



TRANSCIENCE

TRANSITIONING TOWARDS AN EFFICIENT,
CARBON-NEUTRAL CIRCULAR EUROPEAN
INDUSTRY

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D8.1 – Scenario analysis using the individual modules

WP8 – Stakeholder validation –
policy & industrial needs



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Responsible Author	Meta Thurid Lotz	Email	meta.thurid.lotz@isi.fraunhofer.de	
	Fh ISI	Phone	+49 1517 2210669	
Contributors	Simon Lukas Bussmann, Tobias Fleiter, Marius Neuwirth, Paul Bluemle, Anas Atiah [Fh ISI]; Leonie Schweiger [PIK]; Tom Terlouw [PSI]; Gergő Sütő [UU]; , Mathieu Saurat, Lukas Hermwille, Alexander Kling [WI]; Maro Baka, Margarita Efthymiadou, Kostas Fragkiadakis [E3M]			
Reviewer(s)	Alexandros Nikas, Natasha Frilingou, Christina Tigka [ICCS]; Vasileios Rizos [CEPS]; Panagiotis Fragkos [E3M]; Iñigo Muñoz [TECNALIA]			
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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This deliverable documents the application and validation of individual modules developed within the TRANSIENCE project through stakeholder-driven case studies. The report is intended for consortium partners involved in the development and integration of the MIC3 modelling framework, providing evidence on the applicability and limitations of the individual modules. It is also intended for actors outside/beyond the project, particularly researchers, industrial stakeholders, and policymakers interested in approaches for and results of assessments of circularity and decarbonisation.

3. Short summary of results (<250 words)

This deliverable presents five case studies developed to test and validate individual modules developed within the TRANSIENCE project. The five case studies address stakeholder-relevant research questions concerning circularity and decarbonisation of EU industries while evaluating whether the individual modules provide the functionalities required in the development and application of the integrated MIC3 ecosystem. The Brussels/EU-wide Case Study tests the material flow and trade modelling modules by analysing the impact of circular economy strategies for passenger cars and plastics packaging on trade flows and industrial resilience. The Rhine-Ruhr case study explores the use of macroeconomic and energy-system modelling to assess the implications of circularity strategies for industrial competitiveness in the chemical industry. The Basque Country case study demonstrates the application of the FORECAST-Sites model for analysing industrial decarbonisation pathways for pulp and paper, glass, and cement at site level. The Silesia case study applies the ITOM-cement model to investigate industrial transformation pathways in the sector. Finally, the Port of Rotterdam case study evaluates the environmental LCA module and its ability to assess environmental trade-offs associated with industrial decarbonisation pathways. The case studies attest to the individual modules capacity to address the intended research questions and generate relevant insights. At the same time, the results highlight the importance of further model integration to capture interactions between socioeconomic aspects, material flows, industrial production, energy systems, and environmental impacts. Our findings therefore provide a strong foundation for the final stages of the development and integration of the satellite modules into the MIC3 modelling ecosystem.

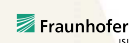
4. Evidence of accomplishment

This report.

Preface

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is growingly gaining attention in the policy world, stimulating the development of new industrial policies in Europe and worldwide. Currently, however, there is little progress in conceptualising the circular economy and understanding its interactions with climate action. State-of-the-art modelling capacity to capture the interplay of the two agendas and their implications for energy-intensive sectors as well as to represent the European industry's transformation in line with the region's vision for climate neutrality is not yet fully developed. TRANSIENCE will undertake a comprehensive characterisation and assessment of circularity principles and measures vis-à-vis decarbonisation, by looking at the twin transition of European industries through the lenses of global competitiveness, innovation, and holistic sustainability. It will then produce MIC3, a consistent, fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability. A series of interoperable modules on the socioeconomic, service and product, material, industrial, energy-system, and environmental perspectives of the transformation of European industry will be developed and integrated, building on and opening the code of leading modelling tools. MIC3 will finally be used in extensive scenario modelling to produce diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry. Transparency, openness, and knowledge sharing will be promoted, and technical capacities will be developed in four industrial agglomerations in the EU, moving beyond stakeholder consultation, onto model co-development, continuous validation of assumptions, co-creation of scenario modelling, evaluation of the desirability and usability of the developed model and insights, and eventually co-production of science and action.

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fh ISI – Fraunhofer Institute for Systems and Innovation Research ISI	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
TECNALIA – Fundación Tecnalia Research & Innovation	ES
UU – Universiteit Utrecht	NL
WI – Wuppertal Institut für Klima, Umwelt, Energie gGmbH	DE
PSI – Paul Scherrer Institut	CH
UCL – University College London	UK



Executive Summary

As a key step towards the development of MIC3 integrated modelling framework, this deliverable tests the functionality and applicability of the individual modules through a series of stakeholder-driven case studies. The objective is not a comprehensive assessment of circularity and decarbonisation, but rather to evaluate whether the individual modules can address relevant research questions and provide the functionalities required for the development of MIC3. The case studies build upon the individual modules and stakeholder engagement. The modules are available as open source, including their online documentation. Regional and sector-specific stakeholder workshops identified priority research questions related to circularity and decarbonisation. These questions were subsequently matched with the capabilities of the modules, resulting in five case studies. The sectoral scope of each case study was guided either by stakeholder input or by the need to test and demonstrate the newly developed functionalities of the individual modules.

The **Brussels/EU-wide Case Study** applied the material flow and trade modelling modules to analyse how circular economy strategies for passenger cars and plastics can affect EU trade flows and thus, industrial resilience. The results indicate that circularity measures influence trade patterns, but their impact on overall import dependence remains highly context-dependent and strongly influenced by the sectoral scope and trade assumptions applied. The case study demonstrated the ability of the coupled material flow and trade modules to assess interactions between circularity strategies, material demand, and international trade.

The **Rhine-Ruhr Case Study** explored the applicability of macroeconomic and energy system modelling modules for analysing the competitiveness implications of circularity strategies in the chemical industry. The study highlighted both the analytical potential of linking economic and energy system models and the need for further methodological development to adequately represent emerging circular economy pathways such as chemical recycling and reliably assess their competitiveness impacts.

The **Basque Country Case Study** tested the FORECAST-Sites model as a tool for analysing industrial decarbonisation pathways at site level. Applied to the glass, pulp and paper, and cement industries, the model successfully identified sector-specific transition pathways and investment decisions. The results illustrate the value of combining simple abatement-cost screening with a site-level optimisation model and demonstrate the usefulness of the model for analyses of industrial transformation at the site level.

The **Silesia Case Study** focused on the application of the ITOM module for the cement sector. The case study illustrates how sector-specific industrial transformation pathways can be analysed, including the role of alternative fuels, clinker substitution, carbon capture and storage, and evolving energy and carbon price conditions. It further demonstrates the ability of the module to incorporate regional stakeholder inputs into scenario development.

The **Port of Rotterdam Case Study** evaluated the LCA module and its capability to link industrial transformation pathways with prospective life cycle assessment in the chemical sector. The results show that while deep decarbonisation pathways can substantially reduce greenhouse gas emissions, they may simultaneously increase environmental pressures in other areas, particularly regarding resource depletion and critical material requirements. The study demonstrates the feasibility of extending industrial transformation analysis beyond climate impacts.

Across all case studies, the results confirm that the individual modules are capable of addressing the specific research questions they were matched with. At the same time, the case studies highlight important limitations, in particular regarding the integration of socioeconomic aspects, material flows, industrial production, energy system, and environmental impacts. The findings reinforce the central objective of TRANSIENCE developing an integrated modelling framework, namely MIC3, to consistently capture all these dimensions in a unified framework. Additionally, the case studies highlight the value of stakeholder engagement. The case studies not only tested technical model functionality but also provided an opportunity to evaluate the relevance and usability of model outputs contributing to the broader TRANSIENCE objective of developing modelling tools that are scientifically robust while remaining applicable to decision making processes. In this way, the lessons learned through the present deliverable provide an important foundation for the subsequent development, integration and application of MIC3.

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1 Introduction

The purpose of this deliverable is to assess whether the individual TRANSIENCE modules can address stakeholder-relevant research questions and provide the functionalities required for the future integrated modelling framework MIC3. Rather than applying MIC3 as a fully integrated model ecosystem, the deliverable focuses on testing individual modules or combinations of modules through a set of case studies developed in close interaction with stakeholders. The case studies therefore serve a dual purpose. First, they provide initial insights into research questions related to circularity and decarbonisation. Second, and more importantly for the development of MIC3, they allow assessment of the applicability and limitations of the individual modelling approaches.

The case studies build upon the model development carried out in WP4 and WP7 as well as the stakeholder engagement carried out in WP8. Within WP4 the first versions of the modules were completed including their conceptual framework as well as data inputs and outputs. In WP7 and, more specifically, in the MS13 report, further development of the modules has been advanced, particularly the development of online documentation for each module. Through a series of regional and sector-specific workshops in WP8, stakeholders from industry, policy, research, and civil society identified relevant challenges, discussed future industrial transformation pathways and formulated priority research questions. These inputs were subsequently matched with the capabilities of the available modules to develop case studies that are both stakeholder-driven and technically feasible. The process and rationale underlying the selection of research questions and module applications are documented in the corresponding MS14 report. The sectoral scope of each case study was guided either by stakeholder input or by the need to test and demonstrate the newly developed functionalities of the individual modules. Together, the case studies shown in the table below cover key components of the future MIC3 framework and provide an initial assessment of their functionality.

Table 1. Overview of case studies

Case study	Research aim	MIC3 module	Sector	Region	Time
Brussels/EU-wide case study	Impact of circular economy strategies on industrial resilience	EU MFA, REMIND-MFA	Steel in passenger cars and plastics in packaging	EU	2050
Rhine-Ruhr case study	Implications of circularity strategies for industrial competitiveness	OPEN-GEM, OPEN-PROM	Chemicals industry	EU	2050
Basque country case study	Industrial decarbonisation pathways	FORECAST-Sites	Pulp and paper, glass and cement sector	Basque country	2050
Silesia case study	Industrial transformation pathways	ITOM cement	Cement sector	EU	2050
Port of Rotterdam case study	Environmental trade-offs associated with industrial decarbonisation pathways	LCA module	Chemicals sector	Port of Rotterdam	2050

The rest of the deliverable is structured as follows. **Section 2** presents a summary of the five case studies, including their research questions, applied modules, key findings, and implications for module testing. The full case study reports are provided in **Sections 3-7** and serve as detailed documentation. **Section 8** finally concludes by reflecting on the extent to which the tested modules meet their intended objectives and discusses implications for the further integration and development of the MIC3 framework.

2 Summary of the Case Studies

2.1 The Brussels/EU-wide Case Study: Impact of circularity strategies on trade flows and industrial resilience

This case study (**Section 3**) investigates the extent to which circular economy strategies, specifically material efficiency and reuse, can influence EU trade flows and thereby contribute to industrial competitiveness and resilience. Industrial resilience is closely linked to global trade dynamics, as many sectors rely on internationally sourced materials or products. Circular economy strategies are increasingly discussed to enhance resilience by reducing EU's exposure to trade dependencies through lowering material demand and potentially import reliance. In this context, the case study addresses the following research question: Which effect can circularity strategies have on EU trade flows and industrial resilience?

To answer this research question, the present study examines two representative products for the steel and plastics value chain, i.e. passenger cars and packaging. For both products, circular economy strategies focussing on material efficiency and reuse are assessed through scenario-based modelling. The methodology combines a detailed EU material flow analysis (EU MFA), capturing material demand and circularity measures within the EU, with a global material flow model (REMIND-MFA), which determines the resulting trade flows and their evolution. The sectoral scope of this case study was guided by the relevance of steel and plastics in trade context, while the choice of products was guided by the need to test the newly developed functionalities of the EU material flow model (EU MFA), in particular the integration of bottom-up and top-down approaches.

The results show that circular economy measures lead to moderate reductions in steel demand used for passenger cars. At the same time, secondary steel availability is reduced in the short to medium term, especially under reuse scenarios, reflecting the diversion of material from the scrap stream. These changes in material demand translate into changes in trade flows. However, the contribution of passenger cars to total steel demand in the EU is limited. Consequently, circularity strategies in this single sector are insufficient to substantially change overall trade dependence of the EU.

The plastics packaging case highlights different dynamics due to the structural importance of packaging within the PET system. Circular economy measures in this sector affect a much larger share of total material demand. However, their effects depend on the assumed impact on domestic production. Both reuse and material efficiency measures can decrease total material demand over time, whereas combined strategies have the greatest impact. However, reductions in import dependency only emerge under the assumption that domestic production does not decrease proportionally to demand but is maintained at the same level as without circularity measures.

Overall, the findings suggest that while circularity measures do affect trade flows, their impact on import reliance remains limited and highly context-dependent, particularly regarding the sectoral scope and the underlying trade assumptions. While our findings show that circular economy strategies can reduce primary material demand, previous studies focussing on increasing recycling rates found that they may lead to increased exports of scrap rather than enhanced domestic circularity due to quality constraints and current trade patterns. Furthermore, circular economy strategies may shift import dependencies from primary to secondary materials.

Finally, several limitations of the study need to be considered when interpreting the results. First, the analysis focuses on material efficiency and reuse for a limited set of products. Second, the analysis is based on physical materials and trade flows not explicitly accounting for energy use or emissions. Third, the analysis is subject to uncertainties inherent to scenario modelling. Despite these limitations, the case study provides a robust methodological framework and highlights the need for further model integration within MIC3 to capture different perspectives.

2.2 The Rhine-Ruhr Case Study: Which effect can circularity strategies have on resilience and competitiveness of EU chemical industries?

This case study (**Section 4**) examines the role of chemical recycling in strengthening the resilience and competitiveness of the Rhine-Ruhr chemical cluster, one of Europe's largest petrochemical hubs. The study is motivated by growing concerns regarding the dependence of the European chemical industry on fossil-based feedstocks, increasing global competition and competitiveness concerns, high energy prices, and the need to decarbonise industrial production. The central research question is: Which effect can circularity strategies have on the resilience and competitiveness of EU chemical industries?

To address this question, the case study tests and validates the integration of the OPEN-GEM computable general equilibrium model and the OPEN-PROM energy system model within the MIC3 framework. A key methodological innovation is the explicit representation of chemical recycling (one of the most promising circularity options in the sector), as a dedicated industrial activity in the models. The focus on chemical recycling was informed by stakeholder engagement in the Rhine-Ruhr region, where industry representatives identified it as a strategically relevant but highly uncertain future pathway for improving circularity, reducing dependence on virgin fossil feedstocks, and maintaining competitiveness in the plastics value chain. In OPEN-GEM, a new chemical recycling sector is introduced, producing secondary feedstocks that compete with conventional fossil-based chemical intermediates used in plastics manufacturing. In OPEN-PROM, pyrolysis oil derived from plastic waste is represented as a substitute for naphtha in petrochemical production, while accounting for the additional electricity required by pyrolysis processes. The two models are soft-linked, allowing the analysis of both economy-wide competitiveness effects and energy-system implications.

The results show that chemical recycling can significantly reduce the petrochemical sector's dependence on fossil feedstocks by substituting naphtha with pyrolysis oil. From a competitiveness perspective, however, the benefits depend strongly on investment dynamics. Scenarios without additional productive capacity led to higher production costs, reduced international competitiveness, and deteriorating trade performance due to increased pressure on domestic capital and intermediate-input markets. In contrast, scenarios assuming that additional investment in productive capacity across the German economy is synchronised with the additional demand generated by chemical recycling allow the economy to absorb the expansion of chemical recycling with limited adverse effects on industrial competitiveness. The analysis therefore identifies investment as a critical enabling factor for a successful circular transition.

The study also highlights an important resilience benefit. Under high oil-price conditions, chemically recycled feedstocks become relatively more attractive, reducing exposure to fossil fuel price volatility and improving the resilience of the plastics value chain. From an energy-system perspective, chemical recycling substantially lowers naphtha demand but has only a limited impact on overall greenhouse gas emissions and electricity prices. This is because the substitution primarily affects the source of carbon feedstocks used

in petrochemical production rather than fuel combustion, while the additional energy required for pyrolysis partly offsets the emissions benefits. As a result, the direct effect on overall emissions remains modest compared with the much larger influence of climate policies, electrification, and fuel switching.

The case study demonstrates the applicability of the OPEN-GEM and OPEN-PROM modules for analysing the interactions between circularity, competitiveness, energy security, and industrial decarbonisation. While the study addressed the absence of chemical recycling through dedicated model adaptations in both OPEN-GEM and OPEN-PROM, these representations remain stylised and rely on simplified assumption regarding feedstock consumption, technology deployment, and investment requirements. The case study therefore serves both as a policy analysis and as a validation step for the MIC3 framework, highlighting the value of combining macroeconomic and energy-system perspectives and pointing towards future integration with material-flow, industrial-process, energy system and lifecycle assessment models. For further details, the reader is referred to the full case study presented in the Annex.

2.3 The Basque Country Case Study: Decarbonisation pathways for industry in the Basque Country

This case study (**Section 5**) demonstrates the application of the FORECAST-Sites model to analyse decarbonisation pathways for energy-intensive industry in the Basque Country. The region provides a useful test case because it combines several industrial sectors with different process characteristics, investment cycles, and mitigation options. The analysis focuses on the three sectors showing highest transformation potential and which have been represented in the workshop with regional stakeholders: glass production, pulp and paper production, and cement production. The case study is designed less as a final regional roadmap and more as an example of how a site-level model can support technology screening, industrial decarbonisation pathway modelling, and stakeholder-oriented discussions on industrial transformation.

The analytical approach follows two steps. In the first step, a transparent CO₂ abatement-cost comparison is used to compare low-carbon options with conventional reference technologies. This step helps to identify which mitigation technologies appear promising under the assumed cost, energy-price, and CO₂-price conditions. In the second step, FORECAST-Sites is applied to translate this technology comparison into a dynamic transformation pathway for the three sectors. The model represents investment timing, technology availability, process-specific energy requirements, energy carrier choices, capital and operating costs, and CO₂ costs.

The sectoral representations are process-specific. In glass production, the model focuses on furnace processes, with separate representations for container glass, flat glass, and special and other glass. Considered options include regenerative furnaces, hybrid furnaces with a high electricity share, fully electric furnaces, recuperative furnaces, and CCS. In pulp and paper, the process structure separates pulp production, paper production, and steam generation. This allows the model to analyse steam supply options such as CHP, biomass boilers, natural gas, hydrogen or electric boilers, heat pumps, and CCS. In cement, the model represents calcinators, rotary kilns, burner processes, and a proxy cement process, enabling the distinction between energy-related emissions and process-related emissions from calcination.

