valuable today as a feedstock for chemical conversion, such as steam cracking, where it is transformed into olefins and other building-block chemicals. Longer-chain paraffins are also essential in specialty chemicals, surfactants, and high-performance lubricants, highlighting their versatility across both energy and material value chains.

3.1.3 Handling and global trade of the key precursors

Methanol, ethanol and paraffins are all well-established, widely traded commodities with large-scale production and distribution networks. Their extensive use as feedstocks for chemicals, fuels, and materials has led to mature transportation and storage infrastructure, including pipelines, terminals, tankers, and blending facilities. This existing infrastructure not only supports current demand but also provides a scalable foundation for future low-carbon and circular production pathways, enabling a rapid transition toward renewable or recycled feedstocks without the need for entirely new logistics systems.

3.1.4 The feedstock transformation trends for the production of fuels and chemicals

The fuels and chemicals industry has a strong structural preference for feedstocks whose molecular composition most closely resembles that of the final products. The closer a resource is, in molecular terms, to the desired fuels or chemical building blocks, the less conversion effort is required, resulting in higher carbon efficiency, lower energy demand, and ultimately lower production costs.

The legacy industry relies predominantly on fossil resources. Crude oil and natural gas are refined and separated into fractions that are either blended directly into fuels as blendstocks or further converted - most notably through cracking - into chemical feedstocks. Over

[30] Brovko, R.V., Sul'man, M.G., Lakina, N.V. et al. Conversion of Methanol to Olefins: State-of-the-Art and Prospects for Development. Catal. Ind. 14, 42–55 (2022). https://doi.org/10.1134/S2070050422010032

decades, this system has been optimised for efficiency, scale, and cost, with conversion routes and infrastructure finely tuned to fossil-derived molecules. This is shown in the top of **Figure 3.2**.

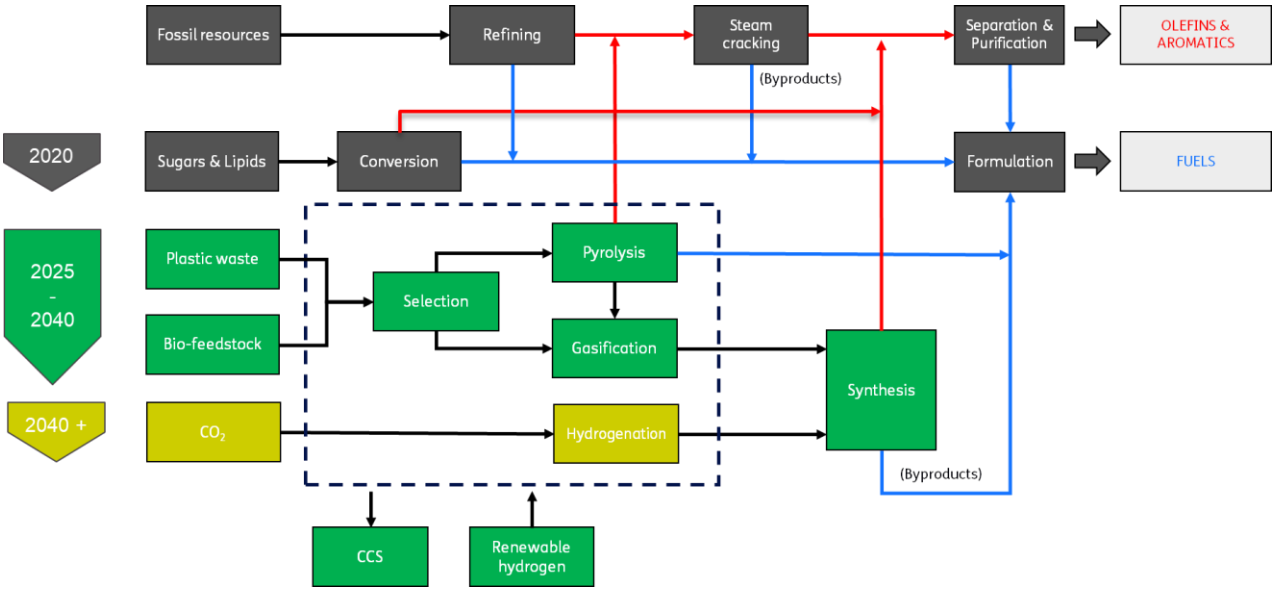


Figure 3.2: The evolution of feedstock resources, exchanging fossil for waste and biomass. The dark blocks represent mainstream pathways, the green are the next pathways to come into play as they can unlock the next category of feedstock (https://publications.tno.nl/publication/34644228/CrRTZakN/kranenburg-2025-circular.pdf).

Sugars and lipids represent the first and most mature category of non-fossil substitutes. Their molecular structures are already relatively close to those of conventional fuels. Ethanol produced via fermentation of sugars can be readily blended into petrol-type fuels, while lipids can be converted into HEFA and HVO and blended into diesel-type fuels or SAF components for aviation fuels. These conversion pathways are technically well developed, commercially deployed, and require only limited additional processing effort compared to fossil routes, resulting in relatively low incremental costs.

A subsequent category consists of plastic waste and bio-feedstock in the form of lignocellulosic biomass. The molecular structures of these resources are more heterogeneous and further removed from the target products in fuels and chemicals. As a result, their conversion requires more intensive processing, which typically leads to lower overall carbon efficiency and higher energy demand. Nevertheless, waste and biomass are attractive from a systems perspective, as they can introduce non-fossil and often otherwise discarded carbon into the production chain. Today waste and biomass are incinerated for energy, which in time can and therefore should be replaced by renewable electricity.

Beyond the milder conversion routes such as sugar fermentation and biomass hydrolysis, the two principal processing pathways for more complex waste streams and lignocellulosic biomass are pyrolysis and gasification. Owing to their harsh operating conditions, these processes are comparatively insensitive to feedstock heterogeneity and contamination, making them particularly suitable for mixed and low-grade carbon resources. They are most effectively deployed in close proximity to enable heat and energy integration, internal use of intermediates and by-products, shared feedstock preparation infrastructure, and the

controlled blending of biomass and plastic waste streams to achieve feedstock compositions that are suitable for stable and efficient operation[31].

Pyrolysis yields bio-oils, char, and non-condensable gases. Bio-oils can be upgraded and integrated into existing refinery or steam-cracking infrastructure, either as chemical feedstocks or as blending components for fuels, while char and off-gases can be utilised as internal energy carriers or routed to gasification. Gasification, by contrast, converts solid or heterogeneous feedstocks into synthesis gas (syngas), which constitutes a universal starting point for synthetic chemistry and enables the synthesis of a wide range of fuels and chemical intermediates. The close integration of pyrolysis and gasification therefore supports flexible feedstock allocation, maximises carbon and energy efficiency, and underpins the development of scalable non-fossil pathways to fuels and chemicals.

Although pyrolysis and gasification can internally supply a significant portion of their process energy by combusting part of the feedstock, this approach inherently reduces the overall carbon efficiency. Oxidation of carbon-containing components releases CO_2, which represents a loss of valuable carbon that could otherwise be retained in fuels or chemical products. Since these processes typically produce relatively concentrated CO_2 streams, a logical first step to mitigate emissions is the implementation of carbon capture and storage (CCS), which can prevent a substantial fraction of the carbon from being released to the atmosphere.

Beyond CCS, the way to increase the carbon yield for processing is hydrogen injection. Such improvements in carbon efficiency then depend on the availability of renewable electricity. Hydro-deoxygenation, for example, removes oxygen from biomass streams through reaction with hydrogen rather than oxidation, preserving more carbon in the product streams and significantly increasing the overall carbon yield.

Taken together, these strategies illustrate a progressive pathway: from reliance on feedstock-derived energy, to partial carbon mitigation via CCS, to full electrification and hydrogen-assisted conversion, each step incrementally improving the carbon efficiency of pyrolysis and gasification-based routes and bringing them closer to fully circular, low-fossil-carbon operation.

Finally, once the sustainable potential of sugars, lipids, waste, and biomass has been fully exploited and further reductions in fossil resource use are required, carbon dioxide itself may become a feedstock. Converting CO_2 into fuels or chemicals is only viable if sufficient low-cost renewable energy is available, as these pathways are highly energy-intensive. In such a future system, CO_2 conversion would represent the most resource-distant but also the most circular option, enabling the closure of the carbon cycle when all higher-efficiency alternatives have been exhausted.

3.2 Deep dive 2 - Chemicals production in the TCR is entwined in global supply chains

We have investigated the production of chemicals and use of naphtha feedstock within the TCR and the trade with the rest of Europe and the rest of the World. This would enable us to

[31] Co-processing plastics waste and biomass by pyrolysis–gasification: a review. Peter Nai Yuh Yek, et al. Environmental Chemistry Letters (2024) 22:171–188

assess on a product-basis the relation between production in the TCR and global trade and therefore the exposure to change drivers that affect products and their markets.

Appendix A is an extract of the data on production and trade of chemicals and the use of feedstocks in chemicals production that was produced in the 3CVaCS project. The full data set is not published as it is not sufficiently self-explaining, it is available from TNO on request.

Based on this data we aimed to understand dependencies and potential vulnerabilities of the chemical industry supply chains, which can be used to develop effective mitigation strategies. For this it is important to gain visibility on supply and demand flows, as well as interconnections of key chemicals and feedstock fulfilled both from local production and from global trade.

This deep-dive should then enable us to perform these three assessments:

Section 3.2.2	How sustainable carbon feedstock can propagate along the supply chain from resources towards consumer products through the TCR/European asset-base of the global chemical industry
Section 3.2.3	How TCR regions are specialised and linked
Section 3.2.4	Which sections of the TCR/European supply chain may be most vulnerable to disturbances caused by the parallel transitions, especially related to CO_2 pricing and clean energy mandates

3.2.1 General findings about data collection on capacities, actual production and trade

Much of the detailed operational data in the chemical industry is proprietary and of critical strategic importance to the companies that it concerns. For these businesses, such data is so commercially sensitive that they would not share it with this project.

We did obtain data from public sources: from national statistical offices, regulatory filings, and other official sources such as environmental permits. However, these public datasets often contain inconsistencies or gaps that reflect the need to protect commercially sensitive information.

While countries collect and publish data, it is usually not available on a level of regions (Flander, North Rhine-Westphalia). This limits the possibility to produce insights from data for the Trilateral Chemical Region only. For the Netherlands the earlier MIDDEN project (2018-2021) has delivered detailed qualitative and quantitative mapping of its industry sectors. For Germany and Belgium similar information is available about the clusters in publications of the Wuppertal institute, but raw data has not been published.

We base this deep-dive on the public data that we could retrieve from public sources. The main results on three assessment topics are summarised in sections 3.2.2, 3.2.3 and 3.2.4.

3.2.2 The propagation of sustainable carbon along the TCR's supply chains

The petrochemical pathways of **Figure 2.4** describe the technical and chemical relationships between molecules - how feedstocks are converted into olefins, aromatics, and their derivatives - while remaining largely agnostic to how these molecules are produced, traded,

and distributed across global supply chains, or how assets, regions, and market structures are organized at system level.

In this work we aimed to construct a map of how chemicals production is organized in the Trilateral Chemical Region, however primary data appears insufficient as we indicate in Appendix A. Hence below we reflect the literature.

For the Netherlands, the MIDDEN reports provide the installed **production capacities** shown in **Figure 3.3**. Important to note that the numbers are not the actual production for a particular period. While for some products the actual production may be obtained from the PRODCOM database, many are not shown because when there are too few producers, the actual production of competitors may be derived from own production data. Any attempts to derive an actual flow map though calculation are therefore necessarily an estimate, as we have done for the preparation of **Figure 3.9** of Section 3.2.4. in this work.

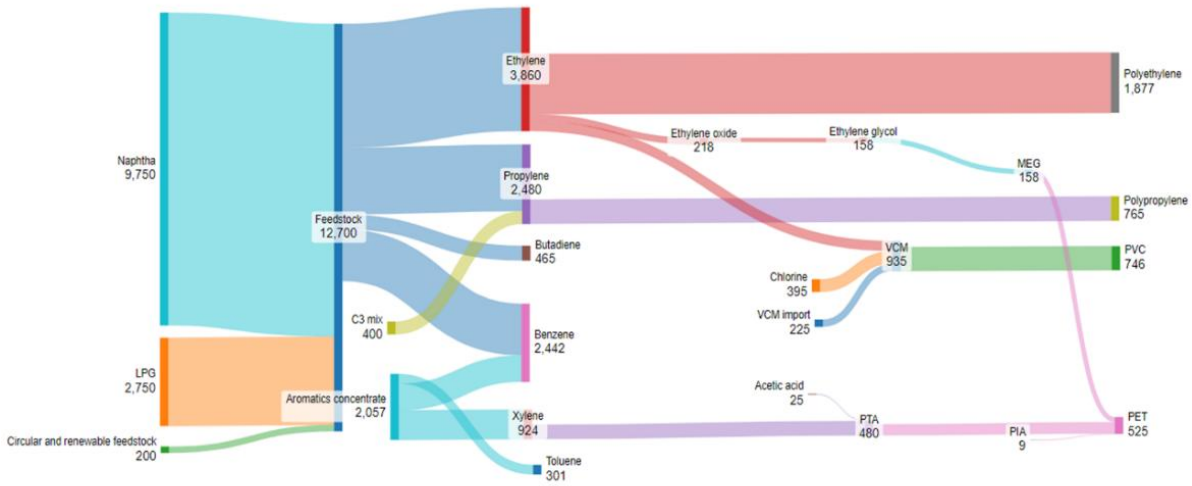


Figure 3.3: Installed production **capacities** (kton per year) for chemicals in The Netherlands 2018 (based on data from MIDDEN Decarbonisation Options for Large Volume Organic Chemicals Production reports)

Such an estimation effort was undertaken by the Wuppertal Institute for the German chemical industry, as shown in **Figure 3.4**. This Sankey diagram shows the **estimated production** of chemicals in the year 2018. The diagram seems incomplete because not all inputs to each node in the diagram can be matched with outputs, which illustrates the shortcomings of the approach.

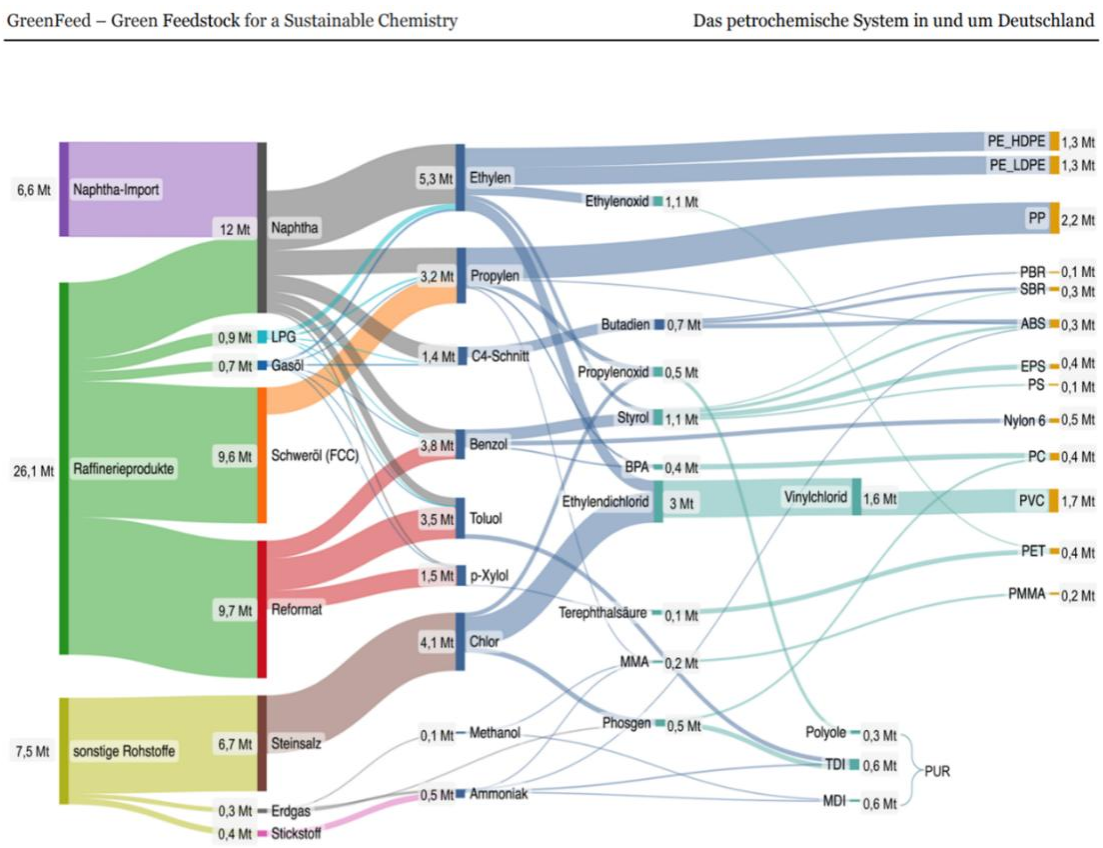


Abb. 2-2 **Sankey-Diagramm zur Polymerproduktion in Deutschland. Die Werte entsprechen modellierten Produktionsmengen im Jahr 2018.**

Figure 3.4: Sankey diagram of polymer production in Germany, showing **actual** production data for 2018.

For the Sankey diagram do the Antwerp cluster, shown in **Figure 3.5**, the authors apparently had even less data to build and could not provide estimated numbers. As they indicate the diagram was constructed through calculating the mass flows and make a remark about the 'entsprechenden Unsicherheiten' (respective uncertainties) that should be taken into account using the information in the diagram.

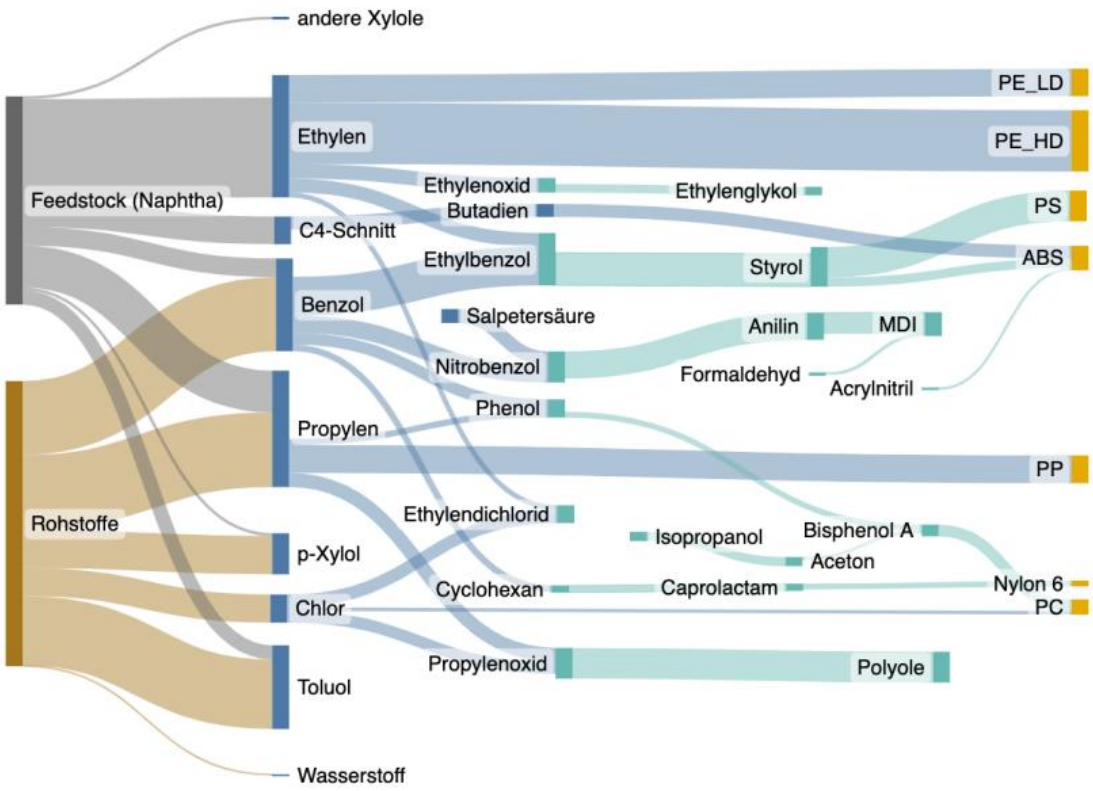


Abb. 10-3 **Sankey-Diagramm zur Produktion innerhalb des Clusters Antwerpen.** Alle hier dargestellten Produktionsvolumina und -Prozessketten basieren auf eigenen Modellergebnissen und sind mit entsprechenden Unsicherheiten behaftet. Die Ausgangsbasis "Rohstoffe" ist hier als Sammelbegriff für Inputstoffe wie Rohöl, Erdgas, Biomasse, Salze etc. zu verstehen, die sich von dem Feedstock Naphtha abgrenzen.

Figure 3.5: Sankey diagram of the Antwerp chemical cluster, taken from[37] and probably representative for Belgium as a whole since the chemical industry is centred in Flanders. The publication shows no numbers, likely because of uncertainties. Also, resource data seems to be aggregated upwards from available data.

Given the uncertainties in each region, it would not be justified to combine these diagrams into one in an attempt to create a picture of the Trilateral Chemical Region as a whole. What does become clear from the above Sankey diagrams is that they show similar products and structure, and follow the petrochemical pathways in **Figure 2.4**, as was to be expected. Also the regions have overlapping capabilities not only to produce the olefins and aromatics, but also their derivatives.

What cannot be seen in these Sankey diagrams is where the production centres are located. This is shown in a map of **Figure 3.6**, indicating the pipeline connections of regional clusters for ethylene, propylene and naphtha. However this map does not show how the cluster as a whole is connected to the Rest of Europe and the Rest of the World through trade of the derivatives from olefins and aromatics.

Focussing on the propagation of sustainable carbon feedstock into the supply chains, it does become clear that providing sustainable varieties of ethylene, propylene and naphtha into the network will make all embedded carbon in the derived products sustainable.

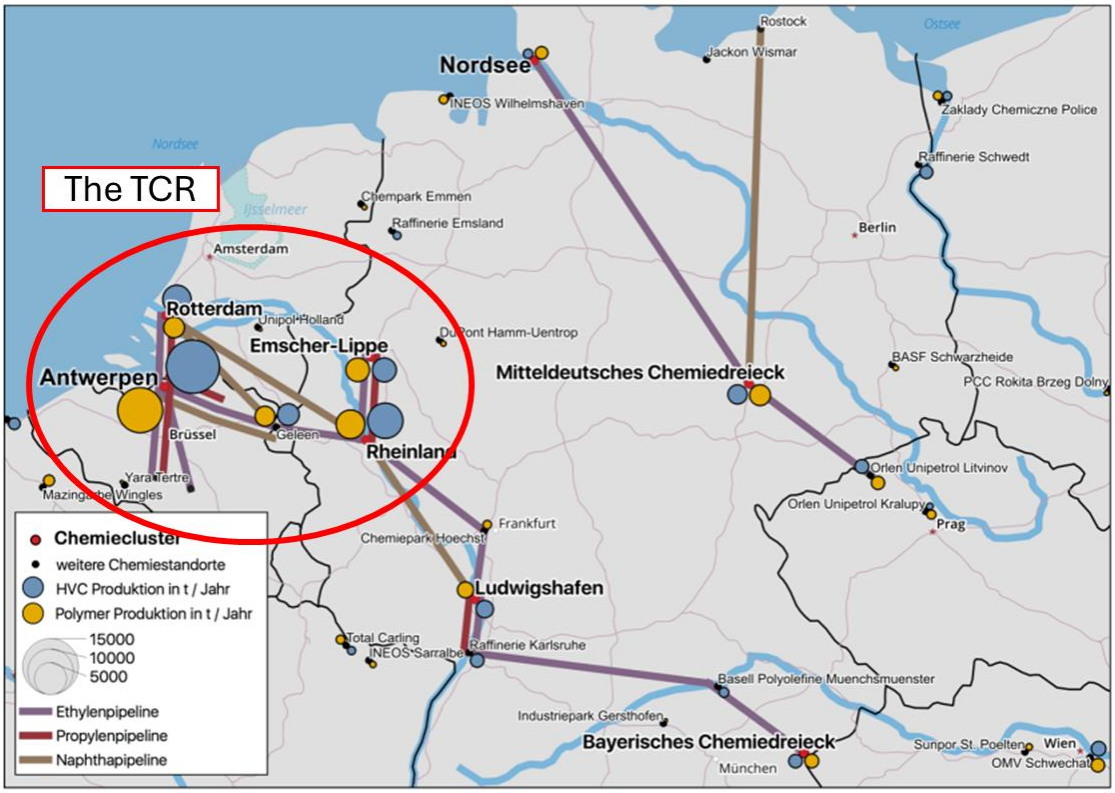


Abb. 2-1 **Überblick über alle relevanten Chemiestandorte und Erdölraffinerien in und um Deutschland, inklusive Produktionsvolumen an High-Value-Chemicals und Polymeren sowie infrastruktureller Verflechtungen.**
Quelle: Eigene Darstellung auf Basis eigener Modellrechnungen.

