SYSTEMIQ

Fossil Free Plastics

Driving Clean Industrial Leadership in Europe

MAY 2025

Preface

Plastics play a central role in our daily lives and our modern economy. They also bring three inter-linked challenges: 1) how to reduce plastic waste and pollution through circular economy strategies, 2) how to decouple plastics from fossil carbon and achieve the goal of a net-zero emissions economy by 2050, and 3) how to strengthen the competitiveness of the European plastics industry in a challenging global market.

In recent years, Systemiq has built system models of global and regional plastic flows containing environmental and socio-economic impacts, and published scenario analyses to inform strategic choices for the future of plastics. Our previous system modelling studies (notably ReShaping Plastics and Planet Positive Chemicals) have shown unequivocally that circular economy strategies have a critical role to play in a sustainable plastics system, but new “virgin” plastics will also be required to meet societal needs. Methanol-to-Olefins (MTO) technology was highlighted in these studies as a viable pathway to produce fossil-free virgin plastics at scale. MTO enables the production of standard-grade plastics using renewable carbon and green hydrogen, while offering full traceability compared to mass balance approaches, alongside compatibility with existing infrastructure and product standards. Pioneering this novel approach to plastics manufacturing in Europe could help to reinvigorate a beleaguered European plastics industry.

This report draws on data analysis and systems modelling to evaluate the role of fossil-free plastics via MTO in a future sustainable plastics system. While no solution is without limitations, our findings suggest that this approach could deliver significant emissions reductions, reduce reliance on fossil feedstocks, complement circularity strategies and support industrial competitiveness in a decarbonising global economy. Importantly, it underscores the unique potential for plastics system stakeholders to become proactive agents of carbon stewardship, managing scarce carbon resources more responsibly across the lifecycle, and potentially sequestering more carbon than they emit. The evidence indicates that this approach merits serious consideration as part of the policy and investment agenda for the sector’s transition. As ever, we would welcome your feedback on our analysis and our recommendations.

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About this publication

About the study

This report has been prepared by Systemiq as an independent study, building on internal system modelling, previous publications, and new analysis to explore the potential role of the bio-methanol-to-olefins technology pathway in a sustainable plastics system. While funded by Vioneo, the report reflects Systemiq's own perspective and has been developed with editorial independence. The analysis and conclusions are data-driven and grounded in Systemiq's wider theory of change for the sector. Insights have also been shaped through engagement with a diverse expert panel, including voices from industry, academia and civil society, to ensure a broad and balanced perspective. The views presented here remain those of Systemiq.

About Systemiq

Systemiq is a systems change company that works with businesses, policymakers, investors and civil society organisations to reimagine and reshape the systems that sit at the heart of society - energy, nature and food, materials, built environment, and finance - to accelerate the shift to a more sustainable and inclusive economy. Founded in 2016, Systemiq is a certified B-Corp with offices in Brazil, France, Germany, Indonesia, the Netherlands, and the UK.

Find out more at www.systemiq.earth or via LinkedIn

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Report design

Yesify

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Expert panel

To ensure the objectivity and technical accuracy of this study, Systemiq assembled a panel of experts representing different stakeholder groups and parts of the value chain including representatives from academia, civil society and industry. The Expert Panel reviewed detailed assumptions and provided input into the approach. We are deeply grateful to all the organisations and individuals who contributed their deep content expertise.

David Carroll, Director of External Affairs, Plastics Europe

Davide Tonini, Scientific Policy Officer, Joint Research Centre of the European Commission

Fridtjof Unander, former CSO, IEA and Aker-Horizons

Joan Marc Simon, Founder and Executive Director, Zero Waste Europe

Prof. Kim Ragaert, Chair of Circular Plastics, Maastricht University

Lars Börger, co-CEO, Nova Institute & Renewable Carbon Initiative

Miguel Mendonça Reis Brandão, Associate Professor in industrial ecology and life cycle assessment, Royal Institute of Technology in Stockholm

Raoul Meys, Managing Director and co-Founder, Carbon Minds

Stéphane Arditi, independent expert on circular and bio economy, climate and industry. Former co-director of a major European civil society organisation

Disclaimer Endorsements reflect expert support for the overall approach and key findings of the report. They do not necessarily imply agreement with every statement or represent the official views of the individuals' affiliated organisations.

Endorsements

“In a truly circular economy, the use of plastic is decoupled from the consumption of finite resources. While this decoupling should happen in the first place through reducing the use of virgin plastic, it's also important that over time any remaining virgin inputs shift to renewable feedstocks where environmentally beneficial. This is not just my view but that of over 1,000 organisations around the world who have endorsed the common vision of a circular economy for plastics in the Global Commitment. This important new report reinforces this vision and the need for renewables to be part of the picture to achieve decoupling from finite resources. It shows how fossil-free plastics produced via MTO, using renewable feedstocks and clean energy, can be an important pathway to bring this vision one step closer.

Rob Opsomer, Executive Lead, Plastics & Finance, Ellen MacArthur Foundation

“This report makes clear that all solutions are needed to work towards a low carbon and circular European plastics system, including plastics made from green methanol, and this must be recognised in EU policy. Clear definitions, robust sustainability criteria, and early policy signals—well before 2030—are essential to provide industry with the certainty and incentives needed to act decisively and secure Europe's leadership in this transition.

David Carroll, Director of External Affairs, Plastics Europe

“All scientific studies on a future circular plastics system indicate that a significant share of virgin feedstock will still be needed. Preferably, this is not fossil based, and MTO can make a valuable contribution to meeting that demand.

Prof. Kim Ragaert, Chair of Circular Plastics, Maastricht University

“Transitioning to sustainable plastic production—especially via scalable methods like methanol-to-olefins—is vital for Europe's climate goals. This commendable study powerfully illustrates how plastics, when paired with circular strategies and fossil-free feedstocks, can shift from being climate problems to climate solutions, delivering significant environmental, economic, and policy advantages.

Lars Börger, CEO, Nova-Institute

“Using renewable and low-emission methanol for plastic production is one key technology to achieve net zero. The report is well aligned with other studies conducted for global associations and chemical companies.

Raoul Meys, Managing Director and co-Founder, Carbon Minds

“This report reminds us of the urgency to act to make the plastics sector future proof. It makes clear how fossil free plastics based on sustainable renewable feedstock can complement circular strategies to defossilise the sector. Beyond convincing modelling and clear limits on sustainable biomass use, it also proposes policy interventions to secure investments and galvanize a fossil-free chemicals industry in Europe. These are goals that simplification and deregulation alone may not fulfil.

Stéphane Arditi, independent expert on circular and bio economy, climate and industry.
Former co-director of a major European civil society organisation

Key terms and definitions

Bioplastic: Used in this report to refer to a broad range of plastics that may be fully or partially made from bio-based materials/technologies. This term also refers to biodegradable plastic, which covers polylactic acid (PLA) or polyhydroxyalkanoates (PHAs) designed to decompose after use. This term includes 'fossil-free plastic' (see distinct definition below) which is derived from biomass/biogenic feedstock.

Biomass or biogenic feedstock: Organic matter, i.e. biological material, available on a renewable basis. Includes feedstock derived from animals or plants, such as: wood and agricultural crops/residues; organic and biogenic waste from livestock, municipal and industrial sources; or algae.

Carbon stewardship: Activities which involve taking greater and more proactive responsibility in management of carbon resources (particularly scarce carbon resources) across the entire chemicals and plastics lifecycles, from feedstock supply to consumption and end-of-life. This includes scaling reuse, recycling, and carbon circularity in the form of carbon capture and utilisation.

Cradle-to-gate: System boundaries of a life cycle assessment study that consider the life cycle stages from raw material extraction to the production of the end product (before consumption/use phase) in its final form at the factory gate.

Gate-to-grave: System boundaries of a life cycle assessment study that consider the life cycle stages from the end product final form at the factory gate, transport, use and final disposal at end-of-life (i.e. grave).

Cradle-to-grave: System boundaries of a full life cycle assessment study that consider all life cycle stages from a linear model including raw material extraction (cradle), production, transport, use and final disposal (grave).

Fossil-free plastic: Virgin plastic derived from renewable carbon sources such as certified biogenic feedstocks and atmospherically-sourced carbon such as direct air capture. This includes the methanol-to-olefins production pathway (with green methanol) as well as other non-fossil production routes.

Green methanol: In this document, this refers to either biomethanol or e-methanol. Biomethanol is produced from gasification of biomass. E-methanol is produced from hydrogenation of renewable CO_2 (derived from renewable carbon) and green hydrogen. Note that this term differs from the European Commission's definitions for e-methanol as renewable methanol and biomethanol as a bio-based feedstock.

Linear (vs circular): A Linear plastics system is characterised by a one-way flow of resources which involves extracting raw materials, manufacturing products, and end-of-life waste disposal. In contrast, a Circular plastic system promotes resource efficiency and sustainable use by encouraging reusing and recycling materials and products to eliminate waste and regenerate resources.

Methanol-to-Olefins (MTO): An industrial process converting methanol to olefins (ethylene and propylene).

Negative emissions: Term used by the IPCC used to define activities, practices or technologies that remove CO_2 from the atmosphere (rather than emit to the atmosphere). In this document, negative emissions refer to the potential for fossil-free plastic to be produced from carbon from the atmosphere, which is later stored in the ground at end-of-life.

Renewable carbon: Includes all carbon sources that avoid or substitute the use of any additional fossil-based carbon from the geosphere. Renewable carbon can come from the biosphere, atmosphere or technosphere, but not from the geosphere.

Utility (of plastic): The services that are provided by plastic under a business as usual scenario. In alternative scenarios, services of equivalent value could be provided in other ways with less plastic. In other words, all scenarios analysed in this study have the same plastic utility (e.g., consumer demand for services), but the way which this utility is delivered can vary significantly. In some scenarios it is done via virgin plastic, in others with recycled plastic, and in others with new delivery models (e.g. reuse) or material substitution/reduction.

Virgin plastic: Polymer resin that has not previously been used by consumers. Produced directly from petrochemical feedstock (i.e. virgin fossil plastic) or sustainable biogenic or atmospherically-sourced feedstock (i.e. virgin fossil-free plastic). Does not include pre-consumer recycled plastic.

Executive summary

1 Most plastics today are produced from fossil feedstocks and used once before disposal, creating an emission-intensive system which will continue to escalate towards 2050.

Plastics play a vital role across modern economies, from keeping food fresh and supporting healthcare, to construction and transportation. However, the chemicals and plastics sector currently drives 4% of global greenhouse gas (GHG) emissions and is on track to grow this share significantly over the next years.

In Europe, nearly 80% of plastics are produced from virgin fossil feedstocks, and only 19% from recycled fossil materials and 1% from bio-based feedstocks, with most plastics incinerated after a single use. Recent studies have shown that producing fossil plastics and then burning them in waste incineration plants emit up to five tonnes of CO_2 equivalents (CO_2eq)[1] per tonne of plastic over their lifecycle. This is higher than previously estimated due to improved tracking of upstream methane emissions, a powerful greenhouse gas released in oil and gas extraction and production. With this current system, plastic production and disposal in Europe alone is on track to increase emissions by a further 40 million tonnes of CO_2eq per annum by 2050.

~80% of plastics are currently produced from fossil feedstocks

40 Mt CO2eq projected annual emissions increase in Europe by 2050

2 Even in a highly circular European plastics system, half of all market demand (28 million tonnes per year) would likely still be required from virgin sources.

To make our use of plastics sustainable, it is crucial to use fewer resources and get more value out of the plastics we do use. System modelling and scenario analysis suggests that ambitious yet realistic measures for reduction, reuse, and substitution could lower plastic demand in 2050 by up to 20% (a reduction of approximately 15 million tonnes) compared to a business-as-usual scenario. However, even in the most optimistic circularity scenario, recycling would only produce half of the plastic required to meet this system demand annually, meaning **Europe will likely still require around 28 million tonnes of virgin plastic in 2050.**

28 Mt of virgin plastic demand in Europe in 2050

Therefore, decoupling from fossil feedstocks and achieving "defossilisation" is the other essential part of creating a future plastics system that does not add to net GHG emissions.

1 CO_2 equivalents: standard unit of measurement used to measure the environmental impact of one tonne of greenhouses gases (carbon dioxide, methane, nitrous oxide, fluorinated gases) vis a vis one tonne of CO2.

3 Fossil-free virgin plastics made from renewable carbon are a critical pillar of a circular, net-zero aligned plastics system. Established "reduce-reuse-recycle" circular economy strategies and efforts to reduce emissions from fossil-based plastics are essential, but not sufficient on their own to align the system with Europe's net-zero targets.

Fossil-free virgin plastics are manufactured from renewable sources of carbon (atmospheric carbon from biomass or direct air capture). System modelling carried out for this study focuses on the use of Methanol-to-Olefins (MTO) technology to produce polyethylene and polypropylene plastics from green methanol (based on renewable carbon and green hydrogen), creating identical, fully recyclable products compatible with today's systems. This MTO pathway is segregated, thus does not rely on mass balancing or mixing of fossil-free and fossil feedstocks, enabling greater transparency for customer assurance.

Fossil-free plastic production via this MTO pathway can **reduce emissions by 5-7 tonnes of CO_2eq per tonne of plastic production**, based on a -1/+1 carbon accounting methodology. At a system level, this provides the opportunity for negative emissions from the plastics system, moving carbon from the atmosphere into durable plastics or long term sequestration.

5–7 tCO_2eq
reduction in emissions per tonne of plastic production via the MTO pathway

Without intervention, the **European plastics system's emissions could rise to 180 MtCO_2eq annually by 2050.** In a highly circular system, fossil-free plastics can make up to ~30% of production (~15 Mt), compensating for residual emissions from fossil plastics production and recycling and drive the European system to net zero emissions overall. In combination with circular economy strategies, the transition from fossil-based to fossil-free plastics would avoid 180 MtCO_2eq of emissions annually by 2050.

The success of this transition hinges on securing **high-integrity, sustainable biomass (e.g. agricultural residues) and captured biogenic CO_2 feedstocks,** as global demand for these resources is expected to outstrip supply by up to 10-20 times. Scaling circularity alongside fossil-free plastics is essential to achieve a resource efficient system, and justify the use of scarce available sustainable biomass for plastics production by almost halving feedstock requirements.

Furthermore, a strategy that combines fossil-free production with high levels of recycling and careful management of carbon all along the value chain is less dependent on any single new technology. This integrated approach reduces the overall risks involved in making the big shift to a net-zero emissions plastics system.

4 At scale, fossil-free plastics could be cost-competitive with fossil production, if carbon costs are factored in, and would deliver multiple socio-economic benefits to the system.

Currently, virgin fossil-based plastics are undeniably cheaper to produce at scale, in part because full lifecycle emissions and other externalities are excluded from their costs. However, the cost of green methanol is expected to decrease, and the technology in the MTO production pathway is advancing. Both factors will make fossil-free polyolefin plastics (polyethylene and polypropylene) increasingly affordable. At scale, the cost of producing fossil-free olefins could drop by 30-50%. This could result in cost parity with fossil-based olefins in the region of €2,000/t olefins when future carbon costs are included. Scaling the MTO value chain in Europe could also drive €30-40bn capex investment, provide new opportunities for suppliers to meet up to 40Mt of new green methanol demand per annum and contribute up to 50,000 direct and indirect jobs, which can protect the domestic workforce from deindustrialisation pressures in the chemicals and plastics sector.

-30–50%
potential reduction in the cost of producing fossil-free olefins by 2050

5 Scaling fossil-free plastics has broader strategic implications for European clean technology leadership, industrial resilience and competitiveness on a global stage.

For offtakers, fossil-free plastics match the performance of virgin fossil plastics, meeting strict specifications without constraints of mechanically recycled plastics. They can offer clear scope 3 emissions cuts that help companies meet their net-zero targets, in line with the Science Based Targets initiative (SBTi) Corporate Net-Zero Standard[2]. Fossil-free plastics offer segregated supply and full traceability, offering advantages over other bio-based or recycled plastics that rely on mass-balancing.

For the EU chemicals and cleantech sector, fossil-free plastics offer a scalable, proven abatement route, helping Europe's chemical sector transition competitively and with lower risk. Fossil-free plastic scale up can unlock synergies in other adjacent sector transitions such as aviation, shipping, fertiliser and agriculture via scale up of renewable energy, electrolyser capacity and high-integrity sustainable biomass supply chains. Early investment would allow Europe to leverage its technological lead, export clean technology capabilities and intellectual property, and reinforce its **industrial geo-political autonomy.**

6 Industry players are investing to scale fossil-free plastic production in Europe, but require early adopter customers, bold industrial strategy with definitive policy signals, clear market foundations and structural market support to develop a mature market.

Much of the technology and supply chain for fossil-free plastics is ready, with first-of-a-kind projects in Europe nearing final investment decisions. To demonstrate **first projects at commercial scale, early adopter customers must be mobilised** that recognise the strategic advantages of being a first mover. In parallel, **decisive industrial strategy is required to send clear demand signals** to the broader market, stating clearly that fossil-free plastics will be a central element of future plastics policy in Europe.

In the near term, clear market foundations are required to build market confidence and demand, including a legal definition of green methanol based plastics in key policies, as well as harmonisation of accounting methodologies to recognise and fairly value the benefits of fossil-free plastics. In turn, value chain players need to align internally and collectively advocate externally for an enabling policy environment for fossil-free plastics, as well as potentially explore innovative value chain partnership models to redistribute commercial risk and cost.