The results illustrate different sectoral transition logics. In glass, the first-step comparison and the model results both point to hybrid electrification as a cost-attractive near-term mitigation option. The modelling shows a substantial shift from natural gas to electricity, while full electrification becomes more relevant under higher CO₂ prices and further technology maturity, especially for rotary kilns and glass melting. In

pulp and paper, heat pumps are identified as a key option for low-temperature steam, while biomass-based steam generation plays an important role for higher-temperature demands. The model pathway strongly reduces natural gas use and increases electricity and biomass demand. In cement, no single mitigation measure is sufficient to ensure deep decarbonisation: the model combines fuel switching, Leilac calcination technology, and CCS to address both energy-related and process-related emissions.

Overall, the case study shows that FORECAST-Sites can be used as a bridge between simple technology comparison and more detailed regional pathway analysis. It is particularly useful for assessing when technologies become cost-optimal, how investment timing interacts with technology (and energy) availability, and which infrastructure-related signals emerge from industrial transformation pathways. The case study also highlights important limitations and further development needs, including biomass availability constraints, flexible fuel switching, high-resolution electricity market representation, and explicit infrastructure constraints for electricity, hydrogen and CO₂ transport and storage.

2.4 The Silesia Case Study: Mapping European Decarbonisation Pathways and the Regional Impacts of Carbon Infrastructure Bottlenecks with ITOM-Cement

This case study (**Section 6**) evaluates the decarbonisation pathways of the European cement industry through 2050, serving as a comprehensive empirical validation of the ITOM-Cement model under divergent regulatory and infrastructure frameworks. It addresses two primary research questions: first, what an ambitious transformation pathway for the European cement industry looks like under an idealised infrastructure rollout regarding absolute emission reductions, capital investments, and energy mix evolution through 2050; and second, how this pathway structurally adapts if transport, storage, and biogenic supply chains are significantly delayed or geographically restricted within specific regions like Silesia in Poland. To answer these questions, the study utilises ITOM-Cement, a sectoral optimisation model driven by exogenous cement production demand and carbon price trajectories.

Under an Ambitious Transformation Baseline Scenario featuring an idealised, widespread rollout of CO₂ infrastructure and carbon prices reaching €311/t in 2050, the European cement sector achieves deep defossilisation. Thermal energy shifts entirely from coal to biomass and renewable waste, cement composition optimises around alternative materials, and total electricity demand of the cement sector doubles to power technologies like oxyfuel kilns and post combustion carbon capture.

The regional case study of Poland under a Delayed Regional Infrastructure Scenario highlighted the high economic stakes of localised supply chain bottlenecks. When unconstrained inter-regional clinker trade interacts with a complete absence of local CO₂ pipelines and onshore storage sinks, the model reveals a profound operational and financial penalty for decarbonisation. Deprived of low-cost carbon transport networks, the Polish cement sector experiences a significant marginal production cost premium, peaking at an additional €23/t compared to the baseline scenario by 2050.

Ultimately, this application successfully validates ITOM-Cement as a mathematically robust, behaviourally descriptive optimisation tool. By simultaneously processing interconnected variables like shifting SCM availabilities, cross-border trade optimisation, and localised logistics constraints, the model proved its structural capacity to simulate complex investment, market, and policy realities at local and national levels, confirming that its core modules function cohesively.

2.5 The Port of Rotterdam Case Study: Exploring future environmental burdens and trade-offs of decarbonisation pathways in the chemical sector

This case study (**Section 7**) investigates the following research question: How can local industrial transition pathways for the Port of Rotterdam be coupled with environmental life cycle assessment (LCA) to assess the broader environmental burdens of low-carbon industrial energy transitions? A detailed description of the methodology, assumptions, data sources, and results is provided in the corresponding chapter.

The environmental life cycle assessment (LCA) module, developed within the TRANSIENCE project, is used to evaluate the environmental burdens of annual polymer production in the Port of Rotterdam. To achieve this, the module couples industrial transformation pathways generated by the Port of Rotterdam ITOM model (and other MIC3 modules, such as FORECAST) with prospective life cycle inventories based on the ecoinvent database and the premise LCA tool. Model outputs from ITOM, including production volumes, technology deployment, market mixes, and energy demand, are coupled to life cycle inventories and linked to prospective background LCA databases that reflect future developments in, among others, electricity generation and material supply chains (such as cement and steel). Environmental impacts are evaluated using a wide set of environmental indicators, including climate change, human toxicity, ecotoxicity, acidification, resource depletion, and critical raw material extraction.

The results indicate that the assessed Carbon Looping (CL) scenario substantially reduces climate change impacts between 2025 and 2050, mainly due to electricity-system decarbonisation and the deployment of low-carbon production routes. However, several environmental trade-offs emerge, particularly for resource depletion and the extraction of (critical) raw materials such as lithium, cobalt, iridium, and dysprosium. Our preliminary findings for the Port of Rotterdam further demonstrate that focusing on greenhouse gas (GHG) emissions may overlook important environmental burdens (e.g., those on critical raw materials) elsewhere in the supply chain.

Overall, the case study demonstrates the applicability of the TRANSIENCE environmental LCA module for assessing industrial transformation pathways beyond climate change impacts. While the current implementation should be regarded as a first proof-of-concept and would benefit from further validation and harmonisation with other MIC3 modules, the case study demonstrates the feasibility of coupling industrial transition pathways with (prospective) LCA. The resulting LCA framework provides a flexible approach for evaluating not only climate impacts, but also broader sustainability trade-offs associated with industrial decarbonisation pathways across regional, national, and European scales.

3 The Brussels/EU-wide Case Study: Impact of circularity strategies on trade flows and industrial resilience

Introduction

Industrial resilience is closely linked to the dynamics of global trade flows, as many sectors rely on internationally sourced materials or products (European Commission, 2024b; Grabbe & Moffat, 2024). Thus, disruptions, such as the current closure of the Strait of Hormuz, can affect production stability and costs. Within this context, circular economy (CE) strategies are increasingly discussed to enhance resilience by reducing demand for materials and products and thus exposure to trade dependencies (Haque, 2026; Le et al., 2025). By lowering the demand for primary materials and products, circularity can potentially reduce import reliance. At the same time, this will affect international trade flows. In this context, this study addresses the following research question: Which effect can circularity strategies have on EU trade flows and industrial resilience?

To answer this research question, the present study examines two representative products for the steel and plastics value chain, i.e. passenger cars and packaging. The sectoral scope was guided by the relevance of steel and plastics in the trade context, while the choice of products exhibits distinct trade patterns, enabling a comprehensive assessment of trade-related impacts across diverse applications. For both products, CE strategies focussing on material efficiency and reuse are assessed regarding their impact on material demand and resulting changes in trade flows. This distinguishes the present from existing studies that focus on recycling (Fellner et al., 2018; Pauliuk et al., 2017). By analysing the impacts in a scenario-based framework, the study aims to quantify the impact of circularity strategies on trade flows and, consequently, import dependence and industrial resilience.

Method and data

The research process for answering the research question shown below consisted of three key elements, namely the scoping of relevant CE measures, the development of scenario narratives via stakeholder engagement, and the modelling of scenarios. Method and data related to each of these three elements is described in detail in the following sections.

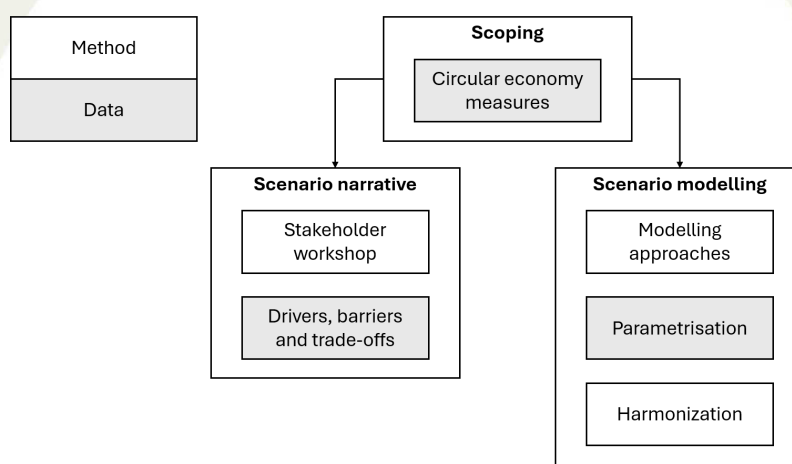


Figure 1. Main phases of the research process, associated methods (white) and data (grey)

Scoping

The scoping involved compiling a short list of CE measures affecting steel use in passenger cars and plastics use in packaging. In a first step, this list was derived from Domenech et al. (2025). The measures were chosen based on their compatibility with the study scope, ensuring the analysis of material efficiency and reuse measures. In a second step, further details regarding the CE measures were researched to facilitate the subsequent modelling. This led to the differentiation or aggregation of individual measures. The resulting scope of CE measures for the two representative products are shown below.

Table 2. Short list of circular economy measures

Passenger cars	Plastics packaging
Material efficiency • Substitution with advanced high strength steel (AHSS) & high strength steel (HSS) • Downsizing • Redesign Reuse • Remanufacturing of steel components & car panels	Recycling • Collection targets for mechanical recycling • Recycled content quotas • Deposit return systems Reuse • Reusable packaging quotas • Deposit return systems Reduce • Lightweighting • Material-efficient design

Scenario narrative

The development of scenario narratives was based on the inputs gathered during a stakeholder workshop in Brussels on December 10, 2025. Stakeholders were invited to discuss technical, economic, environmental, policy, and social barriers/enablers as well as trade-offs related to material efficiency and reuse. These findings summarised by Hermwille (2025) were synthesised to a scenario narrative for resilience through material efficiency and reuse for passenger cars and plastics packaging.

Scenario modelling

The scenario modelling covers the modelling of circularity strategies at EU-level and their integration into global trade flow modelling. The following subsections describe this procedure and the models in detail.

EU MFA

The EU MFA module is a dynamic material flow analysis (MFA) model focused on Europe and designed to evaluate the impacts of circular economy on industrial decarbonisation. The module tracks three emission-intensive based materials (steel, plastics, and cement) alongside their primary end-use sectors. Driven by the use phase and trade dynamics, the model projects future material production volumes and secondary raw material availability. It handles a diverse range of items, from complex composite products like passenger vehicles to standalone mono-material components and packaging.

A core aspect of the EU MFA module lies in its integration of top-down and bottom-up approaches, going beyond traditional soft-linkages to maintain comprehensive coverage and granular detail. The module is structured around several sub-modules, with possibility for further modular expansion:

- Buildings: A bottom-up, stock-driven approach determined by structural development of the buildings stock and material accumulation over time.
- Vehicles: A bottom-up, inflow-driven approach determined by new passenger car registrations.
- Steel: A top-down, inflow-driven approach tracking consumption shifts across 19 steel product types within 7 major use sectors, and copper contamination in steel scrap.
- Plastics: A top-down, inflow-driven approach monitoring consumption changes for 14 polymer classifications across 7 broad application sectors.
- Cement: A top-down, inflow-driven approach evaluating demand fluctuations across building and infrastructure developments.

The inflow-driven sub-modules are production-driven when running historical baselines based on statistical data. When building scenarios, these sub-modules are final demand-driven. Production volume is then a model output. Overlapping use sectors are handled systematically by subtracting highly detailed bottom-up flows from broader top-down sectors, with the remaining residual extrapolated via external economic scaling factors. This ensures that distinct circular economy interventions can independently influence top-down and bottom-up inflows without creating structural imbalances.

All sub-modules are built using the open source flodym framework to support clean multi-module coupling (Dürrwächter et al., 2026). Prior and relevant to this case study, the newly integrated passenger vehicle module was linked to the MIC3 energy system model OPEN-PROM (<https://github.com/e3modelling/OPEN-PROM>) rather than macroeconomic indicators, as future vehicle demand is closely linked to the transformation of the transport sector. Additionally, the integration architecture to map buildings and vehicles directly to steel and plastic top-down sub-modules was successfully generalised.

In this case study further development (presented in the following sections) occurred in the vehicle and plastics sub-modules, and in trade flow harmonisation with the global MFA module REMIND-MFA.

Passenger cars

Adaptations for passenger car measures quantification have been implemented on the vehicle's bottom-up module by introducing new parameters or adapting the current ones, where the model introduced above has been adapted, as shown in Figure 2. For advanced high strength steel (AHSS) and high strength steel substitution and redesign, a parameterisation based on adjustments of steel intensities reflects the reduction in material demand. A time dimension has been defined for the steel intensity parameter to quantify the impact of measures, reflecting the transition over time. The downsizing measure did not require a core model adaptation, as the predefined parameter technology share was tailored to reflect the increase in the small car segment. For reuse measures, a reuse parameter has been defined with dimensions of region, vehicle type, steel product, and time to enable the evaluation of reuse of different products, to capture transitions over time, and to ensure consistent flow model computations. The reuse parameter is used to quantify the stock-to-stock flow, which is then subtracted from the inflow.

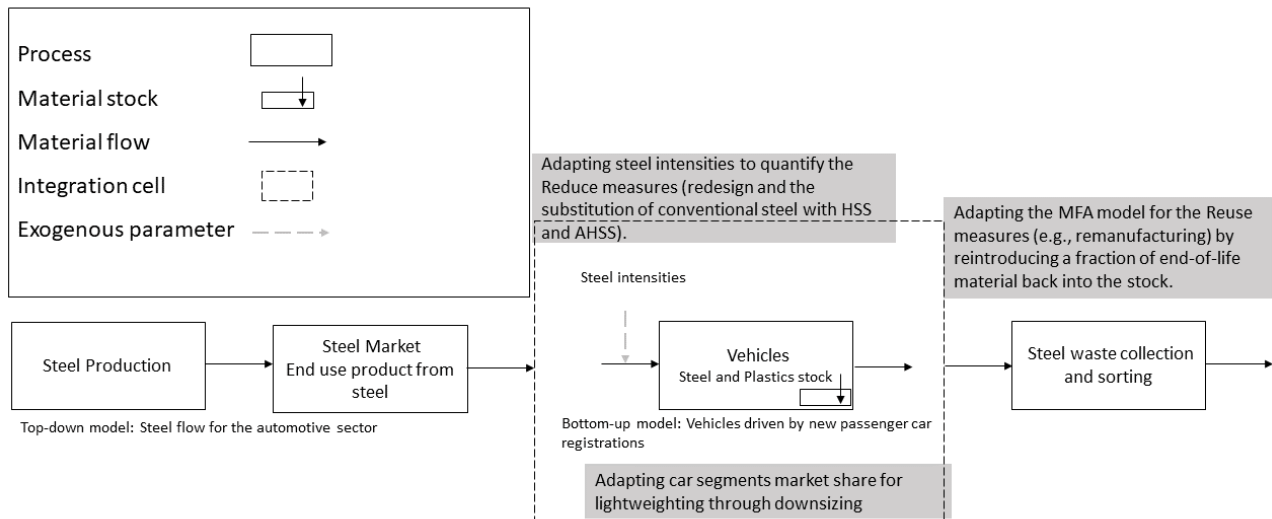


Figure 2. Adaptation of passenger car measures for the integrated steel and plastics top-down and vehicle bottom-up MFA model

Plastics packaging

The EU MFA plastics module in its form up to this case study was linear by design. The impact of R-strategies such as recycling or reuse on the demand for polymers would have to be assumed and applied exogenously onto input parameters. For this case study, we extensively refactored the EU MFA plastic module. It now offers the following features:

- The model explicitly tracks materials through multiple recycling loops and reuse cycles, combined. The latter means that, for example, a reusable bottle in its fifth reuse cycle may contain recycled polymer in its third mechanical recycling loop. Both dimensions are tracked. New input parameters allow the user to set a maximum limit on the number of reuse cycles and recycling loops a particular polymer in a particular application can undergo. This limit can also vary over time, e.g. to account for improvement in product design or post-consumer product management.
- The model endogenously calculates the impact of effectively reused and recycled materials on the demand for virgin polymers. The user inputs exogenously the final demand for polymers that results from consumer demand for certain product categories (e.g. bottles). The model then endogenously allocates reused products and recycled material to cover this demand. The remainder of the demand needs to come from virgin polymers.
- The model can run with an intra-yearly temporal resolution. This is particularly important when modelling the circularity of short-lived products such as plastic packaging. A reusable beverage bottle, for instance, may undergo 20 reuse cycles within three to four years.

Figure 3 presents a simplified flow diagram of the plastics MFA module. The flow entering the *End-use stock* process is the final demand, whose composition for each polymer and use application is a result of the model computation:

- Non reused – primary: demand for virgin polymers (0th recycling and reuse cycles)
- Non-reused – secondary: demand for new recyclates (xth recycling loop, 0th reuse cycle)
- Reused: materials in product put (back) on the market (xth recycling loop, zth reuse cycle)

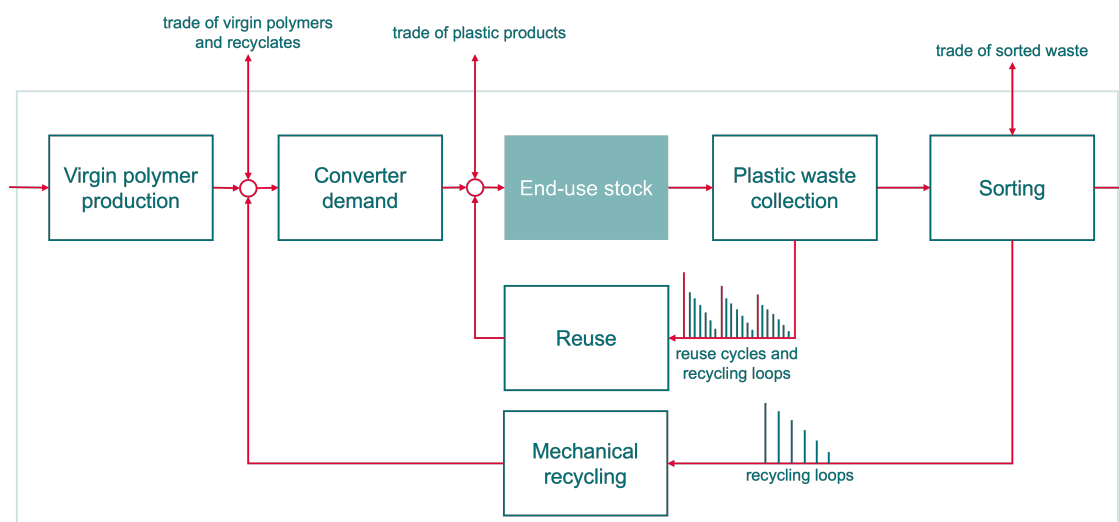


Figure 3. Extension of the plastics MFA module to explicitly account for mechanical recycling loops and reuse cycles and endogenously calculate their impact on the demand for virgin polymers.