Figure 3.6: The industry clusters in North Western Europe, indicating the Trilateral Chemical Region, adapted from [37].

Conversion to sustainable production

In the quest for sustainable products and competitive production, the extensive pipeline network for ethylene & propylene and the infrastructure for transporting other chemicals by road or waterways can be an excellent basis for producing the products from *sustainable carbon* that is provided through *sustainable* olefins and aromatics produced from *sustainable* **methanol, ethanol and paraffins** (see Section 3.1) that are derived from waste and biomass.

The circular carbon commodities methanol, ethanol and paraffins are key molecules in the transformation to non-fossil carbon products. They can be the basis of all fuels and chemicals the region will need:

- Imported from overseas in large volumes, avoiding competition for resources with the fuels industry, through the existing ports infrastructure.
- Production from local waste and biomass resources in various European inland locations and supply to the chemical industry through the infrastructure.

The opportunity for the chemical industry in the Trilateral Chemical Region is then to reduce the **CO_2 footprint of its products**, not only through the electrification of heat and power generation in its processes, but enabled through the intake of non-fossil feedstock.

3.2.3 How TCR regions are specialised and linked

We aimed to explore the interconnections between production sites and the specialization patterns of industrial clusters and regions. Our approach focused on analysing supply chains at the product-node level, in order to capture the detailed linkages and flows that connect local, regional, and global production networks. Examining the system at this level would be particularly valuable for understanding business dynamics, as it reveals how products, processes, and capabilities interact across the network, highlighting dependencies, opportunities for optimization, and points of strategic leverage within clusters and regions.

For ethylene and poly-propylene we have been able to derive Sankey diagrams that reflect the flows between TCR regions and with the rest of the world. **Figure 3.7** shows the Sankey-node diagram for the actual ethylene production in 2019. Ethylene produced within the TCR is mainly converted further locally or traded within the TCR via the ARG pipeline network. Limited trade takes place with other EU or rest of world regions, likely due to the cost involved with cryogenic transport of ethylene. Ethylene is heavily traded between TCR regions, however this trade may mean transfer of ownership title rather than actual flow of materials, this could not be made certain at this moment.

The Netherlands exports large volumes of ethylene to Germany and Belgium. Germany subsequently exports large volumes to Belgium, where further conversion takes place. Majority of the EU trade is with France and Finland and majority of the rest of world trade is with the UK and Norway. Belgium importing and subsequently further converting large volumes of Dutch and German ethylene suggests a stronger downstream specialisation for the Flanders cluster compared to the Dutch and German clusters.

It is noteworthy that in 2019 the registered ethylene production in the Netherlands was 2012 kt (see **Figure 3.7**), while the production capacity was 3860 kt (see **Figure 3.3**). This points to an average capacity utilization of 52%, which is very low compared to the usual industry targets, which are usually 75 % or more. Maintenance stops may be an explanation, however this was not verified.

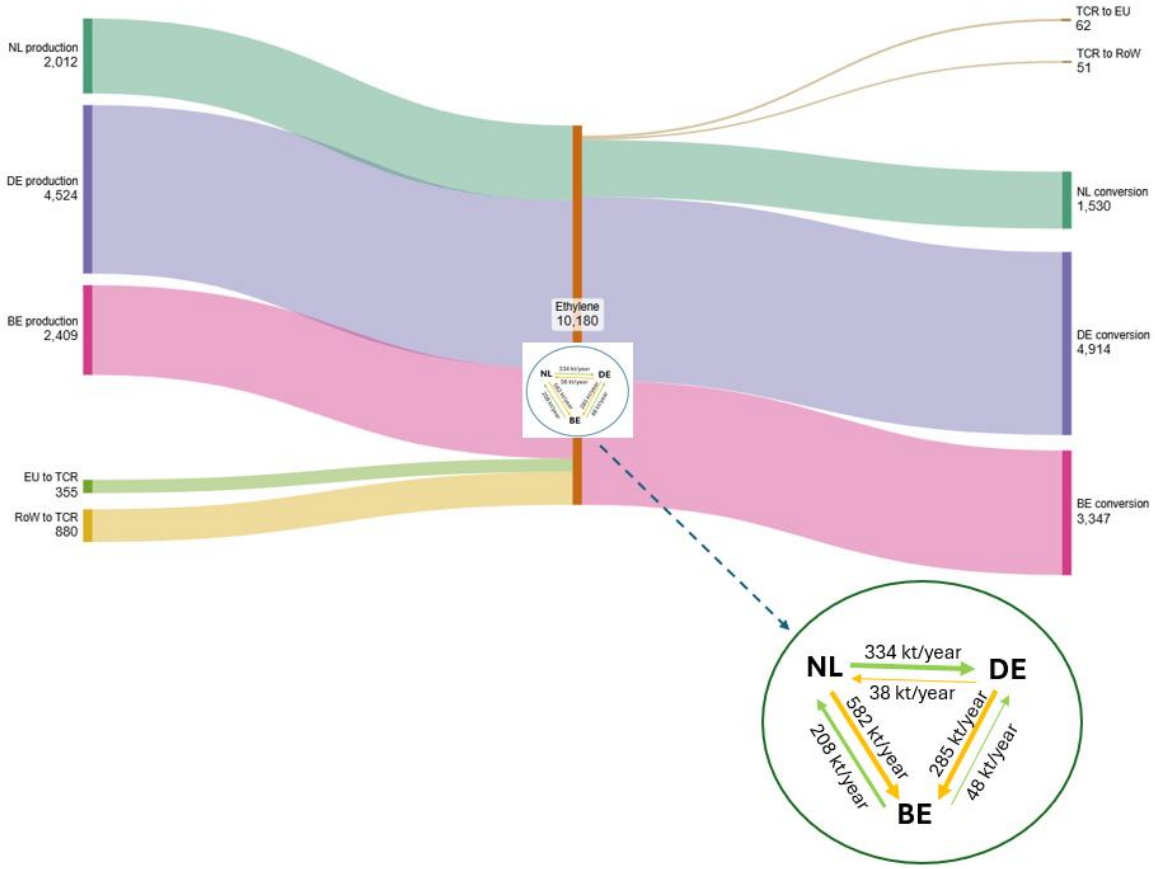


Figure 3.7: Product-node Sankey diagram for the actual production of ethylene in 2019 in TCR countries. This shows the actual production, not the production capacity.

Figure 3.8 shows a product-node Sankey diagram for poly-propylene. More substantial trade with EU and non-EU regions is observed for poly-propylene as compared to ethylene. Poly-propylene is an easy-to-transport, commodity product, with trade volumes largely going to Italy, Spain, Poland, and China. Belgium exports significant volumes to Germany, with less volumes going to the Netherlands.

This may be similar for other products further down the value chain, where transport is less challenging due to the nature of the molecules.

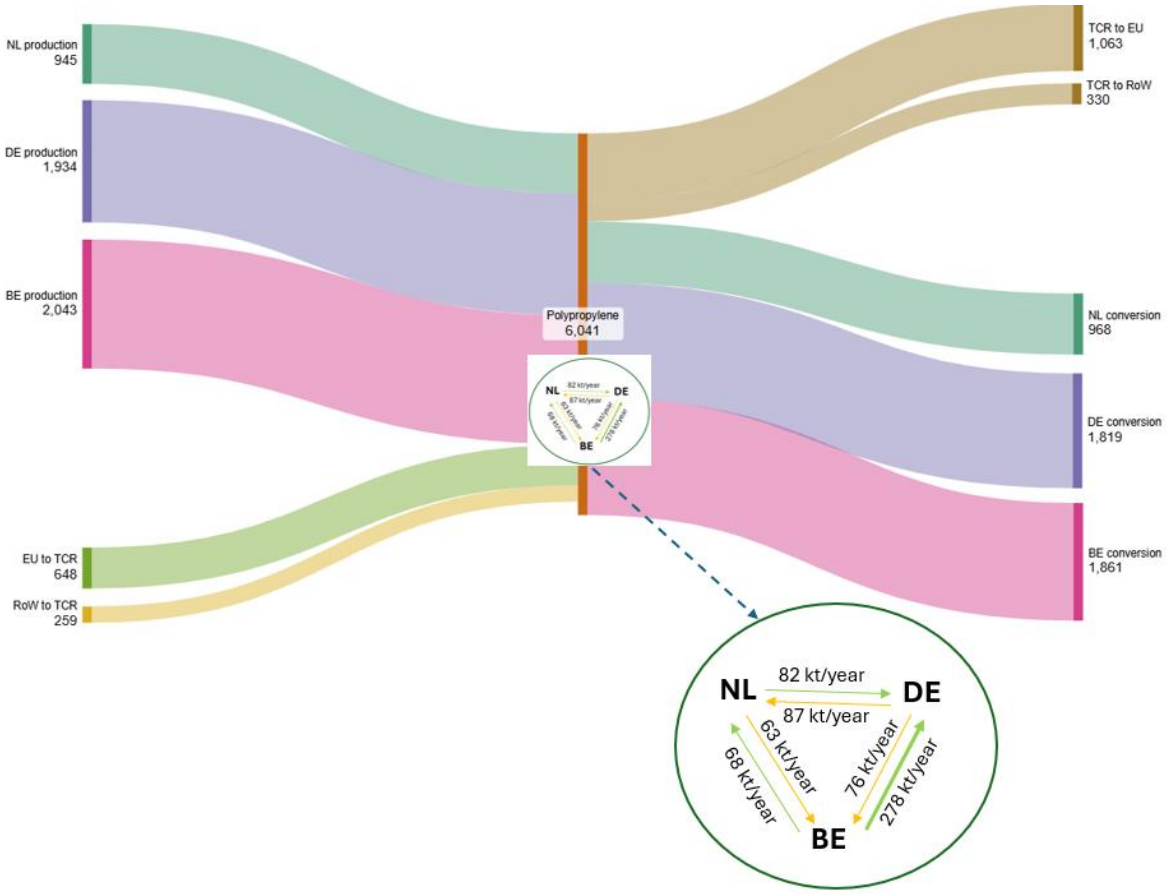


Figure 3.8: Product-node Sankey diagram for the actual production of **poly**-propylene in 2019 in TCR countries. This shows the actual production, not the production capacity.

Ideally, we would have created a data-set and analysis to perform such analysis for each (key) chemical product in the TCR, allowing for a products-level analysis of clustering and global positioning in trade flows. Although we do believe that the goal is achievable, we did not manage to extend this analysis beyond ethylene and propylene due to limitations of available data and the required effort.

3.2.4 Vulnerability of supply chain sections for import

Another dimension of vulnerability arises from the displacement of local production by imports, driven by competitive pricing in both contracted supply and spot market trading. At the product-node level, data would enable a more precise assessment of the techno-economic feasibility of such imports, as well as the evaluation of potential mitigation measures at the level of individual production sites, including alternative sourcing, local capacity adjustments, or resilience-enhancing investments.

To investigate this from the available data, the Sankey map of production capacities for the Netherlands (**Figure 3.9**) was scaled based on the known input of naphtha and LPG in 2019 (**Figure A.4**), and complemented with the trade data on the product nodes. Each node now shows the origin of the supply and the destination of the demand. The origin of supply may either be import or production within The Netherlands, and the destination can be export or further conversion to other chemicals along the petrochemical pathways. The end-node “NL Conversion 2,177 (ktpa)” in the bottom right indicates to further conversion in The

Netherlands that we did not specify in this diagram. The resulting diagram is shown in **Figure 3.9**.

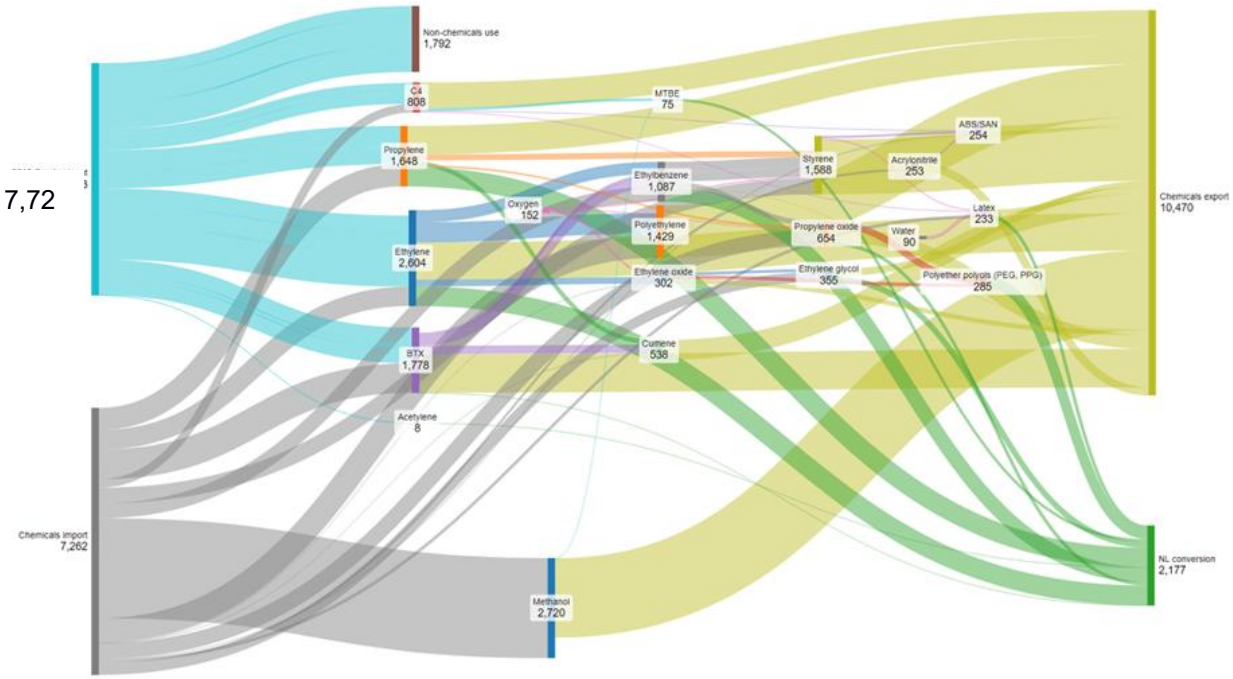


Figure 3.9: Sankey diagram for the Netherlands, combining data about chemicals production and trade (ktpa) in 2019.

The supply of olefins (ethylene, propylene, C4) and aromatics (BTX) is produced by Dutch crackers and imported. For the production, in 2019 these crackers consumed 7,720 kt input of fossil origin: naphtha, LPG and NGL, see Figure A.4 of Appendix A. The import of olefins and , aromatics complements the production to satisfy the demand.

The total demand for olefins and aromatics is from local conversion and from export. As **Figure 3.9** shows, a significant share of the demand is from exports, while the smaller share is converted within The Netherlands to chemical intermediates. The export of olefins from The Netherlands remains mainly within the Trilateral Chemical Region. Shown in this diagram, the conversion of olefins in The Netherlands is mainly to polyethylene, polypropylene, and ethylbenzene & styrene and ethylene oxide. Propylene oxide according to the diagram is mainly imported and partly converted to polyether polyols, while the remainder is likely exported.

We notice in the diagram that a major share of chemicals import is methanol, and most of the methanol is re-exported. The Netherlands has no active production of methanol [32]. Also we notice that this diagram does not show chemicals that are only produced locally for local consumption, like hydrogen or the very toxic phosgene.

Clearly the chemicals imports take place in all layers of the industry. This highlights the global character of the chemical industry, that allows it to optimize its position in supply chains through a combination of local production and trade. While on the one hand this strengthens supply chains, it also makes the local production vulnerable when market conditions see a

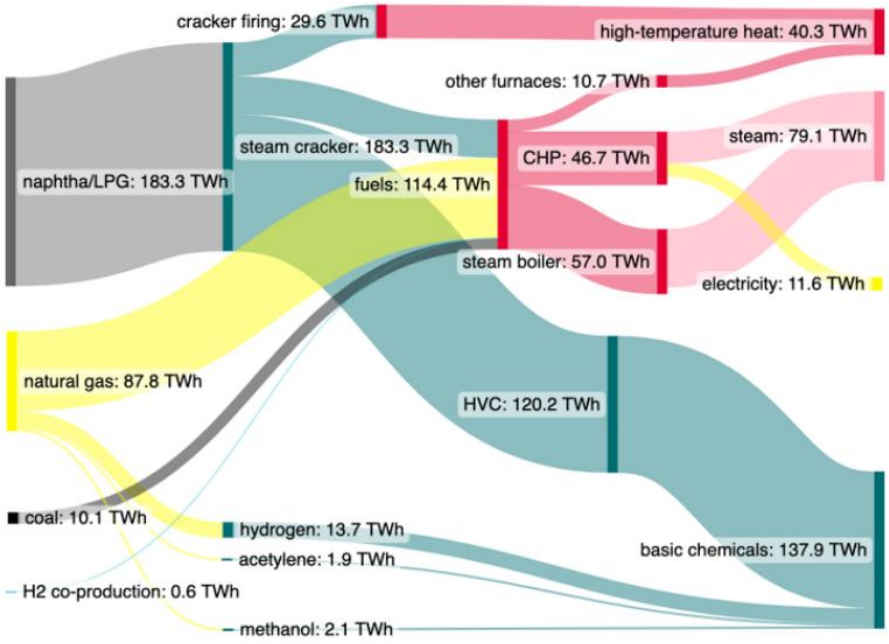
[32] The production capacity in Delfzijl has been ‘mothballed’.

significant shift in cost structures, as the system allows to respond by scaling production between regions.

Our deep-dive on supply chains has shown that the available data should allow to dissect the global network of chemicals production and trade by country. Today, the regional granularity of the TCR is not achievable because the data is not publicly available. Therefore after an initial effort it had to be deprioritised within the scope of this project in the perspective of the main research question.

Analysis of energy demand

The intention was to analyse sections of the supply chains in the TCR for their vulnerability for disturbances by the multiple transitions of Section 2.1, especially CO_2 emission pricing and clean energy mandates. The work would have allowed to analyse sections of the supply chains on a product-level to assess the energy demand, similar to the work of Scholz by the Wuppertal institute[38] and shown as an example in **Figure 3.10**.



Sankey diagram of modeled primary energy demand for the production of basic chemicals in Germany in 2018. Data refers to the complete chemical industry without pharmaceuticals. External electricity procurement is not included here. Source: Translation of previous work (Scholz et al., 2023).

Figure 3.10: Primary energy demand of the German basic chemicals production, taken from [38].

A deeper analysis of the energy demand for each production step in the chemical pathways could reveal the vulnerability of each node in the supply chain for CO_2 emission pricing and the possibilities to use renewable electricity. This may reveal the sensitivity of individual nodes to emissions pricing and renewable energy mandates, and allow to assess whether, or how, the downstream nodes in the supply chain can remain competitive in the global network.

At this moment a collection of such detailed public data about the industry is not available, and the effort to collect, validate and harmonize it is beyond the reach of this work.

3.3 Deep dive 3 - Waste and bio-based feedstock availability in the TCR for synthetic chemistry

If the chemical industry of the Trilateral Chemical Region is to displace fossil feedstock, it will need waste and biomass as carbon source.

Appendix B and Appendix C are an analysis of the availability of waste and biomass in The Netherlands, Germany and Belgium. Data for the availability on a regional level is not readily available as public information.

3.3.1 Carbon potential from biomass

While there are more biomass categories defined, ligno-cellulosic biomass is a sufficiently defined category, and also taken as basis for the estimates of conversion efficiencies in section 2.4.4. For the three countries of the TCR we estimate the potential between 60 Mt to 100 Mt dry biomass, which corresponds to 30 Mt to 50 Mt carbon. These refer to potentials that comply with the sustainability criteria introduced under Renewable Energy Directive (RED) for use in transport sector and correspond to 2030 as outlined in Appendix C .

Table 3.1: Estimate of ligno-cellulosic biomass availability and carbon content

Ligno-cellulosic biomass				
2030 estimate	**Low**	**Medium**	**High**	
Netherlands	2867	2520	4833	
Germany	53083	66023	85816	
Belgium	3683	3406	6136	
Lignocellulosic biomass	59633	71949	96785	kt (dry)
	60	72	97	Mt (dry)
Carbon content	50%			
Carbon	29817	35975	48393	kt
	30	36	48	Mt

3.3.2 Carbon potential from plastic waste

Plastics are produced, used, recycled and disposed of. This results in a complex cycle with hold-up, in-flows and out-flows. The best estimate for the availability of plastics waste to follow the pyrolysis and gasification pathways is the flows that are currently disposed of through incineration and landfill. These are shown in **Table 3.2** and are in the order of 5 Mt waste, corresponding to about 3 Mt carbon. They refer to 2023 and are explained in Appendix B.

Table 3.2: Plastic waste potential based on current waste streams to energy recovery and landfill, data form Appendix B

2023 data	Energy recovery	Landfill	Total	
Netherlands	684	2	686	kt
Germany	3500	34	3534	kt
Belgium	382	10	392	kt
			4612	kt
			5	Mt
			70%	Carbon
			3228	Kt C
			3	Mt C

3.3.3 Plastics and chemicals production volume in the TCR's countries

Appendix B contains data on the plastics production in the three TCR countries. Combining the production data, an estimated total of 23 Mt plastics is produced, corresponding to roughly 16 Mt of carbon.

Table 3.3: Plastics production in the TCR's countries, data taken from Appendix B for 2023

	Production	(2023)
Netherlands	5519	
Germany	10420	
Belgium	7282	
Total	23221	kt Plastic
	23	Mt Plastic
	70%	Carbon
	16255	kt Carbon
	16	Mt Carbon

Some 90 % of the entire petrochemical output (which is dominated by olefins and aromatics) ultimately goes into polymers[33]. Therefore the total carbon demand for olefins and aromatics may be estimated in the order of 16 Mt / 90% = **18 Mt carbon demand** for the current chemical industry in the countries of the TCR.

[33] J.-P. Lange, Towards circular carbo-chemicals – the metamorphosis of petrochemicals, Energy Environ. Sci., 2021, 14, 4358-4376

3.3.4 The volume of carbon in fuel products

The volume of carbon in chemicals needs a perspective of the volume of carbon in other products. A detailed analysis is certainly beyond this work, however an estimate would be useful to provide a context.

A very rough estimate of carbon content in products that are not chemicals may be derived from the CO_2 emissions of the countries, by dividing by 3,67.

Table 3.4: Context of carbon in products of the chemical industry

	CO_2_e emission	Carbon content
	Mt	**Mt C**
Netherlands	150	41
Germany	670	183
Belgium	100	27
Total	920	251

With a total carbon mass of around 250 Mt C, as derived above from the CO_2 emissions, it becomes clear that even with a large margin of error the carbon in products of the chemical industry is less than 10% of carbon in all products that eventually incinerated.

Much of this demand should be expected to electrify when mobility, domestic heating and industry make the energy transformation. Still then a large amount of carbon will be required to satisfy the demand for fuel products in heavy duty applications, aviation and shipping. Clearly this amount of carbon would exceed the supply from biomass and waste in the countries of the Trilateral Chemical Region.

This means that, just to fulfil the carbon balance, imports of waste, biomass and the derived ‘circular carbon commodities’ like methanol ethanol and paraffins will be necessary - just like oil and gas today.

4 Discussion and conclusions

The research question of TNO's contribution to the work in the 3C-VaCS project is:

How can chemical conversion pathways in the Trilateral Chemical Region be reconfigured to enable resilient, non-fossil supply chains for sustainable consumer products, while building on existing chemical production infrastructure and reducing exposure to geopolitical risks?

In this section, we discuss this research question by its separate elements.

4.1 Sustainable consumer products

The objective for industry is to produce sustainable consumer products, as brought forward in Section 2.7.

To date, regulatory attention for the chemical industry has focused predominantly on greenhouse-gas emissions from the production phase. This has been pursued through CO_2 (and CO_2-equivalent) pricing, alongside mandates for energy-efficiency improvements, increased use of renewable electricity, and the adoption of green hydrogen. In effect, governments have mainly concentrated on prescribing **how** products should be produced. While this has driven important efficiency gains and innovation, it has also led industrial companies to rationalize global production activities in response to regulatory differences. Relocation of production and the risk of carbon leakage are rational outcomes of a framework that targets production emissions in isolation, rather than the sustainability of the product itself.