The technology is ready, mobilising pioneer customers is now essential to unlock the first wave of commercial-scale production

In the medium term, structural support is required to overcome market failures and reshape the European value chain for scale. This includes creating **stronger demand** by setting clear targets and requirements in upcoming plastics policies. These should encourage or mandate the use of fossil-free alternatives. Europe should also **create a level playing field** between fossil-free plastics and more emissions-intensive products, both domestic and international. In parallel, **new market structures for public funding** are needed to overcome high initial costs of production and mitigate uncertainty on value chain revenue, price fluctuation and counterparty risk. If governments show strong leadership with these policies, Europe can protect the future of its chemical industry, reduce its dependence on fossil fuels, and become a world leader in producing green materials.

2 The SBTi draft Corporate Net-Zero Standard v2.0 emphasises the importance of actions that can be fully traced through the corporate value chain using credible chain of custody models including identity preservation, segregation, and controlled blending.

CHAPTER 1

The imperative to act

The fossil plastics system is highly emissions intensive and should aim to decouple from fossil feedstock dependence

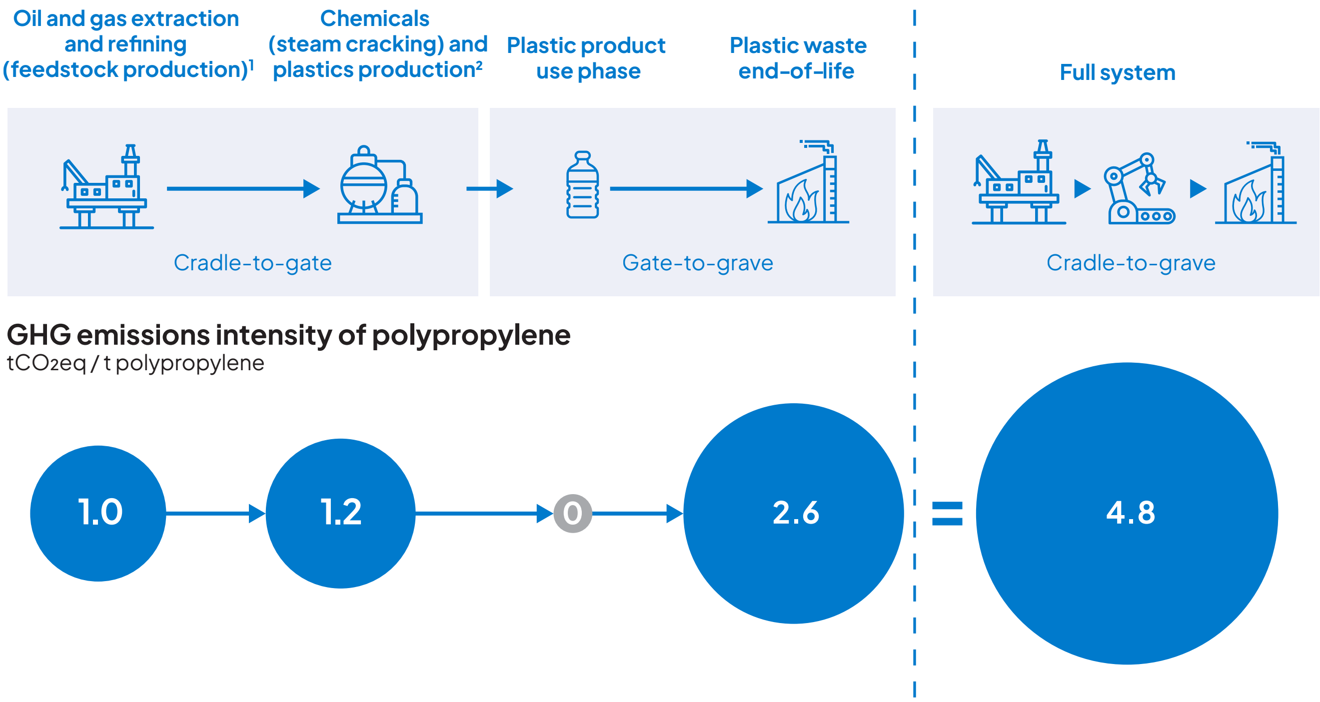
The fossil-feedstock dependent plastic system is responsible for up to five tonnes of CO_2 emissions for every tonne of plastic produced.[a] Today, producing virgin plastics from fossil feedstocks (oil, coal, natural gas) generates emissions at every stage of the value chain: fossil feedstock extraction and refining (21% of total lifecycle GHG emissions); petrochemical and plastic production, polymerisation and conversion (25% of total); through to end-of-life disposal emissions (54% of total)[3,b], As seen in Exhibit 1, for each tonne of virgin fossil plastics used in our modern economy ~2 tonnes of CO_2eq are emitted from production (cradle-to-gate) and ~3 tonnes of CO_2eq is embedded carbon in the plastic if/when it is incinerated (gate-to-grave). These figures assume plastic waste is incinerated at end-of-life as this is the dominant pathway in the European system today.

~80%
of plastics are currently produced from fossil feedstocks

3 As the assessment of fossil-based production emissions becomes more accurate, the emissions from methane leakage, venting and flaring in the upstream supply chain are shown to have been underestimated in industry datasets. Global lifecycle assessment databases are revising upward the carbon footprints of fossil derived products such as polyethylene (PE), polypropylene (PP) and PET to account for these upstream impacts. For example, the Ecoinvent database has increased the upstream carbon footprint for PE and PP by as much as 30% between versions 3.9.1 and 3.10.1, and with increased scrutiny and data granularity on a regional and country specific basis (to account for crude oil supply sources) the true impact may be further recognised. In this report, plastic GHG emissions per unit mass assume polypropylene as an example. Estimated emissions values for other plastics will vary.

EXHIBIT 1

Plastics production by fossil feedstocks is highly emissions intensive at all stages of production and disposal



Notes: 1) Includes naphtha production and other fossil feedstocks to steam crackers (e.g. butane, ethane). 2) Includes polymerisation plant. 3) Emissions factor for incineration shown given majority of plastic waste today in Europe in incinerated. Lower emissions factor may apply for different end-of-life destination (e.g. 0.1 tCO_2eq/t polypropylene for landfill). Incineration emissions factor is also highly dependent on type of plastic (e.g. up to 3.1 tCO_2eq per tonne of polyethylene). Excludes plastic product use phase emissions given these are highly variable and typically low/negligible compared to production and end-of-life emissions.
Source: Systemiq analysis (2025) based on Ecoinvent v3.11 (European polypropylene granulate production).

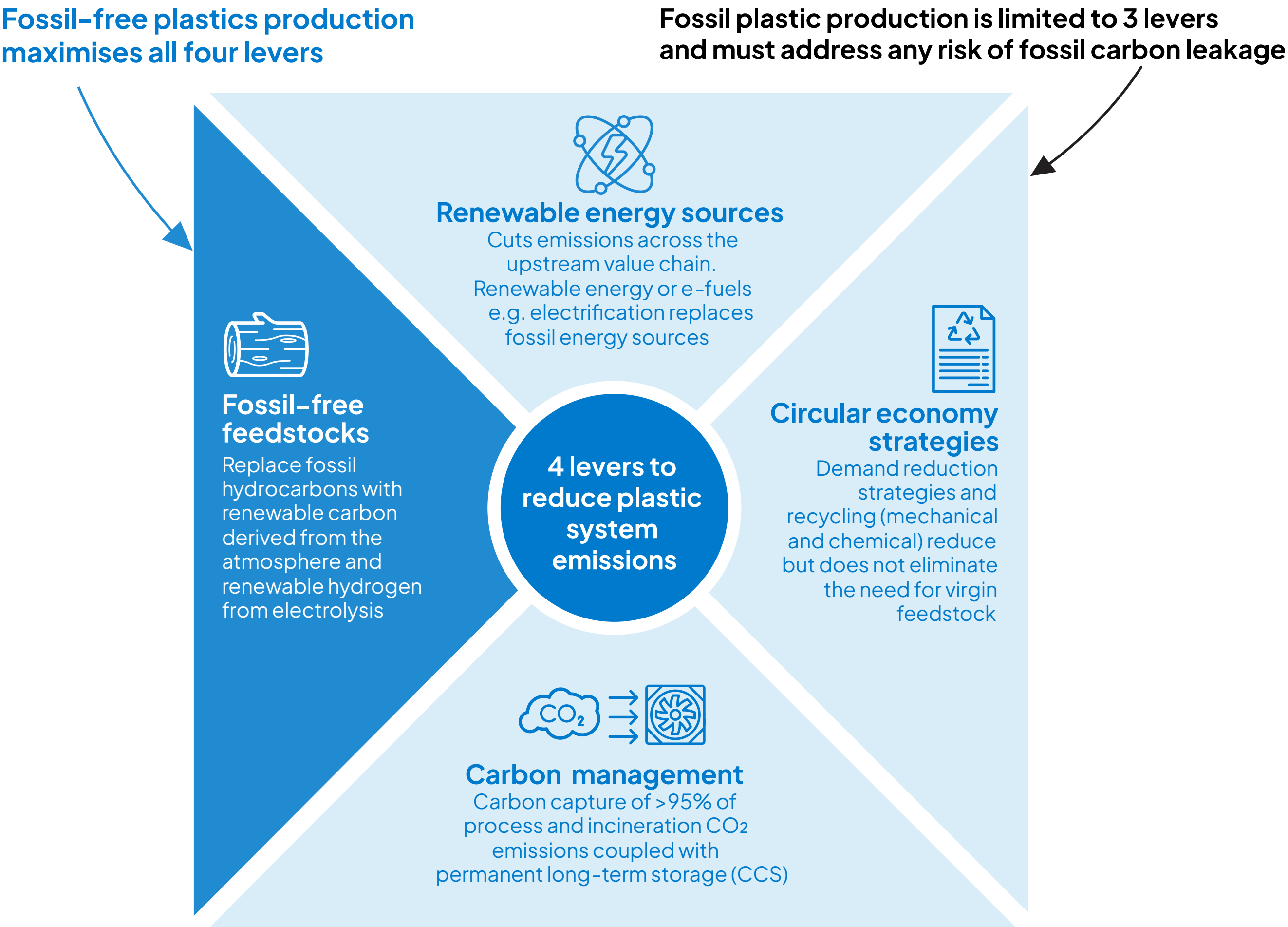
The system today remains highly linear with ~80% of the ~54 Mt of plastics produced in Europe today derived from virgin fossil feedstocks.[c] Although circular mechanical and chemical recycling technologies are making progress, the post-consumer plastic waste recycling rate stands at ~27% of plastic waste sent to recycling today, with ~23% of plastics waste sent to landfill and ~50% incinerated[4] in Europe.[d] Globally, emissions from plastic are rising rapidly, with plastic demand expected to double or even triple by 2050.[e] Mitigating the plastic system's emissions is non-trivial and will require a mix of solutions.

4 The increase in waste to energy incineration of plastic waste is partly driven by the EU's Landfill Directive which aims to minimise the negative impacts of landfilling waste, placing regulation and limits on types of waste that can be landfilled and targets for pre-treatment of waste, thus making incineration a more straightforward option.

To achieve a sustainable, low-emissions, resource efficient plastics system, four critical groups of levers exist to transition to a sustainable net-zero system and should be deployed to the full extent possible (Exhibit 2).

EXHIBIT 2

Delivering a sustainable and resource efficient plastics system requires implementation of four critical levers



Scaling circular economy strategies to reduce virgin plastic demand: this can be achieved through plastic elimination, reuse and substitution for alternative materials. This goes hand in hand with circular technologies, including plastic elimination, reuse and substitution for alternative materials, as well as the mechanical and chemical recycling of plastic waste.

Switching to fossil-free feedstocks: renewable feedstocks such as sustainable biomass and green hydrogen can displace the need for additional fossil extraction.

Switching to renewable energy sources: sources such as electrification powered by solar, wind or hydroelectric sources can reduce process emissions. Finally,

Carbon management: carbon capture and sequestration (CCS) may manage residual carbon emissions along the value chain from production, circularity and incineration infrastructure[5].

[5] The end of life perspective is critical to the whole lifecycle emissions of any product. Plastic waste from leakage, scrap and product disposal must face an end of life scenario whereby carbon in the plastic either re-enters the recycling loop, remains captured in the product (landfill, leakage) or returns to atmosphere through incineration. With the potential scale up of CCS and its application to waste to energy plants (incineration), there is an opportunity to reverse the current ground to air system, and ensure carbon flows from the atmosphere to permanent storage.

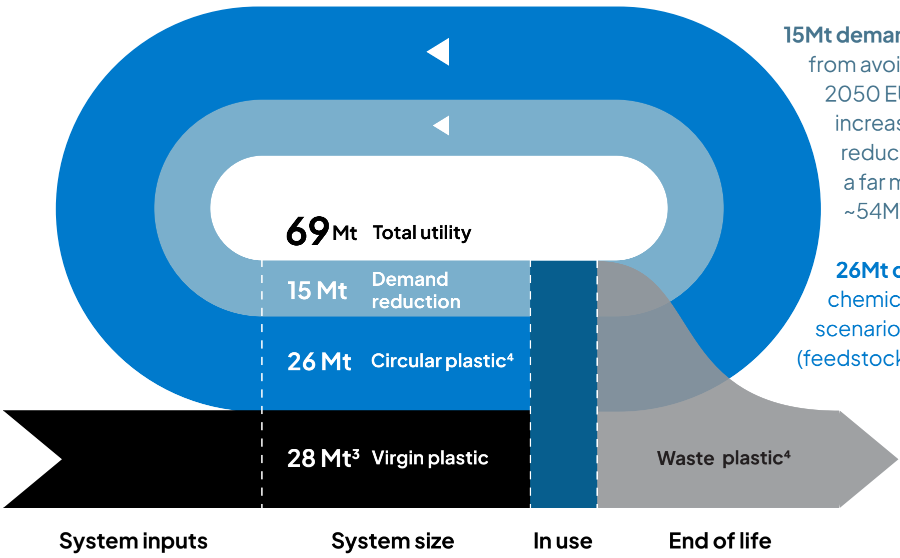
Even in a highly circular European system, over half of all plastic would still need to come from virgin sources.

Under the most ambitious application of circularity technologies available to us today, the European plastics system will still require 52% (28 Mt) of all plastics in 2050 to be from virgin carbon sources (fossil and/or renewable). The European system demand for plastic goods and products is expected to grow from ~54 Mt of plastic today towards ~69 Mt by 2050 (shown in Exhibit 3).[6] Demand reduction through elimination, reuse and substitution can decouple the growth in demand for plastic applications (plastic utility) from the need to produce more plastic itself by 15 Mt. This means the volume of physical plastic required to operate the larger system remains largely flat at around 54 Mt. While mechanical and chemical recycling technologies have been advancing in recent years, even in the most ambitious scenarios they are only expected to scale from providing ~18% of plastic today to 26Mt by 2050.[f] Furthermore, while mechanical recycling plays a vital role in circular strategies, limitations in material quality and substitution rates mean it may not always meet the performance and aesthetic requirements of certain applications, such as medical, automotive, and food-contact packaging. While chemical recycling can meet requirements, there will there will still be a need for around half of all plastic in the system (28Mt, 52%), to be met by virgin plastic sources (either fossil or non-fossil) in 2050.

EXHIBIT 3

By 2050, a highly circular European plastics system could still require as much as 28 Mt virgin plastics production

European plastics production (2050 forecast), million tonnes of plastic



15Mt demand reduction and increased utility results from avoided plastic use via upstream circularity. The 2050 EU system demand is expected to be 69MT, increasing by 15MT from today. However, with reduction, reuse and substitution we can achieve a far more efficient system that requires only ~54MT of input from virgin and circular sources.

26Mt circular plastic from mechanical and chemical recycling may scale in the most ambitious scenarios to provide ~48% of the system input (feedstock material) by 2050

28Mt **Virgin plastic** from carbon sources never processed before will be required to provide at least ~52% of the plastic system input to meet demand in 2050[2]. **In a highly circular future, virgin plastic still accounts for over half of plastic supply.**

Notes/sources: 1) Plastics – the fast Facts 2024 (Plastics Europe). 2) Volumes of primary vs circular levers based on ReShaping Plastics (2022), "Net Zero System Change" scenario. 3) Includes fossil, fossil-free, and bio-based production pathways. 4) Includes mechanical and chemical recycling pathways. 4) There is a significant data challenge around plastic waste generation in Europe. Ssome plastic enters long-term usage above 1 year in sectors such as construction and automotive which can account for delta between system plastic input and waste generation Never the less by 2050 the system will have achieved equilibrium with as much waste being generated from circular and virgin applications as virgin plastic being required to support the system.