Parametrisation of circular economy measures

Passenger cars

As described above, four CE measures for steel in passenger cars have been parameterised for quantification through the EU MFA, comprising measures under material efficiency ((i) material reduction through AHSS and HSS substitution, (ii) redesign, and (iii) downsizing), and reuse ((iv) remanufacturing of steel components and car panels). For the parameterisation, all measures share the same ramp-up period, where the respective scenario starts from 2027, 25% of the scenario is realised by 2030, and 100% is realised by 2040. This pathway aligns with the implementation curve adopted in the ODYM-RECC framework for material efficiency measures (Pauliuk et al., 2021). It is also compatible with the central scenario horizon of the World Energy Outlook (IEA, 2015), in which 2040 is consistently applied as the projection endpoint across the global energy outlook, including for the assessment of material efficiency potentials in energy-intensive industries. What-if scenarios considering conservative and highly ambitious cases are defined based on the implementation potential of each measure. Table 3 describes all parameter assumptions used in defining the implemented scenarios.

Table 3. Parameter assumptions for circular economy measures in passenger cars

Circular economy measure	Parameter assumptions
AHSS & HSS substitution	- Target material: 100% body-in-white and 25% of the chassis as primary components, with secondary mass reduction effects applied to the powertrain, suspension, and interior systems - Conservative: 12.5% direct steel mass reduction achieved through steel substitution, resulting in 5.5% overall steel mass reduction. - Highly ambitious: 25% direct steel mass reduction achieved through steel substitution, resulting in 11% overall steel mass reduction.
Downsizing	- Conservative scenario: Shared Socioeconomic Pathway 1 (SSP1), assuming all countries adopt the vehicle distribution of the countries with the lowest-value trajectory. - Highly ambitious scenario: Low Energy Demand (LED), assuming all countries adopt the vehicle distribution of the countries with the lowest-value trajectory.

Circular economy measure	Parameter assumptions	
Redesign	- Conservative: 4% reduction of the steel content - Highly ambitious: 6% reduction of the steel content	
Remanufacturing	Steel components	- Target material: Long steel product, 23% of the steel content (12% powertrain, 7.5% suspension and 3.5% interiors). - Remanufacturing fraction: 20% of the target material for the conservative scenario and 40% for the highly ambitious scenario. - Remanufacturing yield: 80% across all target components.
	Car panels	- Target material: cold-rolled galvanised steel, 6% of the steel content - Remanufacturing fraction: 10% for the conservative scenario and 20% for the highly ambitious scenario. - Remanufacturing yield: be 30% for the conservative scenario, and 50% for the highly ambitious scenario.
Combined scenario	- Conservative combined: Conservative downsizing, AHSS & HSS substitution, and remanufacturing. - Highly ambitious combined: Highly ambitious downsizing, AHSS & HSS substitution, and remanufacturing.	

AHSS & HSS substitution: The parameter governing the scenarios is steel intensity. The scenarios are built based on the work established by (Modaresi et al., 2014). The key differentiating parameter between the two scenarios is the assumed percentage of direct weight reduction achievable through steel substitution.

Downsizing: the parameter for downsizing is defined based on the change in technology share by assuming an increase of smaller over larger car segments. The technology share is a predefined parameter in the vehicle bottom-up model. The technology share is derived from the dataset ODYM-RECC 3_SHA_DownSizing_Vehicles_V2.3 (Klose & Pauliuk, 2022). The downsizing scenarios are quantified using a uniform vehicle segment distribution across all regions, based on the assumption that CE strategies are primarily influenced by European-wide regulations. The downsizing scenario represents a potential future pathway rather than a current trend requiring strong policies, incentives, and changes in cultural norms.

Redesign: the resulting scenarios are intended to reflect changes in steel intensity by projecting the weight reduction achievable through topology optimisation. Redesign parameter is based on the study by (Tschorn et al., 2021), which estimates the potential vehicle-level weight reduction achievable through topology optimisation and additive manufacturing.

Remanufacturing of steel components & car panels: the remanufacturing parameter is controlled by the remanufacturing fraction, which is the portion of the material sent to remanufacturing as shared with recycling, direct reuse, and energy recovery; the remanufacturing yield, which is the material that can be recovered through the remanufacturing process; and the target components for remanufacturing (Zhang et al., 2021). Steel components are treated separately from car panels, as the remanufacturing of steel components is more established than that of car panels, which is still at an experimental stage; therefore, they have different parameters. The scenarios built for remanufacturing assume that steel components are limited to long steel products, while car panels are limited to cold-rolled galvanised steel (Öko-Institut, 2025).

- **Steel components:** the maximum portion of steel suitable for remanufacturing is assumed to constitute 23% of the total steel content, representing the powertrain, suspension components, and interior. The remaining 73%, comprising the body-in-white and chassis, is assumed to undergo alternative end-of-life processing pathways, consistent with the steel distribution in the scenario framework of (Modaresi et al., 2014). The combined remanufacturing and direct reuse fraction in Europe are less than 10% at the vehicle level (Bobba et al., 2020). The remanufacturing fraction assumptions are based on data for Germany, which indicate a direct reuse-to-remanufacturing ratio of 45:55 (International Resource Panel, 2018).
- **Car panels:** the target material represents 6% of the vehicle steel content (Abdullah, 2023). Given the limited data availability and the experimental status of steel panel remanufacturing, the assumptions for the parameters were set at conservative levels based on the experimental work of (Farioli et al., 2024).

Combined scenarios: the combined scenarios quantify the combined effect of downsizing, AHSS & HSS substitution, and remanufacturing sequentially, excluding redesign in favour of AHSS & HSS substitution given its higher steel reduction potential, as both measures act on the same parameter.

Plastics packaging

As listed in Table 2 above, the scenarios for plastic packaging revolve around three R-strategies: (mechanical) recycling, reuse, and reduce. Within the limited scope of this case study, we apply the refactored EU MFA plastics module to:

- Polymer: PET (polyethylene terephthalate)
- Products: single-use beverage bottles, reusable beverage bottles, single-use non-beverage bottles, reusable non-beverage bottles, sheet (trays), flexible packaging (e.g. film), other (e.g. strapping).

Covering all forms of PET packaging in the EU27+3 between 2018 and 2050, we modelled three scenarios, which, although distinct from one another, build on one another:

- R1 – baseline (mechanical) recycling
- R2 – recycling + reuse
- R3 – recycling + reuse + reduce

Table 4 below presents the assumptions made for the input parameters in the three scenarios R1, R2, R3.

Table 4. Parameter assumptions for PET packaging circular economy scenarios

Parameter	R1 - baseline (mechanical) recycling	R2 - recycling + reuse	R3 - recycling + reuse + reduce
Final demand	ICIS (2022) assumed 2% growth rate for beverage bottles in their baseline scenario “Mandated targets”. A factor for a stronger growth could be some retailers switching materials for their pots, tubs, and trays (PTT) to PET. A factor for stagnating demand could be future crises (demand stagnated or somewhat decreased during COVID around 2020). As a balance, we assume conservatively 1% annual growth rate for all types of PET packaging.		

Parameter	R1 - baseline (mechanical) recycling	R2 - recycling + reuse	R3 - recycling + reuse + reduce
Sorting rates for mechanical recycling	Values based on ICIS (2022) for 2020 and 2022. Linear interpolation between assumed values. Beverage bottles: 75% (2022), 77% (2025), 90% (2030), 90% (2050) => SUPD target for 2025 and 2030, assumed constant afterwards. Other bottles: 42% (2022), 80% (2050) => Own assumption for 2050 (lower than beverage due to less volume, more contamination issues, less standardisation). Trays: 5% (2022), 30% (2025), 50% (2050) => In 2022 about 25% of trays collected and sent to recycling but of this only around 5% in tray-to-tray recycling (the rest goes to low viscosity applications like textiles, outside the scope of this packaging case study). The difference comes from bottle flakes or recyclate imports. Due to the pressure on the flake/pellet market and increasing shares of recycled content (either voluntary or legally mandated) dedicated tray-to-tray sorting facilities are developed so that the sorting rate could reach 30% in 2025. We assume it increases up to 50% in 2050, considering that PET thermoforms have a large variety of packaging types and materials ranging from mono/multi materials to differing colours, lids, labels, etc. (almost 60% of trays placed on the market are multi-layer). Flexible packaging & Other: no significant recycling.		
Recycling losses	According to ICIS (2022) bales to rPEt yield is about 70% in 2020-2022. Better sorting should increase that yield, but increased collection of more contaminated, less standardised packaging counteracts that. We assume constant loss rates. Beverage bottles have lower losses, while other bottles and trays have higher losses. Yields: beverage bottles (73%), other bottles (60%), trays (55%)		
Recycled content	Values based on ICIS (2022) for 2020 and 2022. Linear interpolation between assumed values. Beverage bottles: 24% (2022), 25% (2025), 30% (2030), 65% (2040), 65% (2050) => SUPD target for 2025, 2030, 2040, assumed constant afterwards. Other bottles: we assume same development as for beverage bottles, which is conservative because non-contact sensitive packaging would allow for more. Trays: 44% (2022), 65% (2050) => Already at 44% in 2022, we assume it will reach the same level as bottles in 2050. Flexible packaging (films): 0% Other (strappings etc.): 80%		

Parameter	R1 - baseline (mechanical) recycling	R2 - recycling + reuse	R3 - recycling + reuse + reduce
Max. mechanical recycling cycles	After about seven cycles of mechanical recycling the length of the PET polymer chain is shortened so that the quality is no longer sufficient for high viscosity application (bottles, trays). All packaging: 7		
Reusable shares	n. a.	Beverage bottles: 1% (2022), 10% (2030), 25% (2040), 50% (2050) => Data from ICIS (2022) for 2022 overall in EU27+3, although there are large differences between countries. For 2020 and 2030, targets from SUPD and PPPWD. Own assumption for 2050, expecting DRS to expand in Europe. Other bottles: like beverage bottles => We assume refill-at-home and refill-on-the-go schemes to gain relevance Trays: 0% (2022), 5% (2030), 12.5% (2040), 25% (2050) => No official target for trays but PPWD has turned reusability as a legal mandate. Reusability for certain types of applications (e.g. B2B loose fruits and vegetables logistics) or trays (e.g. not sealed with glue). Assume half the values as for bottles. Flexible packaging and other applications are not assumed to develop meaningful reusable schemes.	
Reuse rates	n. a.	As model parameters, the reuse rates have the same function as the sorting rates for mechanical recycling. We assume that DRS schemes for reusable packaging develop together with similar schemes for single-use. We therefore assume the same values as for sorting rates. Beverage bottles: 75% (2022), 77% (2025), 90% (2030), 90% (2050) Other bottles: 42% (2022), 80% (2050) Trays: 5% (2022), 30% (2025), 50% (2050) Flexible packaging & Other: no significant recycling.	

Parameter	R1 - baseline (mechanical) recycling	R2 - recycling + reuse	R3 - recycling + reuse + reduce
Max. reuse cycles	n. a.	According to the packaging engineering giant ALPLA Group (ALPLA, 2026c), their returnable PET bottles engineered for major markets (including Coca-Cola variants and Central European water brands) are designed for a minimum of 15 to 25 cycles, which directly translates to an active market lifespan of 3 to 4 years. We assume the same for other reusable PET packaging. All packaging: 20	
Packaging weight	Beverage bottles (with cap and label): 42g (single-use), 103g (reusable) => Representative 1L non-carbonated drink from ALPLA (ALPLA, 2026a). Ratio single-use to reusable from Fehringer (2019). Other bottles (with cap and label): 42g (single-use), 105g (reusable) => Representative 750mL spray bottle from ALPLA (ALPLA, 2026b). Ratio single-use to reusable from Fehringer (2019). Trays: 20.6g (single-use), 51g (reusable) => Average between 96ml (PLUSPACK, 2026b) and 2126ml (PLUSPACK, 2026a) clear trays as representatives. Ratio single-use to reusable like for bottles.		Representative beverage bottle: existing 1L non-carbonated mineral water from Fehringer (2019). The weight ratio with the assumption in R1 and R2 is 0.7. We conservatively assume half the weight savings for non-beverage bottles and trays that both require higher structural strength due to usage. Reusable packaging gets lighter in the same proportions as single-use, based on the case of beverage bottles in Fehringer (2019). Weight reduction starts in 2022 linearly until 2030 where the ratios above are reached.

The main driver for all the plastic flows (virgin, recycled, reused, waste) and stocks is the final demand for PET packaging by the consumers. Figure 4 shows how the same assumption (1% annual growth) drives very different levels of polymer demand in each scenario. To provide the same service (i.e. meet the same demand for packaging), the R2 and R3 scenarios require more PET than R1 because of the increasing share of reusable packaging (bottles, trays) in the demand. We run the R1, R2, and R3 scenarios through the refactored EU MFA plastic module to quantify how this level of demand is met, which gives a first insight into the resilience of the system: How much is circular (recycled or reused)? How much must come from virgin polymers? The linkage to REMIND-MFA (see below) provides the impact on trade for virgin polymers and recyclates, which addresses another aspect of resilience.

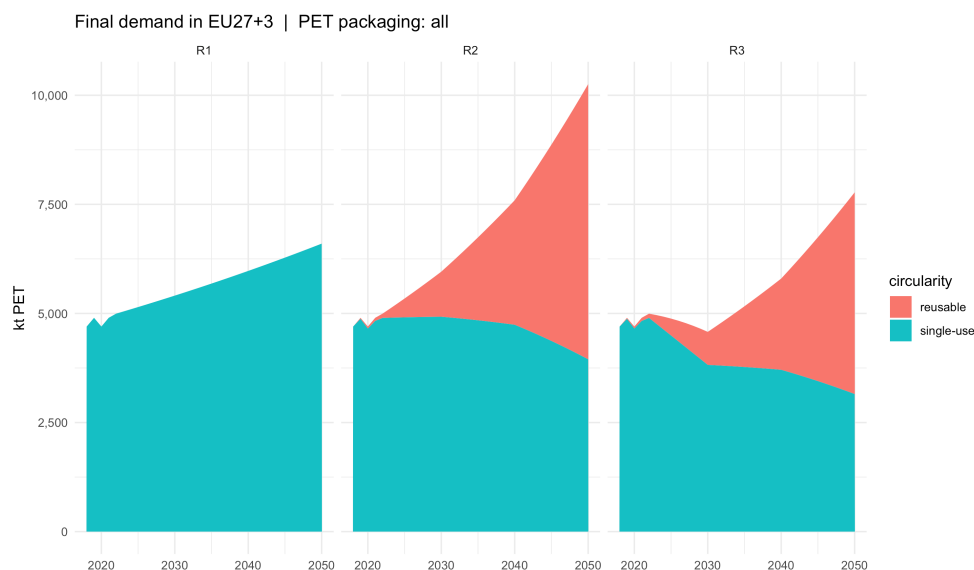


Figure 4. Final demand for PET in the EU27+3 fed to the EU MFA as an exogenous input parameter, distinguishing between demand for single-use and reusable packaging.

REMIND-MFA

REMIND-MFA is a global dynamic MFA model covering 12 world regions – one of them being the EU region - through the year 2100. REMIND-MFA covers the basic materials steel, plastics, and cement; the present case study draws on the steel and plastics modules only. The madrat-based input data pipeline (Dietrich et al., 2023) allows the regional resolution to be adapted flexibly. Reflecting the regional definitions of the respective EU MFA sub-modules, the model is run at a resolution where the EU region corresponds to EU27+1 (including UK) for the steel module and to EU27+3 (including UK, Norway and Switzerland) for the plastics module.

General modelling paradigm: Each material model in REMIND-MFA consists of a historical and a prospective dynamic MFA. In the historical phase, in-use stocks are reconstructed from empirical production and trade data: production volumes are translated into inflows to the stock of end-use goods — accounting for trade and processing losses at each supply chain stage — and an inflow-driven dynamic stock model with a product lifetime distribution then yields the historical stock build-up over time. The prospective phase is stock-driven: per-capita in-use stocks are extrapolated as a function of GDP per capita, and a stock-driven dynamic stock model derives the future material inflow demand. All other flows are computed from this demand by working backwards through the supply chain — through fabrication and raw material processing to primary production — with trade flows at each stage closing the regional mass balance. The approach is well-established in the literature, as in-use material stocks, rather than production volumes, are the quantity providing services to society (Haberl et al., 2017; Pauliuk & Hertwich, 2017).

Crucially, for the EU region itself, REMIND-MFA does not project demand independently but instead adopts material flows directly from the EU MFA, ensuring consistency between the two models (as described later). The stock-driven demand projection described below therefore applies only to non-EU regions.

Stock projection: For all non-EU regions, future in-use stocks are projected through a three-step procedure. In a first step, in-use stock per capita for every region and end-use category is regressed to a common logistic function over the logarithm of GDP per capita. In a second step, the common parameter set is adapted for each region individually, balancing two competing objectives: matching the observed stock level and its trend at the last historical year, while not deviating excessively from the common regression. This is achieved by minimising a weighted penalty function combining terms that penalise absolute and relative deviations of the curve from the historical stock value at the last historical year, a term penalising deviation of the curve's slope from the historical trend, and terms penalising deviations of each parameter from the common regression values. In a third step, a smooth transition from the historical stock trajectory to the regionally adapted logistic curve is constructed, blending the projected trajectory toward the logistic target such that 95% of any initial discrepancy is resolved within approximately 50 years.

Trade extrapolation: REMIND-MFA represents trade at multiple life-cycle stages: trade in raw materials or intermediate products, trade embodied in finished goods, and trade in scrap. At each stage, a regional mass balance must hold:

$$p_r(t) + i_r(t) = e_r(t) + d_r(t)$$

where p_r , i_r , e_r and d_r denote regional production, imports, exports, and demand in region r at time t . Trade flows are extrapolated from the last historical year t_0 using a heuristic consisting of two steps: regional extrapolation followed by global market clearing.