For carbon-based products, most notably organic chemicals such as plastics, this production-centric focus misses a critical part of the system. For these products, a major share of lifecycle CO_2 emissions, on the order of 60%, does not arise during manufacturing, but at end-of-life, when products are incinerated to recover their energy value. The energy obtained in this way, typically low-temperature heat or electricity, is of relatively low quality and should, in a sustainable future, be supplied by renewable sources such as wind or solar. From a chemical and thermodynamic perspective, incineration represents a full oxidation of carbon-based molecules, permanently destroying their molecular structure and the high-quality chemical energy embodied in them. Recreating this molecular quality, through carbon capture, hydrogen production, and synthesis, is energy-intensive and costly. From a systems viewpoint, therefore, incineration is a highly inefficient use of carbon and should be avoided wherever possible, as reflected in the Waste Framework Directive[34] that sets incineration below recycling.

To have sustainable consumer products, it may be more effective to shift the regulatory focus from production processes to product standards that reflect sustainability across the entire life cycle. Such an approach would complement the current approach of 'telling industry how to produce' with specifying **what** should be produced in sustainability terms. Once these

[34] DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098

boundary conditions are clear, industry is well positioned to reorganize supply chains, technologies, and business models to deliver compliant products at least cost and maximum value for consumers. In doing so, responsibility for sustainability moves closer to the point of consumption, explicitly acknowledging the shared responsibility of producers and consumers in shaping material demand and waste pathways.

Importantly, life-cycle-based product standards would also create a more level playing field for globally operating industries. Rather than regulating production locations, they would regulate products placed on the market, independent of where they are made. Such standards could, for example, be based on criteria like the absence of fossil carbon content, high circularity, or demonstrable long-term carbon retention. In this way, policy would align market incentives with system efficiency, preserving molecular value, reducing end-of-life emissions, and supporting a structural transition toward a circular, low-carbon industrial system.

To fully realize the embedded sustainability of these commodities, a distinct standard must be established to differentiate them from fossil-derived equivalents. These standards would capture the intangible value of low-carbon feedstocks - reflecting reduced lifecycle emissions, circularity, and preservation of molecular carbon - while ensuring that the sustainability claims are verifiable and enforceable. By formalizing this value through standards, markets can recognize and reward products that carry real system-level benefits, creating transparency for regulators, consumers, and industry alike, and providing a credible foundation for the scaling of circular and bio-based chemical and fuel production.

4.2 Non-fossil supply chains for both chemicals and for fuels

Carbon-based molecules remain indispensable for products both the chemicals and fuels sectors. Historically, these industries have evolved hand-in-hand, with the petrochemicals sector largely following the trajectory set by fuels production. Fossil fuels provided both the energy to drive chemical processes and the carbon feedstock for a vast array of synthetic molecules. This interdependence has defined industrial growth for over a century, making carbon the central nexus of energy and material production.

Looking forward, much of the fuel demand for mobility, heating, and industrial energy can and likely will be electrified, driven by breakthroughs in materials science that have made electricity generation, storage, and conversion increasingly cost-competitive and efficient. However, certain sectors, aviation, deep-sea shipping, and possibly some heavy-duty land transport, will continue to require carbon-based fuels due to their high energy density and storage advantages. Consequently, carbon-based molecules will remain a scarce and strategically important resource, needed simultaneously for both fuels and chemicals.

As both sectors pursue sustainability targets, they will inevitably compete for the same - sustainable carbon resources. Yet, this competition need not preclude collaboration and synergy. Significant synergies also exist in chemistry pathways that produce high-value molecules from renewable or waste carbon streams. Aligning the fuels and chemicals sectors around these pathways can preserve shared benefits while avoiding redundant investment in separate feedstock infrastructures. Current legislation determines which feedstocks are eligible for maritime and aviation fuels, e.g. plastic waste based fuels are not eligible. The consequences of this regulation for the effective co-development of fuels and chemicals industry needs to be assessed.

A natural first step is the establishment of integrated facilities that recover carbon from complex waste and biomass streams through pyrolysis, gasification, or other thermochemical conversion technologies. Early-generation facilities should focus on demonstrating the technical feasibility of integration between waste streams, conversion processes, and downstream chemical synthesis. Subsequent generations can improve carbon efficiency by incorporating hydrogen processing, unlocking higher-value molecules and enabling more flexible fuel and chemical production. These facilities form the backbone of supply chains that divert carbon from incineration, preserve its energy and chemical quality, and maximize its life-cycle value.

In terms of resource availability, for chemicals production alone, the countries of the TCR indicate a domestic requirement of roughly 18 Mt C. Potential feedstock sources include ~3 Mt C from waste streams and 30–50 Mt C from biomass, suggesting sufficient local capacity to satisfy chemical demand. Fuels, by contrast, will require multiples of this carbon volume, necessitating the development of global supply chains for sustainable methanol, ethanol, and paraffin-type molecules. Together, these strategies illustrate a joint opportunity for fuels and chemicals: leveraging the same sustainable carbon resources through integrated, circular, and system-optimized pathways, thereby preserving molecular value and advancing both industrial sectors toward net-zero futures.

4.3 Existing production infrastructure

The legacy production infrastructure of the Trilateral Chemical Region, and more broadly of the ARRRA cluster, represents a strategic industrial asset, one that goes far beyond the value it provides to individual companies. It underpins the region’s capacity to transform ambition into tangible outcomes, enabling society to achieve climate, circularity, and industrial policy goals without needing to start from scratch. The scale, integration, and connectivity of these assets, pipelines, reactors, storage, and logistics networks, are difficult and costly to replicate, giving the region a structural advantage in advancing sustainable chemistry.

A large portion of this infrastructure is fully functional, but also, crucially, largely paid off, meaning that the capital burden is low and the path to profitability is clearer when transitioning to sustainable feedstocks. Within the chemical industry’s carbon supply chains, product-level sustainability can be realized by replacing fossil-derived olefins and aromatics with molecules sourced from waste streams and biomass. To make this transition viable, however, it is essential that the businesses operating these assets can capture a fair operational margin from the sale of sustainable products. Profitability is not an optional luxury, it is the mechanism that allows existing infrastructure to support the transformation while remaining financially sustainable.

It is true that producing olefins and aromatics from renewable or waste carbon will carry higher production costs than traditional fossil feedstocks. Yet it is claimed[35] that this increase translates only modestly to the consumer level, because a large share of the final product price comes from downstream manufacturing, branding, and distribution. In practical terms, the price impact for end consumers is often limited to a few percent, while society gains the full environmental benefit of carbon-efficient, circular products. This demonstrates a critical leverage point: the combination of legacy infrastructure, low capital burden, and the ability to integrate sustainable feedstocks allows the region to unlock system-level value - preserving

[35] https://www.deloitte.com/content/dam/assets-zone2/nl/en/docs/industries/energy-resources-industrials/2025/Deloitte-EU-Demand-Creation-report.pdf

molecular capital, reducing emissions, and delivering societal impact - without imposing prohibitive costs on consumers or loss of autonomy.

4.4 Reconfiguring the chemical industry

The chemical industry benefits from a high degree of integration, particularly through its extensive pipeline networks for olefins and aromatics, which means that the downstream operations of crackers require minimal reconfiguration to accommodate sustainability measures. At this stage - covering the final conversion of olefins and aromatics, as well as the production of chlorine and ammonia - electrification will be the primary lever for reducing fossil energy use. Advances in high-temperature electric heating, plasma, and renewable-powered electrochemical processes can replace much of the conventional natural-gas or coal-based energy, enabling a near-term decarbonization pathway without disrupting downstream flows.

The upstream end of chemical production, where feedstocks are prepared and integrated, is where most of the material reconfiguration occurs. Here, integration with fuels production can still be preserved, but in a “reverse” relationship: unlike today, where chemicals largely derive from fuels production, a substantial share of future fuels will be generated through synthetic chemistry, using molecules such as methanol and paraffins derived from waste and biomass, rather than fossil feedstocks. This preserves the synergies between chemicals and fuels sectors while enabling both to transition toward low-carbon, circular supply chains.

This upstream reconfiguration is anchored on three key commodity molecules: methanol, ethanol, and paraffins. Ethanol production is already largely bio-based, while methanol and paraffins can be synthesized from complex waste and biomass streams through pyrolysis and gasification, unlocking carbon that would otherwise be lost to incineration. These commodities form the building blocks for both chemical and fuel production, enabling a systemic, integrated approach to sustainable carbon utilization.

4.5 Exposure to geopolitical risks

Geopolitical risk is deeply embedded in the industrial production of chemicals, arising from a complex web of dependencies, concentrations, and strategic vulnerabilities. At its core, the industry relies on critical feedstocks and raw materials - fossil hydrocarbons, key minerals, or bio-based inputs - many of which are concentrated in a handful of countries. This creates a structural vulnerability: political instability, trade restrictions, or conflicts in those regions can ripple through chemical supply chains, affecting everything from plastics and fertilizers to pharmaceuticals.

The strategic importance of chemical products further amplifies these risks. Ammonia and chlorine, for instance, are essential for agriculture and public health, while polymers and solvents underpin countless industrial and consumer applications. Disruptions in production, whether from conflict, sanctions, or export controls, can quickly become matters of national and international concern.

Energy dependence compounds the challenge. Chemical production is notoriously energy-intensive, and reliance on fossil fuels or electricity from politically unstable regions creates additional exposure. Even the transition to low-carbon alternatives - green hydrogen, renewable electrification, or waste- and biomass-based feedstocks - can introduce new

geopolitical dimensions, given the need for rare metals, specialized technologies, and cross-border infrastructure.

Taken together, chemicals production is not merely an industrial activity - it is a geopolitically sensitive system, where feedstocks, energy, infrastructure, trade networks, and technology intersect. Mitigating these risks requires diversification, circularity, and resilience: reducing reliance on concentrated sources, integrating renewable and waste-based feedstocks, and leveraging existing infrastructure to maintain autonomy.

4.6 Conclusions

The reconfiguration of pathways in the chemical industry is first and foremost a systems challenge. Today, regulatory focus is largely on production-phase emissions, which has driven efficiency gains but leaves the majority of carbon impacts, particularly from end-of-life incineration, unaddressed. To move toward a truly sustainable chemical industry, the focus must shift to include product-level lifecycle impacts, capturing emissions, circularity, and molecular carbon value from production to disposal.

The pathway forward leverages the region’s existing, and largely paid-off infrastructure, which allows downstream processes, such as cracking, polymerization, chlorine, and ammonia production, to adopt electrification and low-carbon energy with minimal disruption. Upstream, the transition requires integrating waste- and biomass-based feedstocks, producing methanol, ethanol, and paraffins through pyrolysis, gasification, and hydrogen-enabled synthesis, and enabling synthetic fuels. These measures preserve synergies between chemicals and fuels while unlocking circular, low-carbon supply chains.

Realizing this future also depends on embedding the value of sustainability into markets. Sustainable feedstocks currently carry higher production costs, but when translated through the value chains of consumer products, the price impact is modest. By establishing verifiable product standards that distinguish sustainable from fossil-derived molecules, policy can make embedded sustainability tangible, incentivize innovation, and reward circular, low-carbon production.

Finally, the pathway requires resilience against geopolitical and supply-chain risks, through diversified feedstocks, renewable energy integration, and strategic use of regional industrial clusters like the Trilateral Chemical Region. By combining lifecycle-focused regulation, infrastructure leverage, feedstock transition, market recognition, and systemic resilience, policymakers can enable the chemical industry to meet society’s needs in a sustainable, economically viable, and geopolitically robust way, laying the groundwork for actionable policy recommendations that align industrial strategy with climate and circularity objectives.

5 Recommendations

The reconfiguration of pathways in the chemical industry is ultimately about enabling the global industry to realize society's ambitions for sustainable products through using non-fossil resources. Today, regulatory attention focuses largely on production-phase emissions, which has driven efficiency improvements but leaves the broader system - particularly end-of-life impacts and lifecycle carbon - largely unaddressed.

5.1 Leverage industry's nature through a business-oriented framework

Current policies that focus primarily on mandating how industry should produce often generate unintended side effects, while the ultimate sustainability goals remain elusive. A more effective approach is to enable the transformation through a framework that leverages industry's capabilities to excel, innovate, and compete, rather than constrain it. To achieve the desired transformation, industry must operate in a framework that combines three critical enablers.

- Markets must value sustainable products. The intangible benefits of embedded sustainability, reduced emissions, circular feedstocks, and preserved molecular carbon, need to be recognized, quantified, and rewarded. Verifiable product standards allow producers to capture the economic value of responsible production, creating a market signal that aligns profitability with societal goals.

- Industry must have reliable access to energy and non-fossil carbon feedstocks. This includes waste, biomass, renewable hydrogen, and CCS infrastructure, enabling production at scale without reverting to fossil dependence. A secure, diversified supply of low-carbon resources is essential for both chemical and fuel pathways and for maintaining global competitiveness.

- The transition requires facilitation through permitting, infrastructure, and clean-energy availability. Streamlined permitting, coordinated infrastructure development, and predictable access to renewable electricity allow plants, integrated hubs, and upstream facilities to be deployed efficiently and cost-effectively, minimizing bottlenecks and accelerating system-wide adoption.

By addressing these three pillars, policymakers can unlock the full potential of the chemical industry to deliver on society's ambitions: preserving molecular value, reducing lifecycle emissions, leveraging existing industrial assets, and enhancing resilience against geopolitical and supply-chain risks. This approach provides a clear bridge from system-level analysis to actionable policy, ensuring that sustainability becomes not only a societal imperative but also an economically viable and operationally achievable reality.

5.2 Effective framework interventions require structured public information

Change in the chemical industry, and in industrial production more broadly, requires investment, and from a business perspective, only products are investable. Capital flows to opportunities where returns can be realized, which makes it essential to understand how businesses perceive product opportunities and how markets for these products are organized. Three fundamental principles ultimately define how change progresses in the system:

- Global product markets are the primary organizers of supply and demand. Industrial production tends to follow where these markets naturally develop, reflecting both the scale of demand and the logistics of distribution.
- Businesses retain freedom to choose where they do not operate production plants. Decisions to locate, expand, or withdraw production are driven by competitiveness, regulatory frameworks, and access to feedstocks and energy.
- Government interventions adjust conditions to align industrial activity with strategic objectives. Rather than exerting direct control over production decisions, policy should primarily focus on shaping incentives, mitigating externalities, and ensuring the availability of critical capabilities within their jurisdictional boundaries.

Acknowledging the above principles, the precision of interventions determines the success of sustainability policies, and accurate information is the foundation of effective control. The main policy levers to intervene include:

- Pricing undesirable externalities, such as CO_2 emissions, to steer markets toward lower-impact alternatives.
- Subsidies, whether one-off capital expenditure (CAPEX) support or sustained operational expenditure (OPEX), to drive strategic objectives, such as the scaling of sustainable feedstocks or maintaining local production capabilities.
- Mandates for product use, which create lead markets for sustainable goods and allow the additional costs to be passed on to end consumers, as is already seen with bio-component requirements in fuels.

For industrial businesses, the supply options in product markets form the basis of their survival and growth. A critical gap today is the absence of a harmonized public repository of supply options, detailing available feedstocks, conversion technologies, and capacity across regions. Such a repository would allow policymakers to assess how pricing, subsidies, and mandates impact the competitiveness of local production, and to anticipate the system-level effects of interventions before implementation.

As sustainability becomes a recognized feature of products, it is equally essential to measure, monitor, and verify compliance. This requires advanced analytical tools, traceability solutions, and digital tracking systems capable of following sustainability claims throughout complex supply chains, ensuring that market signals are grounded in reality.

Moreover, analysis of global trade trends provides insight not only into how businesses organize industrial production, but also into how geopolitical actors position themselves to influence global flows of energy, feedstocks, and products. In a world where supply chains are tightly interconnected, this intelligence is critical for proactive, strategic policymaking.

Looking forward, governments aiming to lead rather than react should consider developing a digital twin of industrial production infrastructure. Such a model would simulate feedstock flows, product markets, and technological options, enabling scenario analysis, rapid response to shocks, and precise targeting of interventions to maximize sustainability, economic competitiveness, and resilience.

5.3 Suggested areas for further research

This work has explored the technical and systemic possibilities for the de-fossilisation of carbon-based chemicals and fuels. However, technological feasibility alone is insufficient to drive change. Transition pathways in the chemical industry are ultimately shaped by investment decisions, and capital will only be allocated to solutions that can deliver competitive products under realistic market conditions.

From this perspective, policy makers may benefit from viewing the transition not primarily as the cumulative outcome of incremental regulatory measures, but as a fact-based, system-level process aimed at achieving credible long-term objectives while engaging constructively with market forces. Against this background, several areas emerge where further research and policy-relevant analysis would materially strengthen the foundations for an effective and durable transition:

- **Sustainability as a product differentiator**, including the development of credible markets for low-carbon and circular chemical products
- **Measurement, monitoring, and verification of product sustainability**, enabling transparency, comparability, industry standards and trust across value chains
- **Vulnerability and resilience of chemical value chains**, including exposure to feedstock scarcity, geopolitical risks, and infrastructure dependencies
- **Industrial investment and divestment dynamics** in global chemical supply chains, and their implications for regional competitiveness
- **Future synergies between the fuels and chemicals industries**, particularly in the context of shared feedstocks, infrastructure, and conversion platforms
- **Financing of First-of-a-Kind (FOAK) capital projects**, including risk-sharing mechanisms and the role of public–private partnerships
- Cost of sustainability, including cost pass-through along value chains and the resulting impacts on consumer prices and demand
- **Supply chains of critical chemicals and their strategic importance** for the economic security and industrial resilience of the European Union

Together, these research directions point to the need for an integrated understanding of technology, markets, and policy. Such an understanding is essential to ensure that the transition toward sustainable chemical production strengthens, rather than erodes, the long-term competitiveness and strategic autonomy of the chemical industry in the Trilateral Chemical Region and beyond.

Appendix A

Public data on chemicals production and trade in the trilateral chemical region

Marcelle Senekal, Frank Wubbolts

TNO, The Netherlands

To understand dependencies and potential vulnerabilities of the chemical industry supply chains, and to develop effective mitigation strategies, it is important to gain visibility on supply and demand flows, as well as interconnections, of key chemicals and feedstock fulfilled both from local production and from global trade.

- Which sections of the TCR/European supply chain may be most vulnerable to disturbances caused by parallel transitions.
- How ‘sustainability’ can propagate along the supply chain from resources towards consumer products through the TCR/European asset-base of the global chemical industry.
- How the TCR can organize its feedstock to fulfil regional demand for critical fuels and chemicals through supply from local production and trade.

Therefore this work made an attempt to gather public data and present a picture of the chemical industry in the TCR, with specific attention placed on The Netherlands.

- Fossil feedstock origin and uses in a reference year (2019).
- Installed nameplate capacities of chemicals production (2019-2022).
- Chemicals production in a reference year (2019).
- Trade of chemicals in a reference year of TCR regions between themselves, with the Rest of Europe and the Rest of World in a reference year (2019).

Data collection ambition

The table below shows the data collection ambition, which could only partially realised due to lack of reliable data and time constraints.

Products	(> olefins, aromatics, NH3)	Trade			Actual production			Production capacity		
		NL	F	NRW	NL	F	NRW	NL	F	NRW
	C2=		(Country)			(Country)	Country / conf			
	C3=		(Country)			(Country)	Country / conf			
	C4=/==		(Country)			(Country)	Country / conf			
	B		(Country)			(Country)	Country / conf			
	T		(Country)			(Country)	Country / conf			
	X		(Country)			(Country)	Country / conf			
	NH3		(Country)			(Country)	Country / conf			

Feedstock	(< olefins, aromatics, NH3)	Trade			Production / Availability			Use for chemicals			Use for energy			Use for feed		
		NL	F	NRW	NL	F	NRW	NL	F	NRW	NL	F	NRW	NL	F	NRW
Classic feedstock	Naphtha		(Country)	Country		Country & ?	Country		Country & ?	Country		Country & ?	Country			
	NGL		(Country)	Country		(Zero)	(Zero)		(Zero)	(Zero)		(Zero)	(Zero)			
	LPG		(Country)	Country		Country & ?	Country		Country & ?	Country		Country & ?	Country			
Fossil-based	Fossil Methanol		(Country)	Country		(Country)	Country									
Circular commodities	c/e-Methanol															
	r-Ethanol		(Country)	Country		(Country)	Country									
	r/c-Paraffins															
	UCO, black liquor, others	Probably known	Probably known	Probably known	Probably known	Probably known	Probably known									
Circular (waste)	C2= based polymers		Country	Country		Unknown	(Report?)	(zero)	(zero)	(zero)	Need to find	Need to find	Need to find			
	C2Ph= based polymers		Country	Country		Unknown	(Report?)	(zero)	(zero)	(zero)	Need to find	Need to find	Need to find			
	VCM based polymers		Country	Country		Unknown	(Report?)	(zero)	(zero)	(zero)	Need to find	Need to find	Need to find			
	Other plastics		Country	Country		Unknown	(Report?)	(zero)	(zero)	(zero)	Need to find	Need to find	Need to find			
Renewable (bio)	Agricultural residues	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	Manure	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	Biowaste	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	Lignocellulosic crops	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	Wood	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	Forestry residues	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	Secondary forestry residues	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	OF-MSW	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown
	Residual oils	2019, country	2019, country	2019, country		Country	Country	(zero)	(zero)	(zero)	CBS, available	Probably known	Probably known	CBS, available	Unknown	Unknown

Table with targets for data collection on:

(1) Basic chemicals, intermediates and chemical products and their trade, production and production capacity
(2) Classic feedstock trade, extraction & production and competing use for chemical, energy
(3) Renewable and circular commodities production, trade and use
(4) Circular complex feedstocks trade, production and their use for chemicals, energy and feed → see Appendix B
(5) Renewable complex feedstocks and their use for chemicals, energy and feed → see Appendix C

The public data sources
The consulted public data sources for feedstock and chemicals production were:

	Installed production capacity	Production	Trade
The Netherlands	MIDDEN reports [36]	PRODCOM	COMTRADE
North Rhine Westphalia	Wuppertal Institute reports [37, 38]	PRODCOM	COMTRADE
Flanders	VITO, ESSENSCIA	PRODCOM	COMTRADE

The PRODCOM database from Eurostat on the production of manufactured goods is based on data from national statistics offices. Data gaps are present when insufficient independent data points are available, as this would reveal proprietary data that is of commercial interest to chemical businesses.

UN COMTRADE international trade data on a bilateral country-level is based on data from national statistics offices. In principle, export and import data between countries should match, but it is known that this is not always the case. Harmonized data-sets are available, such as BACI, but those were not yet used for this work.

MIDDEN reports are the result of a project between TNO and PBL between 2019 and 2022 where public data was collected and interviews with companies were held and reported on segments of the Dutch industry with obligation to report its CO_2 emissions. The work reports on the current processes and origins of CO_2 emission and investigates technical interventions to reduce those emissions.

The Wuppertal Institute reports provide maps of chemical industry clusters in Germany, Netherlands and Belgium. These reports analyse how the current clusters operate, from naphtha to products. The study has detailed information on the current products, production capacities, resource and product exchange, infrastructure and energy demand.

The result of our data analysis
We did not manage to realise our ambition as we had envisioned it from the start within the anticipated timeframe and budget. This is mainly due to unavailability and inconsistency of data. We report below on our incomplete findings in the form of Sankey diagrams:

(1) Installed production capacities from the cracker to intermediates
(2) Estimated production combined with trade for 2019
(3) Fossil feedstock supply and end-use in chemicals for 2019

➔ This incomplete and unfinished work should however show what analysis of public data may contribute to understanding the complexity of the chemicals industry, the dependencies, and the importance of global supply chains.

[36] https://www.pbl.nl/en/middenweb
[37] Scholz, A., Schneider, C., Saurat, M., & Theisen, S. (2023): Das petrochemische System in Deutschland und Westeuropa: Regionale Analyse der Polymer-Produktion in Deutschland, den Niederlanden und Belgien ; Ergebnisse aus dem Forschungsprojekt “Green Feedstock for a Sustainable Chemistry - Energiewende und Ressourceneffizienz im Kontext der dritten Feedstock-Transformation der chemischen Industrie”, Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal.
[38] Scholz, A., Theisen, S., Schneider, C., & Kloo, Y. (2024). Structural analysis of petrochemical clusters in Germany: What can be learned for the transformation towards climate-neutrality? Journal of Business Chemistry, 21(1), 2–27.

➔ The raw data is not published here and may be made available upon request to TNO
➔ We feel encouraged to enrich and extend the data-sets so that they may in the future highlight trends and dependencies

(1) Installed nameplate production capacities of the chemical industry in the TCR
Maps were produced of the Dutch chemical industry by combining data from different reports on the sections of the chemical industry.