6 Current production (2023) from: Plastics – the fast Facts 2024 (Plastics Europe). Future (2050) production based on low circularity projection from ReShaping Plastics (Systemiq, 2022)

Traditional fossil pathways face limitations in their absolute emissions reduction potential, meaning renewable carbon feedstocks are the key to a climate neutral system. While electrification, carbon capture, and circularity can reduce emissions within a fossil-based system, residual fossil emissions, including embodied carbon in materials — will remain due to unavoidable fossil extraction methane emissions, production process emissions and CCS emissions leakage. Electrifying steam crackers and switching to renewable hydrogen are potential abatement options for legacy infrastructure, but these emerging decarbonisation technologies face significant technical and capital challenges to scale. Furthermore, investing in new electric crackers, with ~60-year lifespans, risks locking in fossil-based plastic production beyond 2050[7]. Retrofitting existing furnaces for hydrogen may offer more flexibility but it is a technology not yet proven at scale and with economic challenges.[9]

Traditional fossil pathways face limitations in their absolute emissions reduction potential, meaning renewable carbon feedstocks are the key to a climate neutral system

In a sustainable plastics system, switching to renewable feedstocks offers aan essential solution to minimise the emissions impact and reach net zero. The opportunity to decouple from fossil feedstocks can be achieved through use of renewable carbon sources such as sustainable biomass, point source carbon capture[8] and direct air capture technology (DAC). Several production routes exist to make plastic out of renewable carbon, such as bio-ethanol to ethylene route, available at increasing scale in regions with high biogenic feedstock availability, such as Brazil. However, these routes can face potential feedstock and product slate constraints[9]. Methanol is a chemical that potentially offers a new, complementary platform to unlock a sustainable chemical system. It faces fewer feedstock limitations, is produced from a broader range of sustainable carbon sources and is able to produce a broader product slate. The most advanced of these methanol pathways is the emergent green methanol-to-olefins (MTO) route, to serve the largest existing polymer markets of polyethylene and polypropylene.

7 While electric crackers can use bio-based oils as feedstock, it is currently unclear if there will be sufficient volume of this feedstock to feed many electric crackers, hence there is a potential risk to lock in virgin fossil production.

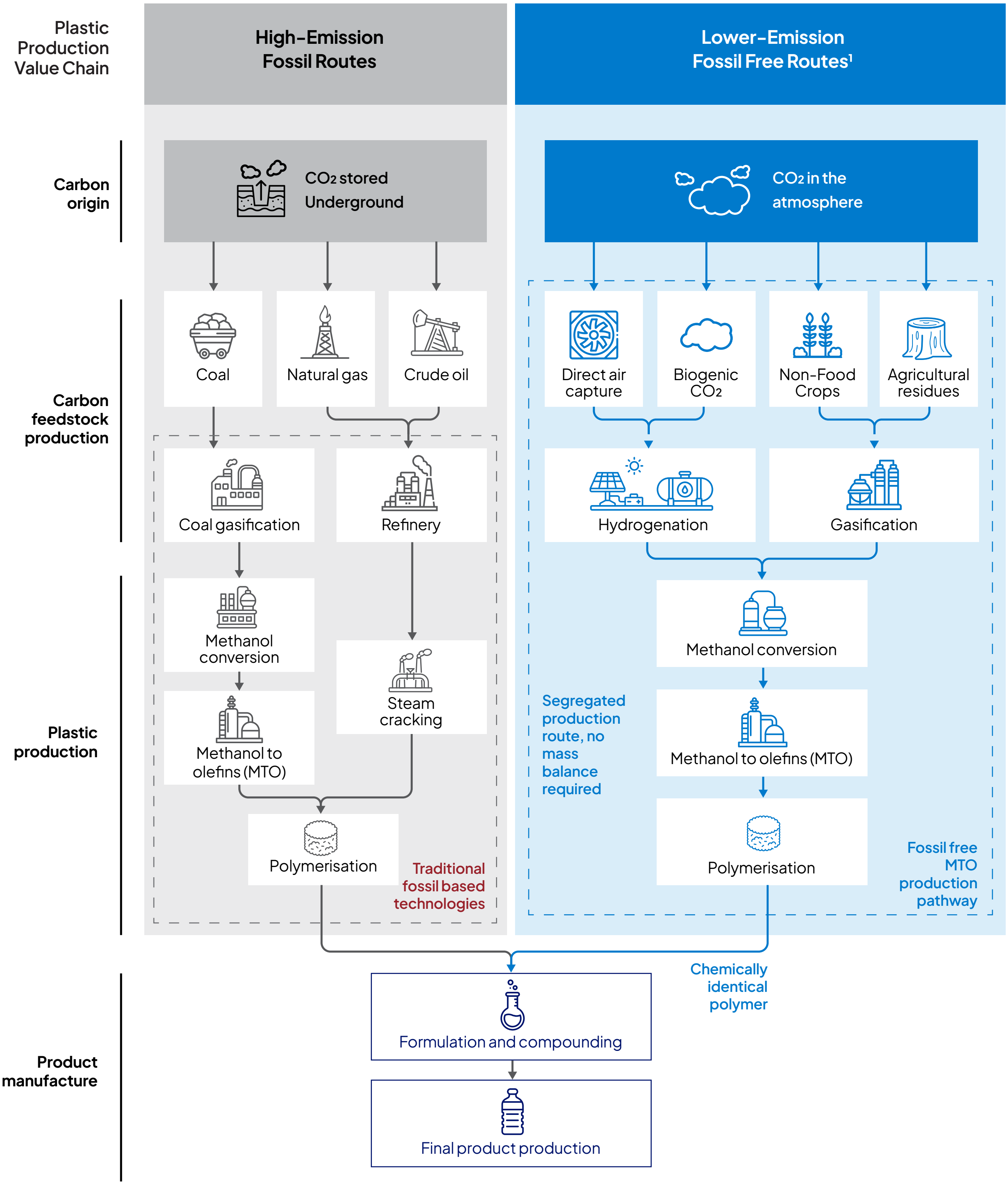
8 Point source carbon capture on processes that utilise renewable carbon such as bio-waste for the production of bio-methene, therefore capturing a waste stream of CO2 where carbon molecules originated from the atmosphere. Renewable carbon does not include point source capture of emissions from industrial process using fossil fuels/feedstocks.

9 Product slate refers to the range of derivative products that can be produced from the associated feedstocks and production pathways.

EXHIBIT 4

Methanol-to-olefins production can play a major role in decoupling the plastic system from the fossil economy

Not exhaustive



Note: 1) Alternative bio-production routes exist today aside from the methanol-to-olefins route described in this exhibit. These alternative production routes face certain issues such as limitations on renewable carbon feedstocks and issues regarding the final product quality and performance matching that of current virgin fossil produced polymers. MTO: methanol-to-olefins

Fossil-free plastics produced via MTO offers a new production pathway with a technology proven at scale today (Exhibit 4).[10] Originally developed in the 1970s in the US and now most prevalent in China as the coal-to-olefins process,[h] MTO can enable the production of fossil-free plastics, integrating the use of sustainable feedstocks, green hydrogen and renewable electricity into a highly efficient production pathway.[11] In the fossil-free MTO process, green methanol (bio- or e-methanol[12]) is vaporised and passed over a solid acid catalyst at high temperatures, converting it into light olefins, mainly ethylene and propylene. These are then polymerised into polyethylene and polypropylene, two of the most widely used plastics in packaging, automotive parts, textiles, and many everyday products. The final polymers are identical to existing virgin fossil plastics, thus have complete recycling compatibility and can be considered 'drop-in' for applications and products requiring virgin quality.[13] The MTO technology is a commercial-scale production process today, offering the potential to switch from fossil to renewable carbon feedstocks and thus apply all four groups of plastic abatement levers to achieve a climate neutral system.

MTO can enable the production of fossil-free plastics, integrating the use of sustainable feedstocks, green hydrogen, renewable electricity into a highly efficient production pathway

Segregated production

MTO offers segregated production, avoiding some challenges of mass balance approaches

A **segregated supply chain** keeps low-carbon materials physically separate from conventional ones at every stage, from sourcing to distribution, ensuring the final product can be fully made from renewable inputs and decoupled from fossil feedstocks and production infrastructure. This aligns with the Science Based Targets initiative (SBTi) draft Corporate Net-Zero Standard v2.0, which emphasises the importance of "direct mitigation" actions that can be fully traced through the corporate value chain using credible chain of custody models including identity preservation, segregation, and controlled blending, all of which establish a physical relationship between input and output.

In contrast, the **mass balance approach** allows renewable or recycled feedstocks to be blended with fossil-based materials, while tracking their proportions through a certified accounting system. This enables the allocation of low-carbon content to specific outputs without physical separation. The SBTi is exploring in its draft Corporate Net-Zero Standard V2.0 allowing use of mass balance approaches as a time-limited measure to address indirect emissions where direct traceability is not possible or where persistent barriers prevent mitigation at the source.

Utilising a mass balance versus segregated process is a technical and strategic decision. Both approaches have advantages and trade-offs. **Mass balance** is more flexible and cost-effective for existing producers, as it leverages current infrastructure and avoids the need for dedicated production lines. However, it can be less transparent to consumers, raising concerns about product integrity and verification. **Segregated supply**, while offering full traceability and consumer assurance, is more complex and costly due to the need for parallel systems. However, for **new or dedicated low-carbon suppliers**, this complexity is less of a barrier and can offer a more straightforward path to delivering verified sustainable products and emissions reductions.

10 While MTO is a proven technology today, there are alternative Methanol-to-X technology pathways in development, but yet to reach a high TRL.

11 Emissions are still attributable to green methanol production route due to by-products of the MTO process, positive emissions factors attributable to mixed electricity generation and the emissions associated to bio, point source and DAC feedstock sourcing.

12 Biomethanol is produced from gasification of biomass. E-methanol is produced from hydrogenation of renewable CO_2 and green hydrogen.

13 When considering biodegradable and compostable bioplastics, they are designed for different purpose/application and end-of-life end-of-life scenarios compared to conventional plastics. While they can offer environmental benefits in appropriate applications, they require specialised composting conditions, limiting their recyclability and risking contamination if mismanaged. Plastics Europe (2025) - bio-based and biodegradable plastics. S., Nizamuddin, Sabzoi et al. (2024) Bio-based plastics, biodegradable plastics, and compostable plastics: biodegradation mechanism, biodegradability standards and environmental stratagem.

While MTO technology is proven at scale with fossil-based methanol, deployment with green methanol is nascent. Commercial scale plants are under development in Europe today, and the use of renewable carbon feedstocks is gaining global acceptance.

In 2012, Carbon Recycling International built the George Olah renewable methanol plant in Iceland; the first to use CO_2 waste gas from a nearby geothermal plant. The facility produces 4,000 tons of e-methanol per year by combining captured carbon with low-emissions hydrogen. The company has since designed several other e-methanol plants, including a facility in China that uses recycled CO_2 from a petrochemical complex as feedstock for plastics production, and a 170kt plant using biogenic carbon, set to begin operation in 2025.[i]

Image credit: Carbon Recycling International

The first renewable methanol plant was established in Iceland in 2012, producing 4,000 tons of e-methanol per year using waste CO_2 from a nearby geothermal plant

In terms of fossil-free plastics production, Vioneo is the first company to announce a large-scale MTO plant that uses renewable (bio- and e- methanol) for polypropylene and polyethylene production.[j] Initiated by A.P. Moller Holding, Vioneo plans to have a 300,000t/year facility operational by 2028, located in Antwerp. The methanol will initially be sourced from China, using a mix of bio-methanol (from agricultural waste) and e-methanol (from biogenic CO_2 and green hydrogen) leveraging renewable carbon from sustainable and certified sources that do not compete with food production. To minimise emissions end-to-end, the MTO and polymerisation processes have been designed to be highly electrified and will use a small volume of renewable hydrogen produced locally. In addition, Blue Circle Olefins is planning an MTO plant in the Netherlands, using circular methanol made from plastic waste, bio-based sources, and CO_2. It will produce ethylene and propylene, key feedstocks for circular plastics and other chemicals.[k]

High integrity sourcing of renewable carbon feedstocks is imperative for green methanol production

Biogenic carbon is the most readily available and affordable sources of renewable carbon to produce green methanol today. The other main potential source of atmospheric renewable carbon being explored is Direct Air Capture (DAC). DAC offers a theoretically unlimited source of renewable carbon with negative emissions potential longer-term. However, it remains in early-stage development, with high costs (up to around \$350 per tonne of CO_2 captured) and relatively low readiness for deployment. In comparison, some biogenic carbon sources are already available today, for example from bioethanol facilities, which could cost as low as \$30 per tonne of CO_2 captured.[l]

Biomass can support emissions reductions in key heavy industrial and transportation sectors, but only if sourced sustainably to avoid serious environmental and social harm. If biomass is not sustainably sourced, the negative impacts to ecological, food and water systems could undermine climate goals and risk simply replacing one problem with another, giving rise in recent years to scandals around unsustainable sourcing of Indonesian palm oil,[m] Brazilian sugar cane[n] and American corn ethanol.[o] Furthermore, sourcing biomass feedstocks with high integrity and certification is essential to accurately assess the overall climate impact of sectors like fossil-free plastics, including their carbon-neutral or carbon-negative potential. Biomass production must adhere to clear criteria to be considered sustainable, as outlined in Exhibit 5. These safeguards help prevent irreversible impacts, such as peatland destruction or reduced access to food and water.[p]

EXHIBIT 5

Biomass sustainability criteria are essential to ensure carbon sources are renewable

Note: High level summary of criteria. Detailed sustainable biomass criteria vary across international organisations, standard-setting bodies, and government agencies, e.g. Roundtable on Sustainable Biomaterials, Forest Stewardship Council, EU's Renewable Energy Directive.
Source: Adapted from ETC (2021), Bioresources within a Net-Zero Emissions Economy

If used efficiently, fossil-free plastics are an appropriate priority application for scarce sustainable biogenic carbon.

Truly sustainable biomass availability is constrained by environmental criteria and available volumes are disputed. Estimates on sustainable supply vary widely due to differing assumptions, making it difficult to establish a reliable global figure. Analysis carried out by Systemiq for the Energy Transition Commission (ETC) projected supply up to 110 exajoules (EJ) per year by 2050 in the Maximum Potential Scenario (with 1 EJ equivalent to ~55 Mt of dry biomass), but this depends on highly ambitious systems changes and cannot be guaranteed. This includes improvements in waste collection, the development of macro algae technologies, and the release of agricultural land from food production if (but only if) it were possible to dramatically reduce animal meat consumption. In the ETC's Prudent Scenario, where major systems changes do not materialise, sustainable biomass availability is estimated at 40-60 EJ per year by 2050, similar to the ~40 EJ/year consumed today.[14,q]

Biogenic carbon is the most readily available and affordable source of renewable carbon to produce green methanol today

As shown in Exhibit 6, demand for sustainable biomass is expected to vastly outstrip sustainable supply by 10-20×. With demand surging and more sectors turning to biomass for emissions reductions, strategic planning and careful allocation of scarce bio-resources is critical. The ETC recommends allocating sustainable biomass based on the availability of alternative decarbonisation options and the relative advantages of biomass across four key dimensions: current and projected costs (to 2050), resource efficiency (especially land use), technical readiness of both bio- and non-bio-based routes, and achievable carbon abatement.[r] These factors guide a prioritisation for biomass applications as follows:

1. **Carbon-dense materials** (e.g. wood, paper & pulp products, fossil-free plastics)
2. **Hard-to-abate sectors with a lack of alternatives technologies** (e.g. sustainable aviation fuel) and thereafter depending upon availability,
3. **Lower-priority niche uses** with viable alternatives (e.g., long-distance shipping, industrial heat, and seasonal power balancing)

14 These figures compare with more ambitious estimates by other organisations such as the IEA, which projects 100 EJ/year in its Net Zero Emissions by 2050 Scenario; and IRENA, which projects of 135 EJ/year in its 1.5°C Scenario by 2050 can supplied sustainably, although this is on the higher end. Sources: IEA (2023 Update), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach; IRENA (2023), World Energy Transitions Outlook 2023 1.5° C Pathway

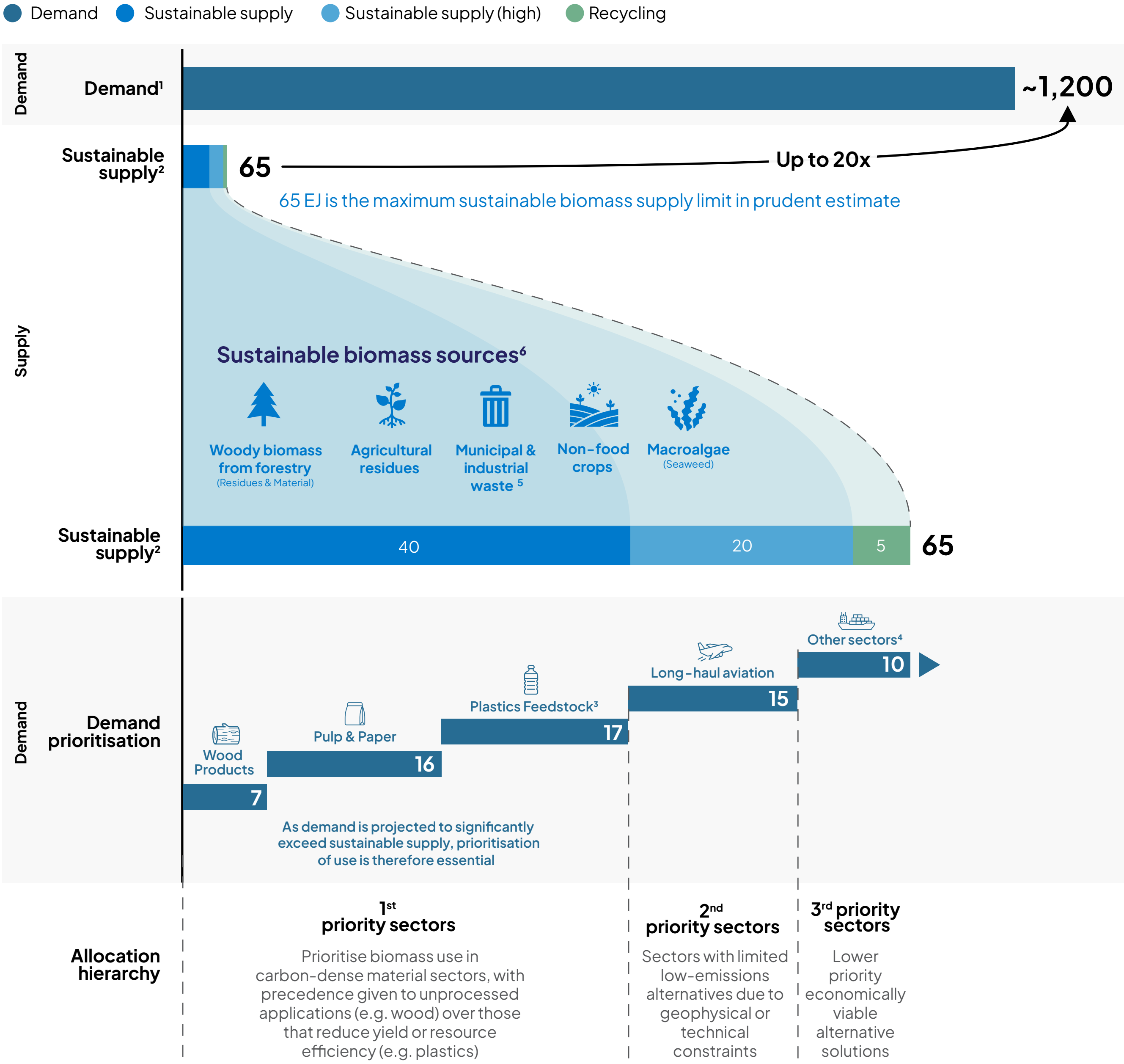
EXHIBIT 6

Sustainable biomass supply is limited, necessitating its prioritisation for sectors where it is most essential, of which plastics is one