Regional extrapolation: Future trade flows are extrapolated from the last historical year t_0 under the baseline assumption that import shares relative to demand and export shares relative to production remain constant at their t_0 levels:

$$\frac{i_r(t)}{d_r(t)} = \frac{i_r(t_0)}{d_r(t_0)} \frac{e_r(t)}{p_r(t)} = \frac{e_r(t_0)}{p_r(t_0)}$$

For demand-driven life-cycle stages (trade embodied in goods and raw material trade), imports are determined directly from the known demand variable; exports depend on production which in turn depends on exports through the mass balance, so this sub-system is resolved by fixed-point iteration. For scrap trade, supply is the known quantity, so exports are calculated first, while imports and demand are calculated by fixed-point iteration from the mass balance equation system.

The following modifications to that general extrapolation paradigm are applied: For regions with declining demand, exports are instead held constant at their t_0 level — reflecting the inertia of existing production capacities — while imports continue to scale with demand. For regions with still very low GDP and therefore low domestic demand and production, import and/or export shares are sometimes very high and would propagate unrealistically with the approach described above. Therefore, it is assumed that with strong relative demand growth, import and export shares converge toward their global average at t_0 .

Plastic waste trade is not extrapolated in this way but assumed to decline linearly to zero by 2030. This reflects an observed structural downward trend: global trade in plastic waste and scrap has roughly halved since 2014, driven initially by China's unilateral import restrictions under its "National Sword" policy in 2018 and subsequently by the tightening of multilateral controls like the Basel Convention Plastic Waste Amendments (Brown et al., 2025). Further restrictions — including the EU Waste Shipment Regulation, which progressively bans plastic waste exports from the EU to non-OECD countries — are expected to continue suppressing long-distance waste trade in the coming years (European Commission, 2024a). As EoL flows are not the primary focus of this case study, this simplification has limited bearing on the results.

Global market clearing: Regional extrapolation does not in general ensure that global imports equal global exports. A balancing step is thus applied, rescaling both import and export vectors such that their global sums converge to a common value taken as the harmonic mean of the two pre-balancing global totals.

Data inputs: Population and GDP trajectories are taken from the Shared Socioeconomic Pathways (SSPs) (Kriegler et al., 2012), using the SSP2 for the present case study. Other input data include historical production volumes, historical trade flows^[OBJ] ^[OBJ]. REMIND-MFA is based on historical data until 2022 for steel and until 2019 for plastics.

Trade scenarios

Rationale and relationship to the baseline: In the baseline scenario, future trade is projected with the default demand-driven extrapolation described above: for each traded stage, imports are scaled with the projected regional material demand at that stage, while exports and domestic supply are obtained jointly from the trade mass balance, holding recent historical import-to-demand ratios approximately constant and blending towards global trade shares only for strongly growing demand. The CE scenarios differ from the baseline only in the final material demand delivered by the EU MFA module: reduce measures (e.g. passenger car downsizing) and reuse measures (e.g. refillable PET bottles) both reduce EU final material demand relative to the baseline scenario but originate from physically distinct mechanisms. The EU MFA module supplies REMIND-MFA with measure-specific demand trajectories; the differentiation between material efficiency and reuse therefore enters REMIND-MFA exclusively through these trajectories and is not reconstructed within the trade model itself.

A central modelling decision is how a CE-induced reduction in EU material demand is distributed between a reduction in cross-border trade and a reduction in domestic EU production. Because REMIND-MFA receives demand in material mass units, a reduction of a given tonnage is, at the level of the trade extrapolation, treated identically irrespective of whether it arises from material efficiency or from reuse: the reduction is applied to the market (apparent consumption) at the relevant stage, and the allocation between trade and domestic production is then governed entirely by the choice of trade extrapolation. We make this assumption explicit because it has a direct interpretive consequence: passing the reduced EU MFA demand to a demand-driven extrapolator means that CE measures act on EU apparent consumption, not directly on EU production, and that production responds only from the demand-and-trade mass balance.

It should be stated at the outset that the two CE trade scenarios defined below are normative bracketing assumptions about how a CE-induced demand reduction is absorbed, rather than behavioural predictions or policy-driven narratives. In the present setup, only the two MFA modules (EU MFA and REMIND-MFA) are coupled, without the macroeconomic and industrial modules of the wider MIC3 framework; the modelling chain therefore carries no information on production prices or on CE-induced changes in regional competitiveness or production structure. The two scenarios are therefore best read as bounding the plausible range of trade and production outcomes given the information available in the current MFA-only coupling.

¹ <https://remind-mfa.readthedocs.io/>

To bracket this range for industrial resilience, we define two trade scenarios that share the CE demand trajectories but differ in the allocation between trade and domestic production. They correspond to two limiting assumptions: trade adjusting with regional demand, versus domestic production being defended such that trade absorbs the adjustment. The latter is conceptually related to the capacity-driven trade representation of Pauliuk et al. (2013), who show, for the global steel cycle, that extensive trade in steel can decouple regional production from regional demand and thereby prolong the operating life of regional steelmaking assets under demand saturation. We adopt the analogous idea — that a region may sustain domestic production above the level its own demand would imply, with the difference exported — as the basis for our fixed-supply scenario, while noting that we implement it as a prescribed scenario assumption rather than via an endogenous capacity model. For brevity we refer to the two scenarios as the *demand-following* and *fixed-supply* cases.

Scenario 1 – Demand-following trade: In the demand-following scenario, the CE-reduced EU demand at each traded stage is passed to the standard demand-driven extrapolator, exactly as in the baseline. The implicit economic assumption is that the EU's import dependence at each stage — the ratio of imports to apparent consumption, estimated from recent historical data — is structurally persistent. A CE-induced reduction in EU demand therefore contracts imports and domestic production in proportion to their incumbent shares, with exports retained at least at their prior level. This is the conservative case: it imposes no assumption that the EU defends domestic capacity, and it is the natural counterpart to the baseline. We treat it as the primary CE trade scenario.

Scenario 2 – Fixed-supply (domestic production protected). In the fixed-supply scenario, EU domestic production at the relevant stage is held at its baseline trajectory, and the entire CE-induced change in EU demand is absorbed by trade. This represents a strategic-autonomy or industrial-resilience framing, in which the EU maintains domestic basic-material capacity — for reasons of security of supply, employment, or avoidance of production relocation and associated carbon leakage — so that CE gains manifest as reduced import dependence and/or increased net exports rather than as reduced domestic output. It provides the upper bound on the trade-balance improvement that CE measures can deliver if production is defended, and thus directly addresses the industrial-resilience dimension of the case study.

Formally, let $D_{base,r}(t)$ and $D_{CE,r}(t)$ denote baseline and CE demand at the relevant stage for region r , and define the demand delta for the fixed-supply region (the EU) as

$$\Delta(t) = D_{CE,EU}(t) - D_{base,EU}(t) \leq 0$$

Starting from the baseline future trade, the EU's trade is adjusted as

$$imports_{CE,EU} = imports_{base,EU} + \alpha \cdot \Delta$$

$$exports_{CE,EU} = exports_{base,EU} - (1 - \alpha) \cdot \Delta$$

with $\alpha \in [0, 1]$ the import-adjustment share.

The complementary trade adjustment is distributed across non-EU regions in proportion to their share of global imports and exports in order to ensure global market clearing. This proportional re-allocation is an approximation of which trading partners absorb the EU's reduced net imports.

We treat α as an explicit scenario lever rather than fixing it at an arbitrary central value and report the two interpretable endpoints. With $\alpha = 1$ (import substitution), the CE demand reduction is met entirely by lower extra-EU imports, with EU exports unchanged; this is the most defensible reading of "strategic autonomy" and serves as the headline resilience case. With $\alpha = 0$ (export expansion), defended domestic output is redirected to export markets.

Application across trade stages: Both the steel and the plastics systems trade material at different stages — an upstream stage (intermediate products for steel, the primary/polymer market for plastics) and a downstream finished-goods stage — as well as an end-of-life (EoL) scrap/waste stage. The trade scenarios defined above are applied only to the two forward stages. EoL trade is held at its baseline behaviour in both CE scenarios and is not subjected to the demand-following/fixed-supply distinction, because the case study focuses on higher R-strategy CE measures (material efficiency and reuse) that act by reducing material demand, rather than on measures that increase recycling or otherwise reshape EoL and secondary-material flows. The trade of recovered material is therefore outside the scenario logic, and any differences in EoL flows between scenarios arise only as the downstream consequence of reduced demand, not from a scenario choice about EoL trade.

The CE demand reduction enters at the finished-goods stage (fewer or lighter goods) and propagates upstream through the mass balance to the intermediate/primary stage. The two CE measures map onto these stages differently in interpretation, even though both are delivered as mass:

- *Material efficiency* reduces the material embodied per unit of good while leaving the number of goods unchanged. Its effect is concentrated at the upstream stage (less intermediate steel or primary polymer per good). At the finished-goods stage the *number* of traded goods is unchanged; the reduction in finished-goods trade mass reflects lower material intensity rather than fewer goods. Because the model tracks mass and not units, this distinction is one of interpretation: results at the finished-goods stage should be read as constant goods volumes at reduced material intensity, not as fewer goods traded. Where lightweighting reflects a product or market standard, the reduced intensity applies to goods consumed in the EU regardless of origin, i.e. to imported as well as domestic goods — consistent with the demand-driven treatment, in which the intensity reduction is embedded in the demand scaler that drives both import scaling and production residual.
- *Reuse* reduces the number of new goods demanded and therefore reduces both finished-goods and (via the mass balance) upstream trade in both mass and unit terms. Here the contraction of finished-goods trade is physically a reduction in goods volume.

We apply the fixed-supply assumption at the upstream (basic-material) stage, where the retention of domestic production capacity is the economically and strategically meaningful object for an industrial-resilience analysis — primary steelmaking and polymerisation/cracker capacity are capital-intensive, spatially concentrated, and central to security-of-supply and carbon-leakage concerns in a way that distributed downstream fabrication is not. The demand-following extrapolation is retained at the finished-goods stage in both scenarios, since "defending domestic production" is not a coherent resilience claim at the level of individual fabricated goods.

Harmonisation between EU MFA and REMIND-MFA

The case study couples two MFA models that both follow a demand-driven paradigm but at different resolutions: the EU MFA resolves European material cycles in sectoral detail, whereas REMIND-MFA represents the EU as a single region within a global, mass-balanced system. To attribute changes in EU trade flows to circular-economy measures, the two models must describe the same physical EU system. Harmonisation achieves this by having REMIND-MFA adopt the EU MFA flows for its EU region rather than projecting them independently, so that the trade flows REMIND-MFA computes across EU borders are consistent with the EU MFA result by construction.

The harmonisation proceeds in three steps, implemented in the input-mapping script and in the REMIND MFA's TRANSCIENCE-mode routines.

1. Mapping of EU MFA flows to REMIND-MFA dimensions: Each EU MFA flow is aggregated to the single REMIND-MFA EU region, unit-converted and mapped to the REMIND-MFA's dimensions through a correspondence table. This way, EU MFA's finer categories are aggregated to REMIND-MFA's coarser ones (e.g. mapping “Automotive” and “Other Transport” sectors to “Transport” etc.). The flows mapped this way are the in-use stock inflow (demand) and the EoL flows (for steel: collected and lost EoL, and available scrap; for plastics: stock outflow, collected, sorted, and recycled EoL).

2. Construction of a flow-driven EU stock: In TRANSCIENCE mode, REMIND-MFA does not project the EU in-use stock from the GDP-based stock regression used for other regions. Instead, the EU stock is rebuilt as a simple flow-driven stock whose inflow is the mapped EU MFA demand and whose outflow is the mapped EU MFA stock outflow.

3. Derivation of EU EoL parameters from EU MFA flow ratios: The EoL parameters governing the EU region — collection, recovery, and (for plastics) recycling — are not independent assumptions but are computed as ratios of the mapped EU MFA flows, so that REMIND-MFA reproduces EU MFA's EoL behaviour at its own resolution. For steel, the collection rate is the collected EoL flow divided by total stock outflow (collected plus lost EoL), the sorting rate is available scrap relative to collected EoL, and the EU slice of REMIND-MFA's recovery-rate parameter is overwritten with the product of the two. For plastics, the collection rate (collected EoL over stock outflow), the mechanical recycling rate (sorted over collected), and the recycling yield (recycled over sorted) are derived analogously and substituted into the corresponding EU entries. Defining these rates as ratios of mapped flows — rather than transferring EU MFA's native rates — is what keeps the absolute EoL flows invariant under the dimensional aggregation.

Once demand, stock, and EoL parameters for the EU region are harmonised in this way, REMIND-MFA computes the EU's trade flows endogenously within its globally market-clearing trade model; these are the flows analysed in the trade-flow results.

Results

In line with the research process, the result section is divided into three main chapters presenting the scenario results on passenger cars, plastics packaging, and trade flows. The first two sections follow in general the same structure by initially presenting the scenario narrative followed by the scenario results. The last section presents the impact on trade flows.

Passenger cars

Scenario narrative

Highly ambitious combined scenario: Until 2050, the EU accelerates material efficiency and reuse for passenger cars driven by the EU climate targets, competitiveness concerns, and policies. This reduces total material demand, while secondary material availability also decreases as less waste is generated and products stay in use longer. The net effect reduces exposure to global markets and import dependencies, strengthening the resilience of the EU.

Incentives that once favoured heavier vehicles have shifted: policies, standards, and public procurement now reward material efficient design. Safety concerns were resolved through regulations and advanced engineering. Cultural norms have changed as well. Status is no longer tied to size. Growing climate consciousness strengthened this shift, with consumers actively choosing cars that use less materials (smaller passenger cars). Industry innovations followed. High strength steel became cheaper and the trade-offs between strength, cost, and recyclability were overcome.

Harmonised standards and regulations enable the cross-border reuse of car components, easing concerns about supply security supported by product passports. Waste management systems have evolved, building on long-standing practices for old passenger cars. The export of end-of-life vehicles has been minimised and components flow to reuse. Electric cars have been integrated into this system as new reuse markets emerged for specific components. Reuse is prioritised and remaining components are recycled.

Impact on steel demand

Scenario parameters for the reduce measures were constrained by the plausibility of technical implementation pathways, which bounded the projected reduction in automotive steel demand to a relatively low range. At full scenario realisation in 2040, even the scenario with the highest material demand reduction, the highly ambitious downsizing scenario, does not exceed a 5.5% reduction when expressed as a share of total automotive steel demand, as illustrated in absolute values in Figure 5. However, when the analysis is evaluated at the passenger car level, the material savings for the same scenario reach 11.75%.

Among the individual measures, AHSS & HSS substitution and downsizing consistently exhibit the highest reduction magnitudes across both conservative and highly ambitious configurations. The elevated effect of downsizing reflects Europe's historically established preference for smaller, more fuel-efficient vehicle segments relative to other regions (International Resource Panel, 2020). The strong contribution of AHSS & HSS substitution reflects its established trajectory as a trend material that is progressively replacing mild steel in automotive manufacturing (European Commission, 2021). The effect of redesign was evident to be lower than that of AHSS & HSS substitution, as both measures are quantified based on steel intensity, while redesign achieves a lower reduction in steel intensity.

The conservative and highly ambitious remanufacturing scenarios represent the reuse strategy, where reuse does not produce a direct reduction in material demand, as its effect is governed by steel stock outflows rather than direct steel inflow. The comparatively lower material demand reduction attributed to remanufacturing, as shown in Figure 5, reflects the multiple factors that constrain its scenario parameter.

This combination revealed material savings ranging from 6.6% under the conservative configuration to 13.3% under the highly ambitious configuration, sustained across the full realisation period from 2040 to 2050, as shown in absolute reduction terms in Figure 5. This demonstrates that while measure prioritisation is critical, the adoption of multiple integrated measures is essential. The transparent what-if scenario framework further allows for iterative refinement of the quantification methodology and enables the testing of alternative demand reduction trajectories.

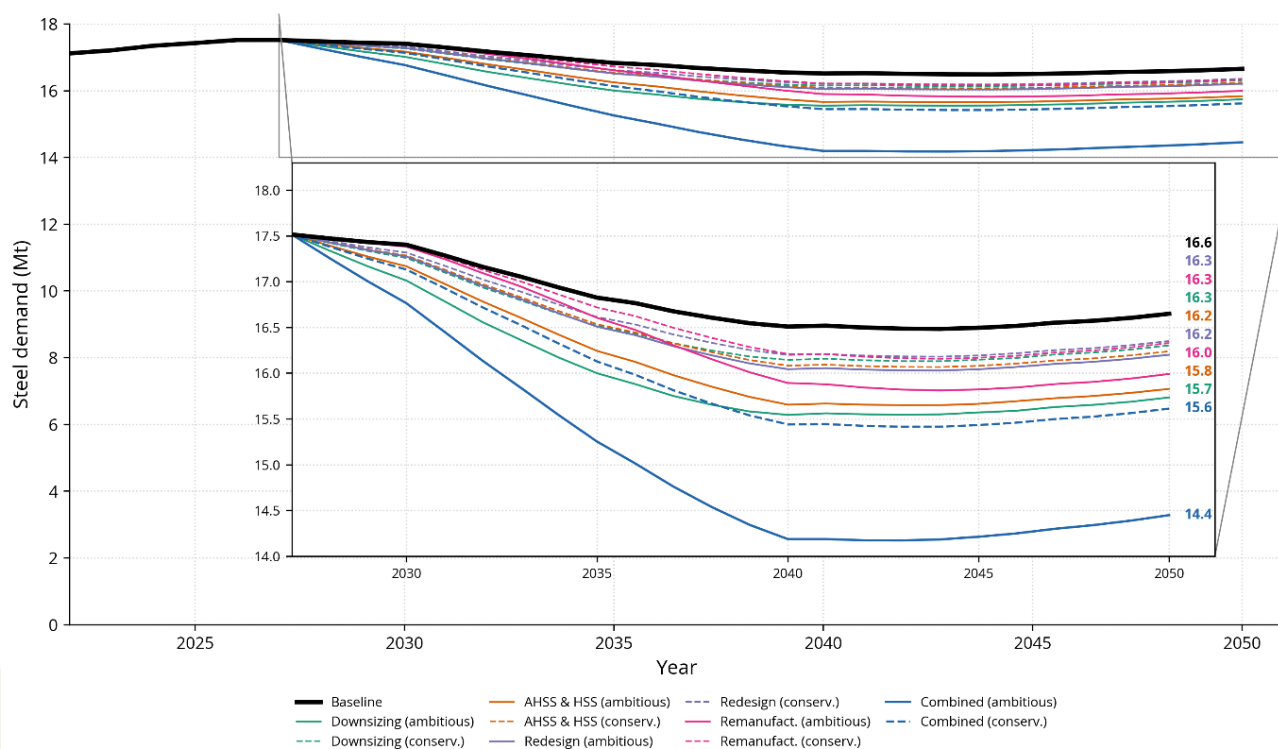


Figure 5. Automotive steel final demand in the EU27+1 under Reduce, Reuse, and Combined scenarios relative to the baseline scenario

Impact on secondary steel availability

With respect to secondary material availability, all reduce scenarios are projected to produce observable effects only after 2035, as shown in Figure 6. This temporal offset is a direct consequence of vehicle stock dynamics: the mean EU vehicle lifetime of 15 years and a standard deviation of 4 years govern the lag between the adoption of reduction measures and their downstream expression in end-of-life steel outflows from the stock, hence the initial decline. Nevertheless, reuse scenarios exert a comparatively stronger influence on secondary material availability, as shown in Figure 6, than the reduce strategies, as they directly divert end-of-life steel from the scrap stream. The combined scenario is more influenced by remanufacturing in terms of secondary steel availability, particularly in the nearer term. As a result, the combined effect is dominated by reuse in the nearer term, while the reduce measures contribute progressively more as the affected stock works its way to end of life, and the full effect is not yet realised by 2050.