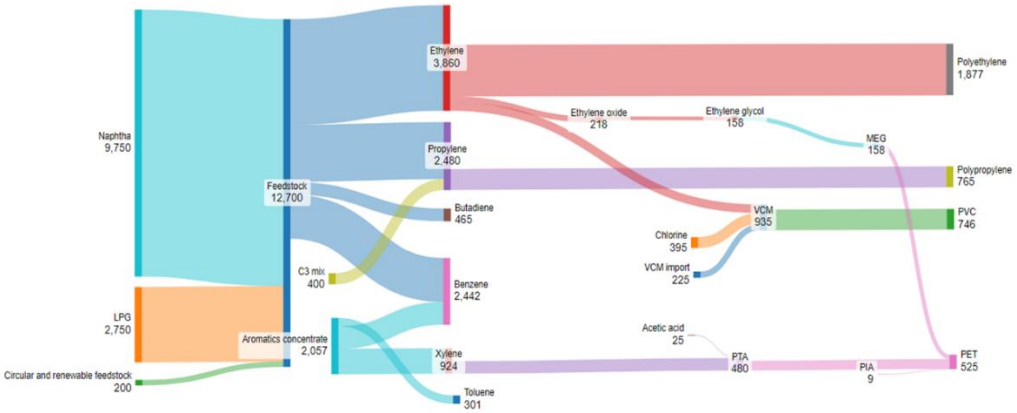


Figure A.1: Installed production capacities for chemicals in **The Netherlands 2018** (based on data from MIDDEN Decarbonisation Options for Large Volume Organic Chemicals Production reports)

For German, Dutch and Belgian industry clusters the Wuppertal institute studies [37,38] have collected the products and production capacities in Sankey diagrams. These studies focus on the clusters, but have less detail on how the production relates to global trade flows. Access to the underlying data, which is with the Wuppertal Institute, would have been very valuable to pursue the approach that we have in mind. The figure below shows the Sankey diagram for polymer production in Germany, as an example.

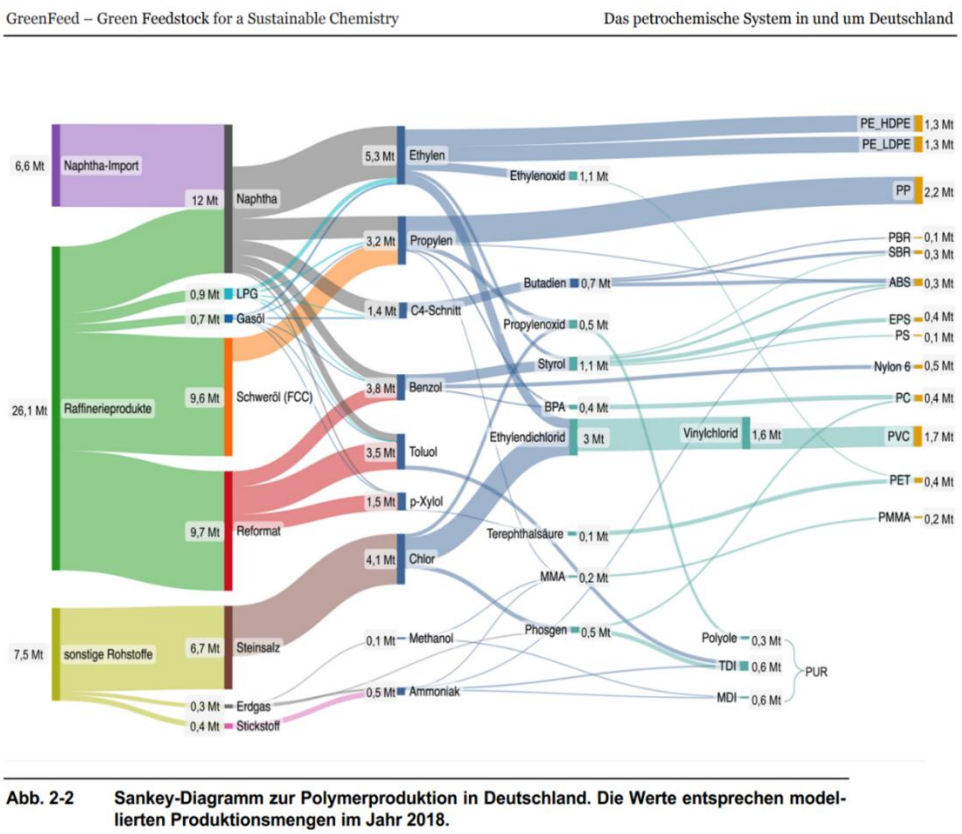


Abb. 2-2 **Sankey-Diagramm zur Polymerproduktion in Deutschland. Die Werte entsprechen modellierten Produktionsmengen im Jahr 2018.**

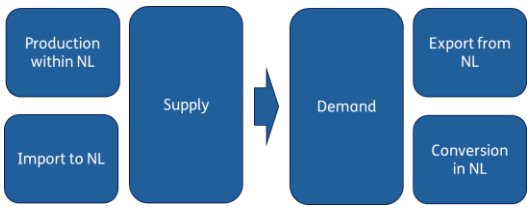
Figure A.2: Modelled production for chemicals in **Germany 2018,** Wuppertal Institut[37] 'Das petrochemische System in Deutschland und Westeuropa: Regionale Analyse der Polymer-Produktion in Deutschland, den Niederlanden und Belgien ; Ergebnisse aus dem Forschungsprojekt.'

[Insufficient data to produce a graph]
*Installed production capacities in **Belgium** (representative for Flanders)*

(2) Production and Trade

This Sankey diagram below combines the production and trade of selected chemicals in The Netherlands. The production has been scaled to represent an estimated 50% capacity utilisation derived from the naphtha use by the petrochemical industry in 2019 and installed capacities.

Each chemical in the chain is either produced domestically or imported, and exported or converted in the selected region. This is show in the figure below:



This model has been applied to the selected chemicals in the scope of this study. In the figure below, from left to right, the cracker input of naphtha and LPG (light blue) is converted into olefins and aromatics. These in turn are either exported or converted. To truncate the Sankey diagram all further conversions that are not displayed are collected in 'NL conversion' on the bottom right.

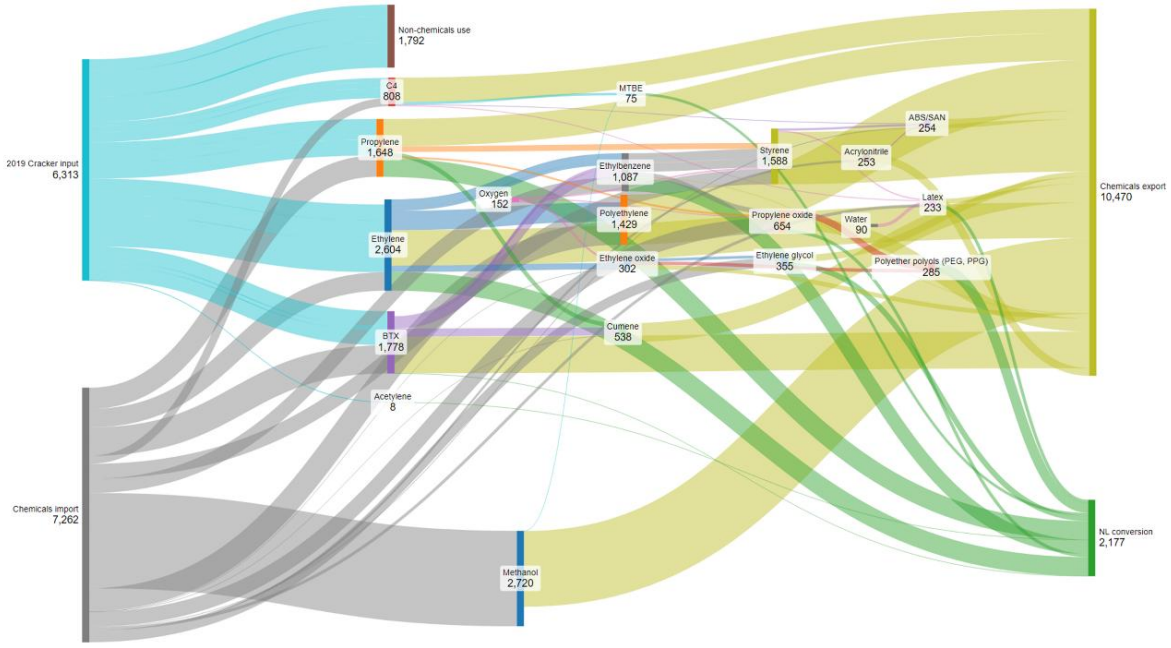


Figure A.3: Production and trade of chemicals in 2019 (ktpa) in the **Dutch chemical industry** (based on data from MIDDEN reports and CBS statistics)

For most chemicals, the intake of the production operations is a combination of local production and significant import flows. The system is highly interconnected, which provides all a combination security of supply and security of demand. The diagram highlights that the Netherlands is generally a net-exporter of chemical products.

[Insufficient data on production, data-gaps in PRODCOM, nameplate capacity not available]

Production and trade of chemicals in 2019 in the **German chemical industry** (not NRW)

[Insufficient data, data-gaps in PRODCOM, nameplate capacity not available]
Production and trade of chemicals in 2019 in the **Belgian chemical industry** (representative for Flanders)

(3) Fossil Feedstock Production and Trade

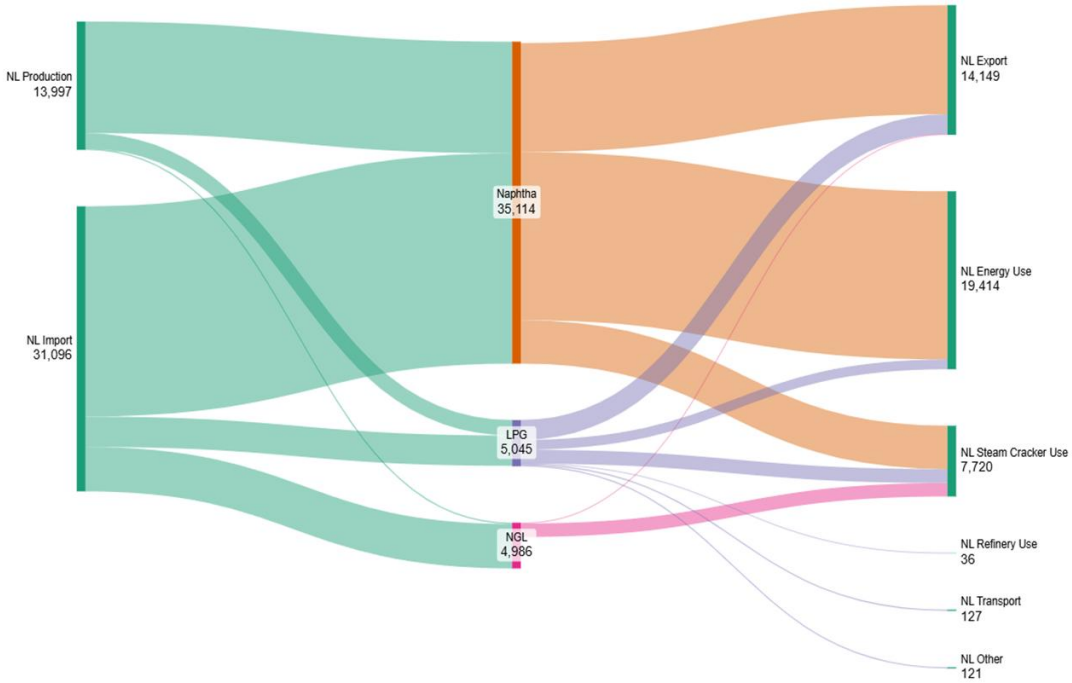


Figure A.4: Fossil feedstock production and trade in **The Netherlands 2019** (based on data from CBS)

Despite The Netherlands importing and trading significantly higher volumes of fossil-based feedstock than Germany and Belgium, only a small portion of the fossil-based feedstock in the Netherlands is used as feedstock by the petrochemical sector. This substantiates its position as a trading hub.

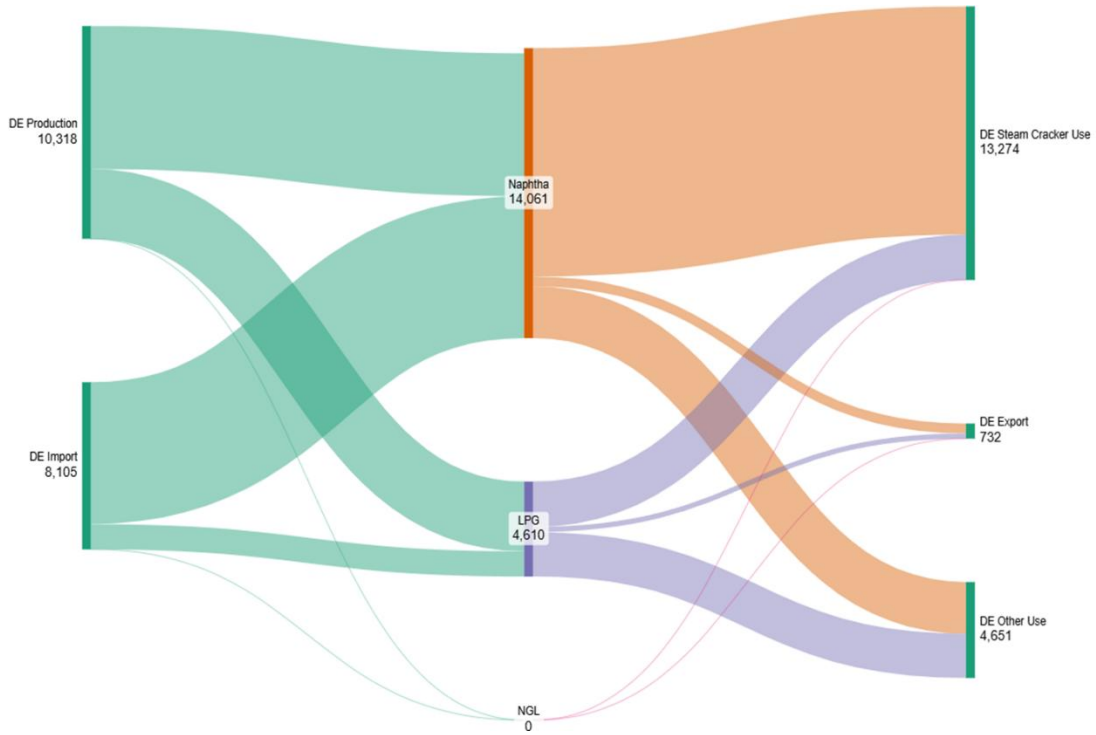


Figure A.5: Fossil feedstock production and trade in **Germany 2019** (based on data from BAFA)

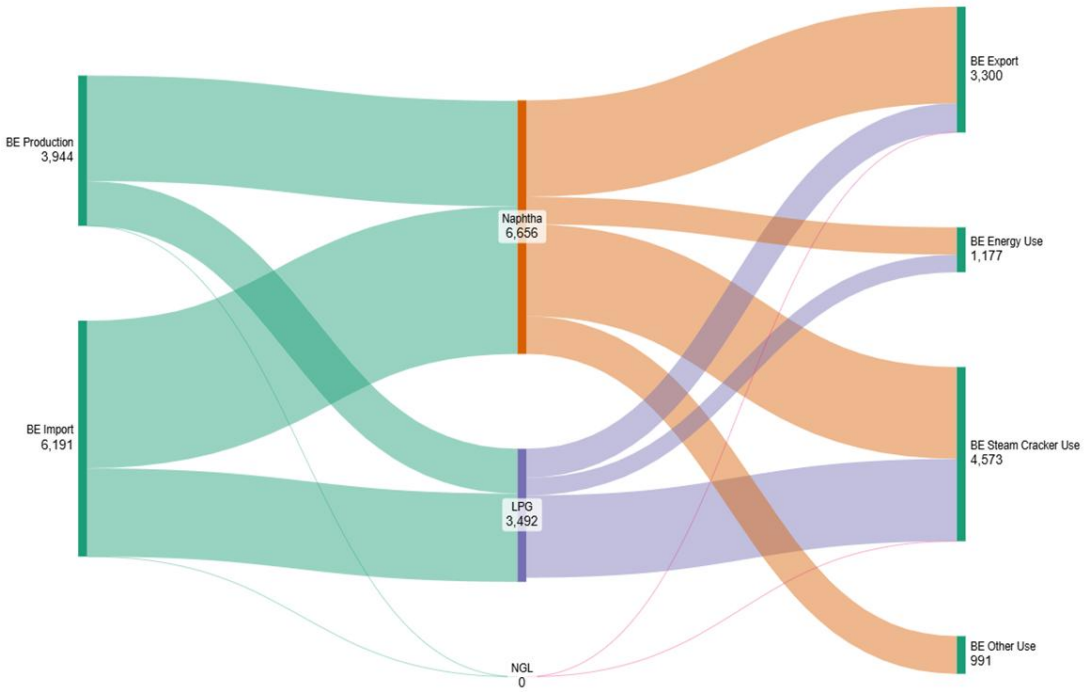


Figure A.6: Fossil feedstock production and trade in **Belgium 2019**, representative for Flanders (based on data from UN Datamarts and Eurostat)

Appendix B

Plastic waste availability in the trilateral region

Tonny Manalal, Marcelle Senekal, Frank Wubbolts

TNO, The Netherlands

In this chapter, the availability of plastic waste as alternative feedstock in the trilateral region of Netherlands, Germany and Belgium is discussed. The different types of waste within each category are identified and the production potential of the regions are also discussed.

To study the plastic waste availability in the region, the types of plastic waste, plastic production, exports and waste handling data were collected and analyzed. The data for the plastics flows is based on publications with varying basis year (in the range of 2022 to 2023). As the information with the same basis year could not be attained, the flow from these publications are used and the analysis is based on this approximation.

Plastics can be categorized as thermoplastics and thermosets, based on their thermophysical properties as shown in Table 1. Thermoplastics are plastics which becomes pliable at elevated temperature and solidifies upon cooling while thermosetting plastics (thermosets) are plastics which cannot be melted and re-shaped after they are cured. Understanding this categorization is important because all the plastic waste cannot be chemically recycled using just one technology due to the differences in the thermophysical properties and based on the type of plastic waste, different chemical recycling technologies might be required. As thermosets cannot be melted again, they cannot be effectively used for pyrolysis or hydrothermal liquefaction while thermoplastics can become tacky in nature upon melting which can sometimes create challenges for gasification. [1] The detailed discussion on different plastic recycling technologies are explained in the plastic waste to olefins and aromatics route Appendix document.

Table B.1: Examples of thermoplastics and thermosets

Thermoplastics	Thermosets
Acrylonitrile butadiene styrene	Cyanate esters
Nylon (Polyamide)	Polyester resin
Polyacrylic acids	Epoxy resin
Polybenzimidazole	Vulcanised rubber
Polycarbonate	Bakelite
Polyether ether ketone	Melamine resin

Thermoplastics	Thermosets
Polyether sulfone	Duroplast
Polyetherimide	Dially-pthalate
Polyethylene (UHMWPE, HDPE, MDPE, LDPE, LLDPE)	Epoxy novolac resins
Polylactic acid	Polyurethanes
Polymethyl methacrylate	Polyimides and bismaleimides
Polyoxymethylene	Urea-formaldehyde
Polyphenylene sulphide	Benzoxazines
Polypropylene	Furan resins
Polystyrene	Silicone resins
Polyethylene terephthalate (PET)	Thiolyte
Polytetrafluoroethylene (Teflon)	Vinyl ester
Polyvinyl chloride	
Polyvinylidene fluoride	

Note: In black thermoplastics with only carbon and hydrogen in molecular structure and in violet thermoplastics with other impurities like sulfur, chlorine and nitrogen.

The purpose of the analysis was to get a snapshot of the plastic flows. The plastic consumption is included as packaging, building & construction, electrical & electronics, houseware, leisure and sports, agriculture, farming & gardening and others. The concept of stock is included in the Sankey diagram as accumulation and unknown, as they are not reported clearly in the references.

1. The Netherlands

The plastic production, export, usage and waste recycling information for the Netherlands were collected from the 'Conversio' report "Substantiation of data for polymer production and processing in the Netherlands" and Circular Plastics NL report "Navigating Volumes and Value Chains Towards Circularity" with the basis year of 2022 elaborated for Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO)[2,3]. The plastic waste incineration information was based on 2022 data from the Circular Plastics NL report "Navigating Volumes and Value Chains Towards Circularity"[3]. The plastic waste export information was based on the 2023 data from the Statista database "Plastic waste exports from the Netherlands in 2023, by destination"[4]. The data from these reports and databases were mapped and analysed to understand the plastic flow in the Netherlands. Due to data limitations, the information from these different studies with varying basis year is used and the potential error or discrepancy in the flows due to the differences in studies and basis years are not analysed in this study.

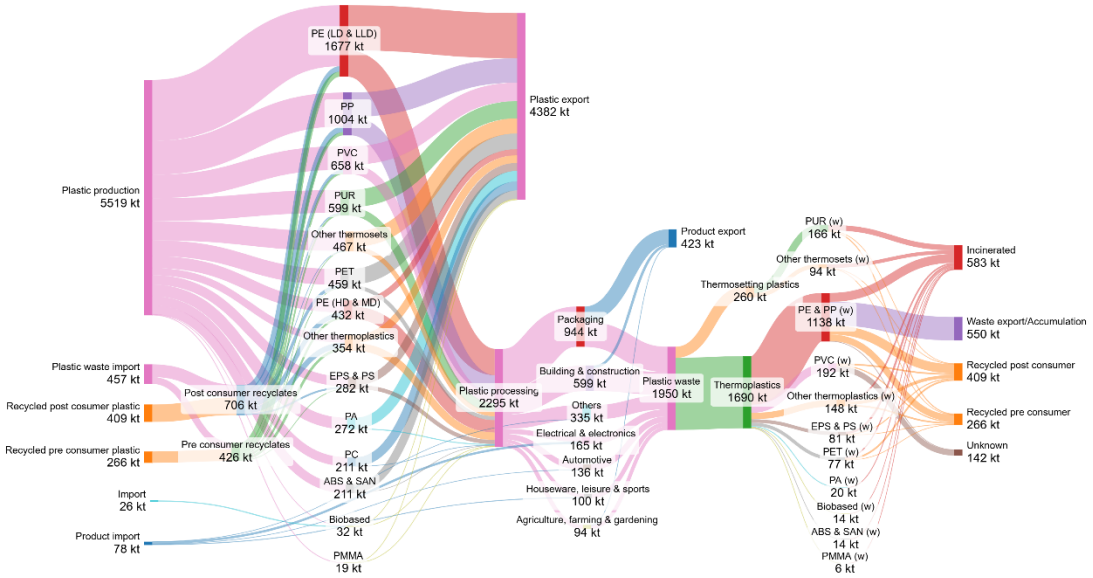


Figure B.1: Plastics flow in the Netherlands

The Netherlands produces around 6.7 million tonnes of raw plastic[2] as shown in **Figure B.1**. About 17% of plastics are produced from recycled plastic waste (i.e., mechanical recycling). Polyolefins like polyethylene and polypropylene account for about 47% of the total produced plastics. In 2022, only 2.3 million tonnes of plastic[2] (i.e., 34% of the produced plastic) was processed, 1.95 million tonnes (i.e., 29% of the produced plastic) used within the Netherlands out of the 6.7 million tonnes and the rest was exported. Thus, majority of the plastic production in the Netherlands is export oriented, which undermines the potential of chemical recycling. As of now, only 457 kt plastic waste is imported compared to the 4805 kt plastic or polymer product export.[2] The major uses of plastics are packaging (41% of total usage) and buildings & construction (26% of total usage).[2]

Around 1.95 million tonnes of plastic waste is consumed in the Netherlands and 86% of the total plastic waste is thermoplastics.[2] The plastic waste can be further classified as pre-consumer waste and post-consumer. Pre-consumer plastic waste is easier to recycle than post-consumer plastic waste as it is purer and typically uncontaminated. Pre-consumer plastic waste are generated during manufacturing from offcuts and trimmings while post-consumer plastic wastes comes from consumers after their end-of-life often in mixed and contaminated manner. Therefore, understanding these classification is important for realizing the potential and challenges of chemical recycling. Based on the data, the pre-consumer plastic waste of 266 kt is recycled in the Netherlands. About 1103 kt of the post-consumer plastic waste is collected and processed in the Netherlands.[2–6] The end-of-life waste disposal for PVC polymers is not well documented in the references and it is classified as unknown in this study. The collected plastic waste, (the thermoplastics and thermosets) are currently sent for recycling, incineration or export. Around 409 kt of plastic waste is recycled[2], 583 kt is incinerated[3] and 550 kt is accumulated (in stock) or exported[4] in the Netherlands.