Global sustainable biomass supply & potential demand, and prioritisation for energy, building, industry and transport sectors

Illustrative scenario to stay within sustainability limits

(EJ/year in 2050)



1) Potential biomass demand if all sectors convert current energy and material demand to biomass estimated at ~650 EJ in 2020 and up to ~1,200 in 2050. 2) ETC's Prudent Scenario, which includes recycled biomass materials in sustainable supply, equating to ~5EJ/year. 3) Plastics sector prioritisation must be accompanied by reduction, reuse, and recycling initiatives to reduce demand. 4) ~10 EJ of sustainable biomass available for second priority or niche sectors and uses (e.g. district heating, high temperature industrial heat, seasonal power generation, shipping, steelmaking). 5) Includes point source capture. 6) Biomass recovered through recycling is excluded here as it has already entered the system. Source: Adapted from ETC (2021), Bioresources within a Net-zero Emissions Economy: Making a Sustainable Approach Possible, Material Economics (2021), EU Biomass Use in a Net-Zero Economy: A Course Correction for EU Biomass

The plastics system is a hard-to-abate, carbon-dense industry that merits priority access to sustainable biomass, predicated on making efficient use of sustainable biomass via the at scale application of circularity levers. As shown in Exhibit 6, plastics are categorised as a 'Priority Sector 1' for sustainable biomass use, reflecting their limited substitutability and critical material role. The sector would require up to ~17 EJ of sustainable biomass by 2050.[s] However, this global estimate depends upon significant increases in material efficiency in plastic reduction, reuse and recycling across the system.[15] Analysis by the Renewable Carbon Initiative suggests that by 2050 sustainable biomass could supply up to 20% of total European carbon demand (44 Mt sustainable biomass[16]) of the chemicals and plastics sector.[t]

20%
sustainable biomass
could supply total global carbon demand of the chemicals and plastics sector by 2050

15 Material Economics has focused on biomass supply in the EU and UK, estimating that ~11-13 EJ could be available by 2050, with ~1-1.3 EJ potentially allocated to plastic production. However, they note that multiple other emissions reduction levers will also need to be deployed. If the same sustainability assumptions used in the ETC's Prudent Scenario were applied, the estimated supply would fall to ~5-7 EJ potentially impact the available supply for the plastics sector. (Source: Material Economics (2021) EU biomass use in a Net-Zero Economy: A Course Correction for EU Biomass, ETC (2021) Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible).
16 Excludes captured biogenic CO_2.

CHAPTER 2

Evaluating the impacts of fossil-free plastics

Scaling fossil-free plastic production can have significant greenhouse gas (GHG), socio-economic and strategic impacts. As Europe advances efforts to meet climate targets and seeks to future-proof its industrial base, fossil-free plastics presents a strategic opportunity to support these goals. In the following four sections of the report the impacts of fossil-free plastics are evaluated against the four categories below, considering the potential benefits, risks and considerations around scaling up this new production route in Europe.

Impacts of scaling fossil-free plastics

1. GHG reduction impacts at value chain and system level
2. Socio-economic impacts
3. Strategic growth and industrial resilience impacts

Value chain GHG impacts

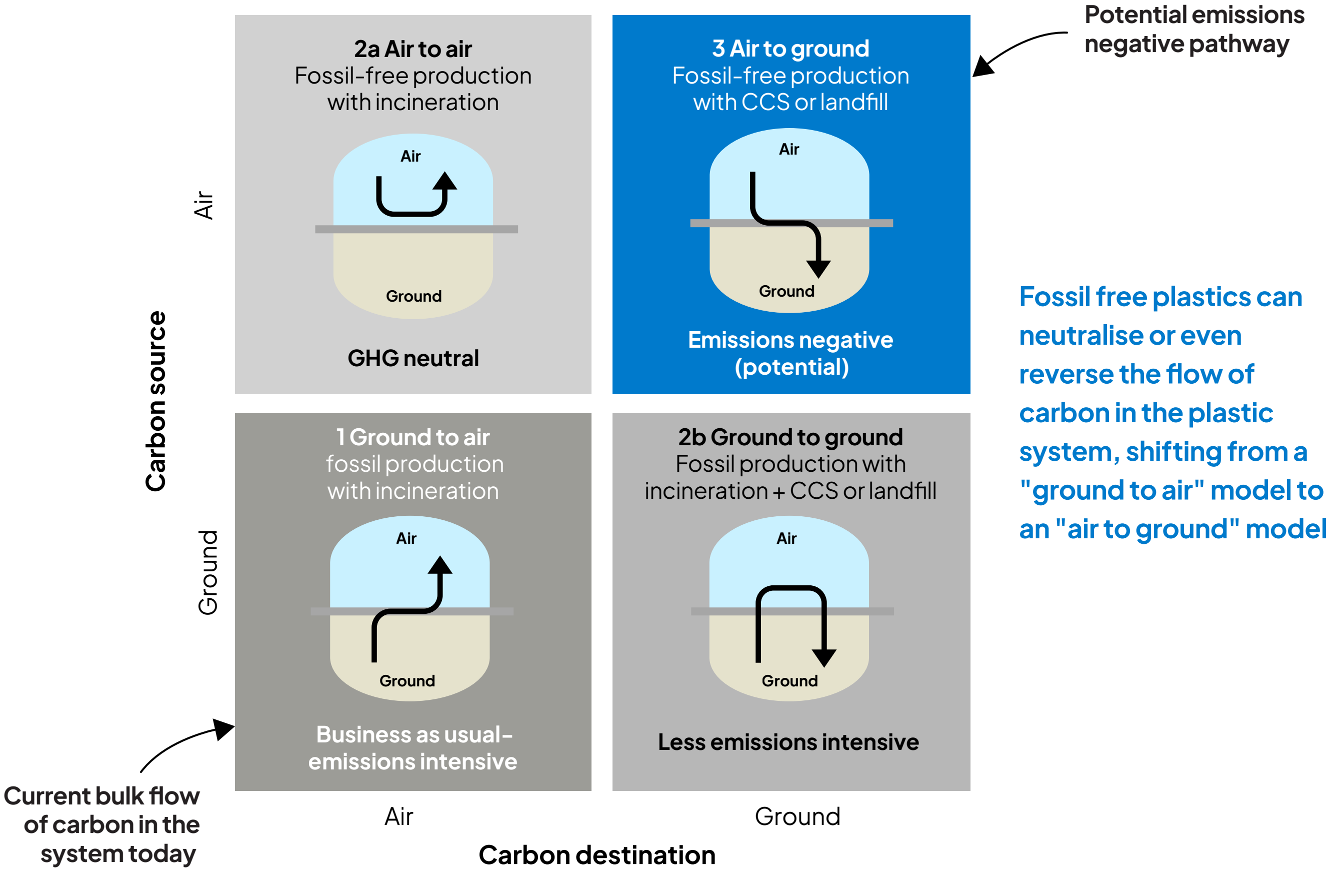
Fossil-free plastics can reverse the system carbon flow and potentially shift from an emissions intensive to a negative emissions model

1. Ground to Air: today's European plastics system is predominantly linear, fossil-dependent and emissions intensive. The predominant system pathway extracts carbon feedstock from the ground, uses it in products once, then at end-of-life releases it into the air via incineration, resulting in a 'ground-to-air' emissions model (see 1 in Exhibit 7 below).

EXHIBIT 7

Long-term carbon pathways through the plastics system

Carbon pathways for the plastics system



Source: Adapted from: Planet-compatible pathways for transitioning the chemical industry (PNAS, 2022)

2a. Ground to Ground: Carbon management via CCS can abate fossil plastic production process and end-of-life emissions, returning carbon to the ground, but this pathway still results in absolute positive emissions. Even with improved tracking and carbon capture, upstream methane emissions from venting, flaring, and leakage cannot be fully eliminated. Carbon capture technologies are typically only efficient up to 95%,[u] meaning fossil-based production systems, even with carbon storage at end-of-life, will always result in net positive emissions and cannot reach true carbon neutrality without offsets. Carbon management of durable materials or materials that circulate in the economy can also act as a carbon sink (temporarily over a long time period and permanently if landfilled at end-of-life).

2b. Air to Air: shifting to renewable carbon feedstocks such as sustainable biomass can decouple the plastics system from fossil and potentially achieve carbon neutrality. Technologies such as methanol-to-olefins and bioethanol dehydration allow renewable carbon sources such as bio-based carbon in forest residues, agricultural waste, and energy crops to replace fossil feedstocks. This approach decouples production from fossil feedstocks by capturing atmospheric carbon and embedding it in physical products. To have a complete lifecycle perspective we must consider the end-of-life pathway. In the worst case of incineration, the carbon is returned to the atmosphere, which may in principle be considered to have a neutral carbon footprint in the long-term.[17]

3. Air to Ground: the plastics system is uniquely positioned to utilise carbon from atmospheric sources and sequester this carbon in durable long-lived products or in the ground at end-of-life. Using renewable carbon and scaling CCS on incinerators, plastics production could shift from a ground-to-air model (1) to an air-to-ground model (3), reversing the system carbon flow. As such, it holds the potential to become a vector for carbon removals. When combined with permanent sequestration, fossil-free plastics can potentially offer a dual value proposition of plastic utility and carbon removals.[v]

Cradle-to-grave emissions accounting approaches often breakdown the full lifecycle emissions into two distinct stages, upstream 'cradle-to-gate' emissions and the use and disposal 'gate-to-grave' emissions. For simplicity, polypropylene has been used as a proxy for broader polyolefins throughout the following section.

Cradle-to-Gate: emissions in sourcing, processing and production for fossil & fossil-free plastics

Fossil-free plastics derived from green methanol can achieve up to ~70% lower cradle-to-gate emissions compared to fossil-based plastics under 0/0 accounting. In the case of polypropylene (Exhibit 8), unabated plastic production via naphtha steam cracking would result in 2.2 tCO_2eq per tonne polypropylene (PP), driven equally by extraction and production emissions. In comparison, fossil-free plastic production cradle-to-gate could be as low as 0.7 tCO_2eq/t PP[18], a 70% reduction. The largest driver of emissions reductions in the fossil-free plastics pathway comes from the olefins production step, utilising low-emissions MTO technology instead of carbon intensive naphtha steam cracking. Fossil-free plastic production achieves lower emissions even when carbon capture is applied to existing fossil-based production (CCS), which reduces overall cradle-to-gate emissions to 1.4 tCO_2eq/t PP, 35% lower than unabated fossil emissions but twice that of fossil-free. While fossil plastic abatement technologies are able to achieve significant reductions in the olefins production step, they do not directly address the 1 tCO_2eq/t PP of upstream emissions associated with fossil feedstock extraction and refining.

~70%
lower absolute cradle-to-gate emissions via fossil-free plastics
compared to fossil-based plastics under 0/0 accounting

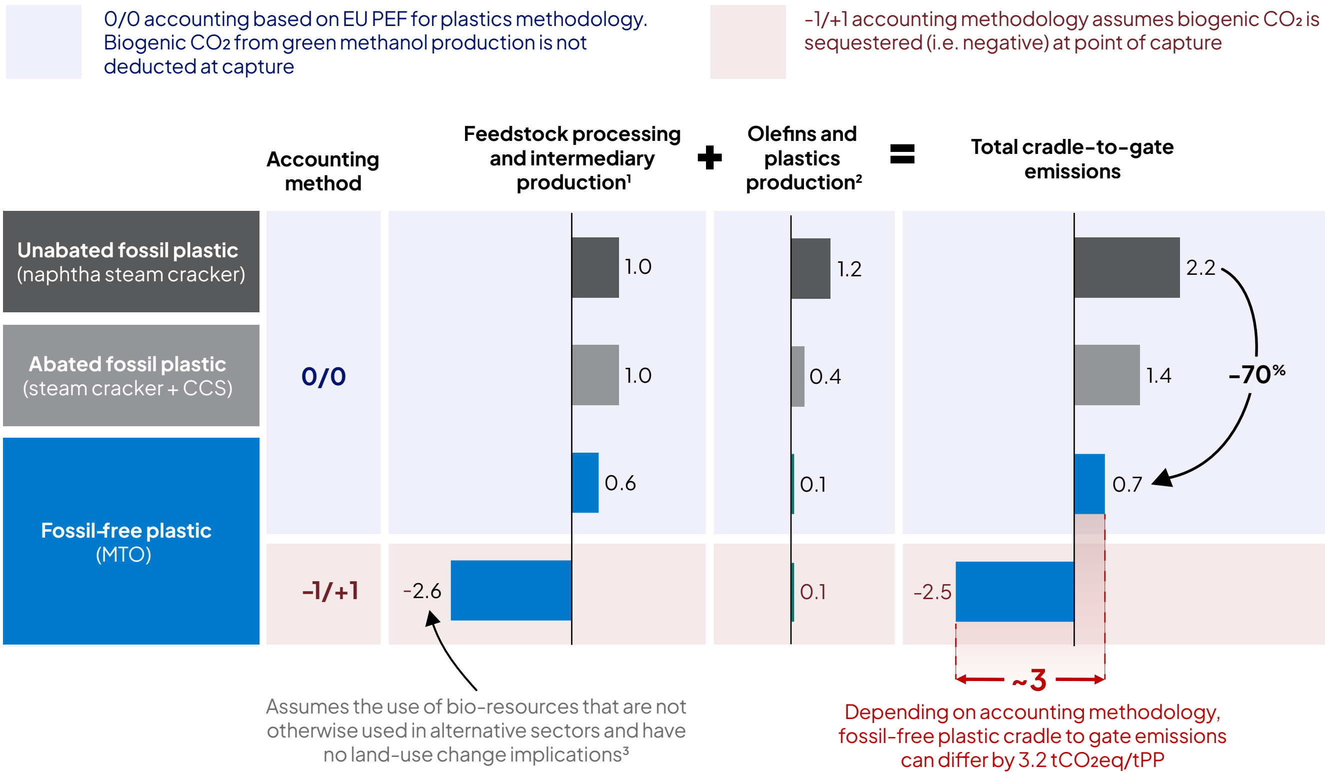
17 When considering the air-to-air model climate neutrality in relation to the embodied carbon may be achieved when discounting for sourcing and process emissions arising from the production, transportation and handling of plastics when using zero carbon energy.

19 Using the 0/0 accounting methodology, which does not account for negative (sequestered) emissions of renewable carbon. Using -1/+1 accounting, abatement potential of fossil-free is 4.7 tCO_2eq/tPP, relative to unabated fossil.

EXHIBIT 8

Fossil free plastic can achieve 70% emissions reductions vs fossil cradle-to-gate, while -1/+1 accounting recognises a further 3 tCO_2e/t emissions reduction impact

GHG emissions intensity of plastic, tCO_2eq / t polypropylene (PP)



Notes: 1) Feedstock and intermediary are crude oil and naphtha, respectively, for fossil plastics. Intermediary for fossil-free plastic is green methanol. Feedstock for fossil-free plastic shown here is biomethanol based on biomass (e.g. agricultural/forestry residues). This could also be e-methanol using biogenic CO2 and green hydrogen. 2) Olefin production via steam cracking for fossil plastic (abated routes includes carbon capture and storage (CCS) and electric steam crackers). Fossil-free plastic utilises methanol-to-olefins (MTO) production technology. 3) If bioresources used for fossil-free plastic were previously utilised (e.g. animal feed, energy production), their diversion could necessitate new resources to fulfil those needs resulting in additional emissions. if bioresources lead to land-use changes (e.g. converting forest/grassland to agricultural land), this can release significant amounts of stored carbon. These examples of additional emissions may need to be considered in future regulations or carbon accounting scenarios.
Sources: Unabated/abated fossil plastic: Systemiq analysis (2025) based on Ecoinvent v3.11 (European polypropylene granulate production). Fossil-free plastic: Vioneo analysis (2025).