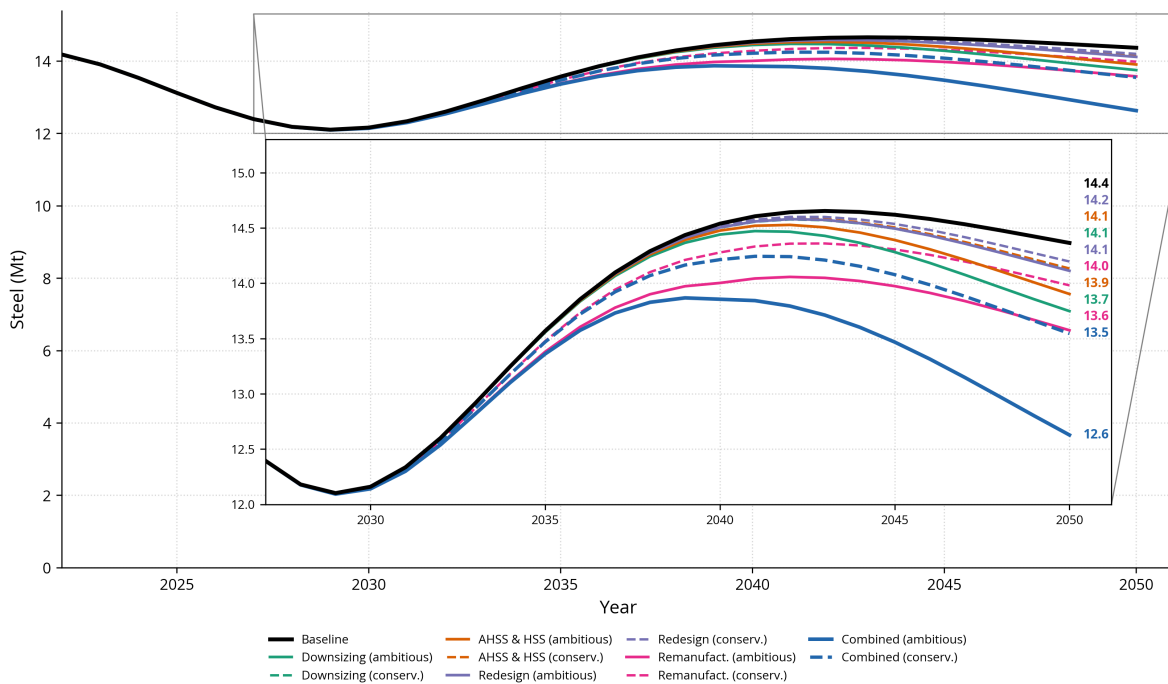


Figure 6. Automotive secondary steel availability in the EU27+1 under the Reduce, Reuse, and Combined scenarios relative to the Baseline scenario

Plastics packaging

We ran the refactored plastics EU MFA model in three-month time steps, essentially divided each year into four quarters. Most of the packaging consumed in each time step is collected as plastic waste and some of it is sorted towards mechanical recycling or reuse, in which case it is available in the subsequent time step as recycled or reused PET. These PET flows' recycling loop and reuse cycle counters are incremented correspondingly. In the results presented below, the time steps are aggregated into whole years. The recycling loop and reuse cycle counters are also aggregated unless specified otherwise.

Scenario narratives

R1 – baseline (mechanical) recycling:

The European PET packaging sector relies on single-use containers. Reusable packaging does not play a role in this scenario. The targets regarding recycled content and collecting / sorting rates for mechanical recycling put forward in the Single Use Plastic Directive (SUPD) and the Packaging and Packaging Waste Packaging Regulation (PPWR) are met for beverage bottles. Deposit Return Systems are powerful schemes in that regard, and they extend to all of Europe over time. Similar improvements, although with less ambitious targets are expected for non-beverage bottles and trays. The weight of a representative packaging unit (e.g. beverage bottle) remains at the level of an average packaging unit in the early 2020s.

R2 – recycling + reuse:

Mechanical recycling and the weight of packaging develop exactly like in scenario R1. In addition, targets for the share of reusable packaging put on the market found in the PPWR are met for beverage bottles. The share of reusable non-beverage bottles is also expected to increase. A fraction of trays made of PET monomaterial (in opposition to multilayer trays) that also do not need to be sealed with glue (e.g. trays for berries, trays used for take-away food) is also expected to put on the market as reusable containers.

Reusable packaging has the same relative recycled content than single-use packaging. Reusability in flexible packaging and other packaging applications is not expected to become sizable. Reusable packaging (e.g. reusable beverage bottles) is manufactured sturdier, heavier than its single-use counterpart, hence an increase in material demand is expected at first to deliver the same service. The rate of reuse is the key parameter counter-balancing this increase. Deposit Return Systems (DRS) for reusable bottles develop in parallel to single-use beverage bottles. Refill-at-home and refill-on-the-go (i.e. in shops) schemes continue to expand in Europe for non-beverage bottles.

R3 – recycling + reuse + reduce:

Developments in mechanical recycling and reusable packaging are the same as in scenario R2. The additional circularity strategy applied here consists in reducing the weight of packaging while providing the same service. Since the early 2000s much progress has been made on weight lighting PET packaging, both for bottles and trays. The main driver was and still is cost reduction for the manufacturers and transporters. This strategy has limits and seems to have reached some sort of plateau in the late 2010s. Increased recycled content and reusability have an adverse effect on reducing packaging weight. No further ground-breaking weight lighting development is expected. We conservatively assume that for bottles and trays (distinguishing between single-use and reusable) the lighter variants of these packaging available in the early 2020s penetrate the market so that they eventually become the norm.

Composition of final demand

The slowly but steadily increasing demand for PET packaging assumed in all three scenarios combined with the penetration of reusable bottles and trays in R2 and R3 drive the overall need for polymers as shown in Figure 4 to meet this demand. Figure 7 below shows how this overall need for PET is actually covered in each scenario, differentiating between virgin (not reused primary), recycled (not reused secondary), and reused polymers. The sum of all curves in each graph corresponds to the overall need mentioned above. The composition and the changes in composition over time, however, vary significantly between scenarios. Figure 8 further below, shows the contributions of each packaging type considered to these three categories of demand (virgin, recycled, reused).

All three scenarios start with the same overall recycled content and therefore the same ratio between demand for primary and secondary polymers. Looking at R1, one can see the effect of mandated recycled content increasing sharply between 2030 and 2040 (from 30% to 65% for beverage bottles, which are by far the main contributors). As a result, demand for virgin polymers decreases accordingly. Recycled content is assumed to remain constant after 2040, while overall demand keeps increasing at a 1% per year steady pace. Demand for virgin and recycled PET both pick up accordingly. From an overall need of 6.6 Mt in 2050, 2.6 Mt (39%) is virgin PET when it was 72% in 2022 (3.6 Mt of 5 Mt).

Looking at R2, the same underlying dynamics of increasing recycled content is also at play. The surge of reused PET (mostly reusable beverage bottles, although non-beverage bottles and trays contribute too) accentuates the downward pressure on primary demand until 2040 so that it is 10% lower than in R1 (2.1 Mt against 2.4 Mt) although the overall need for PET is 27% higher (7.6 Mt against 6 Mt) due to reusable packaging weighting more than single-use for the same service. We assume that the share of reusables put on the market keeps increasing after 2040 (up to 50% for bottles and 25% for trays) which, along with the overall increasing demand, requires ever more polymers. However, the effect of reusing bottles and trays up to 20 times, with increasing efficiency (we assume 90% reuse rate for beverage bottles, 50% for trays in

2050) thanks to DRS schemes, prevents demand for primary polymers from picking up and even reduces the demand for recycled PET compared to 2040. At 10.2 Mt, the overall need for PET in 2050 is 55% higher in R2 than in R1, however, the demand for primary and secondary PET is 20% and 24% (2.1 Mt and 3 Mt) lower thanks to the high level of reused materials making up 50% (5.1 Mt).

As expected, the developments in R3 look like R2, but dampened. The weight of bottles and trays decreases until 2030, which, combined with recycled content mandates and reuse penetration, speeds up the reduction in primary polymer demand and flattens that of secondary polymers. Packaging weight by unit is assumed constant after 2030 but it still contributes to reducing demand for primary and recycled polymers to 1.7 Mt and 2.3 Mt in 2050 (66% and 59% of R1, 82% and 77% of R2, respectively). While the overall need for PET reaches 7.8 Mt in 2050 (18% more than R1, 24% less than R2), the distribution between the three flows is practically the same than in R2: around 50% reused, 30% recycled, and 20% virgin polymers.

Single-use beverage bottles followed by single-use trays are the main drivers of primary and secondary PET demand, although reusable bottles and trays become comparable to single-use trays in R2 and R3 around 2050. Reusable beverage bottles are mainly driving the reused flows in R2 and R3.

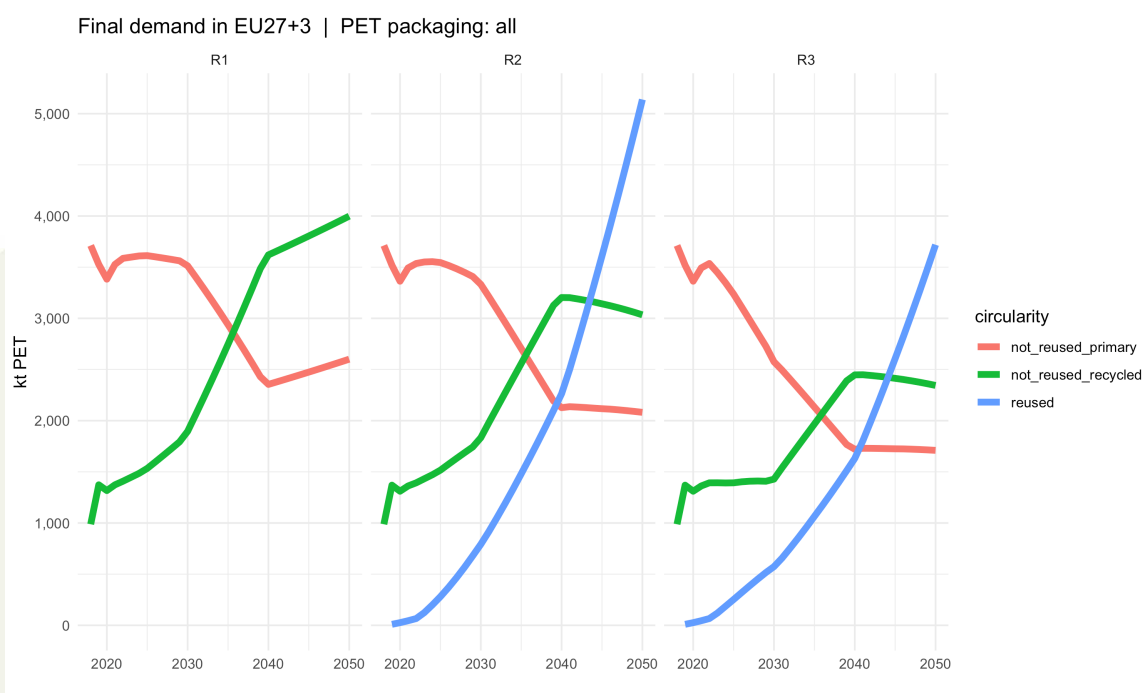


Figure 7. Composition of final demand for PET in the EU27+3 calculated by EU MFA for scenarios R1, R2, R3 and distinguishing between demand for primary and secondary polymers in single-use or first-use reusable packaging (*not reused*) and polymers *reused* in reusable packaging.

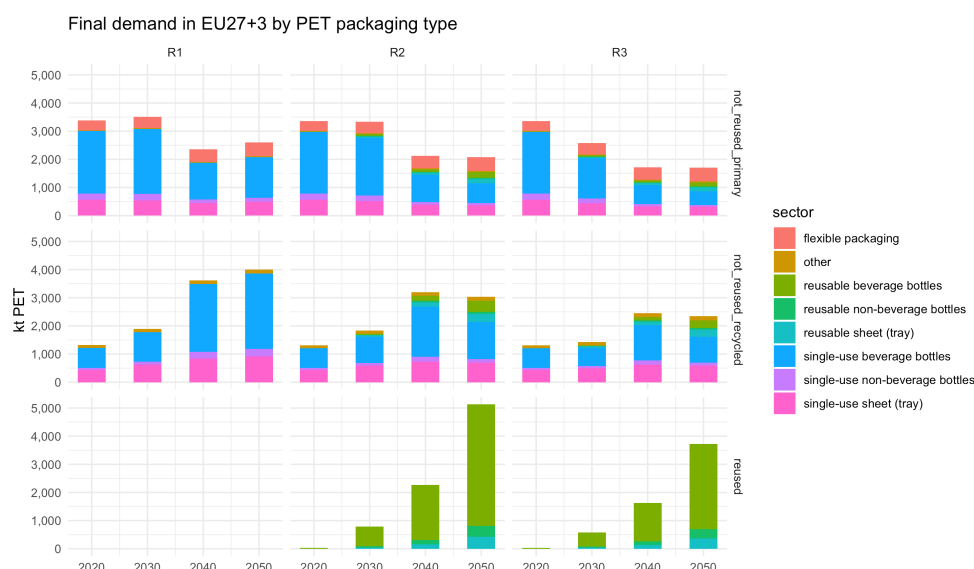


Figure 8. Composition of final demand in the EU27+3 by type of PET packaging in the scenarios R1, R2, R3 (left to right) and for primary and secondary polymers in single-use or first-use reusable packaging (*not reused*) and polymers *reused* in reusable packaging (top to bottom).

Recycling strategy

The previous section showed how recycled content mandates help decrease the reliance on primary polymers in all three scenarios. However, unlike a Reduce strategy, rPET still needs to be produced. In its current form the EU MFA only supports recycling loops within the same application sector (e.g. beverage bottles to beverage bottles), i.e. the EU MFA has no market mechanism to trade rPET between sectors. It is our assumption that, as demand for recycled PET increases for most packaging types, producers and retailers are incentivised to close the loop for each packaging type (e.g. through return schemes, different packaging design, improved sorting etc.). In the early 2020s, the picture was different, with recyclates from beverage bottles being bought for producing other packaging such as trays and non-beverage bottles and other applications such as textiles. The pressure on high-quality bottle recyclates was high so that food-grade recycled pellets had to be imported in 2022 (ICIS 2022). This led to investments into tray-to-tray sorting and recycling facilities, which supports our assumption stated above. Against this backdrop, the figure below shows the balance between rPET production from different types of packaging waste and the demand for rPET for these types of packaging to meet the target recycled content. Until 2030 the recyclates from beverage bottles provide a surplus that can be absorbed by other applications such as trays (negative balance), fibres (not modelled), or exports. As mentioned above, this picture may well be too optimistic considering the actual strain on the rPET market of the early 2020s (ICIS 2022). We may have underestimated the use of rPET in some sectors (e.g. flexible packaging) and overestimated the quality of the recyclates from beverage bottles that may in part not be suitable for contact sensitive bottles or trays. Nevertheless, the development after 2030 is striking. From then on, recycled content mandates keep rising (from 30% in 2030 to 65% in 2040 for beverage bottles) while recycling yields hit a plateau (90% sorting rate to mechanical recycling combined with 27% losses during recycling correspond to an overall maximum yield of 66% for beverage bottles after 2030). The total balance for rPET becomes negative at the latest in 2035 and reaches -0.8 Mt in 2050. At that time none of the considered packaging sectors can sustain itself with rPET (beverage bottles show a light deficit of 0.03 Mt in 2050). Tray-to-tray recycling is assumed to have an overall yield of around 28% in 2050 (sorting 50%, losses 45%) which is much higher than 2022 levels where it was practically

inexistent, which explains a rPET deficit of 0.5 Mt in 2050. Imports of recyclates, investments into collection, sorting and recycling of trays beyond what we have assumed, and/or developing chemical recycling will be necessary to meet 65% recycled content (our assumption) or producers will rely more on virgin PET.

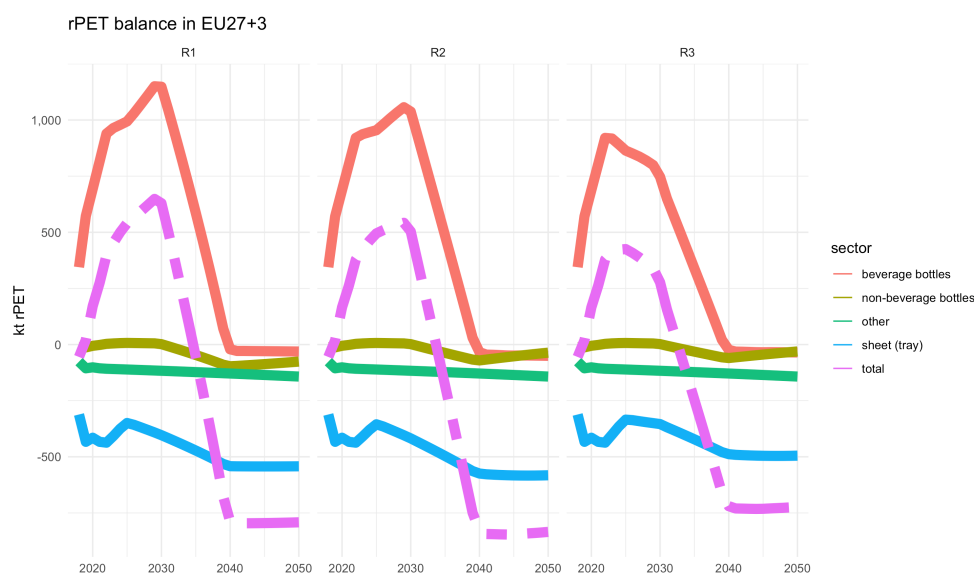


Figure 9. Balance between converter demand for recycled PET (rPET) and rPET production by packaging type in the EU27+3 in the scenarios R1, R2, R3.