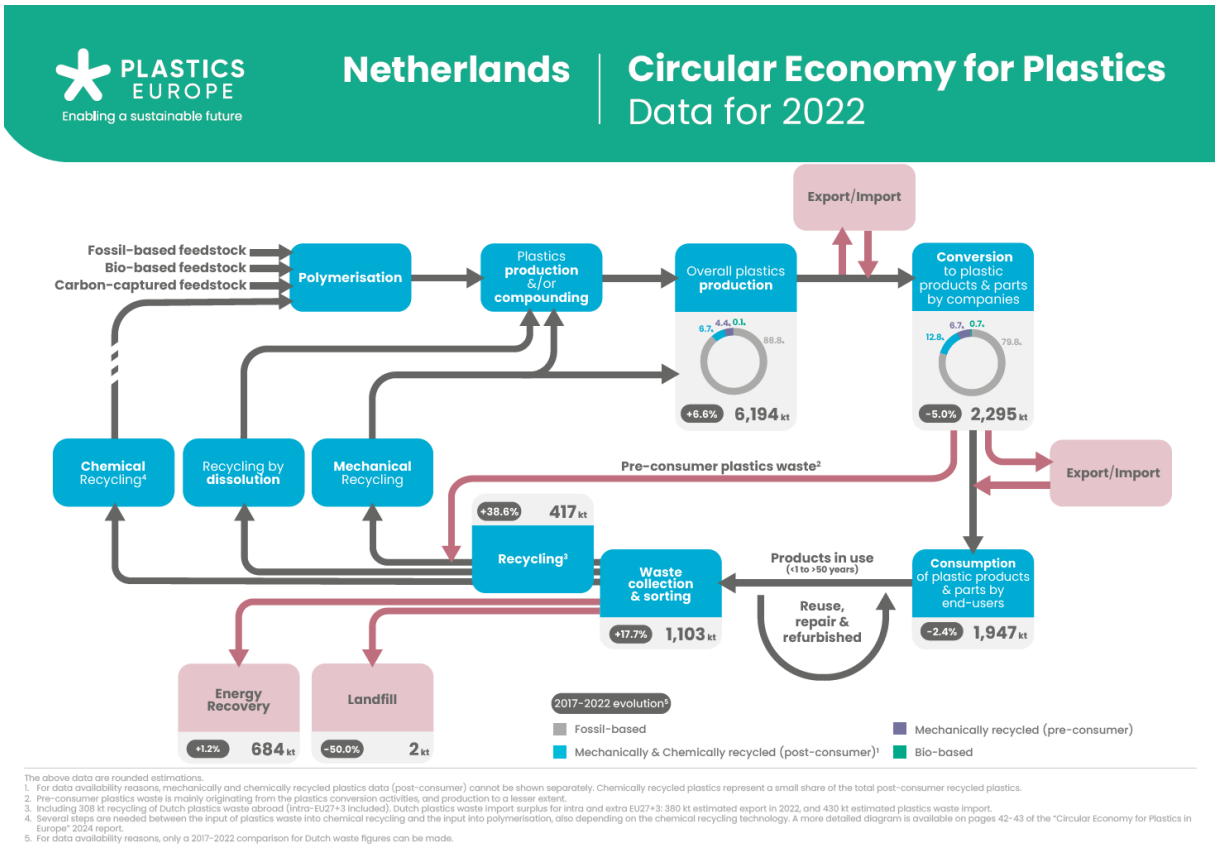


Figure B.2: Plastic flow in the Netherlands as per Plastics Europe data for 2022[7]

Figure B.2 shows the plastic flow in the Netherlands as per Plastics Europe data for 2022. The comparison between **Figure B.1** and **Figure B.2**, shows that the plastic flow data is similar with slight variations in energy recovery and waste export data. **Figure B.2** also provides better understanding of the waste collection rate, which shows the actual potential of plastic waste is lower due to stockpile and uncollected waste.

The insights from the plastic flow analysis (which includes production, usage, and waste disposal) are:

- Almost 65% of the plastics produced in the Netherlands is exported to other countries as product. So, we only have 35% remaining with which we can never close the plastic recycling loop, unless we import that plastic waste or equivalent pyrolysis oil.
- About 86% of the plastic waste is thermoplastics while 14% is thermosetting plastics in the Netherlands. About 23% is PVC and Thermosets, which cannot be used for pyrolysis. About 35% plastic waste is already mechanically recycled.
- One of the aspect which cannot be seen in the Sankey diagram is the quality of the collected plastic waste. Currently, plastic waste which cannot be sorted and cleaned is sent to incineration. So creation of proper sorting mechanism and policies, to prevent the contamination and export of plastic waste, will be critical for encouraging chemical recycling facilities in the Netherlands.

2. Germany

The plastic production, export, usage and waste recycling information for Germany were collected from the ‘Conversio’ report “Conversio Market & Strategy GmbH. Stoffstrombild Kunststoffe in Deutschland 2023: Zahlen Und Fakten Zum Lebensweg von Kunststoffen” with

the basis year of 2023.[8] The plastic waste export information was based on the 2024 data from the Basel action network report “Germany export data annual summary”.[9] The data from these reports and databases were mapped and analysed to understand the plastic flow in Germany. Due to data limitations, the information from these different studies with varying basis year is used and the potential error or discrepancy in the flows due to the differences in studies and basis years are not analysed in this study.

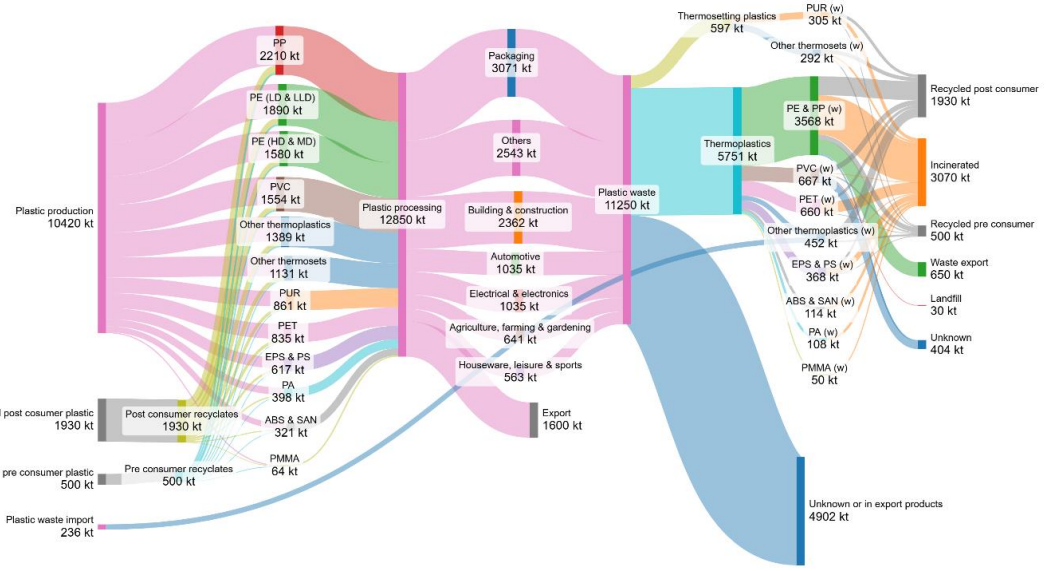


Figure B.3: Plastic waste availability in Germany

Germany produces around 12.85 million tonnes of plastic as shown in **Figure B.3**. About 19% of plastics are produced from recycled plastic waste. Polyolefins like polyethylene and polypropylene account for about 44% of the total produced plastics. In 2023, only 1.6 million tonnes of raw plastic (i.e., 12% of the produced plastic) is exported from Germany out of the 12.85 million tonnes and the rest is used and further converted locally. The major share of usage of plastics is for packaging (27% of total usage), buildings & construction (21% of total usage), automotive (9% of total usage) and electrical & electronics (9% of total usage). There is a high mismatch in the data regarding the quantity of plastic produced and plastic waste collected in Germany. This could be due to Germany being a product export-oriented country, majority of the plastic products in Germany might be sold abroad, which makes recycling highly challenging. As of now, 6348 kt plastic is collected in Germany while about 4902 kt plastic is unknown or accumulated or in export products and only 236 kt plastic waste is imported.

Thus, around 6.3 million tonnes of plastic waste are collected in Germany and 91% of the total plastic waste is thermoplastics. It is assumed that, all the collected non-recycled fraction of thermosets are incinerated, while the collected non-recycled fraction of thermoplastics is incinerated, landfilled, or exported. The end-of-life waste disposal for PVC polymers is not well documented in the references and it is classified as unknown in this study.

For analyzing, the olefin and aromatic production potential from plastic waste in Germany, it can be assumed that all the non-recycled thermosets (like PUR, PET, PA, ABS, SAN, biobased, PMMA and other thermosets) are available for gasification due to its incompatibility with pyrolysis. While all the non-recycled thermoplastics (like PE, PP, EPS, PS and other thermoplastics), except PVC, can be assumed to be available for pyrolysis. The chemical

recycling of thermoplastics like PVC is recommended to be considered standalone due to the complexity of dealing with chlorides, fluorides and sulfides in the streams.

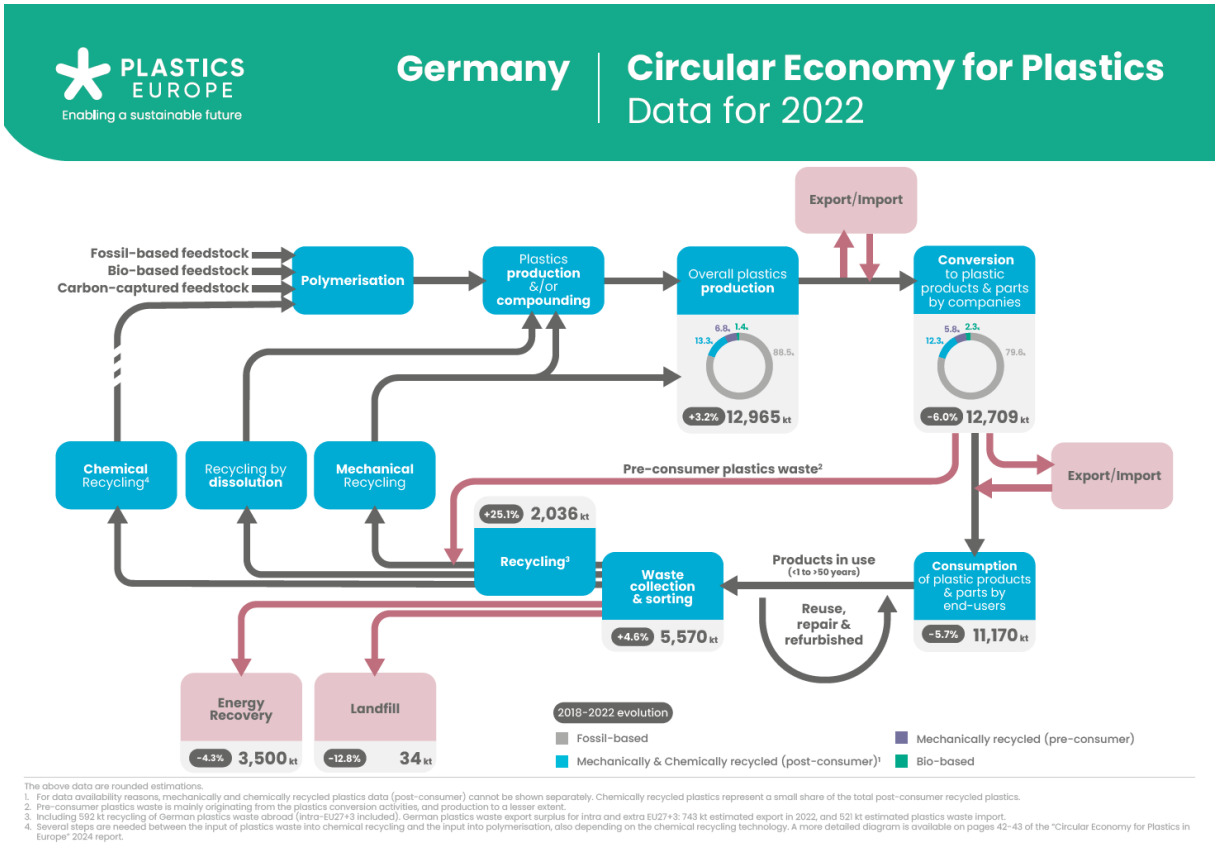


Figure B.4: Plastic flow in Germany as per Plastics Europe data for 2022[7]

Figure B.4 shows the plastic flow in Germany as per Plastics Europe data for 2022. The comparison between **Figure B.3** and **Figure B.4**, shows that the plastic flow data is similar with slight variations in energy recovery and waste export data. **Figure B.4** also provides better understanding of the waste collection rate, which shows the actual potential of plastic waste is lower due to stockpile and uncollected waste.

3. Belgium

The plastic production, export, usage and waste recycling information for Belgium were collected from the 'Plastics Europe report "Circular Economy for Plastics Data for 2022 Belgium" with the basis year of 2022.[7] The plastic waste export information was based on the 2023 data from the OVAM report "Plastics Implementation Plan 2020-2025".[10] The data from these reports and databases were mapped and analysed to understand the plastic flow in Belgium . Due to data limitations, the information from these different studies with varying basis year is used and the potential error or discrepancy in the flows due to the differences in studies and basis years are not analysed in this study

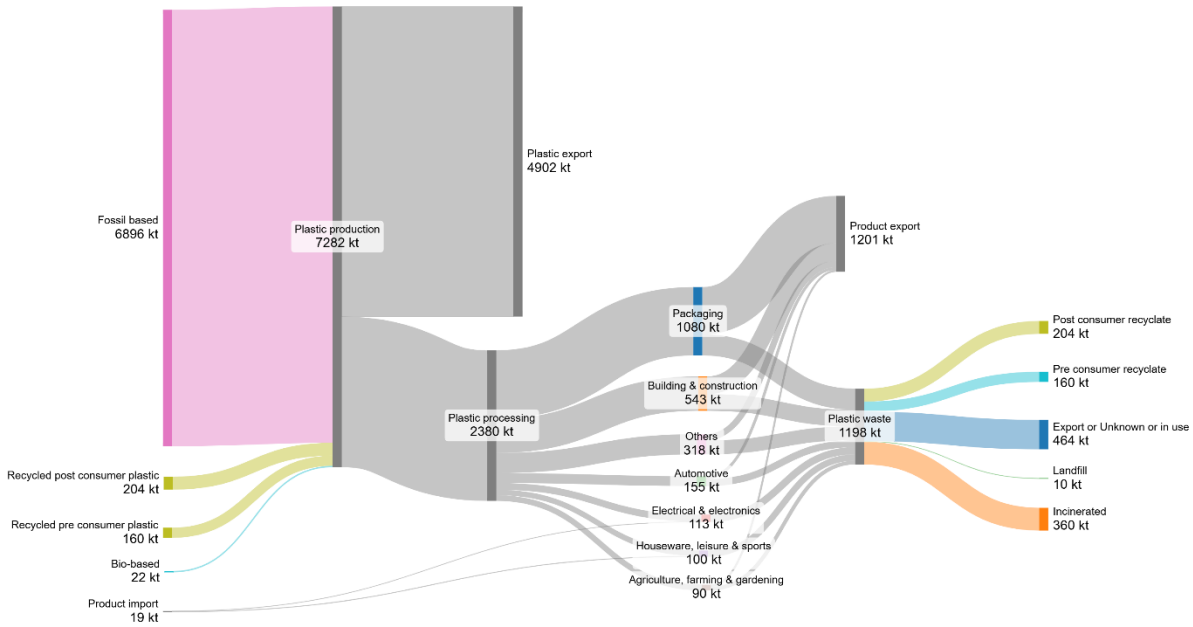


Figure B.5: Plastic waste availability in Belgium[7]

Belgium produces around 7.3 million tonnes of plastic as shown in **Figure B.5**. About 5% of plastic is produced from recycled plastic waste. In 2022, only about 1.2 million tonnes of raw plastic (i.e., 16% of the produced plastic) is consumed within Belgium out of the 7.3 million tonnes and the rest is exported as polymer or products. The major share of the usage of plastics is for packaging (28% of total usage), buildings & construction (22% of total usage), automotive (9% of total usage) and electrical & electronics (9% of total usage). As majority of the plastics and plastic products in Belgium are sold abroad, recycling is highly challenging. The reference did not mention the type of plastic production or waste as detailed in the above cases for the Netherlands or Germany. For further analysis, it can be assumed that the plastic waste fraction of Belgium is equivalent to that of Germany due to the similarity in the fraction of plastic used in the different sectors like packaging, building & construction, automotive, electrical & electronics etc.

According to the source[7], only about 0.6 million tonnes of plastic waste is collected compared to the 1.2 million tonnes of plastic used in Belgium. 60% of collected waste is incinerated, 39% is recycled and 2% is landfilled. The plastic waste export in Belgium is estimated to be around 270 kt[10] and about 100-300 kt plastic waste is not well documented in the references and it is classified as unknown in this study.

The details regarding the type of plastic in not available in the references and these aspects are not analyzed further in this study.

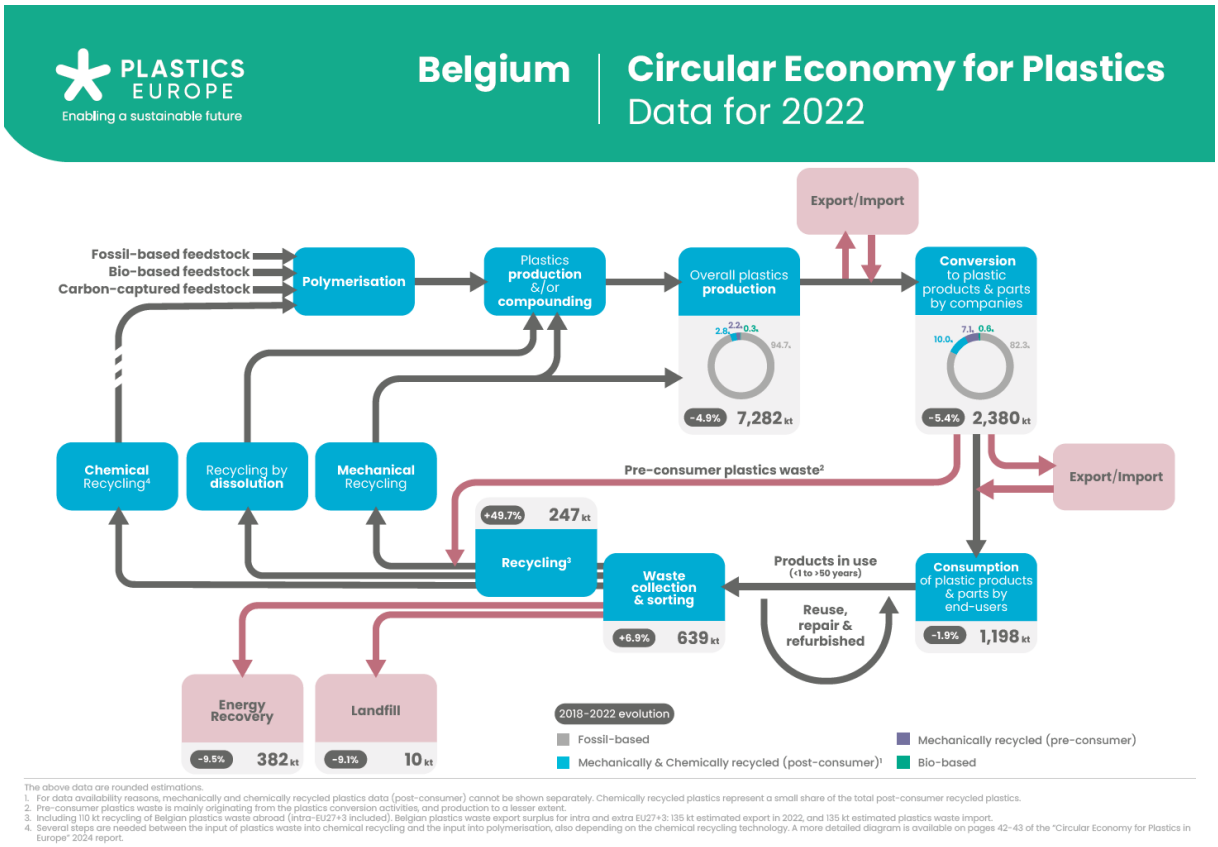


Figure B.6: Plastic flow in Belgium as per Plastics Europe data for 2022[7]

Figure B.6 shows the plastic flow in Belgium as per Plastics Europe data for 2022. The comparison between **Figure B.5** and **Figure B.6**, shows that the plastic flow data is similar with slight variations in energy recovery and waste export data. **Figure B.6** also provides better understanding of the waste collection rate, which shows the actual potential of plastic waste is lower due to stockpile and uncollected waste.

This document will be part of Appendix for the report written by VITO for the 3C-VaCs project.

B.1 References

(1) Ciuffi, B.; Chiaramonti, D.; Rizzo, A. M.; Frediani, M.; Rosi, L. A Critical Review of SCWG in the Context of Available Gasification Technologies for Plastic Waste. *Appl. Sci.* **2020**, *10* (18), 6307. https://doi.org/10.3390/app10186307.

(2) Conversio. *Substantiation of Data for Polymer Production and Processing in the Netherlands*; 2024. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjeq5uQhs6QAxXZ2QIHHVlFMfYQFnoECBwQAQ&url=https%3A%2F%2Fwww.internetconsultatie.nl%2Fnationale_circulaire_plastic_norm%2Fdocument%2F12507&usg=AOvVaw02NqutZ1bIsBdrE4iCb.

(3) Circular Plastics NL. Circular Plastics NL - Navigating Volumes and Value Chains Towards Circularity; 2025.

(4) *Plastic waste exports from the Netherlands in 2023, by destination*. Statista. https://www.statista.com/statistics/1357887/plastic-waste-export-volume-netherlands-destination/ (accessed 2025-05-26).

(5) de Leeuw, M.; Koelemeijer, R. Decarbonisation Options for the Dutch Waste Incineration Industry.; 2022. www.pbl.nl/en.

(6) *Plastic use and plastic waste processing in the Netherlands*. CE Delft. https://cedelft.eu/publications/plastic-use-and-plastic-waste-processing-in-the-netherlands/ (accessed 2025-05-26).

(7) Plastics Europe. Circular Economy for Plastics Data for 2022; 2024.

(8) Conversio Market & Strategy GmbH. *Stoffstrombild Kunststoffe in Deutschland 2023: Zahlen Und Fakten Zum Lebensweg von Kunststoffen*; 2022. https://plasticseurope.org/de/wp-content/uploads/sites/3/2022/11/Kurzfassung_Stoffstrombild_2021.pdf.

(9) Basel action network. *Germany Export Data*. https://www.ban.org/plastic-waste-project-hub/trade-data/germany-export-data-annual-summary (accessed 2025-06-06).

(10) OVAM. Plastics Implementation Plan 2020-2025; 2023.

Appendix C

Biomass availability in the trilateral region

Tonny Manalal, Jonathan Moncada, Marcelle Senekal, Frank Wubbolts

TNO, The Netherlands

In this chapter, the availability of biogenic waste in the trilateral region of Netherlands, Germany and Belgium is discussed. The different types of biogenic waste within each category are identified. The report considers the categorization of biomass feedstocks as sugar-based, oil-based, lignocellulosic and other organic wastes & residues. The potential availability of only second-generation options like lignocellulosic and other organic wastes & residues are considered for biobased production in this study due to concerns related to food security, competition for arable land, and ethical considerations. Thus, the focus is set on feedstock categories listed under the Renewable Energy Directive (REDII) annex IX.[1,2] While the annex IX refers to feedstocks that are eligible for biofuels production they are also considered as potential feedstock for the chemical industry.

Feedstocks for the production of basic chemicals can be classified based on their origin, as first generation, second generation and third generation feedstocks. Third generation (3G) feedstocks refers to emerging resources, mainly aquatic biomass and are not considered in this study, due to the potential uncertainty.

First-generation (1G) feedstocks are derived from food and feed crops. These feedstocks have traditionally been mainly used in biofuel production and also serve as raw materials for the chemical industry. They are typically rich in fermentable sugars or oils, making them suitable for producing bioethanol, biodiesel, and other platform chemicals.1G feedstocks can be broadly classified into two categories:

- *Sugar-based crops*: These crops are rich in carbohydrates that can be readily converted into fermentable sugars for example for alcohols production.
- *Oil-based crops*: These crops contain high levels of triglycerides, which can be processed into biodiesel or used as chemical feedstocks for the production of oleochemicals.