Fossil-free plastics 'lock-in' renewable carbon derived from the atmosphere into the polymer, but this is not universally recognised across accounting methodologies, as discussed in the following section. Under current EU Product Environmental Footprint (PEF) "0/0" accounting rules, fossil-free plastics are counted as having positive emissions, in this instance of 0.7 tCO_2eq/tPP, because the atmospheric carbon in the biogenic or captured bio-CO_2 feedstock is assumed to be fully released at end-of-life. In reality, atmospheric carbon is locked into the plastic itself cradle-to-gate, with end-of-life as yet undetermined. Conversely, using a "-1/+1" accounting methodology (as does the GHG Protocol Product Standard), this embedded carbon is recognised as a negative emission, giving fossil-free plastics a negative cradle-to-gate emissions factor, in this case of -2.5 tCO_2eq/t PP, resulting in a full 3 tCO_2eq/t PP difference between accounting methods for fossil-free plastic. Adopting this approach is key to accurately reflecting how fossil-free plastics made with green methanol (bio or e-) move molecules through the value chain and valorise their neutral or negative cradle-to-grave lifecycle emissions, especially when carbon is not released back to the atmosphere.

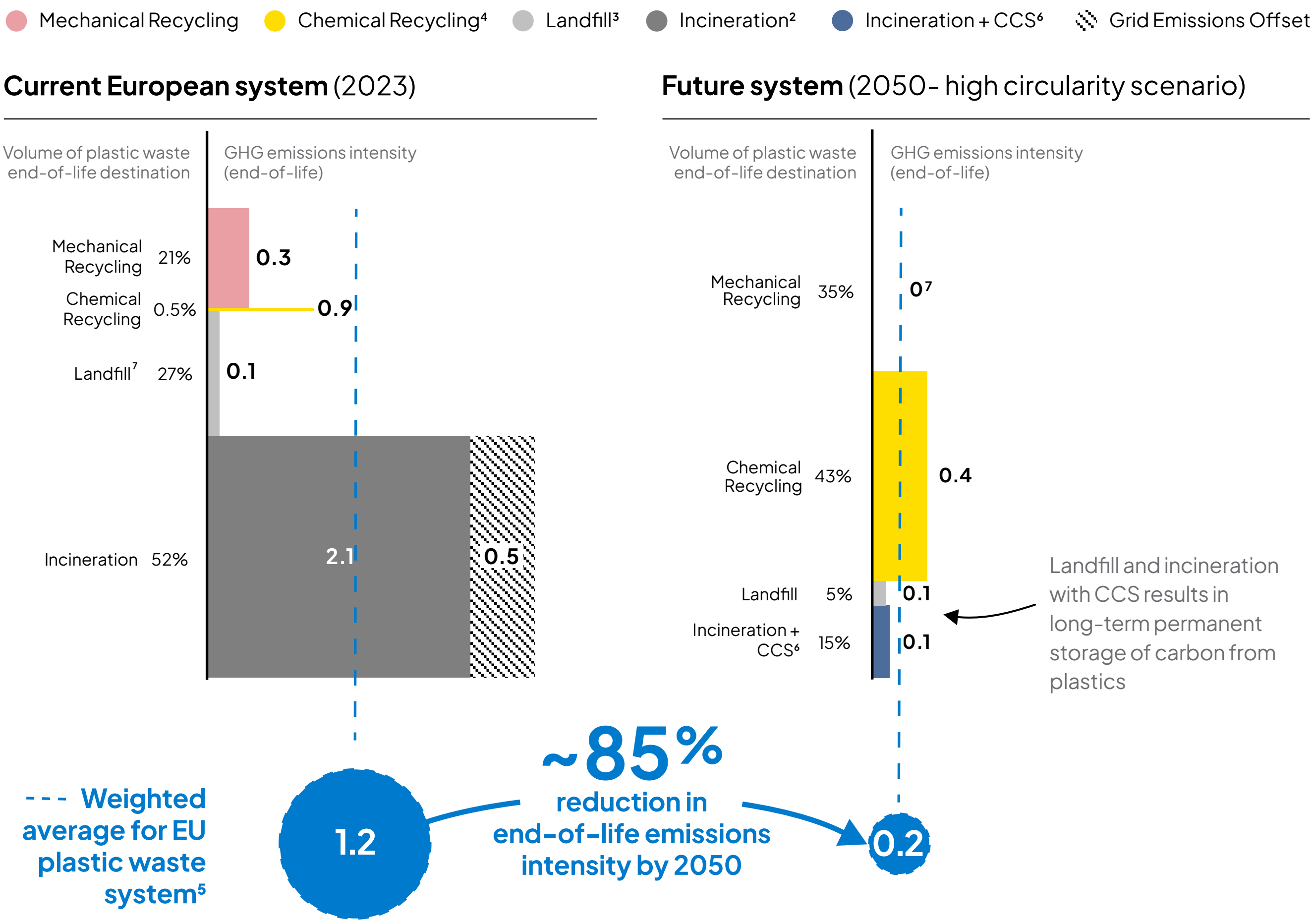
Gate-to-Grave: assessing the emissions from all plastic waste at end-of-use/end-of-life destinations to enable a full lifecycle perspective

Polypropylene plastic waste in Europe produces a weighted average of 1.2 t CO_2eq per t today and could reduce to 0.2 t CO_2eq per t by 2050, a reduction of ~85%. As shown in Exhibit 9, depending on end-of-life destination, there are a broad spectrum of emissions for plastic waste. For example, polypropylene waste emissions range from 0.1 when landfilled, to 2.1 tCO_2eq/tPP if incinerated via waste-to-energy. Averaging the pathways out provides a weighted average end-of-life emissions intensity of 1.2 tCO_2eq/tPP. In a high circularity scenario with a large proportion of incineration using CCS, the weighted average emissions intensity could drop to 0.2 tCO_2eq/tPP. This applies to all plastics, fossil-free and fossil-based alike, as end-of-life treatment does not depend on how they were produced.

EXHIBIT 9

By 2050, the emissions intensity of the European plastic waste system could reduce by ~85%

Volume of plastic waste end-of-life destination[8] (%), GHG emissions intensity (end-of-life)1 (tCO_2eq/t polypropylene)



Notes/sources: 1) Systemiq analysis (2025) based on Ecoinvent v3.11, Yadav et al. (2023), Hermanns et al. (2023), ReShaping Plastics (2022) and expert review/input. 2) Average value of 2.1 $tCO2eq$/t PP assuming average EU power grid emissions intensity in 2023 of 242 $gCO2/kWh$. Low value of 1.2 $tCO2eq$/t PP for Poland (662 $gCO2/kWh$), high value of 2.5 $tCO2eq$/t PP for Sweden (41 $gCO2/kWh$) (Ember, 2024). 3) Assumes pure polypropylene waste stream (i.e. not mixed biological/food and plastic waste). GHG Protocol accounting for landfills requires reporting of other emissions such as methane emissions from decomposing organic waste, which are not captured in this emissions factor. 4) Chemical recycling emissions based on pyrolysis, assuming ~50% abatement potential (of thermal energy emissions) by 2050. Emissions factor varies across studies and subject to uncertainty as the technology is scaling up,e.g. 1.2–1.6 $tCO2e$/t plastic waste for pyrolysis (Climate impact of pyrolysis of waste plastic packaging in comparison with reuse and mechanical recycling, 2022). 5) Note: this assessment assumes an approx. weighted emissions factors for PP based on the broader plastic waste end-of-life split in Europe. Future consideration should be given towards the end-of-life destinations for specific plastics, which will differ from the European average of all plastic waste, as well as differ within specific countries/markets. 6) Based on downstream abatement assuming 100% of incinerators adopt CCS, requiring a fleet of ~50 large-scale incinerators (average capacity of 100 kt waste annually). Scaling CCS on incineration will necessitate strong government coordination and centralised planning, in contrast to the current trend of smaller/decentralised facilities. 7) Assumes mechanical recycling emissions (electricity/heating inputs) can be fully abated by 2050. 8) Excluding exports and mismanaged waste.

While recycling and landfilling present potentially lower end-of-life emissions pathways, there are commercial, environmental, and regulatory factors that limit their adoption. Recycling technologies face scale challenges to 2050 including the complexity and cost of nascent chemical recycling processes, and contamination of waste streams and poor design of plastic products undermining mechanical recycling feedstocks. Although landfilling stores plastic and its carbon underground, it poses pollution risks (soil/water contamination) if mismanaged and is restricted by location constraints. Many European regions lack suitable geologically stable, remote and environmentally compatible new sites for landfill. These issues have resulted in the EU Landfill Directive, which caps municipal waste sent to landfill at 10% by 2035. As a result, incineration could continue to play an ever increasing role in the coming decade.

Unabated incineration is currently the most emissions-intensive end-of-life treatment for plastic waste and makes up the largest share (~52%) in Europe today.[19] While incineration plants generate energy for local grids and receive emissions offsets, these benefits will decline as power systems decarbonise, raising the effective emissions of incineration over time. Incineration plants have been assessed to have emissions intensities on par with coal plants and typically have alarmingly low efficiencies for generating electricity, raising concerns about their environmental impact.[w,x] In a future with limited recycling and increasing incineration, this is a further rationale for demand reduction measures, inclusion of waste-to-energy in the European Emissions Trading System and incentivising CCS deployment across the residual incinerator base.[20]

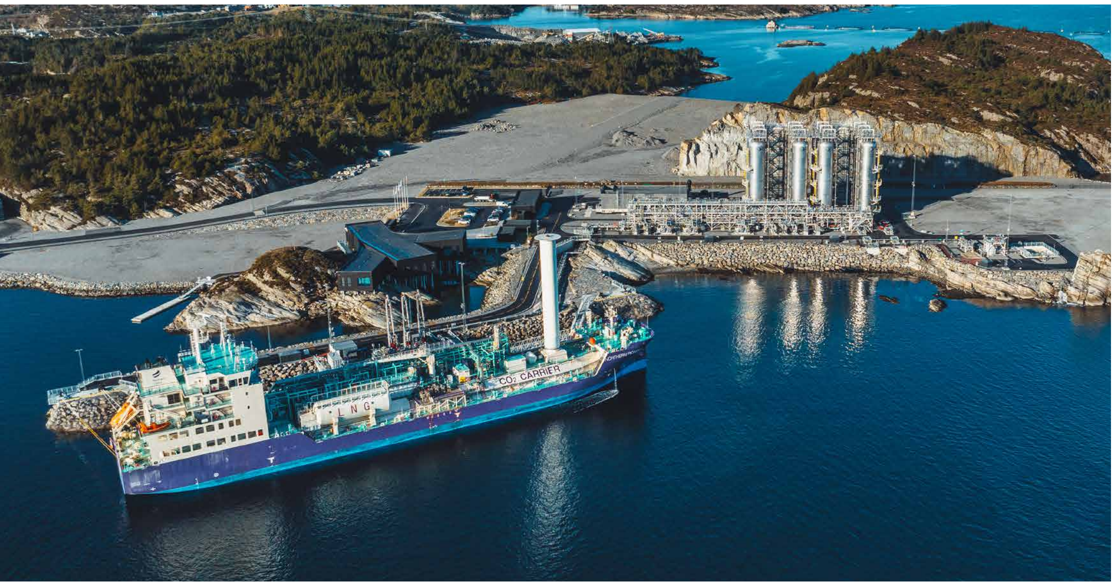


Image credit: Northern Lights

Cradle-to-Grave: whole lifecycle emissions comparison between fossil and fossil-free routes

From a cradle-to-grave view, fossil-free plastics cut greenhouse gas emissions by up to 5–7 tCO$_2$e per tonne, depending on waste treatment and carbon accounting methods. This variance is caused by accounting methodology and different end-of-life pathways for plastic waste (see Exhibit 10). For unabated fossil plastic, total cradle-to-grave emissions intensity is estimated at 3.4 tCO$_2$eq / tPP in the current European market but in the dominant and growing pathway today, fossil plastic to incineration, this reaches 4.9 tCO$_2$eq / tPP. Today, fossil-free plastics could achieve an average negative

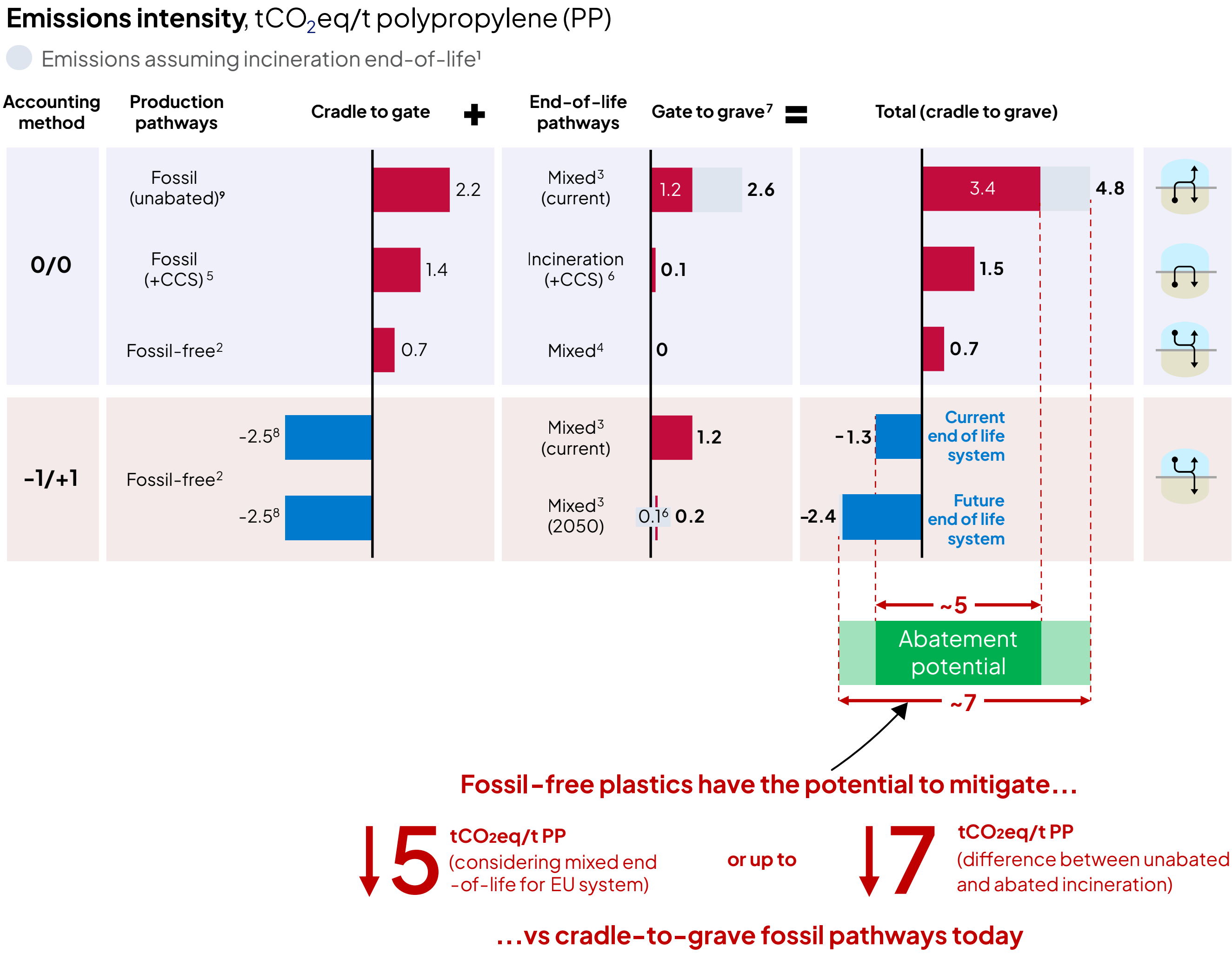
19 Claim on emissions intensity excludes mismanaged landfills with methane generation, where insufficient data is available.

20 Carbon captured from incineration is less likely to be used for CCU because there is likely to be greater volumes from other CO$_2$ sources that are economically and technically preferable for CCU before incinerators (e.g. biogenic/industrial captured CO$_2$).

emissions factor as low as -1.3 tCO_2eq/t cradle-to-grave. This assumes a mixed end-of-life pathway reflective of the current EU plastic waste end-of-use/life. Relative to the counterfactual fossil unabated pathway, fossil-free plastic would mitigate ~5 tCO_2eq/t PP. When considering only the 0/0 accounting method, fossil-free plastic would outperform fossil by ~2.7 tCO_2eq/t PP today (the difference between 3.4 and 0.7 tCO_2eq/t PP).

EXHIBIT 10

Fossil-free plastics offer the potential to mitigate up to 5-7 tonnes of CO_2eq per tonne of plastic on the European market



Notes/sources: 1) Assumes incineration emissions do not take into account power emissions credit (i.e. highly decarbonised or net-zero power grid). 2) Lower range of cradle-to-gate emissions factor for fossil-free plastics used here as an example. 3) Mixed end-of-life assumes weighted average of destination mix including mechanical recycling, chemical recycling, incineration, and landfill. 4) For fossil-free plastics 0/0 accounting, emissions in all end-of-life pathways are zero. 5) Cradle-to-gate for fossil plastic assumes steam cracker abatement with CCS. 6) Gate-to-grave emissions factor for incineration (abated) includes remaining 5% of emissions not captured (i.e. 95% capture rate on incinerators). 7) Excludes plastic product use phase emissions given these are highly variable and typically low/negligible compared to production and end-of-life emissions. 8) Value assumes the use of bio-resources that are not otherwise used in alternative sectors and have no land-use change implications. 9) Refers to European production pathway (i.e. naphtha steam cracking). Emissions may be higher in other fossil plastic production pathways (e.g. coal-based methanol-to-olefins in China).