Reuse strategy

The results in the section “Composition of final demand” showed the large savings that reusable packaging can provide for the demand for primary and secondary polymers. In our scenarios, reusable beverage bottles are the main contributors. The two figures below detail the PET final demand for reusable beverage bottles. The first figure presents the demand for virgin and recycled PET (mechanical recycling cycle = 0 and > 0, respectively). It shows a distinctive “lump” of virgin polymer demand between 2022 and 2030 as the share of reusable beverage bottles went up tenfold, from 1% to 10% of the beverage bottles put on the market. The growth in reusable demand continues but slows down after 2030. The reuse rate is assumed to be on par with the collection and sorting rate of single-use beverage bottles destined to mechanical recycling (75% in 2022, 90% in 2030) but then without the subsequent losses coming from the recycling process and with up to three times as many reuse cycles compared to recycling loops. Under these assumptions reuse quickly gets momentum so that in 2030 the amount of PET reused in beverage bottles is 7 times higher than the demand for virgin and recycled PET combined to make new reusable beverage bottles (0.7 Mt against 0.1 Mt). This ratio then remains stable throughout the modelling period, so that in 2050 4.3 Mt PET comes from reuse vs. 0.6 Mt from primary and secondary sources.

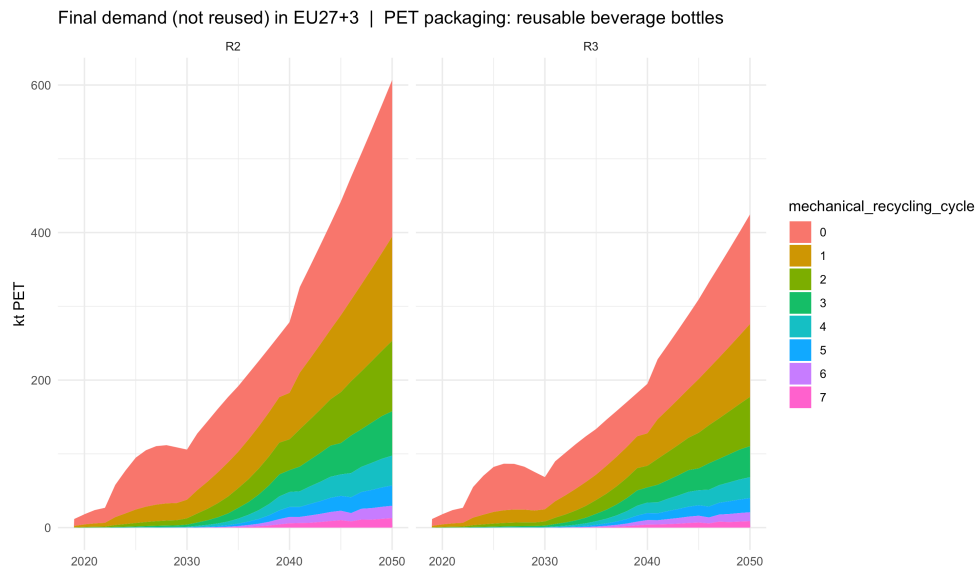


Figure 10. Final demand in the EU27+3 for PET reusable beverage bottles in the scenarios R2 and R3 for primary (mechanical recycling cycle = 0) and secondary (mechanical recycling cycle > 0) polymers in the first-use cycle (not yet reused).

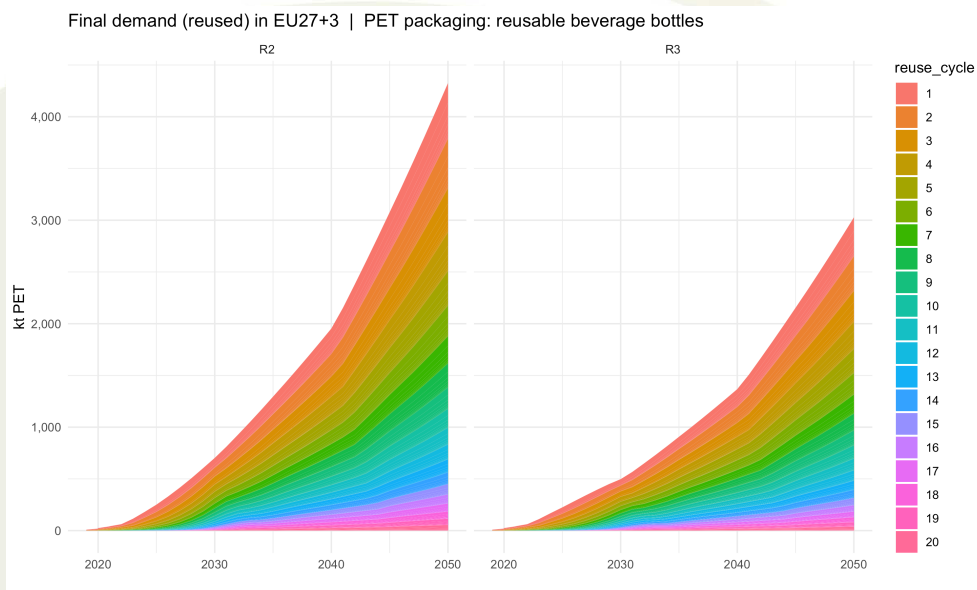


Figure 11. Final demand in the EU27+3 for PET reusable beverage bottles in the scenarios R2 and R3 for reused polymers (reuse cycle > 0). The faint white lines in each reuse cycle show the shares of each mechanical recycling cycle (primary, i.e. mechanical recycling cycle = 0, on top).

Reduce strategy

The results in the section “Composition of final demand” showed what reducing the weight of packaging (bottles and trays in particular) could contribute to diminish the pressure on primary and secondary polymer demand. Weight lighting packaging has been an ongoing trend for at least 20 years, mainly for economic reason. What our scenario R3 does not consider is any potential rebound effect, meaning that economic savings by the producers or the consumers may lead to additional production or consumption thus potentially compensating the material savings. This put aside, Figure 12 shows that the relatively limited “Reduce” strategy (we did not assume further massive packaging weight reduction) in R3 results in about 20% less primary PET demand cumulatively over the modelling period (2018-2050).

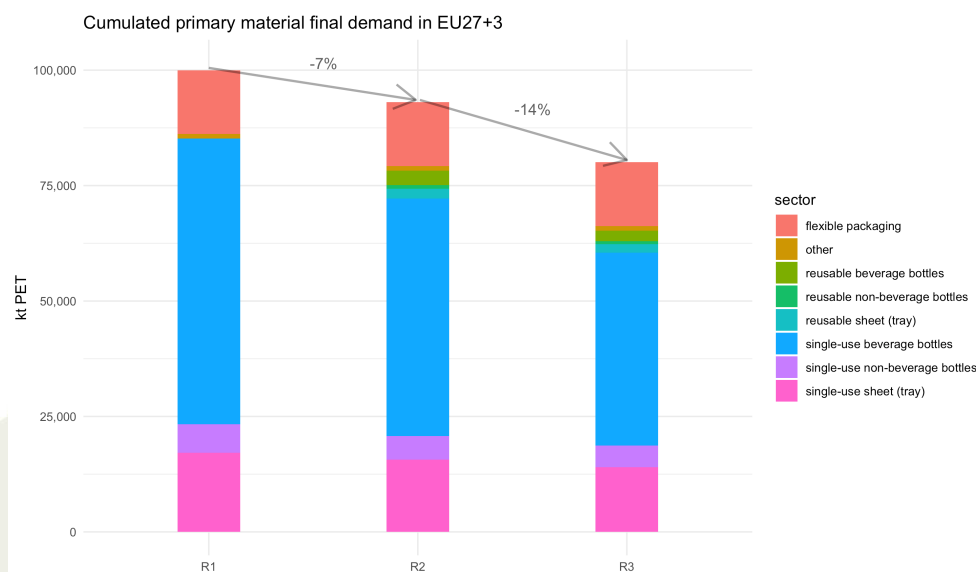


Figure 12. Cumulated final demand (2018-2050) in the EU27+3 for primary PET by type of packaging in the scenarios R1, R2, R3.

Measuring circularity

One goal of a circular economy is to relieve the pressure on primary natural resources. Another is to reduce the dependence on imports. The previous sections assess the impact of three circularity measures in PET packaging on the demand for polymers, especially virgin and recycled polymers, where it shows positive effects on the former and potential issues with the latter due to increased imports. Scenario R3, combining all three strategies, shows the best results on both aspects. Other indicators exist to assess the circularity of an economy, such as the Circular Material Use Rate (CMUR). We calculated it in R1, R2, R3 as the share of recycled and reused PET in total final PET demand. The results are shown below, and although R2 and R3 are significantly ahead of R1, scenario R3 performs slightly worse than R2 with this metric. This goes to show that such an indicator, although useful, should be complemented with the analysis of the development of absolute material flows over time.

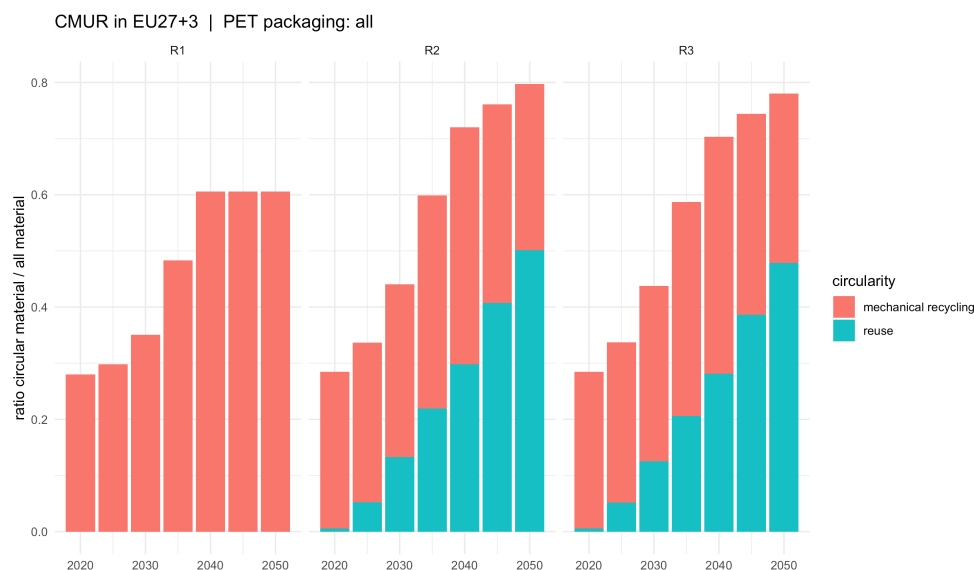


Figure 13. Circular Material Use Rate (CMUR) in final demand in the EU27+3 for PET packaging in the scenarios R1, R2, R3, showing the contributions of recycled content and reuse.

Trade flows

Passenger cars

Baseline scenario

Before turning to the circular-economy scenarios, it is worth characterising the baseline trajectory that the CE scenarios perturb. The two stages of the supply chain start from very different positions. For steel embodied in transport goods, the EU is a near-balanced, high-throughput trader: gross imports (~20.6 Mt) and gross exports (~18.6 Mt) are each almost as large as domestic demand (~20.0 Mt) and supply (~17.9 Mt) in 2022 (last year with historical data, see Figure 14 and Figure 16), so the import-to-demand and export-to-supply ratios that are kept constant across the projection both are close to one. The baseline transport-good demand projected by the EU MFA does not show a consistent trend and stays within the range of demand in recent years: it grows slightly until 2030 to 20.8 Mt, followed by a slight decline until 2040 and another period of growth to 20.4 Mt in 2050 (see Figure 15). With imports scaling with demands and an import to demand ratio of roughly one, the projected imports follow the demand curve, while exports stay nearly constant. Projected net trade in transport goods correspondingly follows the same curve, net imports stay small and within historical patterns that ranged from about –7.3 Mt (2013) to +2.4 Mt (2006).

For intermediate steel products the picture is structurally different. The EU is a persistent net importer since 2014, importing 47.2 Mt and exporting 20.7 Mt in 2022 (see Figure 14 and Figure 16), and the projection continues this pattern. Driven by a consistently rising total steel demand (from 118.7 Mt in 2022 to 150.9 Mt in 2050, due to higher projected increases in the other end-use sectors construction, machinery, and appliances), projected imports increase from 47.3 Mt in 2022 to 56.4 Mt in 2050. In difference to steel in transport goods, the import-to-demand ratio of intermediate steel products is only ~0.4, so the increase in demand is not fully absorbed by imports, but supply and therefore also exports grow, from 20.7 Mt to 29.9 Mt. In consequence, net imports are within 24-26 Mt, continuing the pronounced import dependence seen at the end of the historical record.

The contrast between the two stages — near-balanced and flat for transport goods, structurally net-importing and rising for intermediate steel products — frames the CE results that follow: it is at the intermediate steel product stage that the EU's import dependence is large and growing, yet, as shown below, this stage is barely affected by car-fleet CE measures.

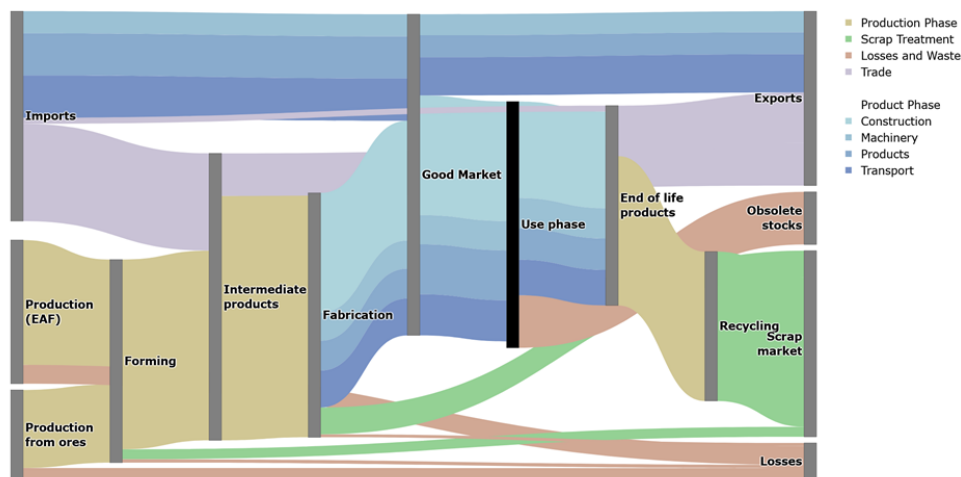


Figure 14. Sankey plot of steel flows in EU27+1 in 2022

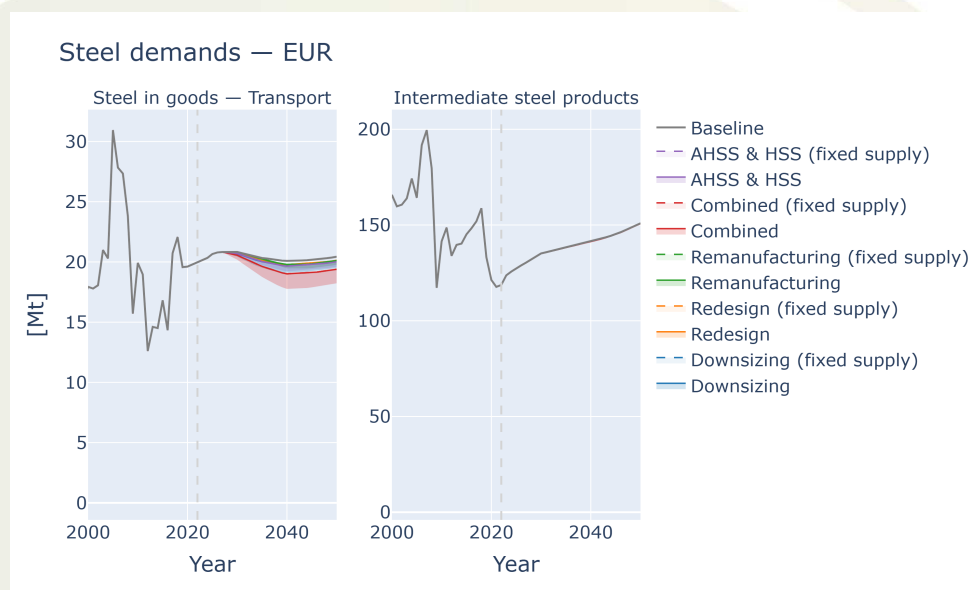


Figure 15. Demand for steel in transport goods (left panel) and intermediate steel product demand (right panel) for the baseline scenario and the CE x trade scenarios (the CE scenarios are differentiated by colour, the range of ambition of the CE scenarios is visualised by the bands, and the trade scenarios are differentiated by line style)

Effects of CE measures on trade: The CE scenarios are modelled to take effect from 2027 onward, so trade flows are identical to the baseline through the mid-2020s and diverge only after. Since the induced reduction in demand is reaching its maximum by 2040, the observed change in trade is also described for 2040.

CE measures reduce imports of transport goods, while exports stay nearly constant: Across all CE scenarios, exports of steel embodied in transport goods remain essentially unchanged from the baseline (19.4 Mt in 2040, against 19.6 Mt in the baseline), while imports fall (see Figure 16). This follows directly from the baseline trade structure: with the import-to-demand ratio close to one, a reduction in domestic transport-good demand is absorbed almost entirely by lower imports rather than by lower exports under the demand-following trade extrapolation. In the scenario with the largest demand reduction (Combined scenario with High Ambition), imports of transport goods in 2040 fall by ~2.2 Mt relative to the baseline, while exports change by only ~0.2 Mt. Because exports are nearly fixed, net imports move closely with imports, declining by ~2 Mt in 2040, and becoming a net exporter under the Combined High Ambition scenario (see Figure 17).