In Europe, corn, cereals and sugar beet have been the primary sugar-based feedstock for bioethanol production due to its high yield and suitability for the European climate.[3] The EU imports bioethanol, including sugarcane-based ethanol from countries like Brazil and corn-based ethanol from the United States.[4] For oil-based crops, rapeseed oil has been widely cultivated and used for biodiesel production, particularly in countries such as Germany and France.[3] Soybean is cultivated primarily in Italy, France, and Romania, and soybeans contribute to biodiesel production and serve various industrial applications. While soybean oil has been used for biofuels production; RED II explicitly identifies soybean oil and palm oil as

high indirect land use change (ILUC) risk.[1] Sunflower is grown extensively in France, Spain, and Romania, sunflower oil is mainly used in the food industry, with a smaller share directed toward biodiesel production. Imported oil-based feedstocks include palm oil from Southeast Asia, mainly from Indonesia and Malaysia,[5] and soybean oil from North and South America, both of which are used in biofuels and chemical applications. Although first-generation feedstocks benefit from established supply chains, their use raises concerns related to food security, competition for arable land, and ethical considerations. These challenges make them a less viable long-term solution for sustainable chemical production.

Second-generation (2G) feedstocks consist of non-food biomass sources that provide a more sustainable alternative to first-generation feedstocks by avoiding direct competition with food production. These materials include:

- Lignocellulosic biomass, such as agricultural and forestry residues including straw, wood chips, and sawdust. These materials are widely available in Europe, particularly in countries with large forestry industries such as Sweden, Finland, and Germany. [6–8]
- Other organic wastes & residue feedstocks (non-oil based), which include municipal solid waste and industrial residues.
- Other organic wastes & residue feedstocks (oil & fat based), which include used cooking oils, crude tall oil and tallow.[9] In Europe, the collection and processing of used cooking oils have expanded, especially in countries such as the Netherlands and the UK, where waste-to-biofuel initiatives are well established.[8,10]

The 2G-biomass is distinguished as lignocellulosic, other organic wastes & residues (non-oil based) and other organic wastes and residues (oil & fat based) due to the wet and/or readily decomposable and oleochemical nature of certain biogenic materials. The biochemical processes like anaerobic digestion suits organic resides & waste (non-oil based) better while organic residues & waste (oil & fat based) are better suited for hydrotreatment based upgradation.

Various subtypes exist within this category. To maintain consistency and comparability with other studies, these feedstocks have been classified into specific categories. The selected categories include agricultural residues, manure, biowaste, lignocellulosic crops, wood, forestry residues, secondary forestry residues, municipal solid waste (MSW), and waste or residual oils[8] (**Table C.1**).

Table C.1: Biomass classification for the evaluation of bio-based chemical value chains[8]

Type of Biomass		Description
Lignocellulosic biomass	Agricultural Residues	Remnants of crops left after harvesting, such as wheat straw and corn stover.
	Lignocellulosic Crops	Crops cultivated for their lignocellulosic content, such as switchgrass and miscanthus, suitable for biofuel or bio-based product production.
	Wood	Biomass derived from trees, commonly available in forms such as logs, chips, or pellets.
	Forestry Residues	Byproducts from forestry activities, including branches, bark, and treetops.
	Secondary Forestry Residues	Waste generated during timber processing, such as sawmill residues.

Type of Biomass		Description
Other organic wastes & residues (non-oil based)	Manure	Organic waste from livestock, including cows, pigs, and poultry, that can serve as biomass.
	Biowaste	Organic material from food scraps, vegetable waste, and residues from kitchens or markets.
	Municipal Solid Waste (MSW)	Household and commercial waste collected by municipalities that contains organic components suitable for biomass applications.
Other organic wastes & residues (oil based)	Waste/residuals oils	Byproducts such as used cooking oils and animal fats originating from industrial or commercial activities.

Second-generation feedstocks support waste valorisation and contribute to circular economy objectives by utilising materials that would otherwise be discarded. Their use helps to reduce environmental impact and reliance on fossil-based raw materials.

Biomass availability

There are several studies in the literature which assess the biomass potential in Europe like the European commission [11–13], Oak Ridge National laboratory[14], bioenergy KDF[15] and Concawe study[16,17]. The Concawe study was used in this write-up as it had a better disaggregated availability data for the trilateral region with different biomass types. The Concawe study,[10] supported by Borzęcka et al.[18], projects an increase in total bioenergy potential from 175 Mtoe in 2020 to a range of 210 to 320 Mtoe by 2030 and 350 to 535 Mtoe by 2050 in Europe. In terms of biomass availability, this corresponds to 437.5 million dry tons (MDT) in 2020, increasing to 525 MDT to 800 MDT by 2030 and 875 MDT to 1338 MDT by 2050. By 2050, the study estimates that 360 Mtoe annually (900 MDT) will be required, with an additional 15 Mtoe per year expected to be imported.

Three scenarios have been analysed in the Concawe study:

1. Low biomass mobilisation (Scenario 1- low)
2. Improved mobilisation in selected countries due to improvements in cropping and forest management practices (Scenario 2- medium)
3. Enhanced availability through research and innovation (R&I) measures as well as improved mobilisation due to improvements in cropping and forest management practices (Scenario 3-High)

The main assumptions of the three scenarios is shown in Table 2 and the detailed assumptions of each scenario can be found in the Concawe report.[17]

Table C.2: Main assumptions of the three scenarios in the Concawe report[17]

Feedstock type		Scenario 1 (low)	Scenario 2 (medium)	Scenario 3 (High)
Agriculture	Removal rate of field residues	40%	45%	50%
	Use of pruning	5%	20%	50%

Feedstock type		Scenario 1 (low)	Scenario 2 (medium)	Scenario 3 (High)
	Moderate yield increases in perennial lignocellulosic crops in unused, degraded and abandoned land	1%	1%	2%
	Share of unused, degraded and abandoned land for dedicated crops, excluding biodiversity rich land and land with high carbon stocks (current share of unused, degraded and abandoned land for dedicated crops: there are no official statistics , only at experimental and demonstration scale)	25%	50%	75%
Forestry	Stemwood used for energy purposes (current stemwood for energy: 45%)	25%	30%	50%
	Primary forestry residues availability for energy production	40%	50%	60%
	Secondary forestry residues and post-consumer wood availability for energy	55%	60%	65%
Wastes	Bio-waste used for energy production (current collection for bioenergy: 40–45%	60% in 2030 (65% in 2050) of bio-waste is recycled and 40% in 2030 (35% in 2050) is separately collected and available for bioenergy	50% in 2030 (55% in 2050) of bio-waste is recycled and 50% in 2030 (45% in 2050) is separately collected and available for anaerobic digestion	40% in 2030 (45% in 2050) of bio-waste is recycled and 60% in 2030 (55% in 2050) is separately collected and available for anaerobic digestion

From the three scenarios the study analysed firstly the sustainable biomass availability for all markets and then estimated the amount that can be available for bioenergy after excluding the so far known demand from non-energy sectors. The main assumption of biomass allocation for bioenergy is shown in Table 3 and the detailed allocation assumptions can be found in the Concawe report[16].

Table C.3: Main assumptions for biomass allocation for bioenergy

Feedstock type		Bioenergy allocation assumption
Agriculture	Cereal straw	Cereal straw is being used for animal feed, animal bedding and mushroom growing The competing use was calculated based on livestock numbers and mushroom production levels. The estimated potential in the previous section is reduced based on demand from non-energy uses that is projected by CAPRI and statistics from JRC.
	Maize and oil crop residues	An average of 20% share is allocated to biobased markets both for 2030 and 2050.
	Manure	All the estimated quantities for manure are assumed to be available for bioenergy production
Forestry	Stem wood	Assumes 25% of stem wood being used for energy purposes as fuelwood in the Low scenario, 30% in the medium and 50% in the high scenario
Wastes	Bio-wastes	According to the Circular Economy Package, 55 % of municipal waste needs to be re-used and recycled by 2025, 60% by 2030, and 65% by 2035. The amount of municipal waste landfilled must be reduced to 10% or less of the total amount of municipal waste generated by 2035. This study applied the above rates to 2030 and to 2050 (the 65% announced for 2035) in the Low Scenario
	Used cooking oil	2030: Household collection rate: 15%; Professional collection rate: 90% and 2050: Household collection rate: 45%; Professional collection rate: 90%

From the three scenarios, the 2030 High scenario is taken as the biomass availability data for the 3C-VaCs project as the goal of the project is the assess the maximum potential of alternative feedstocks to replace fossil based petrochemical production.

Most biomass availability assessments in Europe have primarily focused on bioenergy applications, with few studies evaluating its potential use for the chemical industry such as the Renewable Carbon initiative report[19]. This is because there have been policy push for the bioenergy sectors and not for chemicals. Currently, 2G feedstocks like woody biomass is used for electricity and heating purposes and used cooking oil & animal fats for transport applications, which may cause competition for feedstocks in the future.[20,21]

Despite these challenges, there are opportunities for synergies between the chemical and transport sectors that could improve biomass utilization efficiency. Use of biofuels in the chemical industry could improve further mobilisation of feedstocks and biorefineries could serve both the transport and chemical industry derisking the market potential and improving the economics.

1. The Netherlands

The biogenic waste potential of the Netherlands is estimated to be around 8 million tonnes based on the Concawe scenario 3 (2030 High scenario).[16] About 4.84 million tonnes are estimated to be lignocellulosic waste and 3.14 million tonnes are other fractions like biogenic fraction of municipal solid waste, animal waste, and food waste.

Table C.4: Estimated biomass availability in the Netherlands by 2030

Feedstock type		Estimated availability in 2030 (kt dry biomass)		
		Low	Medium	High
Lignocellulosic biomass	Secondary Agricultural residues	968	1113	1403
	Lignocellulosic Crops	352	352	1056
	Secondary forest residues (incl. post-consumer wood)	596	14	846
	Cereal straw	475	475	644
	Stem wood	183	220	440
	Wood waste	92	126	165
	Maize stover	128	128	140
	Paper cardboard	30	42	55
	Agricultural pruning	18	22	48
	Primary forest residues	9	12	17
	Oil crop residues	16	16	19
Other organic wastes & residues (non-oil based)	MSW (biogenic fraction)	1540	2156	2773
	Animal & mixed food waste	120	165	217
	Vegetable waste	83	115	150
	Manure	0	0	0
Other organic wastes & residues (oil-based)	Used cooking oil	58		

The table highlights the projected distribution of 2G biomass feedstocks in the Netherlands for 2030 by feedstock type. Secondary agricultural residues are expected to be the highest contributor comprise about 29% of the total estimated dry lignocellulosic biomass feedstock, followed by lignocellulosic crops which will account for around 22%. Among the other organic wastes & residues, 88% of the contribution is projected to come from the biogenic fraction of MSW. These proportions illustrate the relative importance of the agriculture sector and municipal solid waste for future biomass applications in the Netherlands.

2. Germany

The biogenic waste potential of Germany is estimated to be around 99 million tonnes based on the Concawe scenario 3 (2030 High scenario).[16] About 85.8 million tonnes are estimated to be lignocellulosic waste and 13.2 million tonnes as other fractions like biogenic fraction of municipal solid waste, animal waste and food waste.

Table C.5: Estimated biomass availability in Germany by 2030

Feedstock type		Estimated availability in 2030 (kt dry biomass)		
		Low	Medium	High
Lignocellulosic biomass	Cereal straw	21967	23166	26762
	Stem wood	10540	15177	25296
	Secondary forest residues (incl. post-consumer wood)	7988	10458	11329
	Lignocellulosic Crops	2504	5009	7514
	Primary forest residues	4640	5950	7320
	Secondary Agricultural residues	3696	4251	5360
	Maize stover	1394	1534	1534
	Wood waste	181	248	325
	Agricultural pruning	115	158	300
	Oil crop residues	48	58	58
	Paper cardboard	10	14	18
Other organic wastes & residues (non-oil based)	MSW (biogenic fraction)	4129	5678	7433
	Manure	12001	14402	5194
	Vegetable waste	240	330	432
	Animal & mixed food waste	102	140	184
Other organic wastes & residues (oil-based)	Used cooking oil	578		

The table highlights the projected distribution of 2G biomass feedstocks in Germany for 2030 by feedstock type. Agricultural residues from cereal straw, maize stover and secondary residues are expected to be the highest contributor comprise about 39% of the total estimated dry lignocellulosic biomass feedstock, followed by stem wood which will account for around 29%. Among the other organic wastes & residues, 56% of the contribution is projected to come from the biogenic fraction of MSW and 39% from manure. These proportions illustrate the relative importance of the agriculture sector for future biomass applications in Germany.

3. Belgium

The biogenic waste potential of Belgium is estimated to be around 9.3 million tonnes based on the Concawe scenario 3 (2030 High scenario).[16] About 6.14 million tonnes are estimated to be lignocellulosic waste and 3.18 million tonnes as other fractions like biogenic fraction of municipal solid waste, animal waste and food waste.

Table C.6: Estimated biomass availability in Belgium by 2030

Feedstock type		Estimated availability in 2030 (kt dry biomass)		
		Low	Medium	High
Lignocellulosic biomass	Cereal straw	1078	1078	1380
	Stem wood	510	612	1225
	Secondary forest residues (incl. post-consumer wood)	679	130	963
	Lignocellulosic Crops	314	314	944
	Secondary Agricultural residues	593	681	859
	Maize stover	249	249	274
	Primary forest residues	86	108	156
	Wood waste	77	106	139
	Paper cardboard	71	97	128
	Agricultural pruning	26	31	68
	Oil crop residues	0	0	0
Other organic wastes & residues (non-oil based)	Manure	2209	2651	2627
	MSW (biogenic fraction)	209	287	376
	Vegetable waste	76	105	138
	Animal & mixed food waste	21	29	39
Other organic wastes & residues (oil-based)	Used cooking oil	70		

The table highlights the projected distribution of 2G biomass feedstocks in Belgium for 2030 by feedstock type. Agricultural residues are expected to be the highest contributor comprise about 41% of the total estimated dry lignocellulosic biomass feedstock, followed by lignocellulosic crops and stem wood which will account for around 35%. Among the other organic wastes & residues, 83% of the contribution is projected to come from manure. These proportions illustrate the relative importance of the agriculture residues and lignocellulosic crops for future biomass applications in Belgium.

This document will be part of Appendix for the report written by VITO for the 3C-VaCs project.

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Appendix D

Plastic waste based pathways for the production of olefins and aromatics

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Base chemicals such as olefins (ethylene, propylene, and butadiene), BTX (benzene, toluene, xylene, and other aromatics), and methanol are essential components of the chemical industry, playing a key role in the production of a wide range of materials and products. The production of base chemicals such as olefins and aromatics predominantly depends on fossil feedstocks, resulting in significant CO_2 emissions due to the energy-intensive processes and scope-3 emissions involved. To address these environmental challenges, the chemical industry is exploring alternative pathways to produce these chemicals with a lower carbon footprint. This report examines the base chemical production routes from plastic waste.

Plastic waste recycling technologies can be classified as physical recycling based and chemical recycling based. Physical recycling technologies transforms plastic waste into new raw materials or products without altering the chemical structure of the polymers. Plastic waste can be physically recycled using mechanical or dissolution recycling (as shown in **Figure D.1**).

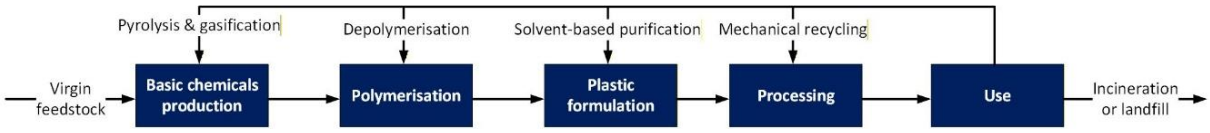


Figure D.1: Ways of recycling plastic waste (adapted from CE Delft report)[1]

The mechanical recycling process involves analysis, sorting, shredding, washing, and melting the plastic, followed by extrusion to create new granules. Mechanical recycling may not be suitable for all types of plastic waste, especially mixed or contaminated materials.1 While generally considered efficient, mechanical recycling usually impact the quality of recycled materials, requiring additional processes to maintain desired properties. The quality will always change (go down) due to the fact that it is not a mono-stream (i.e., different polymer types and colours present) that is recycled this way. In addition, each time plastic is mechanically recycled, the polymer chains within it break down, leading to a decrease in its overall quality. Due to this quality degradation, most plastics can only be mechanically recycled a limited number of times, depending on the target use-case after recycling. If a very low target is set, it might still be possible for higher number of times for mechanical recycling.

All thermoplastics like polyethylene, polypropylene, polystyrene, polyvinyl chloride etc. can be mechanically recycled to the same product. Thermoset plastics are not easy to mechanically recycle to the same product as they cannot be melted and reprocessed. Mechanical recycling of thermosets involves grinding or shredding waste into particles, which can then be used as a filler or additive in new products.

In dissolution, solvolysis, or solvent-based extraction, the plastic waste is dissolved in a solvent to remove additives and contaminants from the waste mixture. The polymer structure itself is not affected in the process (except for solvolysis) and therefore the polymers are extracted as output in the recycling technology. In solvolysis, the polymer can be broken down by the solvent as well. It can be used for recycling products from other sectors such as the electronics, automotive sectors, or for composite materials. Currently, solvolysis is used to recycle expanded polystyrene (EPS), which is commonly used as an isolation material in the construction sector and has been processed with flame retardants.[1] The EPS is separated from the brominated flame retardants, after which the polymers are extracted from the solvent and processed into clean polystyrene (PS). In the case of EPS, a homogeneous feedstock stream is required for the solvolysis process. This means that a clean plastic stream with less than 10% contamination is needed, in the case of solvolysis for EPS.[2]

Chemical recycling on the other hand converts plastic waste into petrochemical feedstocks (like naphtha or syngas) and base chemicals (like ethylene, propylene, benzene and xylene). It complements mechanical recycling by enabling the recycling of different streams of plastic waste that cannot otherwise be recycled, particularly mixed and contaminated plastics, into virgin-like raw materials or monomers. The three types of chemical recycling technologies are depolymerisation, gasification, and pyrolysis.

In depolymerisation, polymers are broken down into monomers and/or oligomers using chemical reactions and/or heat. These monomers and/or oligomers can be used to rebuild new polymers of higher quality or purity, as polymer chain lengths can be restored and contaminants can be removed. For example, depolymerisation can be used for devulcanization of rubber or to directly rebuild recycled PET from waste PET. In this case DKR 328-1 (sorted PET) is first pre-treated to remove impurities, moisture, and volatile components from the PET flakes. Next, the polyethylene terephthalate (PET) molecules are depolymerised into monomers like p-xylene and ethylene glycol. Finally, the monomers are re-polymerised into PET polymers, which are granulated and stored. Depolymerization is often limited to certain types of polymers (like condensation polymers) and may require specific catalysts or conditions.

Table D.1: Example of plastic waste recycling technologies, their input and output

Technology		Feedstock (Input)	Product (Output)
Physical recycling	Mechanical recycling	Sorted plastic waste	Recycled plastic granules
	Solvent-based extraction	Expanded Polystyrene (pre-sorted)	Polystyrene (polymer)
Chemical recycling	Depolymerisation	DKR 328 (PET)	p-xylene and ethylene glycol
	Pyrolysis	DKR 310 (foils), DKR 323 (mixed polyolefins), DKR 324 (polypropylene), etc.	Pyrolysis oil

Technology		Feedstock (Input)	Product (Output)
	Gasification	DKR 350 (mixed plastics), DKR 310 (foils), DKR 323 (mixed polyolefins), DKR 324 (polypropylene), etc.	Syngas (syngas can be converted to chemicals & fuels)

The most mature chemical recycling technologies are gasification and pyrolysis. In the gasification process, plastic waste is heated to very high temperatures under low oxygen conditions using gasifying agents (like steam and/or oxygen), typically resulting in a gaseous output named syngas that can be used as fuel or building block for chemicals and fuels. Pyrolysis involves heating the plastic waste, at high temperatures (typically 300 °C to 800 °C) in the absence of oxygen. Pyrolysis produces a range of products including pyrolysis oil (a liquid fuel), gases (like methane and ethane), and a solid residue (char). These chemical recycling technologies can be used for processing mixed and contaminated plastic waste streams that are difficult to recycle mechanically or with solvent-based processes and can be used to generate fuel or feedstock for the petrochemical processes. Polyolefins (like polyethylene, polypropylene) and other plastics that can be thermally degraded without oxygen are best suited for the pyrolysis process, while gasification can be used for a wide range of plastics that are not suitable for pyrolysis. PVC is not preferred in gasification or pyrolysis processes as chlorine is highly corrosive and reactive and would require pre-processing or use of specialised equipment or materials. Other polymers like PET and polyamide can also be used in the gasification process in addition to polyolefins.

Plastic waste can be converted to olefins (like ethylene, propylene) and aromatics (like benzene and p-xylene) using both gasification and pyrolysis routes which are discussed in detail below.

D.1 Plastic waste to olefins

Plastic waste can be converted into olefins mainly through two process routes as explained below:

D.1.1 Plastic waste pyrolysis + pyrolysis oil steam cracking (using sorted polyolefin based plastic waste)

Pyrolysis involves heating plastic waste in a low-oxygen environment to temperatures above 400 °C, breaking down the polymers into smaller molecules like oil, gas, and synthetic waxes. Plastic waste feedstocks like DKR 350 (mixed plastic waste), DKR 324 (polyethylene) and DKR 329 (polypropylene) can be treated with a pyrolysis technology. The pyrolysis works best with polyolefin plastic like polyethylene (PE) and polypropylene (PP), thus when DKR 350 is used the plastic types like thermosets and other materials like PVC are first removed in a pre-treatment step. Sorted plastic waste can be converted to olefins via low-temperature pyrolysis followed by pyrolysis oil steam cracking.

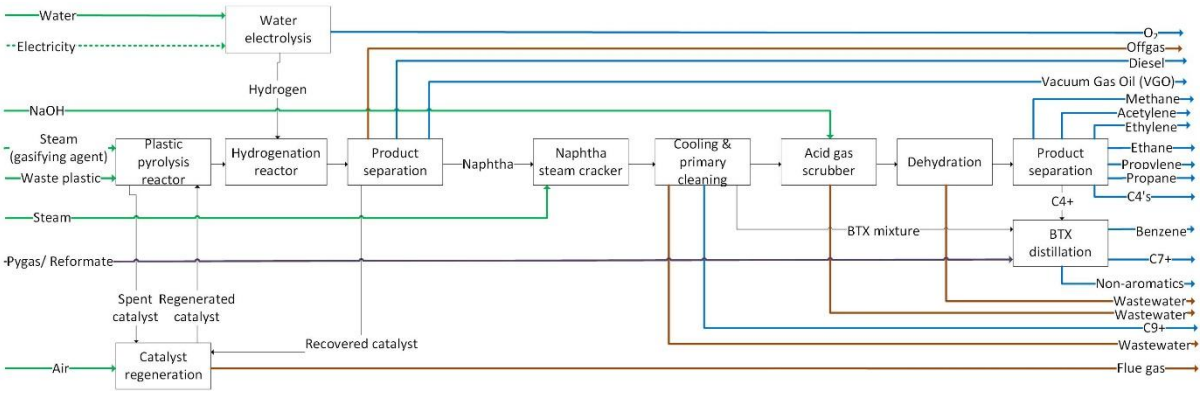


Figure D.2: Block flow diagram of plastic to olefins via pyrolysis process[4]

Plastic is pyrolyzed at 300 °C to 500 °C near atmospheric pressure to yield a hydrocarbon mixture containing off-gas, naphtha (hydrocarbon with boiling point ranging from 26 °C to 183 °C), diesel (hydrocarbon with boiling point ranging from 180 °C to 350 °C), heating oil (hydrocarbon with boiling point ranging from 313 °C to 475 °C) and char. The pyrolysis reactor can be operated as a fluidized bed with catalyst regeneration to clean the char from catalyst in a continuous manner. A set of cyclones and cloth filters are used to remove the entrained catalyst from the reactor outlet and the regenerator. During pyrolysis, unsaturated hydrocarbons are formed and to ensure saturated hydrocarbons, the pyrolysis oil goes through a hydrogenation step. The hydrogen can be supplied via water electrolysis. The hydrocarbon mixture is then separated through vacuum distillation to produce naphtha, diesel, and vacuum gas oil. The pyrolysis oil constitutes about 20% naphtha, 70% diesel and 10% heating oil. The off gases from the distillation section may contain impurities like H_2S and HCl, which can be neutralised with NaOH scrubbing. The naphtha stream (hydrocarbon fraction in the boiling range of 35 °C to 180 °C) can be fed to a steam cracker involving high-temperature pyrolysis (at 850 °C) of saturated hydrocarbons in the presence of steam. During steam cracking, a wide range of lower hydrocarbons are produced, mainly hydrogen, methane, ethylene, ethane, acetylene, propylene, propane, butene, butadiene, benzene, non-aromatics, and aromatics. The other product steams produced during plastic waste pyrolysis like diesel and heating oil can also be steam cracked to produce olefins[3], however, the heavy steam cracking plants are not common within Europe. After steam cracking, the hydrocarbon mixture undergoes downstream purification to remove impurities (like CO_2, H_2S and water) and complex separation processes (like high pressure cryogenic distillation and extractive distillation) to separate the individual components into high-purity product streams, which can then be used to make new polymers.