In a future 2050 system, fossil-free plastics could drive net negative emissions of up to -2.4 tCO_2eq/t PP cradle-to-grave if CCS is applied to incinerators. In this air-to-ground system, fossil-free plastics with CCS on incineration offer the potential to reduce atmospheric GHGs relative to unabated fossil production by ~7 $tCO_2eq/$ t PP (a theoretical maximum from worst case to best case from an emissions perspective). This new negative emissions pathway is compelling to build out from a cost of abatement perspective as will be discussed in later sections.

System-level impacts of fossil-free plastics

Three future scenarios have been assessed to explore the GHG profile of the 2050 European plastics system depending upon the key variables: 1) applying emissions reduction across the fossil system (or not), 2) scaling fossil-free plastics (or not) and 3) scaling circularity (or not). Exhibit 11 provides a short summary of the key factors driving each scenario, as well as their GHG emissions, feedstock use and plastic production outlooks.

Under a business-as-usual scenario, GHG emissions from Europe's plastics system could grow by around 30%, rising from 140 to 180 $MtCO_2eq$ by 2050. In this business-as-usual scenario, demand rises to 69 Mt by 2050 due to limited reduction and reuse efforts, while fossil-based production continues to dominate without carbon capture or the large-scale adoption of circular and fossil-free plastics. Advancing circularity is vital to improve resource efficiency, cutting both system inputs and end-of-life waste with their associated emissions.

+30%
GHG emissions
from Europe's plastics system under Business-as-usual scenario 2050

In the 'Max fossil-free' scenario, the system can pass beyond net zero emissions, but lack of circularity measures make inefficient use of scarce bio-resources and increase climate transition risk. In the 'Max fossil-free' scenario, GHG abatement of virgin plastic production is prioritised above resource efficiency, amounting to 28 Mt (about 40%) of production and ~60 methanol-to-X (MTX)[21] plants operating by 2050. If emissions from remaining fossil-based plastics and end-of-life treatment are abated, the system could not only reach net zero but also deliver negative emissions of up to -30 $MtCO_2eq$.

However, relying on fossil-free plastics to compensate for low circularity is not the most resource-efficient approach, requiring around twice as much sustainable biomass as needed to reach net zero, and with higher overall absolute emissions from abated fossil production and end-of-life. Efficient use of scarce bioresources is essential to justify their prioritisation for the chemicals and plastics sector versus other social and environmental needs. Furthermore, if CCS fails to scale to abate fossil production and end-of-life emissions, then remaining emissions could be as high as 50 $MtCO_2eq$ per annum, a swing of 80 $MtCO_2eq$, putting net zero further out of reach.

Without circularity, the system requires almost 2X the volume of sustainable biomass

An 'Integrated' pathway achieves net zero emissions by 2050 via the most sustainable, resource efficient, low risk transition pathway including the scale up of circularity, fossil-free plastics and abatement of fossil production and end-of-life. With circularity playing an essential role to reduce demand for virgin plastic and technology improvements cutting emissions from recycling processes, fossil-free plastics can drive the system to net zero when comprising just 15 Mt (about 30%) of total production by 2050. Fossil-free plastics are essential to reach a net-zero system as they counteract the positive emissions from the remaining fossil plastic production[22] and emissions from chemical recycling. In an 'Integrated' scenario, should CCS technology fail to be deployed at scale for abating fossil production and end-of-life, a significant reduction (~85%) in system GHG emissions is still possible with circularity measures and fossil-free plastic. The smaller, more resource-efficient system reduces the potential range of 2050 emissions by almost 3× versus the 'Max fossil-free' scenario, from 80 to 30 $MtCO_2eq$. This means in an 'Integrated' scenario where all decarbonisation lever groups are applied, the probability of achieving a system at or very close to net zero, with minimal absolute emissions, is significantly enhanced.

Integrated application of circularity, fossil-free plastics and carbon management, all underpinned by renewable energy can achievenet zero with maximum resource efficiency

21 MTX includes methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) production technologies. Assumes average plant capacity of ~500 kt/annum.
22 Fossil abatement pathways carry residual emissions that are not able to be fully abated (e.g. upstream emissions from oil extraction, CO_2 capture rates for crackers unable to reach 100%).

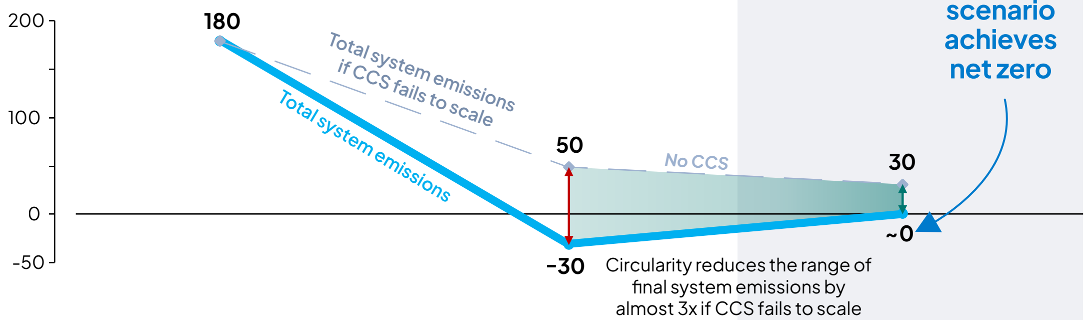
EXHIBIT 11

An ‘Integrated’ scenario presents the most resource and GHG efficient, derisked transition to a sustainable plastics system via application of circularity, fossil-free plastics and carbon management

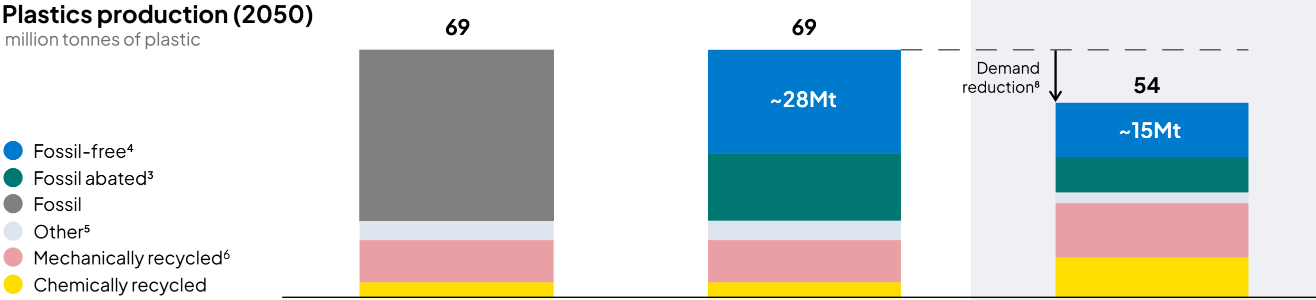
European plastics system future scenarios

	Business-as-usual scenario	Max fossil-free scenario	Integrated scenario
Fossil production	Emissions reduction not applied	Emissions reduction applied	Emissions reduction applied
Circularity measures	Low	Low	High
Fossil-free production	None	Max scale-up	Scale-up
End-of-life pathways	Emissions reduction not applied	Emissions reduction applied	Emissions reduction applied

System GHG emissions (2050)[1]
Million tonnes of CO_2eq



Plastics production (2050)
million tonnes of plastic



Sustainable biomass required for fossil-free plastic[7]	Business-as-usual	Max fossil-free	Integrated
	-	~90Mt **Nearly 2x bioresources** required vs Integrated scenario	~50Mt **Materially efficient** Optimal use of scarce bioresources

Key takeaways from each scenario	Business-as-usual	Max fossil-free	Integrated
	■ Emissions increase from today to 2050 due to system growth if left unabated ■ Essential to drive circularity, decouple from fossil feedstocks and capture carbon in production and at disposal	■ Net-negative emissions are possible. Fossil-free plastics are a powerful lever especially when paired with CCS on incineration.[2] ■ Higher emissions risk without circularity, should CCS fail to scale ■ Inefficient use of scarce bio-resources that could serve the wider transition	■ Brings system emissions to net zero with the highest energy and resource (bio-energy) efficiency ■ Fossil free plastics ‘de-risks’ the transition, delivering big emissions cuts with circularity even if CCS fails to scale

Notes/sources: 1) Systemiq analysis (2025). 2) Negative emissions are achievable only when fossil-free plastics are paired with CCS at end-of-life. Without CCS, the system’s net emissions depend on the durability of the product and the timeframe considered. 3) Volumes of primary vs circular levers based on ReShaping Plastics (2022). Low Circularity based on “GHG Reduction” scenario. High Circularity based on “Net Zero System Change” scenario. Breakdown of primary supply in ‘Max fossil-free’ / ‘Integrated’ scenarios from Planet Positive Chemicals (2022) – Most Economic scenario. 4) Retrofit of steam crackers (hydrogen, electrification and carbon capture). 5) Green methanol-to-olefins/aromatics (to plastics) production. 6) Includes drop-in of bio-oils into existing steam crackers and conversion of bioethanol. 7) Includes pre- and post-consumer recycled plastic. 8) Assumes 50% of green methanol sourced via biomethanol. 9) Reduction, reuse and substitution levers.

Accounting for change: evolving and updating PCFs for fossil-free plastic's full potential

Accurate product carbon footprint (PCF) accounting is critical for the plastics sector to measure emissions consistently across the value chain, enabling transparency and guiding both companies and regulators toward effective abatement opportunities. However, current methods are hindered by inconsistencies, a lack of full lifecycle focus, and fundamental methodological differences. As demand for low-emission materials grows, robust and harmonised carbon accounting will be essential to scale fossil-free plastics and unlock their full climate benefits. Currently, two overarching methodologies are employed in PCF accounting, a 0/0 approach and a -1/+1 method.[23] Exhibit 12 on the following page compares the current applications, emissions accounting, and pros/cons between the -1/+1 and 0/0 methodologies. Key challenges include:

Robust and harmonised carbon accounting will be essential to scale fossil-free plastics and unlock their full climate benefits

Variance in standards and methodologies

Current PCF methodologies, while based on established standards like ISO 14067, PAS 2050 and the GHG Protocol, still allow for significant variation due to differing methodological choices. This can lead to conflicting results that undermine trust and slow adoption of new products such as fossil-free plastic. More prescriptive, sector-specific guidance is needed to harmonise calculations, reduce inconsistencies, and build trust in PCF data as a reliable tool for decision-making and scaling low-carbon products.[y]

Partial or full lifecycle assessment

While the more commonly used cradle-to-gate accounting can be a more feasible and efficient approach for companies to report lifecycle impacts,[z] cradle-to-grave carbon assessments are necessary to credibly capture the full lifecycle emissions of products and avoid misleading carbon-negative claims. This broader approach is essential to drive accountability across the value chain, incentivise better end-of-life design, and enable downstream partners and customers to make more sustainable choices based on complete emissions data.

Recognition of renewable carbon feedstocks

Current approaches like the EU's Product Environmental Footprint (PEF) set the biogenic carbon factor to zero, meaning the carbon uptake (and emissions) from renewable feedstocks is not counted. As a result, the climate benefits of non-fossil feedstocks go unrecognised, unlike in methodologies like Together for Sustainability (TfS), which account for carbon uptake and incentivise renewable use. While both methods track the same physical carbon flows, recognising this potential benefit is key to enabling marketable, net carbon-negative products.

Aligning and streamlining PCF standards is the fastest way to build a credible low-emissions product market, allowing materials such as fossil-free plastics to compete and earn a premium while accelerating industry decarbonisation. Policy makers and regulators should consider transitioning PEF to a consistent, cradle-to-grave -1/+1 methodology in order to capture the full carbon flow and reduce variance in PCF results.

23 The 0/0 approach ignores both carbon uptake and release, while the -1/+1 method credits renewable feedstocks for carbon absorbed and accounts for emissions when released, providing a fuller picture of climate impact.

EXHIBIT 12

PCF accounting methodologies would need to follow the -1/+1 approach, on a cradle-to-grave basis, to fully recognise the negative emissions benefits of fossil-free plastics

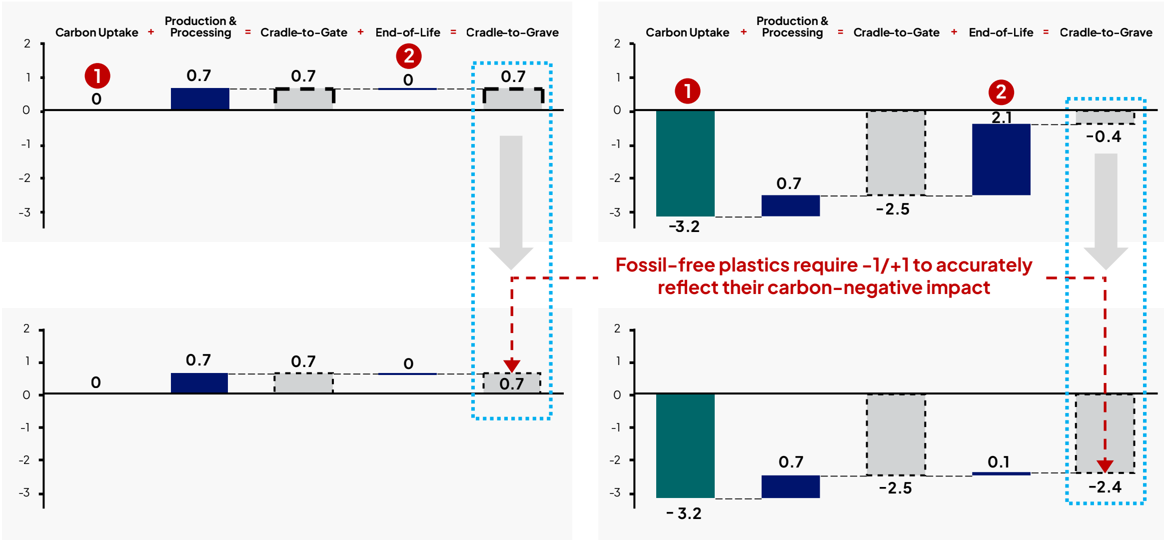
	0/0 Approach	-1/+1 Approach
Approach	EU PEF & JRC Plastics LCA Currently, the EU applies this approach from a cradle-to-grave perspective	TOGETHER FOR SUSTAINABILITY, PACT Currently, these organisations primarily apply this approach from a cradle-to-gate perspective
Description	0/0 considers biogenic carbon cycles balance over time, with end-of-life emissions disregarded under the assumption of equilibrium with biomass growth	Tracks carbon uptake for feedstocks (-1) and end-of-life release (+1), making flows more transparent - providing a fuller picture of biogenic carbon flow

Emissions intensity, tCO_2eq/t polypropylene

Carbon uptake · Emissions · PCF Accounting · **Key methodology differences:** 1 Carbon uptake 2 End-of-life

Current System – Fossil-Free Plastic with EOL Incineration

Future System – Fossil-Free Plastic with EOL Incineration abated by CCS



	0/0 Approach	-1/+1 Approach
Pros	▪ **Prevents misrepresentation:** guards against claims of negative lifecycle emissions at gate ▪ **Simplified accounting:** methodology reduces data requirements, lowering complexity and enhancing usability	▪ **Accurate carbon flow**: Represents biogenic carbon flow from cradle-to-grave ▪ **Allows claims**: Recognises carbon negative claims based on carbon drawdown of bio-feedstock supporting fossil-free plastics by facilitating incentives for carbon removals
Cons	▪ **No biogenic carbon**: Bio-based products have the same footprint as fossil-based ones due to unaccounted biogenic carbon uptake ▪ **Incineration impact**: Shifting to incineration with CCS may prevent fossil-free plastics from being recognised as carbon-negative, limiting access to carbon removal credits and other incentives	▪ **Double counting**: Products sold at gate may be treated as carbon-negative, risking double-counting of short-term biogenic carbon storage ▪ **Increased complexity**: More complex to calculate, with high variation in methods and data assumptions
Key Takeway	**The 0/0 approach disincentivises investments by obscuring atmospheric carbon drawdown, preventing fossil-free plastic producers from fully capturing their emissions reduction**	**The -1/+1 approach aligns with the GHG Protocol's avoided emissions framework, enabling accurate accounting of carbon molecule flows from cradle-to-grave**

Source: Adapted from Systemiq analysis for Neste 2023. Emissions intensity values: Systemiq analysis (2025) based on Ecoinvent v3.11 and Vioneo LCA (2025). CCS capture rate assumed = 95%.