The effect is strongly attenuated at the intermediate steel product stage: Because CE-induced demand reduction is mostly absorbed by imports at the transport good stage, it does not propagate into the demand of intermediate steel products, which only decreases by 0.4 Mt from the baseline to the most ambitious CE scenario in 2040 (see Figure 15). This demand reduction is especially small relative to total demand of intermediate steel products (141 Mt in 2040), and since the import-to-demand ratio of ~0.4 is lower than for transport goods, the trade response at this stage is an order of magnitude smaller under the demand-following trade extrapolation. In the Combined High Ambition scenario, intermediate steel imports in 2050 fall by ~0.12 Mt and net imports by only ~0.03 Mt (see Figure 16 and Figure 17). EU net-import dependence for intermediate steel products is correspondingly unchanged at ~17% of demand with or without CE measures (see Figure 18). Set against the historical variation in EU intermediate net trade the induced change at this stage is negligible.

The domestic production protection matters only marginally upstream: Under the fixed-supply scenarios (keeping EU domestic production at its baseline trajectory) applied at the intermediate steel product stage, the small demand reduction (~0.4 Mt, Combined) is reallocated: with $\alpha=1$ (import substitution) it reduces imports by ~0.4 Mt with exports unchanged; with $\alpha=0$ (export expansion) imports are held fixed and exports rise by ~0.4 Mt (see Figure 16). However, in terms of net imports, both fixed supply scenarios yield the same result. By design, the fixed-supply (resilience-oriented) cases yield a larger reduction in net imports (~0.40 Mt) than the demand-following case (~0.03 Mt, see Figure 17), because under fixed supply the entire demand reduction is forced onto the trade balance rather than partly onto domestic production. Even so, all of these effects remain well under 1% of demand (see Figure 18).

Synthesis: CE measures in the car fleet do reduce EU steel import dependence, and they do so almost entirely by cutting imports of steel embodied in transport goods rather than by changing exports or domestic production—a direct consequence of the EU's near-balanced, high-throughput position in transport goods under the demand-following trade assumption. However, because transport is only responsible for ~12% of total steel demand and the share of steel in passenger cars is even lower, even ambitious CE measures have a very limited effect on the EU's overall steel trade position.

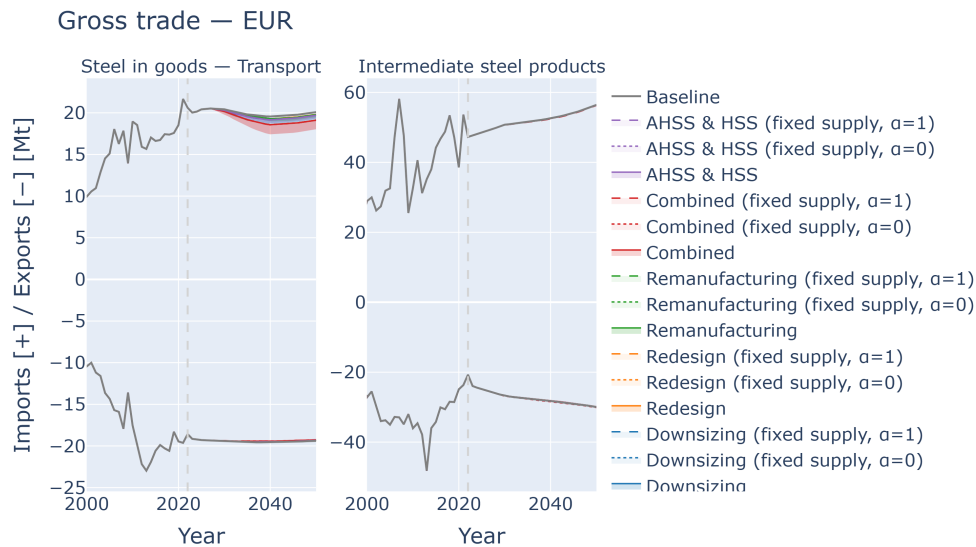


Figure 16. Trade of steel in transport goods (left panel) and intermediate steel product (right panel) for the baseline and the CE x trade scenario combinations (the CE scenarios are differentiated by colour, the range of ambition of the CE scenarios is visualised by the bands, and the trade scenarios are differentiated by line style)

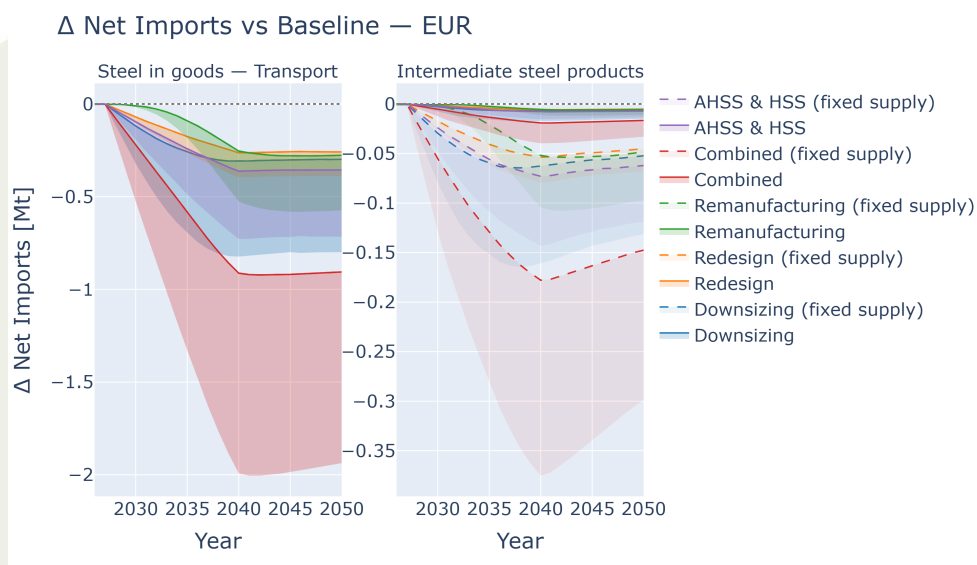


Figure 17. Delta net imports of CE scenarios compared to the baseline for steel goods in transport (left panel) and intermediate steel products (right panel) (the CE scenarios are differentiated by colour, the range of ambition of the CE scenarios is visualised by the bands, and the trade scenarios are differentiated by line style)

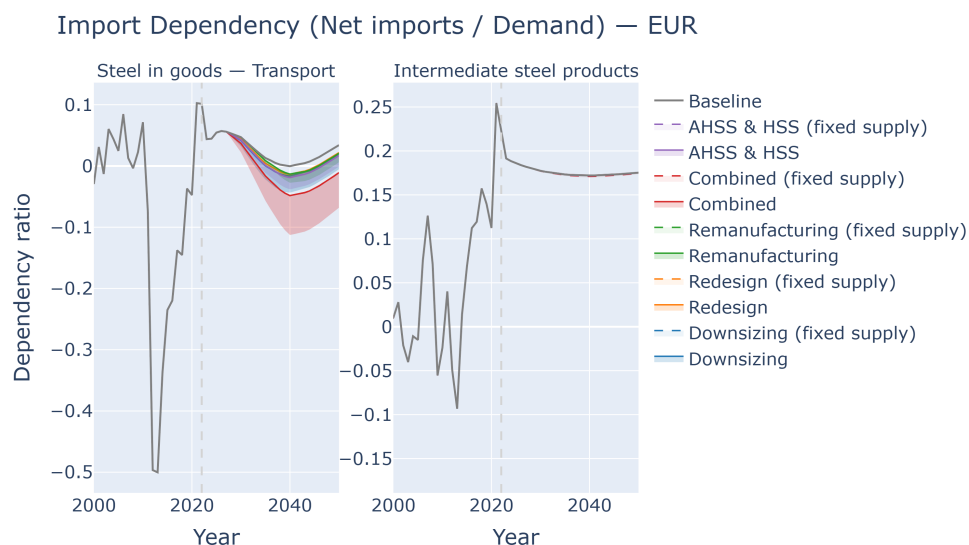


Figure 18. Net import dependency (net imports / demand) for steel goods in transport (left panel) and intermediate steel products (right panel) (the CE scenarios are differentiated by colour, the range of ambition of the CE scenarios is visualised by the bands, and the trade scenarios are differentiated by line style)

Plastics packaging

Baseline scenario (R1): The two traded stages start from very different positions. At the finished-goods stage, trade in finished PET packaging is minor relative to demand: gross imports are ~10% of EU packaging demand throughout the projection (0.54 Mt against ~5.4 Mt of demand in 2030), and because exports are of comparable size, net imports of finished packaging are only ~2-3% of demand (see Figure 19 and Figure 21). Net import dependence at the finished-goods stage is low (see Figure 23).

The EU's import dependence is concentrated upstream, at the primary/polymer stage. The EU is a persistent net importer of PET in primary forms, with gross primary imports of ~25% of total PET demand (1.32 Mt in 2030, rising to 1.60 Mt in 2050 as demand grows) against much smaller exports (~0.17–0.22 Mt, see Figure 21). Net primary imports rise from ~1.14 Mt in 2030 to ~1.38 Mt in 2050, a net import dependence of ~20–21% of demand that persists across the projection (see Figure 23). As with intermediate steel products, it is the upstream stage at which structural import dependence is located, and therefore the stage at which CE measures could in principle reduce it.

In contrast to steel, where the case-study sector (transport) is a minor share of total demand, PET in the EU is almost entirely a packaging polymer: across the projection, packaging accounts for ~99% of EU PET demand (see Figure 20). The plastics CE measures therefore act on essentially the entire PET system rather than on a small sub-sector, and CE effects on upstream PET trade are correspondingly more material than the analogous car-fleet effects were for steel.

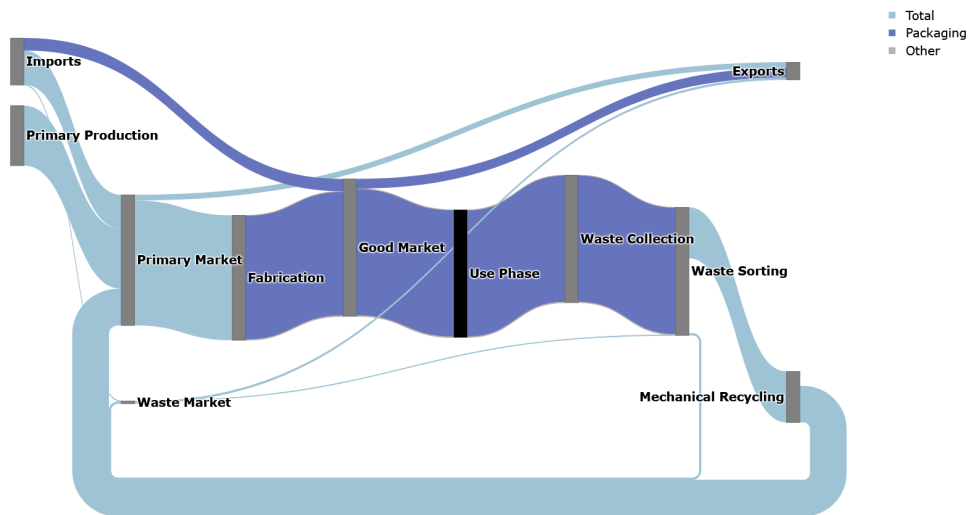


Figure 19. Sankey plot of PET flows in EU27+3 in 2019

PET demands — EU27+3

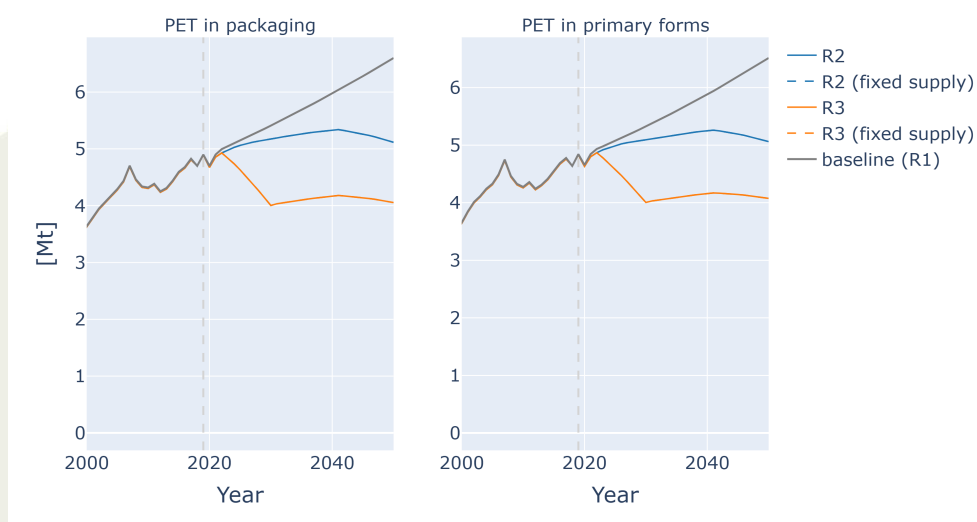


Figure 20. Demand for PET in packaging (left panel) and PET in primary forms demand (right panel) for the baseline scenario and the CE x trade scenarios (the CE scenarios are differentiated by colour, and the trade scenarios are differentiated by line style)

Effect of CE measures on trade: Both CE scenarios reduce PET demand on a sustained basis, but to differing degrees. The reuse scenario (R2) lowers EU PET packaging demand relative to the baseline throughout the projection, with the gap widening over time (−0.24 Mt, ~4%, in 2030; −1.48 Mt, ~22%, in 2050, see Figure 20). The combined reuse-and-lightweighting scenario (R3) reduces demand more strongly and earlier (−1.40 Mt, ~26%, in 2030; −2.55 Mt, ~39%, in 2050), as lightweighting compounds the reuse effect.

Under demand-following trade, CE measures leave net import dependence essentially unchanged. Because the reduction in EU demand is passed to the demand-driven extrapolator, it contracts imports and domestic production roughly in proportion to their incumbent shares — and, in contrast to the transport-good stage in steel, exports here are not retained but fall as well, because the domestic supply that underpins them declines together with demand. As a result, net primary import dependence remains close to the baseline share (~21% of demand, see Figure 23) in all scenarios under the demand-following rule, since both sides of the trade balance move together; in absolute terms net primary imports do fall (e.g. R3: ~0.86 Mt in 2050 against ~1.38 Mt in the baseline, see Figure 22), but this reflects lower total throughput rather than a structural reduction in dependence. This is the converse of the steel transport-good result: there, a near-unity import-to-demand ratio meant demand cuts fell almost entirely on imports and improved the net balance; here, the demand cut is shared between imports and domestic supply, leaving the dependence ratio flat.

A reduction in net import dependence appears only under the fixed-supply scenarios. When baseline domestic production is defended (fixed supply), the entire CE-induced demand reduction is forced onto the trade balance and net import dependence falls markedly, and — because both CE scenarios now reduce demand on a sustained and widening basis — the improvement persists and grows to 2050. Under R2 with fixed supply, net primary imports fall from ~1.14 Mt in the baseline to ~0.90 Mt in 2030 and approach balance by 2050 (≈ -0.07 Mt, i.e. the EU becomes a marginal net exporter, see Figure 22). Under R3 with fixed supply the effect is larger: the EU becomes a net exporter of primary PET already around 2030 (net primary imports of ≈ -0.18 Mt, against +1.14 Mt in the baseline) and the net-export position widens to ~1.05 Mt by 2050. The two import-adjustment endpoints ($\alpha = 0$ export expansion, $\alpha = 1$ import substitution) give the same net-import outcomes, as in the steel case, since the net balance is governed by the demand delta rather than by how it is split between imports and exports.

Synthesis: Plastics packaging CE measures act on almost the whole PET system, so their potential to influence EU PET trade is structurally larger than the car-fleet effect on steel. But their realised effect on import dependence is conditional on the trade assumption. Both reuse (R2) and combined reuse-and-lightweighting (R3) reduce PET demand on a sustained basis, with R3 roughly twice as strong by 2050. Under demand-following trade, however, this lowers imports and domestic supply together, leaving the net import dependence ratio close to its baseline level; a structural reduction in dependence — up to the EU turning net exporter of primary PET under R3 — materialises only if domestic primary production is defended (fixed supply). The headline resilience gain is therefore real and, with the corrected demand trajectories, durable to 2050, but it is contingent on the strategic-autonomy (fixed-supply) framing rather than on the demand reduction alone.