Table D.2: Mass, energy and economic characteristics of plastic pyrolysis process[4] (Note: For energy positive sign means energy need and negative sign means energy production)

	Mass in (kt)		Mass out (kt)	
Mass	Off gas combustion and catalyst regeneration air for heating	39068	Diesel	1456
	Hydrogen	16	Naphtha	1055
	Sodium hydroxide	50	Vacuum gas oil	1333
	Plastic waste (DKR 329 and DKR 324)	5000	Flue gas	40341
	Process steam	100	Waste water	50

Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Cooling water	3385	Low pressure steam	-4872
	Electricity	8	Medium pressure steam	-2986
			High pressure steam	-30966
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	1036		Corrected to 2023 using CEPCI	

Note: The capacity of 5000 kt/y plastic waste is used such as to produce about 1000 kt/y naphtha, which is equivalent to the 1/3rd naphtha demand in the Port of Rotterdam. Such an industrial scale pyrolysis plant does not exist.

As seen in Table 2, the typical naphtha yield from the plastic pyrolysis is only 16%. Thus, significant quantities of plastic waste will be required if only naphtha is used for olefin production. The other byproducts of plastic pyrolysis like diesel and vacuum gas oil can also be steam cracked to produce olefins with yields as shown in Table 3. Such heavy oil crackers or adapting the current steam crackers to handle a wider range of hydrocarbons will be crucial to increase the material usage efficiency and reduce the quantity of plastic waste required to produce olefin.

Table D.3: Yield comparison of naphtha, diesel and vacuum gas oil steam cracking processes (typically example) [3]

	Naphtha cracking (high-severity)	Diesel cracking	Vacuum gas oil cracking
Steam dilution (kg/kg)	0.5	0.8	1
Residence time (sec)	0.493	0.32	0.3
Yield (wt.%)			
H_2	0.99	0.71	0.68
CO	0.06	0.01	0.01
CO_2	0	0.01	0.01
H_2S	0	0	0
CH_4	16.9	10.58	11.08
C_2H_2	0.64	0.38	0.6
C_2H_4 (Ethylene)	30.25	25.93	25.98
C_2H_6	4.32	2.82	2.81
C_3H_4	0.81	0.63	0.97
C_3H_6 (Propylene)	13.63	14.07	16.02
C_3H_8	0.37	0.37	0.42
C_4H_4	0.18	0.12	0.04
C_4H_6	4.2	5.73	8.03
C_4H_8	3.11	3.61	4.14

	Naphtha cracking (high-severity)	Diesel cracking	Vacuum gas oil cracking
C_4H_{10}	0.17	0.05	0.06
Benzene	8.32	5.44	5.64
Toluene	3.4	3.49	2.73
Xylenes	1.14	0.92	0.46
Ethylbenzene	0.44	0.37	0.34
Styrene	1.44	1.18	1.12
Pyrolysis gasoline	5.25	7.28	6.91
Pyrolysis fuel oil	4.38	16.3	11.95

Table D.4: Mass, energy and economic characteristics of naphtha steam cracking process[4] (Note: For energy positive sign means energy need and negative sign means energy production, Solvent are n-formyl morpholine, dimethyl formamide and n-methyl pyrrolidone)

	Mass in (kt)		Mass out (kt)	
Mass	Naphtha	3000	Ethylene	878
	Steam	1500	Propylene	497
	Combustion air	23311	Acetylene	18
	Sodium hydroxide	18	Butene mixture	93
	Dilution water	147	Butadiene	116
	Solvent	0.14	C9+ stream	224
	Make-up water	1.5	Benzene	689
	Hydrogen	1.17	C7+ stream/Pygas tail	279
	Pygas import	372	Nonaromatic stream	295
	Reformate import	417	Propane rich fuel gas	11
	Wash water	6.4	Vinyl acetylene	5
			Flue gas	23984
			Waste water	1683
Energy	Energy in (TJ/y)		Energy out (TJ/y)	
	Low pressure steam	5208	Medium pressure steam	-3461
	Cooling water	26469	High pressure steam	-5970
	Chilled water	997	Very high-pressure steam	-1714
	Electricity	7315		
Economic	CAPEX including product purification section (Million EUR)		Basis year	
	1486		Corrected to 2023 using CEPCI	

D.1.2 Plastic waste steam gasification + syngas to methanol + methanol to olefin (Mixed plastic waste mainly)

Unsorted plastic waste (like mixed municipal plastic waste) can be converted to olefins via steam gasification and methanol to olefin process. Gasification produces syngas (a mixture of CO and H_2) from plastic. The syngas, among other uses, can be converted into basic chemicals such as methanol. The steam gasification occurs at 800 °C to 1000 °C in a fluidised bed reactor with sand bed material near atmospheric pressure. The raw syngas undergoes cleaning to remove impurities (like entrained catalyst, water, tar, acid gases). The hydrogenation of the clean syngas to methanol occurs in a tubular reactor at 69 bar and 255 °C, over a Cu-ZnO-Al_2O_3 based catalyst.

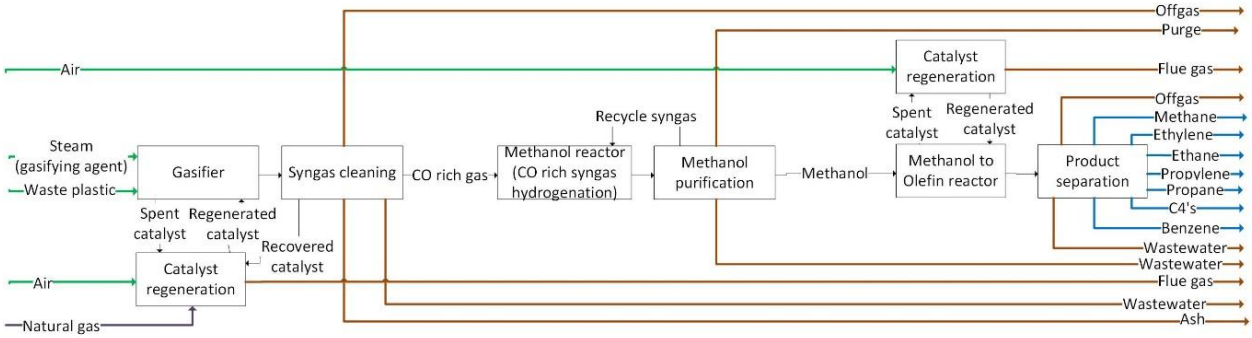


Figure D.3: Block flow diagram of plastic to olefin via methanol process[4]

Note that that in this route, external hydrogen or excess CO_2 removal from syngas is not required, as the syngas has a $H_2/(CO+CO_2)$ ratio above 2 in the input gas to the methanol reactor. The methanol produced (99.9 wt.% pure), after going through a distillation process to remove light gases and water, is sent to the methanol to olefin (MTO) fluidised bed reactor operating at 30 bar and 450 °C. The MTO process produces ethylene and propylene along with other by-products (like methane, ethane, propane, C4's, benzene). The product mixture is separated into high purity products using a series of separation processes (like dehydration, cryogenic distillation, extractive distillation).

Table D.5: Mass, energy and economic characteristics of plastic waste gasification followed by syngas to methanol process[4] (Note: For energy positive sign means energy need and negative sign means energy production, Solvent is ethylene diamine tetra acetic acid and catalyst is silica)

	Mass in (kt)		Mass out (kt)	
Mass	Plastic waste (DKR 350)	310	Methanol	408
	Water	356	Ash	12
	Natural gas for heating	66	Flue gas	4022
	Combustion air	3850	Waste water	244
	Catalyst make-up	1		
	Solvent	104		
Energy	Energy in (TJ/y)		Energy out (TJ/y)	
	Low pressure steam	1792	Medium pressure steam	-1389
	Cooling water	2617	High pressure steam	-615

	Electricity	745		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	530		Corrected to 2023 using CEPCI	

Table D.6: Mass, energy and economic characteristics of methanol to olefin process[4] (Note: For energy positive sign means energy need and negative sign means energy production, catalyst is SAPO-34)

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Methanol	2300	Methane	10
	Combustion air	360	Ethylene	314
	Catalyst	1	Ethane	9
			Propylene	398
			Propane	74
			C4 (assumed to butene)	106
			C5+ (assumed to be benzene)	80
			Flue gas	386
			Waste water	1284
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Low pressure steam	6500	Medium pressure steam	-1104
	Cooling water	9743	High pressure steam	-68
	Electricity	1892		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	423		Corrected to 2023 using CEPCI	

Note: The capacity of 2300 kt/y methanol is used such as to produce about 300 kt/y ethylene, which is equivalent to the 1/3rd ethylene production in the Port of Rotterdam. Such an industrial scale methanol to olefin plant does not exist.

D.2 Plastic waste to aromatics

Plastic waste can be converted into aromatics mainly through two process routes as explained below:

D.2.1 Plastic waste pyrolysis + pyrolysis oil catalytic reforming (using sorted polyolefin based plastic waste)

Sorted plastic waste can be converted to aromatics via low-temperature pyrolysis followed by naphtha catalytic reforming. Plastic is pyrolyzed at 300 °C to 500 °C near atmospheric pressure to yield a hydrocarbon mixture containing off-gas, naphtha (hydrocarbon with boiling point ranging from 26 °C to 183 °C), diesel (hydrocarbon with boiling point ranging from 180 °C to 350 °C), heating oil (hydrocarbon with boiling point ranging from 313 °C to 475 °C) and

char. The pyrolysis reactor can be operated as a fluidized bed with catalyst regeneration to clean the char from catalyst in a continuous manner. A set of cyclones and cloth filters are used to remove the entrained catalyst from the reactor outlet and the regenerator. During pyrolysis, unsaturated hydrocarbons are formed, and to ensure saturated hydrocarbons, the pyrolysis oil goes through a hydrogenation step. The hydrogen can be supplied via water electrolysis. The hydrocarbon mixture is then separated through vacuum distillation to produce naphtha, diesel and vacuum gas oil. The off-gases from the distillation section may contain impurities like H_2S and HCl which can be neutralised with NaOH scrubbing. The naphtha stream (hydrocarbon fraction in the boiling range of 35 °C to 180 °C) can be fed to a catalytic reformer to produce aromatics.

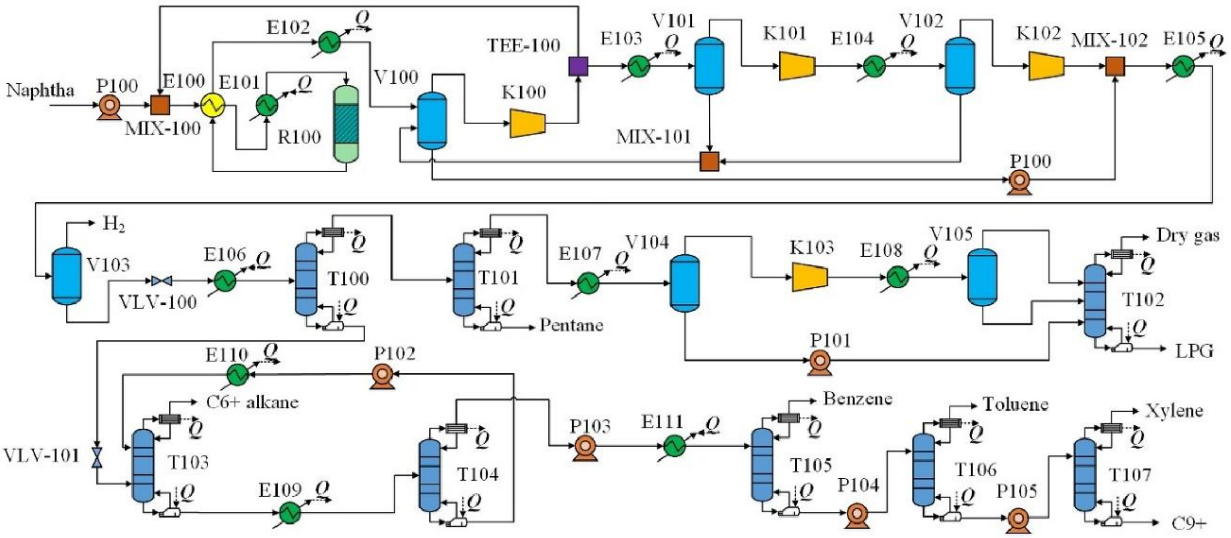


Figure D.4: Process flow diagram of naphtha catalytic reformer process[5]

Catalytic reforming is the primary process used to convert naphtha into aromatic hydrocarbons, including benzene, toluene, and xylenes (BTX), which are valuable petrochemical building blocks. This process involves using a catalyst, typically a noble metal like platinum, on an acidic support. In catalytic naphtha reforming, the temperature typically ranges from 450 to 540°C and pressures of about 5 bars. These conditions, along with a hydrogen atmosphere, facilitate the conversion of naphtha (a mixture of paraffin, naphthene, and aromatics) into high-octane gasoline components and aromatic compounds like benzene, toluene, and xylenes (BTX). A high partial pressure of hydrogen is also needed to favour the desired reactions. The main reactions involved are the dehydrogenation of naphthene to aromatics, isomerization of paraffins, and dehydrocyclization of paraffins to aromatic. Generally, the Continuous Catalyst Regeneration (CCR) reactor configuration is used, meaning the catalyst is continuously circulated and regenerated to maintain its activity during the process. The benzene yield can be increased using toluene disproportion and xylene isomerisation reactors, which are not included in the data given below.

Table D.7: Mass, energy and economic characteristics of naphtha catalytic reforming process[5] (Note: For energy positive sign means energy need and negative sign means energy production, catalyst is platinum on chlorinated alumina support, the refrigeration need was converted to electricity and cooling water needs using a coefficient of performance of 1.91)

	Mass in (kt)		Mass out (kt)	
Mass	Naphtha	456	Hydrogen	47
			Dry gas	0
			Liquified petroleum gas	20
			Pentane	18
			C6+ alkane	67
			Benzene	24
			Toluene	72
			Xylene	133
			C9+	74
	Energy in (TJ/y)		**Energy out (TJ/y)**	
Energy	Medium pressure steam	162	Low pressure steam	-234
	High pressure steam	819		
	Fired heat	541		
	Cooling water	870		
	Electricity	118		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	127		Corrected to 2023 using CEPCI	

As seen in Table 2, the naphtha yield from the plastic pyrolysis is only 16%. Thus, significant quantities of plastic waste will be required if only naphtha is used for aromatics production. The other byproducts of plastic pyrolysis like diesel and vacuum gas oil can also be converted to naphtha to increase the aromatics yields using a fluidised catalytic cracker as shown in Table 8. Vacuum gas oil fluidised catalytic crackers (FCC) already exists in current refineries to convert heavy fraction of crude oil to more valuable light fractions like olefins and naphtha. The heavy oils can also be steam cracked to produce aromatics with yields as shown in Table 3. Such heavy oil crackers or adapting the current steam crackers to handle a wider range of hydrocarbons will be crucial to increase the material usage efficiency and reduce the quantity of plastic waste required to produce aromatics.

Table D.8: Mass and economic characteristics of fluidised catalytic cracker to produce naphtha from heavy oils[6]

	Mass in (kt)		Mass out (kt)	
Mass	Vacuum gas oil	2393	Light gases	76
			Liquified petroleum gas	362
			Naphtha	1189
			Light cycle oil	497

			Heavy cycle oil	169
			Coke	99
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	846		Corrected to 2023 using CEPCI	

D.2.2 Plastic waste steam gasification + syngas to methanol + methanol to aromatics (Mixed plastic waste mainly)

Unsorted plastic waste (like mixed municipal plastic waste) can be converted to aromatics via steam gasification followed by the methanol to aromatics (MTA) route. Steam gasification occurs in a fluidised bed reactor at 800 °C to 1000 °C near atmospheric pressure, using sand as the bed material. The resulting raw syngas is cleaned to remove impurities (entrained catalyst, water, tar, and acid gases). The clean syngas is then converted to methanol in a tubular reactor at 69 bar and 255 °C, using Cu-ZnO-Al_2O_3 catalyst.

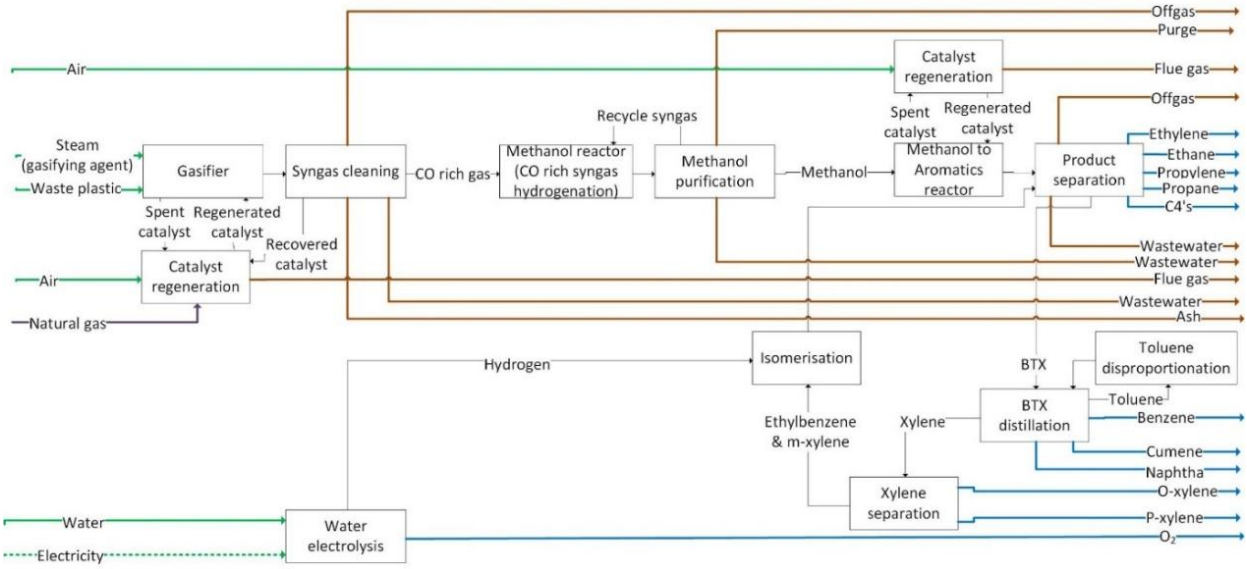


Figure D.5: Block flow diagram of plastic waste to aromatics via methanol process[4]

Unlike the biomass and CO_2 routes, this process does not require additional hydrogen or acid gas removal as the syngas had a $H_2/(CO+CO_2)$ ratio above 2. The resulting methanol was purified (99.9 wt.% pure) via distillation to remove light gases and water. In the second step, methanol is fed into a fluidised bed MTA reactor (60 bar, 450 °C), producing benzene along with by-products like methane, ethane, propylene, propane, C4's, toluene, xylene. To increase the benzene yield, toluene and m-xylene, were further processed using a toluene disproportionation to benzene reactor and a m-xylene isomerisation unit. The final product mixture was separated into high-purity products using a series of advanced separation steps (dehydration, cryogenic distillation, extractive distillation).

Table D.9: Mass, energy and economic characteristics of methanol to aromatics process[4] (Note: For energy positive sign means energy need and negative sign means energy production, catalyst is HZM-5)

	Mass in (kt)		Mass out (kt)	
Mass	Methanol	8800	Ethylene	21
	Combustion air	8733	Ethane	195
	Catalyst	4	Propylene	68
	Hydrogen	17	Propane	641
			C4 (assumed to butene)	921
			Cumene	240
			Naphthalene	32
			O-xylene	5
			P-xylene	972
			Benzene	535
			Flue gas	9012
			Waste water	4914
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Medium pressure steam	4493	Low pressure steam	-12020
	Cooling water	21065	High pressure steam	-15
	Electricity	5122		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	3676		Corrected to 2023 using CEPCI	

Note: The capacity of 8800 kt/y methanol is used such as to produce about 500 kt/y benzene, which is equivalent to the benzene production in the Port of Rotterdam. Such an industrial scale methanol to aromatics plant does not yet exist.

This document will be part of Appendix for the report written by VITO for the 3C-VaCs project.

D.3 References

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Appendix E

Biomass based pathways for the production of olefins and aromatics

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Base chemicals such as olefins (ethylene, propylene, and butadiene), BTX (benzene, toluene, xylene, and other aromatics), and methanol are essential components of the chemical industry, playing a key role in the production of a wide range of materials and products. Olefins, particularly ethylene, propylene, and butadiene, are used in the production of plastics such as polyethylene and polypropylene, as well as synthetic rubbers, which are widely applied in packaging, construction, and consumer goods. Similarly, BTX compounds are important feedstocks for producing polymers like polyethylene terephthalate, synthetic fibres, resins, and coatings. Methanol is extensively used as a precursor for formaldehyde, acetic acid, and fuel additives such as MTBE. It is also attracting increasing interest as a maritime fuel. In addition, methanol serves as a key building block for producing base chemicals, including olefins and BTX, highlighting its importance in the chemical value chain.

The production of base chemicals such as olefins and aromatics predominantly depends on fossil feedstocks, resulting in significant CO_2 emissions due to the energy-intensive processes and scope-3 emissions involved. To address these environmental challenges, the chemical industry is exploring alternative pathways to produce these chemicals with a lower carbon footprint. This report examines three main groups of bio-based chemical production routes, i.e., via methanol, ethanol and naphtha (or liquid hydrocarbons); for olefins and BTX production (see **Table E.1**). Only TRL>5 technologies were selected for the assessment and technologies like hydrothermal liquefaction (HTL) are not considered as the oil from HTL requires further hydrotreatment and the whole system together is at low TRL. Also, decentralised bio-synthetic natural gas (SNG) production was not considered because the focus was on centralised systems as seen in the case of biogas. SNG is an interesting intermediate which can easily be plug-in with existing methanol units, however, this is not considered in the report.

Table E.1: Pathways for the production of base chemicals included in this study

Technology		Feedstock	Product
Methanol pathways	Methanol production via gasification of biomass	Lignocellulosic biomass	Methanol
	Methanol production via biogas	Other organic wastes & residues	Methanol

Technology		Feedstock	Product
	Methanol-to-Olefins	Methanol	Olefins (ethylene, propylene)
	Methanol-to-Aromatics	Methanol	BTX
Ethanol pathways	Lignocellulosic biomass to ethanol	Lignocellulosic biomass	Ethanol
	Ethanol-to-Ethylene	Ethanol	Ethylene
Alternative cracker feed pathways	Biomass pyrolysis and upgrading	Lignocellulosic biomass	Bio-oil (Bio-naphtha and heavier fractions)
	Biomass gasification and syngas conversion (Fischer Tropsch)		Bio-oil (Bio-naphtha and heavier fractions)

The objective of this report is to provide an overview of these alternative pathways by outlining their process descriptions and performance metrics, including key inputs, outputs, and capital expenditures. The structured evaluation aims to support the transition towards a more sustainable and circular chemical industry. The outcomes of this report will contribute to the broader 3C-VaCS project by offering essential data and pathway descriptions to assess alternative chemical production routes.

E.1 Methanol pathways

E.1.1 Methanol production via gasification of biomass

Methanol production through gasification of lignocellulosic biomass consists of several steps. The process begins with biomass pretreatment, which typically includes drying and particle size reduction. This is followed by biomass gasification, where the biomass is converted into syngas, a mixture of carbon monoxide and hydrogen. The gasification process uses oxygen as gasifying agent, thus this step also includes an air separation unit to provide the system with the required oxygen flow. In the final step, syngas is catalytically converted into methanol under high pressure and moderate temperature. Biomass gasification is carried out at 850°C,[1] while methanol synthesis occurs at 300°C and 80 bar.[1]

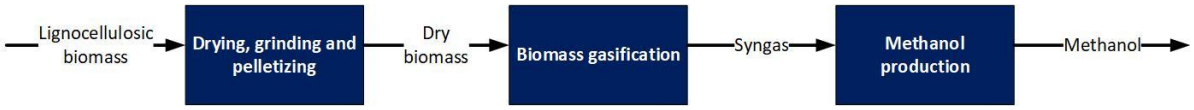


Figure E.1: Simplified block flow diagram of biomass to methanol process[2]

Table E.2 presents the mass and energy balances for methanol production from biomass. The flows indicate a substantial demand for cooling utilities and electricity, primarily due to the air separation unit and the compressors used in the methanol synthesis step. Approximately 50 percent of the initial biomass mass (in dry basis) is converted into methanol, while the remaining carbon is released as biogenic CO_2 in the flue gas stream. The release of CO_2 is inherent to the gasification process, as the hydrogen-to-carbon monoxide ratio in the biomass must be adjusted to meet the requirements for methanol synthesis. As a result, a portion of the carbon leaves the system as CO_2.