2

Socio-economic impacts of fossil-free plastics

Long-term competitiveness and value through clean tech leadership

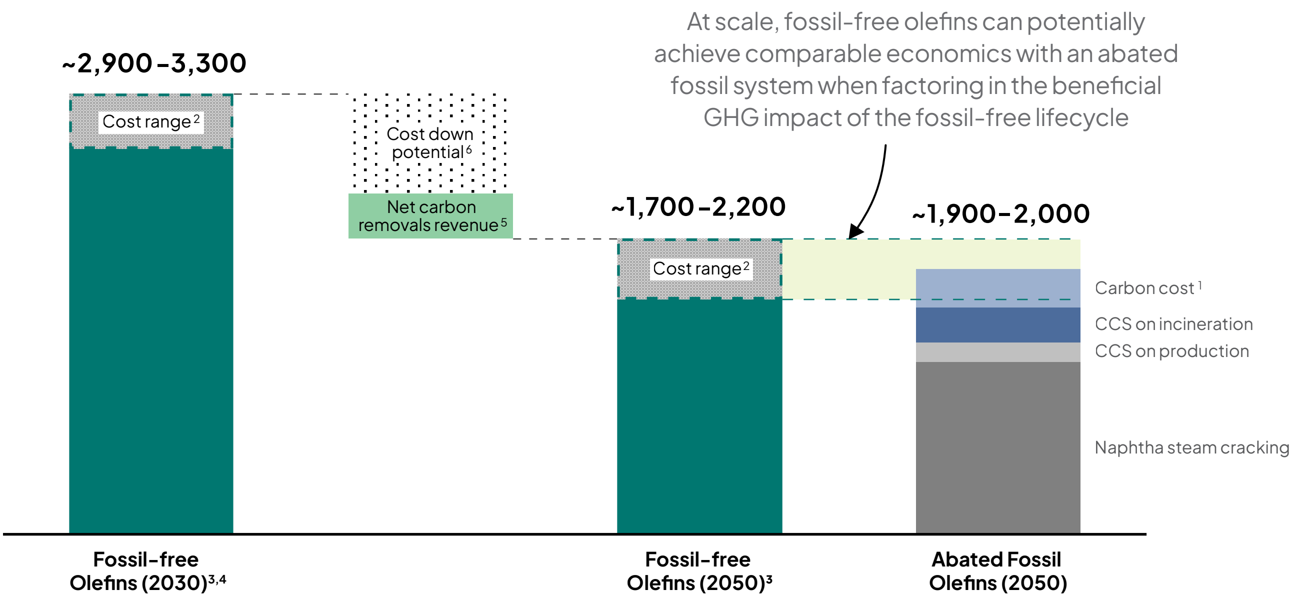
At scale, fossil-free plastics can potentially reach economic parity with abated fossil production, while offering regenerative environmental impacts

Fossil-free plastics could match the economics of abated fossil pathways in a future net-zero system. Fossil-free plastics could match the economics of abated fossil pathways in a future net-zero system. If deployed at scale starting in the 2020s, the cost of fossil-free olefins in Europe is projected to fall to ~€1,700-2,200 per tonne by 2050 (see Exhibit 13), including upstream production and abated end-of-life incineration. In comparison, fossil-based olefins with CCS and carbon pricing may cost ~€1,900-2,000 per tonne, placing both pathways in a similar range.

EXHIBIT 13

Fossil-free olefins at scale in Europe could achieve comparable costs with abated fossil olefins in the long-term

Levelised cost scenarios[7] for the production and end-of-life of olefins
EUR per tonne olefins



Notes: 1) Assumes EU ETS price of €250/tCO_2eq (low) and €350/tCO_2eq (high) in 2050 applied to residual emissions. 2) High/low MTO productions costs are based on estimated difference between biomethanol and e-methanol. Near-term (2030) biomethanol costs are expected to be lower in both EU/China, whereas long-term (2050) e-methanol costs expected to drop below biomethanol. 3) Assumes MTO production in Europe with green methanol supplied from China. 4) Unabated incineration at end-of-life. 5) Assumes 2.4 tCO2e/t olefin carbon removals with revenue of €250/tCO_2eq. Net revenues include costs of abated incineration with CCS. 6) Technology learning and scale-up expected to reduce green methanol costs over time 7) Including aggregated upfront capital investment and ongoing operational costs.

Source: Systemiq analysis (2025). Based on: Planet Positive Chemicals (Systemiq, 2022), Project SkyPower (Systemiq, 2024), expert review/input, and desk research.

Green methanol technology learning effects could result in up to 30-50% cost down potential of fossil-free plastics by 2050. Green methanol constitutes the largest cost component in the levelised cost of fossil-free production. In the near-term, green methanol costs may be as high €1,000–1,300 per tonne in Europe. E-methanol costs are at the upper end of this range as a result of the high costs attributed to renewable hydrogen production. As renewable hydrogen technology scales-up over the coming decades (electrolysers, renewables and energy storage, etc.), unit production costs are expected to fall significantly, with the potential for European green (e-) methanol costs to be as low as €600–700 per tonne by 2050.[24] Europe is well-positioned to supply competitive green methanol in the long-term and supply a growing European fossil-free plastics industry if the initiative is taken early.

Fossil-free plastics offer the potential to take advantage of carbon removals revenue in the future. While recycling is expected to, and should be the primary end-of-life pathway in the long term, directing the remaining fossil-free plastic waste to incineration with CCS offers a viable route to achieving net-negative emissions. In this instance, the majority of the biogenic/atmospheric CO_2 would be sequestered in permanent underground storage. The resulting negative emissions could play an important contributing role in achieving net-zero emissions for the plastics system. In the future, these negative emissions could also be priced as an offset (e.g. benchmarked at a future EU ETS carbon price), thereby reducing the value chain cost of fossil-free plastics by a meaningful margin.

30–50%
cost decrease of fossil-free plastics when at scale,
achieving economic parity with abated fossil production

Offtakers have a strategic rationale for securing early volumes of fossil-free plastic to ensure they meet climate commitments and build momentum for increasing supply. Unless the first wave of fossil-free production plants secure offtake commitments to reach Final Investment Decision (FID) in the coming years, the availability of fossil-free plastic, key to addressing manufacturers' scope 3 emissions, will be severely limited after 2030. Thus, leading companies willing to absorb risk[25] and secure early volumes from the first wave of production facilities would be able to deliver on climate commitments while playing a key role in scale-up of supply volumes.

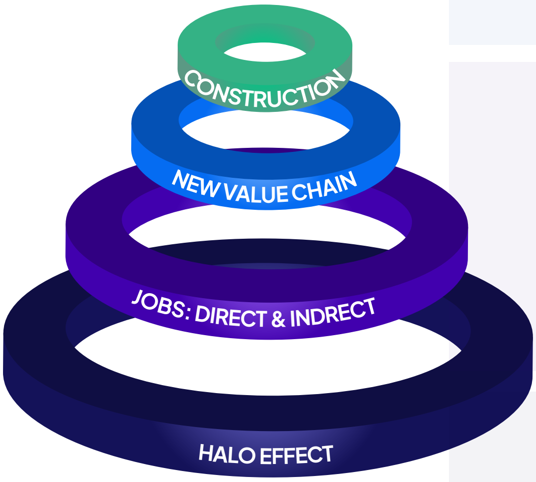
System level economic and social impacts

Scaling fossil-free plastics would drive industrial resilience and significant socio-economic benefits, spurring jobs and cleantech investment for Europe. For example, Vioneo expects that its first 300kt fossil-free polyolefins production plant would bring €1.5 billion of new investment to Antwerp (Belgium) and support approximately 350 direct jobs.[26] As shown in Exhibit 14, scaling methanol-to-X (MTX)[27] technology and fossil-free plastic production across Europe by 2050 could generate €30–40 billion in investment, creating up to 10,000 direct and 40,000 indirect jobs — this will partly involve the reallocation of jobs, strengthening the domestic workforce and supporting industrial resilience against deindustrialisation.

24 Source: Systemiq analysis (2025). Based on: Planet Positive Chemicals (Systemiq, 2022), Project SkyPower (Systemiq, 2024), expert review/input, and desk research. European green hydrogen cost assumed to be ~€6/kg in 2030 and €2–2.5/kg in 2050.
25 Risk could be mitigated by passing additional costs to consumers, as smaller % cost uplifts are expected further down the value chain (product dependent). For example, in 2030, this could translate to a 1–2% cost uplift on a bottle of water produced with fossil-free plastic.
26 It is estimated that around 350 permanent positions will be created once the plant is fully operational. Source: Vioneo to pioneer fossil-free plastics production (Sept, 2024)
27 MTX covers different methanol- -to-chemicals conversion pathways including methanol-to-olefins (MTO) and methanol-to-aromatics (MTA), methanol-to-propylene (MTP).

EXHIBIT 14

Scaling fossil-free plastic technology can act as a significant demand driver, spurring jobs and cleantech investment for Europe



Construction

€1.5bn

Investment into first of a kind 300kt fossil free production facility in Antwerp. Potential for €30–40 bn cumulative investment by 2050[1] to scale fossil-free plastics in Europe.

New value chain

40 Mt

Green methanol demand from European methanol-to-X (MTX[2]) plants by 2050[1]. Europe has a leading position to fulfill this production capacity with already ~10 Mt in the pipeline for 2030[4].

Jobs

350

Direct jobs for first operating plant. Potential for 5–10k jobs by 2050.

40k

Indirect jobs created by 2050[1] though the associated MTX value chains in Europe.

Halo effect

100+GW

Scale-up of renewables (70–130 GW capacity) and **electrolysers** (30–60 GW) for e-methanol production.[3] Growing demand for renewable power and green hydrogen will drive their deployment and cost reductions within the wider net-zero transition.

50+Mt

Sustainable biomass (50–90 Mt) for biomethanol production.[3] Biomass feedstocks will require careful adherence to sustainability criteria and certifications.

Notes: 1) Future jobs, investment, and green methanol estimates in 2050 based on the Integrated Pathway scenario. 2) MTX covers different methanol--to-chemicals conversion pathways including methanol-to-olefins (MTO) and methanol-to-aromatics (MTA), methanol-to-propylene (MTP). 3) Range of renewables and electrolysers capacities reflect volumes of e-methanol required to meet 50% (lower end) up to 100% (upper end) of total green methanol demand. 4) Methanol Institute (Renewable Methanol Tracker; accessed April 2025)

Green methanol demand will be boosted by fossil-free plastics production, offering the potential to drive European green methanol projects to Final Investment Decision. European policymakers, industrial players and financiers could capitalise on this opportunity by working together on building positive business cases for local green methanol production. Europe has a leading position to fulfil this production capacity with already ~10 Mt of green methanol production capacity in the pipeline for 2030. Scale-up of green methanol (in particular e-methanol) could also result in a "halo effect" whereby upstream deployment and cost reductions in renewable energy and green hydrogen would support the wider net-zero transition.

3 Strategic growth and industrial resilience impacts

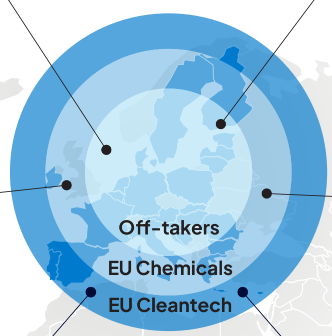
From pioneering offtakers to system wide transformation

For offtakers, fossil-free plastics produced via MTO offer a product matching virgin fossil plastic quality with full segregated traceability and certification. Fossil-free plastics produced from green methanol are chemically identical to conventional fossil-based virgin plastics and can meet the same precise performance specifications required for various industrial applications. Fossil-free plastics produced this way retain full recyclability, equivalent to that of traditional fossil-based plastics.

Moreover, fossil-free plastics can be produced in a fully segregated and traceable manner, with third-party certification, avoiding the need for mass-balance accounting approaches. This segregation enhances transparency and enables downstream pre-consumer businesses to more clearly attribute and account for upstream scope 3 emission reductions. The key benefits of fossil-free plastics are summarised in Exhibit 15.

EXHIBIT 15

Scaling EU fossil-free plastics may both safeguard EU chemicals value chain competitiveness & corporate commitments



Fossil-free plastic offers virgin quality

- Matches virgin fossil plastics in quality and recyclability
- Outperforms lower-grade or recycled polymers
- Supports high-performance applications

Segregated product offering

- Full certification, traceability, and segregation at scale
- Transparent scope 3 emissions abatement without relying on mass-balance

Thriving EU chemicals sector

- Supportive policies and investment in MTO can strengthen the European chemicals value chain
- Global competitiveness enhanced with exportable IP and technology

De-risked industry transition

- Proven MTO-based technology offers a path to carbon neutrality
- Reduces reliance on unproven or emerging technologies like CCS or electrified steam crackers.

Sectoral synergy

- Boosts the methanol industry and EU decarbonisation
- Benefits sectors like shipping and aviation that depend on renewable methanol and green hydrogen

Geopolitical security

- Reduces Europe's reliance on volatile fossil fuels
- Expanding methanol industry strengthens climate commitment certainty

The broader European chemicals value chain can benefit from innovation in a growing suite of competitive production pathways while de-risking the transition to carbon neutrality. With the right policy framework focused on strategic autonomy, investment into leading innovation such as MTO can be unlocked to realise a stable and thriving chemicals value chain. European IP and technological advantage can be harnessed for export, positioning Europe competitively into the future. Fossil-free plastics enable an abatement pathway and route to carbon neutrality with highly proven MTO technology, minimising pathway dependence on scaling nascent technologies (e.g. CCS) or those with lower technology readiness levels (e.g. electrifying steam crackers).

Europe's industrial transition and cleantech leadership can benefit from sectoral synergy on decarbonisation pathways and reduced dependence on fossil fuel imports. Scaling MTO for fossil-free plastics drives wider methanol industry growth. This expansion creates benefits for decarbonisation in sectors like shipping and aviation, which rely on green hydrogen and require green methanol, accelerating economy-wide decarbonisation. From a geopolitical perspective, scaling up the fossil-free plastics value chain and wider methanol industry reduces Europe's dependence on volatile fossil fuels and helps to secure certainty on delivery of climate commitments. In the scenarios explored in this study, Europe could reduce its dependence on oil by up to ~18–34 Mt (or ~130–250 million barrels) annually by 2050[28] with the scale-up of fossil-free plastics. This would equate to a 4–7% reduction relative to the EU's current oil imports.[29]

Impacts of scaling fossil-free plastics

1 GHG reduction impacts at value chain and system level

5–7 tCO_2eq emissions reduction vs existing pathways

Fossil-free plastics integrated with circularity & carbon management can achieve a net zero plastics system most efficiently and reliably

Fossil-free plastics could drive net negative emissions if CCS is applied to incinerators

To fully reflect the negative emissions potential of fossil-free plastics, PCF methods should adopt the -1/+1 cradle-to-grave approach

2 Socio-economic impacts

Fossil-free plastics at scale can achieve cost parity with abated fossil production

Scaling up fossil-free plastics can attract substantial investment in European manufacturing, generate jobs, and accelerate the development of net-zero value chains

Growing demand for green methanol, driven by fossil-free plastics, can help move European projects closer to final investment decisions

3 Strategic and industrial resilience impacts

For customers, fossil-free plastics produced via MTO deliver identical quality as virgin fossil plastics, with fully segregated traceability throughout the supply chain

Fossil-free plastics can drive domestic innovation and boost the competitiveness of the EU chemical sector, while also de-risking the industrial transition to net-zero

By enabling cross-sector synergies and boosting geopolitical autonomy, the development of fossil-free plastics can reinforce Europe's cleantech leadership

28 Estimated reduction in oil dependence based on the volumes of fossil-free plastics that would have otherwise required fossil-based plastics production (i.e. naphtha steam cracking).
29 Based on the EU's 2022 crude oil imports of ~480Mt. Source: Eurostat, 2024. Oil and petroleum products - a statistical overview, imports of crude oil.

CHAPTER 3

Building momentum for fossil-free plastics: Priorities and actions to reach scale

From potential to production: enabling the scale-up of fossil-free plastics through policy clarity and market confidence.

Despite their potential climate, socio-economic and strategic benefits, fossil-free plastics face several policy, regulatory, commercial and operational barriers that hinder their scale up in a competitive net zero system. Europe has strong prospects to lead in fossil-free plastics, with first projects targeting production by 2028. However, this technology leadership opportunity is at risk due to the lack of clear policy signals, regulatory market failures, and commercial risks from within and outside of Europe. Actions to overcome these barriers are summarised in Exhibit 16. Europe needs a supportive policy and market framework, coupled with pioneering industry value chain cooperation, to turn its innovation strengths into real industrial leadership and make fossil-free plastics a reality this decade.

Europe needs a supportive policy and market framework to make fossil-free plastics a reality this decade

To scale fossil free plastics, Europe needs to establish first-of-a-kind projects, announce a bold industrial strategy, establish clear market foundations and provide structural market support

Four stages to unlock scale

First projects: All the critical conditions are in place for first projects, and pioneer customers are the key to unlock deployment. Today, technology is mature, feedstocks available and industry is taking risk to bring this new fossil-free plastic production pathway to the market. However, the market has been focused on circularity and pollution, and is less familiar with the value proposition of fossil-free plastics. Therefore, pioneering customers able to take commercial risk to offtake fossil-free plastic are needed to help demonstrate the proof of concept at commercial scale. Industrial strategy and policy in the EU can provide a framework and confidence into investments not only on the supply side, but also on the demand side.

Bold industrial strategy: Europe can maintain cleantech leadership by driving chemical sector innovation through early markets for fossil-free plastics, but this requires definitive signals to build market confidence and unlock first projects. A clear policy signal from the EU, firm timelines, and the creation of lead markets are essential to overcome offtaker hesitation and prevent further deindustrialisation, particularly as other regions with strong industrial policies increasingly attract advanced manufacturing investment.