The methanol yield from biomass is consistent with values reported in the literature.[2] The waste streams contain a considerable fraction of nitrogen, originating from the air separation

unit. Air separation is required to provide oxygen for the gasification step, which produces syngas from biomass to be used as feedstock for methanol synthesis.

Table E.2: Mass and energy flows of methanol production via biomass gasification.[2] (Abbreviation: ar- as received)

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Biomass ar (moisture content of 30 wt.%)	1429	Methanol	504
	Water	88	Flue gas (94 wt.% CO_2)	932
	Air	1800	Waste water	442
			Nitrogen	1381
			Ash	58
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Electricity	851		
	Heating	1298		
	Cooling	12603		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	710		Corrected to 2023 using CEPCI index	

The capital expenditure (CAPEX) for this process is based on the year 2023. The gasification reactor is a major cost component, which aligns with literature findings indicating the high cost of gasification technologies. Further advancements are necessary to achieve cost reductions in the future. Compressors also represent a significant share of CAPEX, mainly due to the high pressures required in the methanol synthesis step. Separation columns further contribute to overall costs, particularly cryogenic columns used in the air separation unit and those required for methanol separation.

E.1.2 Methanol production via biogas

Methanol production from biogas involves several stages. The process starts with the production of biogas from biomass through anaerobic digestion. The resulting biogas, primarily consisting of methane (CH_4) and carbon dioxide (CO_2), is then upgraded and reformed to produce syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO). This syngas is subsequently converted into methanol through catalytic synthesis under moderate temperature and high pressure as discussed above.

The biogas unit operates at 40 ºC and 1 bar, with a biogas yield of 98 Nm³ per tonne of organic matter in the substrate, which is typical for manure-based digestion. The biogas composition is 64 vol% CH_4 and 36 vol% CO_2, representing a typical biogas composition. The conversion of organic matter in the digester follows these yields: 0.91 kg of digestate per kg of organic matter, and 0.08 kg of biogas per kg of organic matter. The product from the digester is separated into a crude gas stream and a wet stream containing the digestate.

Methanol production from biogas involves several key stages, starting with the upgrading of raw biogas, which consists mainly of methane (CH_4) and carbon dioxide (CO_2), through a separation process to remove CO_2 and produce biomethane. This upgraded biomethane is

then subjected to steam methane reforming (SMR), which converts methane into a syngas mixture primarily containing hydrogen (H_2) and carbon monoxide (CO). The separated CO_2 is not wasted, instead, it is mixed back with the syngas and fed into the methanol synthesis reactor. Methanol production can follow different process schemes, including direct CO_2 hydrogenation, where CO_2 is hydrogenated to methanol in a single reactor, or a reverse water gas shift reaction (r-WGS) step that first converts CO_2 into CO, which is then synthesized into methanol. **Table E.3** presents the mass and energy flows of the process of biomass to methanol via biogas via direct synthesis.

Methanol production via biogas requires significant inputs, including 62,331 ktonnes per year of manure with 90% moisture content and 15,625 ktonnes per year of water, which is used exclusively for anaerobic digestion to maintain the required wet conditions. The process demands for heating and cooling are primarily for steam methane reforming and methanol synthesis.

Table E.3: Mass and energy flows of methanol production via biogas.[3]

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Biomass (Manure at 90 wt.% moisture)	62331	Methanol	504
	Water	15625	Flue gas (Mainly CO_2)	64
			Waste water	70229
			Digestate	7159
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Heating	1128	Electricity	-879
	Cooling	739		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	447		Corrected to 2023 using CEPCI index	

As shown in **Table E.3**, the total CAPEX for methanol production via biogas amounts to 447 million euros, with biogas production representing the 43% share and reforming with methanol accounting for 57% of the investment. This reflects the complexity and infrastructure requirements of anaerobic digestion and biogas upgrading. Steam methane reforming, although a crucial step in syngas production, requires a relatively lower investment, while methanol synthesis contributes significantly to the total cost due to the need for specialized reactors and separation systems.

E.1.3 Methanol-to-Olefins

Methanol is fed to the methanol to olefin (MTO) fluidised bed reactor operating at 30 bar and 450 °C. The MTO process produces ethylene and propylene along with other by-products (like methane, ethane, propane, C4's, benzene). The product mixture is separated into high purity products using a series of separation processes (like dehydration, cryogenic distillation, extractive distillation).

Table E.4: Mass, energy and economic characteristics of methanol to olefin process[4] (Note: For energy positive sign means energy need and negative sign means energy production, catalyst is SAPO-34)

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Methanol	2300	Methane	10
	Combustion air	360	Ethylene	314
	Catalyst	1	Ethane	9
			Propylene	398
			Propane	74
			C4 (assumed to butene)	106
			C5+ (assumed to be benzene)	80
			Flue gas	386
			Waste water	1284
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Low pressure steam	6500	Medium pressure steam	-1104
	Cooling water	9743	High pressure steam	-68
	Electricity	1892		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	423		Corrected to 2023 using CEPCI index	

Note: The capacity of 2300 kt/y methanol is used such as to produce about 300 kt/y ethylene, which is equivalent to the 1/3rd ethylene production in the Port of Rotterdam. Such an industrial scale methanol to olefin plant does not exist.

E.1.4 Methanol-to-Aromatics

Methanol is fed into a fluidised bed MTA reactor (60 bar, 450 °C), producing benzene along with by-products like methane, ethane, propylene, propane, C4's, toluene, xylene. To increase the benzene yield, toluene and m-xylene, were further processed using a toluene disproportionation to benzene reactor and a m-xylene isomerisation unit. The final product mixture was separated into high-purity products using a series of advanced separation steps (dehydration, cryogenic distillation, extractive distillation).

Table E.5: Mass, energy and economic characteristics of methanol to aromatics process[4] (Note: For energy positive sign means energy need and negative sign means energy production, catalyst is HZM-5)

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Methanol	8800	Ethylene	21
	Combustion air	8733	Ethane	195
	Catalyst	4	Propylene	68
	Hydrogen	17	Propane	641
			C4 (assumed to butene)	921
			Cumene	240
			Naphthalene	32
			O-xylene	5
			P-xylene	972
			Benzene	535
			Flue gas	9012
			Waste water	4914
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Medium pressure steam	4493	Low pressure steam	-12020
	Cooling water	21065	High pressure steam	-15
	Electricity	5122		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	3676		Corrected to 2023 using CEPCI index	

Note: The capacity of 8800 kt/y methanol is used such as to produce about 500 kt/y benzene, which is equivalent to the benzene production in the Port of Rotterdam. Such an industrial scale methanol to aromatics plant does not yet exist.

E.2 Ethanol pathways

E.2.1 Lignocellulosic ethanol-to-Ethylene

Lignocellulosic ethanol is a biofuel produced by converting the cellulosic and hemicellulose part in plant cell walls (lignocellulosic biomass) into ethanol through fermentation. It is considered a promising alternative to traditional ethanol, which is often made from food crops like corn or sugarcane.

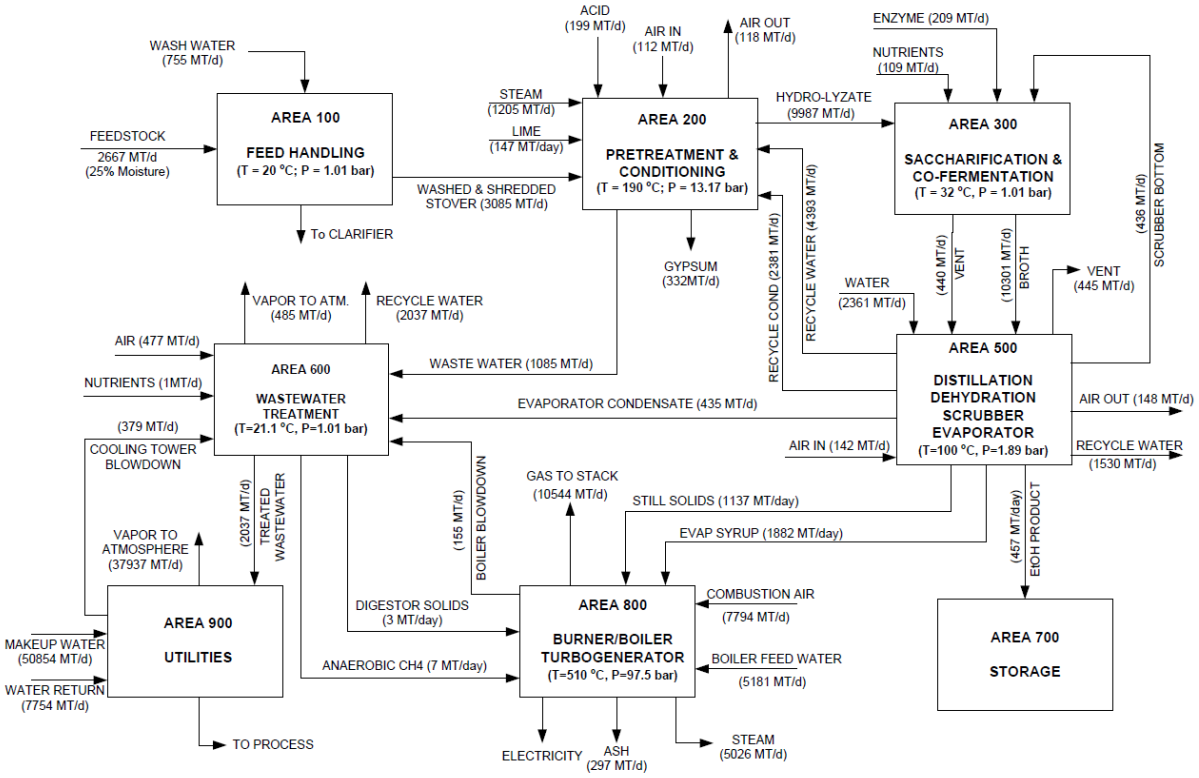


Figure E.2: Block flow diagram of lignocellulosic ethanol process[5]

The process generally involves steps like, pretreatment (to expose the rigid structure of lignocellulosic biomass to make the cellulose and hemicellulose accessible for enzymatic hydrolysis), enzymatic hydrolysis (enzymes break down the cellulose and hemicellulose into fermentable sugars, primarily glucose and xylose), fermentation (microorganisms like yeast or bacteria ferment the sugars into ethanol) and product recovery (the ethanol is separated and purified).

Table E.6: Mass flows and CAPEX for the production of lignocellulosic ethanol[5]

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Stover (with 25% moisture content)	880	Ethanol	151
	Wash water	249	Waste water	358
	Steam	398	Gypsum	110
	Lime	49	Air (out)	88
	Acid	66	Vent (CO_2)	147
	Air (in)	84	Recycle water	505
	Nutrients	36	Evaporator condensate	144
	Enzyme	69	Flue gas (combustion of still solids & evaporator syrup)	3480
	Water	779	Ash	98
	Combustion air	2572	To clarifier	101
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Cooling water	472	Electricity	780
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	529		Corrected to 2023 using CEPCI index	

Ethanol can be converted to ethylene through a dehydration reaction, which involves removing the water molecule. This process typically uses a catalyst, often an acidic material like alumina or a zeolite, and high temperatures. The reaction is endothermic, meaning it requires heat input, and is commonly performed in a fluidized bed reactor or other specialized reactors. The specific CAPEX from the reference for the ethanol dehydration process is around 0.08 EUR/kg ethylene.

Table E.7: Mass flows and CAPEX for the ethanol to ethylene dehydration process[6]

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Ethanol	271	Ethylene	164
			Waste water	107
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Electricity	230		
	Natural gas	432		
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	14		Corrected to 2023 using CEPCI index	

E.3 Alternative cracker feed pathways

One option to decarbonise the steam cracking sector is to replace naphtha with a renewable feedstock. Since the impact of co-processing bio-oils feedstocks is limited to few percentages due to formation of coke because of heavier fractions in bio-oil, the bio-oil is subject to hydrotreating and naphtha separation. It is assumed that this hydrotreated bio-naphtha is compatible with downstream processes such as cracking and separation would remain unchanged from current steam crackers. These downstream processes are not included in this analysis. The focus of this analysis is on various technologies for producing bio naphtha.

- Biomass Pyrolysis and upgrading

The pyrolysis process converts biomass into bio-oil, syngas, and char by heating it to 400–600°C in the absence of oxygen. The process involves drying biomass to remove moisture, followed by thermal decomposition into the three fractions. The volatile vapours are cooled to condense bio-oil, while gases and char are separated. The bio-oil yield of the fast pyrolysis process is around 57 wt.%. However, the bio-oil produced has a high oxygen content, making it unstable and unsuitable for direct use.

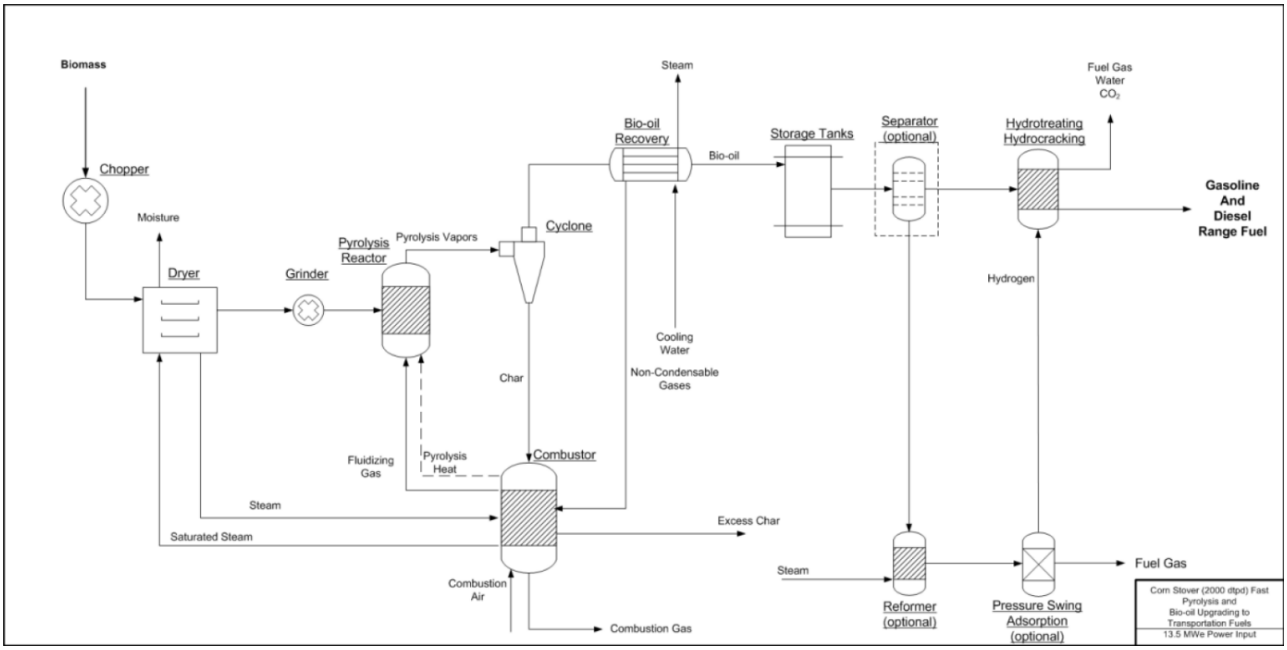


Figure E.3: Process flow diagram of biomass pyrolysis with hydrotreating process[7]

To enhance the quality of bio-oil, hydrotreatment is applied, using hydrogen to reduce oxygen content and convert it into hydrocarbon-rich products such as bio-naphtha. This can be achieved through single-step or two-step configurations, with the latter stabilising the bio-oil before further upgrading for improved results. In some cases, bio-oil is separated into water-soluble and water-insoluble fractions for tailored processing to optimise yield and quality.[8]

Table E.8: Fast pyrolysis yields from corn stover feedstock[7]

Stream	Wt %
Non condensable gas	14.3
Oil	57.6
Water	8.7
Char/Ash	19.4

The upgraded bio-oil is fractionated into hydrocarbon streams, including bio-naphtha, which can serve as a feedstock for steam crackers to produce olefins and aromatics. Other fractions, such as biodiesel, can be used as transport fuels. Despite its potential, the process faces challenges, including high energy and hydrogen demand, as well as catalyst stability and resistance to fouling. Continued advancements in catalysts and hydrogen production are critical to addressing these limitations. Table 9 summarises the key inputs, outputs and CAPEX for producing bio naphtha via pyrolysis.

Table E.9: Mass and energy flows of pyrolysis and upgrading for bio naphtha production. Adapted from Wright et al[7]

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Corn stover (15 wt.% moisture content)	600	Naphtha	75
	Hydrogen	27	Diesel	75
			Non condensable gas	309
			Wastewater	52
			Char/Ash	116
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Cooling water	NA	Electricity	0.33
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	280		Corrected to 2023 using CEPCI index	

E.3.1 Fischer Tropsch

Biomass can be converted to liquid hydrocarbons via syngas (which is a mixture of carbon dioxide, carbon monoxide and hydrogen), through the Fischer-Tropsch process. Although FT technology has traditionally been associated with the production of fuels such as diesel, kerosene, and gasoline, its potential for generating bio naphtha as a renewable feedstock for petrochemical applications is attracting increased attention. In this context, biomass gasification serves as the initial step, providing a renewable source of syngas that is subsequently converted into FT liquids (see **Figure E.4**).

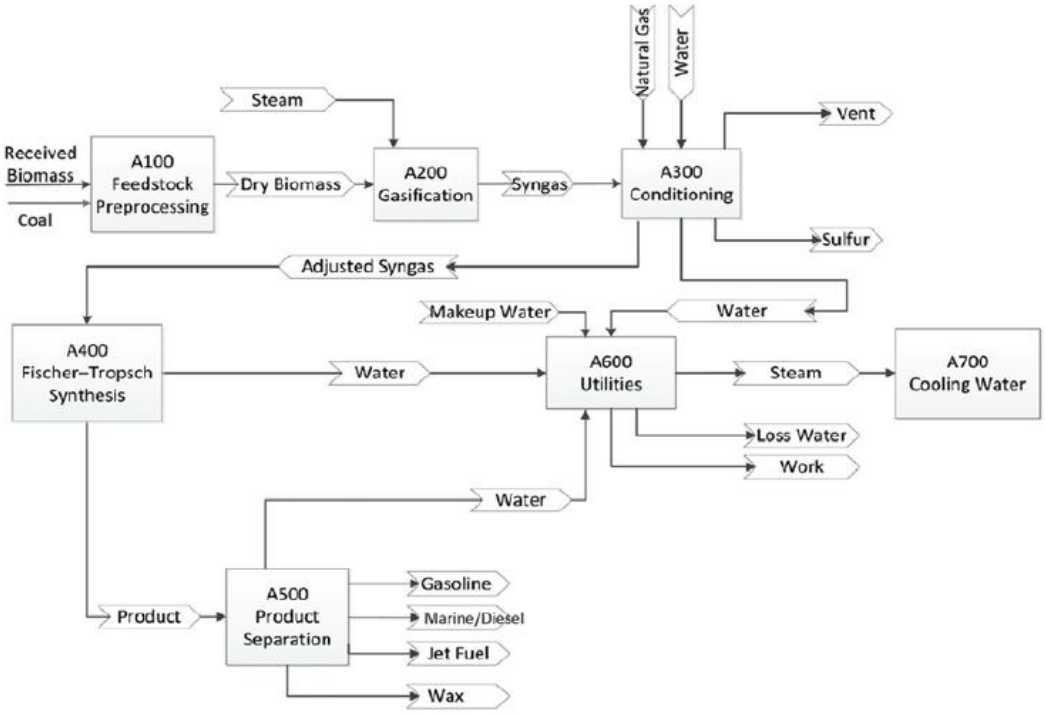


Figure E.4: Block flow diagram of biomass based Fischer Tropsch process[9]

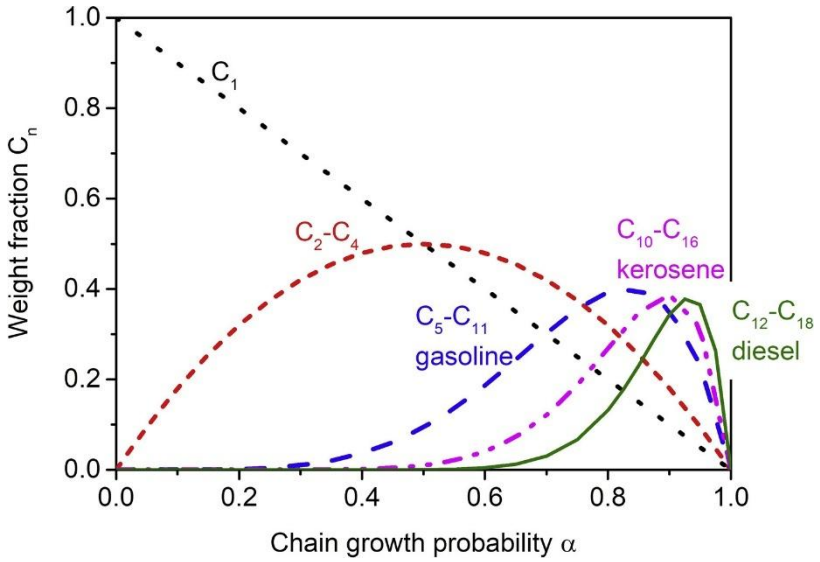


Figure E.5: Anderson- Schulz Flory distribution for the Fischer Tropsch process[10]

The FT process involves the catalytic conversion of syngas into long-chain hydrocarbons. This reaction takes place in the presence of metal catalysts, typically cobalt or iron, under elevated temperatures ranging from 200 to 300°C and pressures between 20 and 50 bar. The distribution of products from this process is influenced by reaction conditions, like temperature, pressure, residence time, and carbon to hydrogen ratio, and catalyst properties and follows the Anderson-Schulz-Flory distribution[10] (see **Figure E.5**); which predicts a mixture of paraffins, olefins, and oxygenates. By carefully adjusting the process parameters, it is possible to target specific product ranges, including naphtha in the FT process.

FT liquids can be separated into distinct fractions. One of these fractions is naphtha, composed of light hydrocarbons in the C5 to C10 range, which is suitable for use as a feedstock in steam crackers for olefin and aromatic production. Other fractions include middle distillates, such as diesel and kerosene, and heavier hydrocarbons like waxes and lubricants. While most research has historically focused on FT middle distillates for fuel applications, there is growing interest in optimising the process specifically for naphtha production. Diverse studies[11–14] have explored several approaches, including the development of catalyst formulations and reactor designs to enhance the production of light hydrocarbons, the identification of operating conditions that favour shorter hydrocarbon chains, and the integration of FT processes into biorefineries to improve yields and reduce costs.

The advantages of FT-derived bio-naphtha lies with its high purity and bio-based nature. Bio-naphtha can serve as a sustainable feedstock for olefin production in steam crackers, enabling the production of ethylene, propylene, and BTX (benzene, toluene, and xylene). FT-derived bio-naphtha can be a direct replacement for fossil based naphtha in steam crackers, thereby offering a viable alternative to fossil-based naphtha. Furthermore, FT-derived bio-naphtha is typically free of sulphur and other impurities, making it a highly versatile and desirable feedstock for petrochemical applications.

Table E.10 summarises the key inputs, outputs, and economics for producing bio naphtha via Fischer Tropsch

Table E.10: Mass, energy and economic characteristics of Fischer Tropsch process. Adapted from Tan et al[9]

Mass	**Mass in (kt)**		**Mass out (kt)**	
	Woody biomass (LHV= 18.27 MJ/kg)	759	Naphtha	53
	Catalyst	2.4	Kerosene	63
	Amine make-up	0.0001	Diesel	29
	Boiler feed water	152	Wax	19
	Combustion air	348	Vent gas (99.9 wt.% CO_2)	893
			Ash	28
			Wastewater	177
Energy	**Energy in (TJ/y)**		**Energy out (TJ/y)**	
	Cooling water	97	Electricity	0.03
Economic	**CAPEX including product purification section (Million EUR)**		**Basis year**	
	841		Corrected to 2023 using CEPCI index	

This document will be part of Appendix for the report written by VITO for the 3C-VaCs project.

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