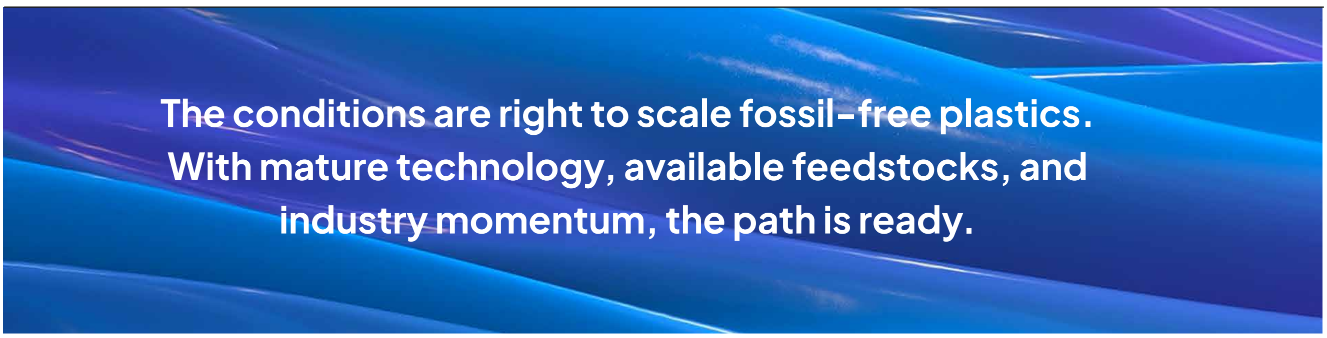
Clear market foundations: Fossil-free (methanol-based) plastics are not yet precisely, legally defined and consistently integrated into EU policy. Without this it is challenging to unlock investment, grow the market with transparent guardrails, and ensure recognition as an essential piece of the future plastic system. Similarly, the lack of accounting system harmonisation today prevents the GHG impacts of fossil-free plastics from being recognised by companies, investors and customers. Equally, plastic buyers are less familiar with the value of fossil-free plastics and unable to account for the benefits in their KPIs, and are often not set up to procure them within their strategies as well as commercially within their procurement processes and incentives. Lastly, securing large-scale, long-term offtake agreements at a premium, a necessary requirement to bring a commercial-scale fossil-free plastics plant to final investment decision (FID) without public support, would place a disproportionate level of risk on a single actor. To enable investment, this risk must be reduced or shared across multiple stakeholders.

Signaling the strategic importance of fossil-free plastics to Europe's plastic system can accelerate industry and investor action

Structural market support: Today, fossil-free plastics face multiple market failures. There is a lack of imperative for customers to address the GHG impact of their virgin plastic procurement, with the focus on circularity policy and a limited voluntary market. Domestically, unabated fossil plastics are not required to reflect the cost of a large proportion of their lifecycle emissions, while internationally there is exposure to high-emissions fossil plastics being imported, thus a lack of a level playing field. Customers face multiple commercial risks: cost premiums for new technology, poor price transparency, and a system that necessitates long-term offtake contracts which exposes them to price risks. There is further uncertainty about when, how and if cost can be passed through onto consumers. Producers also confront major hurdles: uncertainty on market willingness-to-pay, project-on-project risk tied to the slow scaling of critical upstream technologies, first-of-a-kind (FOAK) technology risks, no spot market and counterparty risk for customers unwilling or unable to commit to long-term offtake. Without targeted interventions to build market confidence, support strategic autonomy, and de-risk production, the scale up of critical clean technology may stumble, falling behind those ready to capitalise on future green commodities.

EXHIBIT 16

The successful market formation and scale-up of fossil-free plastics will require pioneering customers, a bold industrial strategy, and a well-coordinated market with structural support



Build first-of-a-kind commercial-scale project(s)

1 Mobilise pioneer customers

Value chain action

Mobilise pioneer customers to get first-of-a-kind plant(s) to final investment decision. Through strategic sectoral partnerships, engage companies that have the greatest imperative and means to act, either in bi-lateral contracts or through demand syndication. In the case of fossil-free plastics, companies and products which have relatively high scope 3 emissions from plastics, low price sensitivity to plastic cost and the need for high quality virgin polymers can be beachhead markets. The strategic exposure of moving alone is a huge barrier and with a few players syndicating demand in such markets, initial validation on smaller volumes can be achieved.

Grow near-term confidence via industrial strategy

2 Send definitive policy signals

Policy action

Send definitive policy signals to give industry and the market clarity and confidence that fossil-free plastics are a strategic imperative and vital component of a net-zero system. The Clean Industrial Deal and upcoming Chemicals Industry Package[30] presents a powerful opportunity to position Europe's chemicals sector at the forefront of innovation and defossilisation. With eight Member States already calling for a Critical Chemicals Act[31] and seven Member States calling for a sustainable carbon policy package to support the transition from fossil to sustainable carbon feedstocks,[32] there is clear momentum—and appetite—for ambitious leadership. Setting a confident policy trajectory that includes fossil-free plastics as a strategic priority in industrial decarbonisation plans would send an essential signal to industry: that Europe is serious about decoupling from fossil feedstocks. Recognising inputs such as green methanol as critical chemicals would not only improve access to funding but also accelerate the development of upstream low carbon infrastructure needed to scale clean processes and products. Additionally, the Packaging and Packaging Waste Regulation (PPWR) and Regulation on Vehicle Design and Management of End-of-Life Vehicles could be amended to explicitly include fossil-free (bio-methanol based) plastics, and include sustainable feedstock criteria (including bio-methanol), recognising their strategic role and eliminating any ambiguity surrounding their eligibility.

30 Set for adoption in late 2025, the Chemicals Industry Package will recognise the strategic role of the chemicals sector as "industry of industries" and of critical molecules. It will propose targeted initiatives to enhance the sector's competitiveness, modernisation as well as support production and innovation in Europe. Communication on the Clean Industrial Deal (EU Commission, Feb 2025)

31 Proposed EU Critical Chemicals Act would protect 18 "building block" chemicals deemed critical to the region (including olefins). The act suggests supporting the modernisation of strategic facilities, protecting against external competition and targeting decarbonisation investment. Source: European states push Critical Chemicals Act (c&en, Mar 2025)

32 Government of the Netherlands: Joint Statement on a European Sustainable Carbon Policy Package (April, 2024)

Enable clear market foundations

3 Establish definitions and harmonise accounting methodologies

Policy action

Establish definitions and harmonise accounting methodologies so that fossil-free plastics are explicitly included in policy frameworks and their emissions reduction benefits clearly recognised, helping to unlock investment and commercial viability. A clear, standardised definition of fossil-free (methanol-based) plastics is needed to establish a shared understanding of defossilisation across EU policymakers, member states, and the public. This is not just a technical step—it is a foundational move to build a credible, investable market for defossilised plastics. Without a unified definition, regulatory ambiguity will stall progress, deter investment, and leave fossil-free alternatives excluded from key EU legislation. Consistency across policies such as Circular Economy Act, EU Bioeconomy strategy, PPWR and End-of-life vehicles regulation is critical to create the legal certainty industry needs to scale solutions. This must go hand-in-hand with robust, sustainability criteria for renewable feedstocks—biomass, captured carbon, and recyclates—and clear eligibility rules.

Furthermore, EU regulators should prioritise a harmonised product carbon footprint (PCF) methodology to fairly credit renewable feedstocks. Updating and aligning PCF accounting offers a key near-term opportunity for policymakers to accelerate fossil-free plastics. A consistent cradle-to-grave -1/+1 approach would more fairly recognise the climate benefits of renewable carbon feedstocks—such as sustainable biomass and those capturing carbon from the atmosphere—while enhancing credibility, reducing variability, and unlocking climate incentives. Clarity today sets the stage for reliable carbon accounting, effective product tracking, and real emissions reduction.

4 Align internally and coordinate externally

Value chain action

Align internally and coordinate externally to position fossil-free plastics as a corporate strategic priority, and seek value chain alignment to drive awareness, investment, and collective momentum. Companies should expand their transition strategy beyond pollution prevention and virgin plastic reduction to integrate fossil-free plastic. Procurement, sustainability and finance teams need to align internal processes and incentives to allow for informed procurement of fossil-free plastics. Furthermore, pioneer value chain players should individually and collectively advocate for near-term policy changes and create an enabling market environment for fossil-free plastic scale up.

Value chain partnership models that share cost and risk can unlock early investment ahead of a fully developed policy environment, which may take years to evolve. Many announced projects struggle to reach FID, as customers hesitate to sign long-term offtakes due to price risk. To overcome the strategic risk of moving alone, customers, producers, and intermediates can form partnerships that syndicate demand, share costs, and reduce exposure. Emerging commercial collaborations in heavy industry show how coordination can redistribute financial burden and operational responsibilities. Sector value chain coalitions and buyers clubs may offer a near-term route to act early in suitable niche markets.

Implement structured market support to drive scale over the medium to long-term.

5 Stimulate demand through targets and mandates

Policy action

To drive uptake of fossil-free plastics, the EU should introduce clear incremental demand-side targets, an approach proven effective in other sectors like maritime and aviation with the FuelEU Maritime and ReFuel EU regulations that would make sense for chemicals.[aa] Quotas and mandates[32] offer strong, predictable signals that help industry plan, invest, and scale, especially in markets competing for scarce feedstocks.[33] Another approach in the plastics sector is to introduce upstream targets, placing obligations on producers to supply a certain share of non-fossil feedstocks, while supporting demand through incentives such as tax breaks or VAT reductions for offtakers and customers of fossil-free plastics.

Embedding fossil-free plastic targets into instruments like the upcoming Circular Economy Act,[34] Regulation on Vehicle Design and Management of End-of-Life Vehicles, and Packaging and Packaging Waste Regulation (PPWR) would give early clarity while shaping a fair, future-ready market. Timing remains a challenge, at present it is unlikely potential targets will have an impact before 2035, heightening the need for strong signals. Specifically, the Bioeconomy Strategy could incorporate a definition for fossil-free (methanol-based) plastics and set targets with a pathway to legislation, feeding into a range of other upcoming EU polices. With careful design to avoid undermining recycled content goals, such measures can kickstart demand, build confidence, and set the EU on a credible path to defossilising plastics.

6 Level the playing field

Policy action

Level the playing field by addressing fossil externalities to help overcome price premiums and protect EU industry in a global market. Today, fossil-free plastics compete with fossil-based plastics that benefit from established scale, price transparency, and an unfair cost advantage due to unpriced carbon externalities and fossil subsidies. To correct this imbalance, EU policymakers could expand the Carbon Border Adjustment Mechanism (CBAM) to include chemicals and plastics, ensuring imported goods reflect their true carbon cost.[35] In parallel, the EU Emissions Trading System (ETS) can support domestic production by phasing in emissions from waste-to-energy incineration, where a majority of fossil plastic ends up. The EU Commission has plans to study the feasibility of including waste incineration facilities in the EU ETS by July 2026, with a potential inclusion by 2028.[36,bb] This would put a carbon price on disposal, internalising fossil-related emissions and help level the playing field for fossil-free alternatives. Together, these measures would reduce cost distortions, promote circularity, and increase demand for fossil-free alternatives.[37]

To further ensure fair competition, stronger market surveillance and enforcement mechanisms are needed to address risks such as product dumping, fraudulent sustainability claims, and imports that bypass EU sustainability standards. Measures such as mirror clauses, robust certification, and auditing can help uphold credibility and protect EU industry to ensure fair trade of decarbonised imports into the EU.

33 To reduce strategic dependencies and strengthen industrial resilience, the Draghi report recommended introducing cleantech quotas to ensure that a minimum share of clean products are produced within the EU. Source: The Draghi report: A competitiveness strategy for Europe (2024).
34 Under the Clean Industrial Deal, the EU Commission plans to adopt a Circular Economy Act in 2026 to ensure scarce materials are used and reused efficiently. This has the potential to extend to renewable carbon feedstocks for fossil-free plastic.
35 CBAM: Carbon Border Adjustment Mechanism. It is the EU's tool to put a fair price on the carbon emitted during the production of carbon intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries. Note, at the timing of this report, the EU Commission has stated plans to consider extending the CBAM's scope to organic chemical and polymers – with a decision expected by the end of 2025. However, implementation plans are not yet announced. (Source: European Commission).
36 Under Article 30 of the EU ETS Directive, the Commission is required to present a report by July 31, 2026, assessing the feasibility of including waste incineration plants in the ETS starting from 2028.
37 Including these measures alongside the upcoming loss of free allowances under the EU ETS would strengthen price signals by raising the cost of fossil-based plastics, and improving the competitiveness of fossil-free alternatives.

7 Implement market structures to deliver public financial support and mitigate risks

Policy action

Public funding is needed now to kickstart fossil-free plastic production in Europe, helping scale early projects through grants, subsidies and guarantees alongside and support for downstream adoption such as tax rebates. The EU's proposed Industrial Decarbonisation Bank in the Clean Industrial Deal is an opportunity to address financing needs. While costs are currently higher than fossil-based plastics, technology improvements and fair carbon pricing will close the gap. Public funding alongside demand syndication, and green government procurement is necessary to get through the hard part of the s-curve before market forces take hold.

While regulation and mandates can catalyse first volumes, they are not enough to rapidly scale markets and address price and delivery risks. Regulations enabling priority access to upstream renewable inputs (e.g. electricity, hydrogen) will be crucial to reduce project-on-project risks across the chemicals value chain. In addition, instruments such as Green Market Makers (GMM)[38] which can overcome multiple market failures can play a role to accelerate the pace and scale of transactions.[cc] A GMM is a form of market intermediary that would seek to procure lowest cost fossil-free plastic from producers and secure highest willingness to pay from offtakers via a double sided auction, efficiently using concessional capital to bridge the price gap, enable price discovery and build market liquidity.[39] Moreover – it overcomes the deadlock between producers that must secure long-term (10-year) supply contracts and potential customers used to buying on shorter (1-3 year) contracts and are unwilling to carry the price risk. By entering the value chain, a GMM can bear this risk, buying on a long-term contracts and selling on short term, enabling market liquidity, production plants to reach FID and first volumes to flow.

Structural interventions to make a positive, de-risked business case for production in the early stages of fossil-free market development is essential to unlock investment so that buying low-emissions plastics can become the norm for consumers

38 GMMs are independent intermediaries setup for buying/selling nascent green commodities in the value chain they operate. The GMM capital can be covered by concessional capital (e.g. government funding) in the first stage, as is the case with H2Global's double-sided auction mechanism for clean hydrogen markets.
39 An alternative approach would be for the GMM to procure and sell green methanol, thereby achieving a similar outcome to reduce the green price premium downstream.

Concluding remarks

Even with the most ambitious recycling efforts, virgin plastics will still be needed by 2050. Fossil-free plastics, produced through scalable, segregated and traceable production routes like MTO with green methanol, offer a credible path to break reliance on fossil resources, reverse carbon emissions, and showcase European cleantech leadership.

The solutions are within reach, but real progress depends on more than technology. It requires a bold industrial strategy, consistent policy signals, harmonised carbon accounting, and pioneer customers ready to commit and shape demand. By aligning these forces, Europe can create a plastics system that is both circular, resource efficient and net zero, while setting a global standard for climate ambition and industrial competitiveness.

Glossary | Extended

Carbon Capture and Storage (CCS): Use of carbon capture technology to extract CO_2 from potential system emissions streams, followed by transport and storage of CO_2 long term in underground saline aquifers or depleted oil and gas fields on a permanent basis.

Carbon Capture and Usage (CCU): Use of carbon capture technology to extract CO_2 from potential system emissions streams and to then utilise it (e.g. to make methanol from CO_2 and hydrogen).

End-of-life: Generalised term to describe the part of the lifecycle following the use-phase. This is often used in the context of end-of-life disposal or end-of-life emissions.

Incineration: Method of waste disposal that involves the combustion of waste as a fuel. Energy recovered in the incineration process is harnessed for re-use, typically for power generation. Also referred to as waste-to-energy.

Landfill: A low cost, readily available and commonly used method of disposal wherein collected waste is deposited in the ground at designated sites.

Mechanical Recycling: Operations that recover end of use plastics via mechanical processes (grinding, washing, separating, drying, regranulating, compounding), without changing the chemical structure of the material.

Methanol to X (MTX): Term referring to MTO and other methanol-to-chemical conversion processes (i.e. Methanol to Propylene, Methanol to Aromatics).

Olefins: A chemical compound consisting of carbon and hydrogen wherein one or more pairs of carbon atoms are linked together by a double bond. Olefins are commonly used as building blocks for many commonly used chemicals like plastics and include ethylene, propylene and butadiene.

Polypropylene (PP): A polymer consisting of propylene monomers and used in a range of applications including in the production of plastic containers, furniture and car parts.

Polyethylene (PE): A polymer consisting of ethylene monomers, and includes low-density polyethylene, used in packaging film and cable insultation, and high-density polyethylene, used in the production of plastic caps and construction films.

Steam Crackers: Petrochemical process wherein long chain hydrocarbon molecules are mixed with steam and heated to break down into smaller chain hydrocarbon molecules, such as olefins.

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Fossil Free Plastics

Driving Clean Industrial Leadership in Europe

Fossil-Free Plastics: Driving Clean Industrial Leadership in Europe is an independent study by Systemiq examining the potential role of fossil-free plastics – particularly via the methanol-to-olefins (MTO) technology pathway – in building a competitive, circular and climate-aligned European plastics system. Commissioned by Vioneo, the report reflects Systemiq's independent perspective and builds on its previous modelling of plastics and chemicals transitions, where MTO has consistently emerged as a high-potential solution. It draws on new system modelling, data analysis, and input from an expert panel spanning academia and civil society, to assess the emissions impact, scalability, and industrial value of fossil-free production. The report highlights that even in a highly circular European plastics system with widely deployed state-of-the-art recycling infrastructure in 2050, half of all market demand would likely still be required from virgin sources. Fossil-free MTO technology offers a scalable route to meet this demand while cutting emissions, strengthening clean tech competitiveness, and reducing fossil dependence.

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