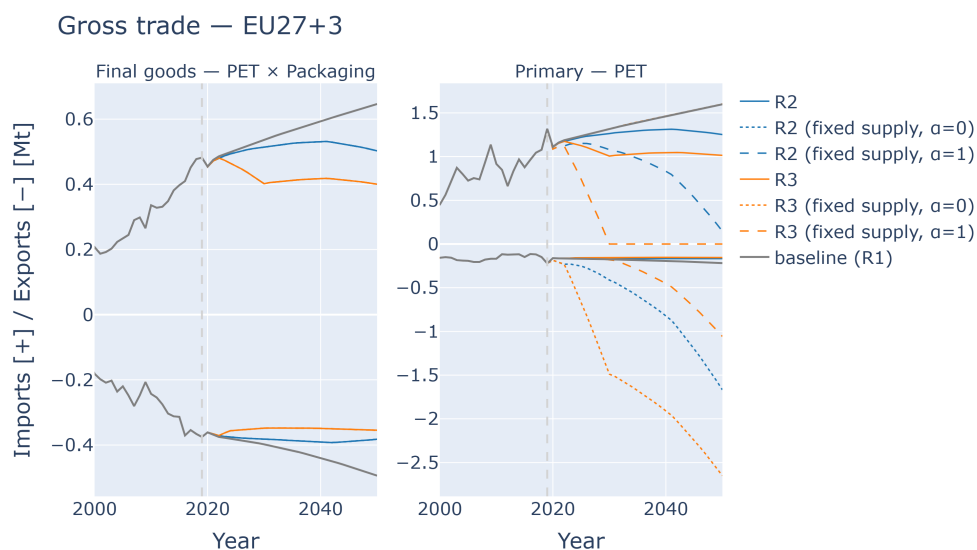


Figure 21. Trade of PET in packaging (left panel) and PET in primary forms (right panel) for the baseline and the CE x trade scenario combinations (the CE scenarios are differentiated by colour, and the trade scenarios are differentiated by line style)

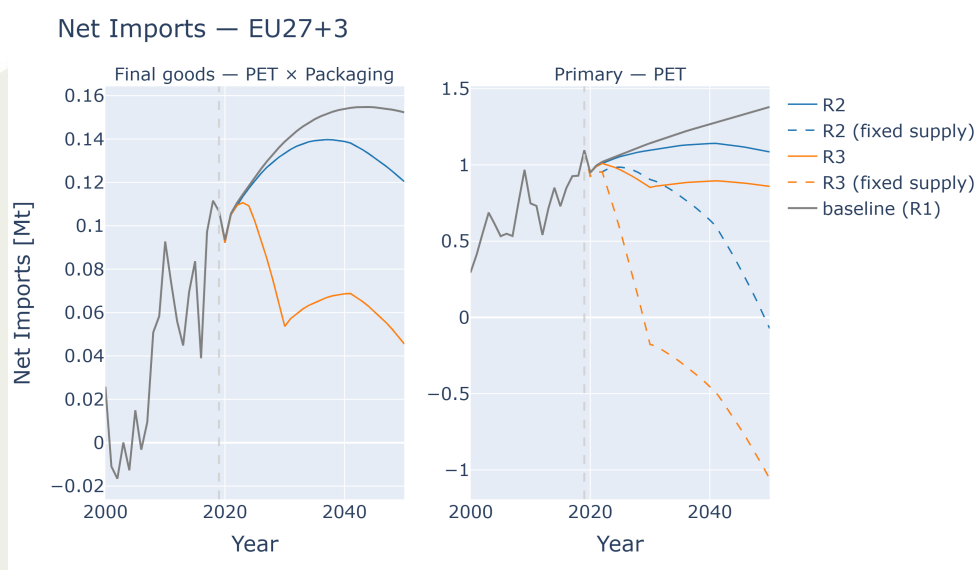


Figure 22. Net imports of CE scenarios and the baseline for PET in packaging (left panel) and PET in primary forms (right panel) (the CE scenarios are differentiated by colour, and the trade scenarios are differentiated by line style)

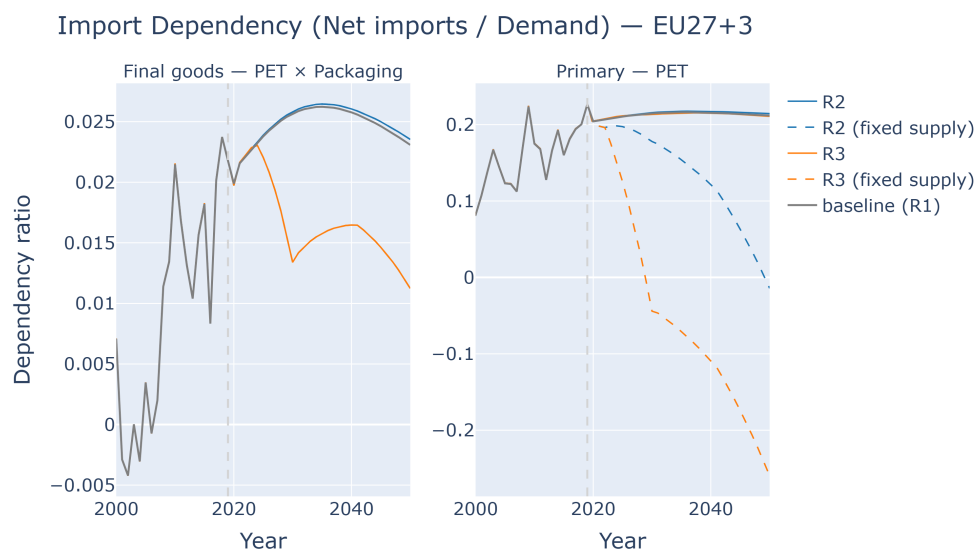


Figure 23. Net import dependency (net imports / demand) for PET in packaging (left panel) and PET in primary forms (right panel) (the CE scenarios are differentiated by colour, and the trade scenarios are differentiated by line style)

Limitation: The trade model does not differentiate recycle from virgin polymer; both are traded in the same primary-material market, because the underlying Comtrade data do not separate them. As a consequence, the trade scenarios cannot depict changes in trade arising specifically from demand for recycled polymer — that is, the trade response to recycled-content targets is not represented within the modelled primary flows.

The EU MFA module does, however, compute the EU's recycle import needs (or the recycle surplus available for export) directly. These results show the EU becoming a net importer of recycle under all scenarios from the mid-2030s onward (around 2035 in the baseline, 2033–2034 in the CE scenarios), as recycled-content targets raise recycle demand faster than domestic recycle supply expands, reaching net recycle imports of ~0.79 Mt (baseline R1), ~0.83 Mt (R2) and ~0.72 Mt (R3) by 2050. This is an important additional consideration for the resilience and import-dependence reading: meeting recycled-content targets is itself a source of material-import dependence that the primary-trade scenarios, which are driven by total demand rather than by recycle demand specifically, do not capture.

This recycle import need also limits the feasibility of the import-substitution fixed-supply scenarios ($\alpha = 1$). In those scenarios the full CE demand reduction is forced onto imports while domestic production is held fixed, driving modelled primary PET imports to zero from 2033 in R3 and to ~0.15 Mt by 2050 in R2. But because the recycle import need is not separable from primary trade, total PET imports cannot in reality fall below the level required to import the necessary recycle: the recycle import need exceeds total modelled primary imports from 2033 in R3 and 2041 in R2 (see Figure 24). The $\alpha = 1$ case is therefore best read as an idealised upper bound on import substitution that becomes infeasible once recycled-content requirements are accounted for, unless domestic recycle capacity (collection, sorting, reprocessing) is scaled up in step. The $\alpha = 0$ (export-expansion) endpoint does not show this conflict.

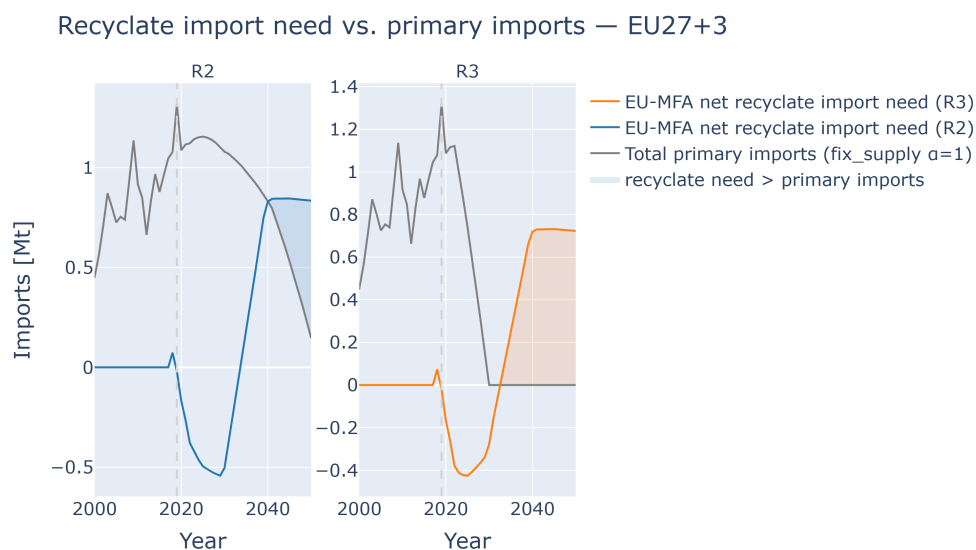


Figure 24. Comparison of total primary imports modelled by REMIND-MFA under the fixed supply assumption for $\alpha = 1$ (demand reduction is directly translated into import reduction) and net-recyclate import need modelled by EU MFA for scenario S1 (left panel) and S2 (right panel). The shaded area highlights where the recyclate import need exceeds modelled primary imports (trade scenario not feasible)

Discussion

The results of this study provide insights into the extent to which CE strategies, particularly material efficiency and reuse, contribute to changes in EU trade flows and, consequently, to industrial resilience. Overall, the findings suggest that while circularity measures (focused on passenger cars and packaging) do affect trade flows, their impact on import reliance remains limited and highly context-dependent, particularly regarding the sectoral scope, and the underlying trade assumptions.

The analysis of passenger cars shows that CE measures reduce EU steel demand and, consequently, imports of steel in transport goods, while exports remain largely unchanged. However, the contribution of passenger cars to total steel demand is limited. Consequently, circularity strategies in this single sector are insufficient to substantially change overall trade dependence. Extending circular economy measures across the wider automotive sector or across multiple steel use sectors would be required for more systemic effects on EU resilience and trade balance. Nevertheless, the findings show the potential of higher R strategies for contributing to EU resilience by directly reducing material demand. Previous studies investigating the impact of CE strategies on primary steel demand have mostly focused on increasing recycling rates and found that these may lead to increased exports of scrap rather than substitution of primary steel due to quality constraints and current trade patterns (Fellner et al., 2018; Pauliuk et al., 2017).

While the CE measures for PET plastics packaging affect a large share of total PET demand, their impact on EU trade flows depends strongly on the assumed impact on domestic production. Both, reuse and material efficiency lead to demand reductions, whereas combined strategies have a greater impact. However, reductions in imports only emerge under the assumption that domestic production is maintained. Moreover, the results point to important interdependencies within the material system. Increased demand for recyclates related to recycled-content targets exceed domestic supply, leading to additional import requirements for secondary materials. This implies that CE strategies for plastics packaging may shift rather than reduce import dependencies if secondary material availability is not expanded at the same time.

Alternatively (but not modelled here) the pressure on high-quality recycle availability may drive investments in chemical recycling if cheap imports are not an option.

More generally, the analysis suggests that resilience implications of CE strategies depend on where in the value chain they are implemented. Traditional resilience assessments often focus on upstream dependencies, such as imports of primary resources (Maury et al., 2025). In contrast, the present study shows that downstream measures may have limited leverage on these dependencies unless they affect a substantial share of total demand for materials and industrial goods. This highlights the importance of combining demand-side CE measures with upstream interventions, such as increased recycling.

Finally, several limitations of the study need to be considered when interpreting the results. First, the analysis focuses on material efficiency and reuse for a limited set of products, which constrains the extent to which conclusions can be generalised to the entire EU economy. However, the method described can also be extended to other products and circularity strategies. Second, the analysis is based on physical material and trade flows. Thus, the study does not explicitly account for energy use or emissions, which are also relevant in the context of industrial resilience. Moreover, the study does not incorporate economic mechanisms and, consequently, the trade scenarios represent normative boundary assumptions rather than behavioural and price-driven outcomes. However, the presented modelling approaches allow for linking with other models (especially macroeconomic models), which can capture such effects. Third, the analysis is subject to uncertainties inherent to scenario modelling, including assumptions on technology adoption, policy implementation, and future demand trajectories. In this context, validating scenarios with stakeholders can strengthen the significance of the results. Overall, this highlights the need for further integration of perspectives to assess the impact of circularity on industrial resilience.

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4 The Rhine-Ruhr Case Study: Which effect can circularity strategies have on resilience and competitiveness of EU chemical industries?

Introduction

The Rhine-Ruhr region hosts one of Europe's largest and most important chemical industry clusters, accounting for a substantial share of German and European refining, petrochemical, and chemical production. The cluster forms a key component of the integrated Northwestern European chemical network. As such, the Rhine-Ruhr cluster represents a strategically important case for studying the future competitiveness and decarbonisation of the European chemical industry.

Various studies have examined alternative pathways for the transition of the Rhine-Ruhr chemical cluster, including circular carbon systems, renewable carbon feedstocks, and carbon capture and storage. However, significant uncertainties remain regarding the economic implications of these pathways and their potential contribution to the long-term resilience and competitiveness of the European chemical industry. In particular, the role of circularity strategies and advanced recycling technologies remains insufficiently understood from both an economic and energy-system perspective.

Against this background, this case study investigates how circularity strategies can contribute to strengthening the competitiveness and resilience of the European chemical sector, using the Rhine-Ruhr chemical cluster as a representative industrial case. To address this question, the study combines the OPEN-GEM computable general equilibrium model with the OPEN-PROM energy system model. The primary objective is not only to assess the impacts of circular economy measures, but also to evaluate the suitability of the linked modelling framework for analysing industrial circularity pathways and identifying relevant methodological gaps.

Context of the Rhine-Ruhr region chemical industry clusters

Within the Rhine-Ruhr region, the chemical industry is the most important industrial employer. In 2023 employment in the petroleum refining (C19 sector in Eurostat sectoral classification) and chemicals and chemical products (C20) categories amounted to 79.000 people, representing just above 12% of all manufacturing jobs in the region and nearly 20% of the sectors' workforce across Germany and 6.6% across the EU. The region's chemical industry is also highly diversified with 621 active companies (Eurostat, 2026).

In terms of infrastructure, the region is highly integrated with the chemical industry clusters of Rotterdam and Antwerp. Feedstocks are imported mainly through a dense network of pipelines connecting the three regions. The Rhine-Ruhr cluster imports crude oil, naphtha as well as ethylene and propylene. About 162.000 barrels of crude oil per day is processed in the Rhine-Ruhr Refinery (operated by Shell) in Köln-Godorf (A Barrel Full, 2015). A second distillation plant with similar size in the adjacent Wesseling site was recently retired and is currently being decommissioned. However, the Naphtha provided by the refinery covers less than a third of the demand of region's five steam crackers (Scholz et al. 2023) with a combined capacity of 2505 kt of ethylene production per annum (Göbler et al. 2026). Two of the crackers are operated by Ineos (1155 kt ethylene p.a.) in the North of Cologne, and three are located in Wessling just South of Cologne – two by LyondellBasell (1040 kt p.a.) and a smaller one (310 kt p.a.) operated by Shell. The total primary energy consumption of the cluster amounts to 100TWh per annum, by far the largest of all chemical clusters

in Germany (Scholz et al. 2023).

Several studies exist to develop a roadmap for the decarbonisation and defossilisation of the industrial cluster (Göbler et al 2026, Scholz et al. 2025) and some companies have started to take initial transformative investments – Shell building a 100MW electrolyser (Shell Deutschland, 20226), LYB building a first of a kind 50 kt/a industrial demonstrator plants for chemical recycling (LyondellBasell, 2026). However, the current economic outlook is challenging for the entire European chemical industry. Due to global overcapacities, the European chemical industry is operating at ~70% utilisation rates which is significantly less than the long term average and, importantly, too little to operate profitably (Cefic and Advancy, 2025, Göbler et al 2026). What is more, due to the dramatic increasing energy cost across Europe after Russia's invasion of Ukraine and the recent USA-Iran war, the European steam crackers face a dramatic cost disadvantage compared to competitors from the US and Gulf Countries (Selting and Carratta 2025). Finally, Chinese chemical companies have dramatically increased their global market shares and are increasingly competing not only on commodity markets but also with respect to specialty chemicals in which European companies had traditionally an advantage (Göbel et al. 2026).

In terms of decarbonisation strategies there is not yet a clear pathway ahead. Scholz et al (2025) juxtapose two scenarios. The “Carbon Looping” scenario emphasises circularity by closing carbon cycles at the European level. This requires a massive build-up of renewable energy and storage capacity. The “Open Carbon Economy” scenario relies on a liquid global market for green methanol as a new platform chemical. This minimises demand for renewable energy in Europe but comes at the expense of relocating important parts of value creation outside of Europe. Meanwhile, Göbel et al. (2026) see the most economically viable option for decarbonisation in the large-scale utilisation of Carbon Capture and Storage.

Case study implementation

Against this background, this report analyses which effect circularity strategies can have on strengthening the competitiveness and resilience of EU chemicals industries (research question). Unlike the various studies cited above, we do so by employing a macroeconomic computational general equilibrium model (OPEN-GEM) and a linked energy system model (OPEN-PROM) to explore the impacts of alternative CE measures in the chemicals industry. The purpose of this study, however, is first and foremost to test and validate the applicability of the two models to the corresponding research question.

In particular, circularity strategies in this context refer to a set of interventions aimed at reducing primary resource use and increasing the retention of materials within the European industrial system. These include increased material efficiency, product lifetime extension, reuse systems, substitution of virgin feedstocks with secondary materials, and most centrally for this analysis, recycling of plastics. In the hierarchy of circularity strategies, mechanical recycling represents the thermodynamic and environmental priority for polymer waste management due to its minimal additional energy requirements. By physically processing plastic waste back into pellets without breaking down the polymer chains, this pathway preserves the energy embedded in the initial material synthesis. However, the potential of mechanical recycling is severely constrained on both the supply and demand sides. On the supply side, heterogeneous and heavily contaminated post-consumer plastic streams are difficult to separate, while specific polymers cannot technically be recycled mechanically due to degradation during processing or inherent chemical characteristics. Coloring, additives, and degradation of polymer properties over successive loops render mechanical recycling of mixed municipal waste economically unviable in many instances. On the demand side, downcycled plastic properties often fail to meet high-performance industrial standards. Most critically,

strict hygiene and safety standards for contact-sensitive materials—such as those in the food packaging and medical sectors—generally disqualify mechanically recycled plastics to eliminate any risk of contamination from previous use cycles, leaving these sectors reliant on virgin-like feedstock purity.

Because of these physical and regulatory boundaries, mechanical recycling alone is insufficient to meet the ambitious circularity and defossilisation targets established for heavy industrial clusters like the Rhine-Ruhr. Chemical recycling is necessary to close this circularity gap by breaking plastic waste down into its chemical constituents, which can then substitute fossil-based inputs in a steam cracker. However, to date, no technologies for chemical recycling are commercially available. Pyrolysis is currently the most advanced technology with a technological readiness level (TRL) of 6–8, with several industrial-scale demonstrators currently under construction and close to completion. Yet, this molecular deconstruction carries a heavy thermodynamic penalty. Producing high-value chemicals (HVCs) from chemically recycled pyrolysis oil is projected to require approximately 2.5 times the primary energy input compared to processing conventional fossil naphtha. This massive energy demand raises significant concerns regarding the long-term economic viability and operating expenditures (OPEX) of chemical recycling pathways.

Stakeholder Insights

During regional stakeholder workshops in the Rhine-Ruhr, local industry representatives expressed skepticism, noting that the business case for chemical recycling remains highly speculative especially due to the low TRL level, unless dedicated market demand is created by corresponding regulation. A key uncertainty raised by these stakeholders was the dynamic relationship between volatile global oil prices and circular feedstock costs: specifically, whether rising crude oil prices would eventually make costly chemical recycling pathways cost-competitive, or if the concurrent rise in energy prices would keep chemical recycling prohibitively expensive.

Model limitations

Quantifying these economic dynamics is vital for regional policy design and industrial investment strategy, yet the analytical tools currently available to researchers are structurally inadequate for the task. During our validation study of the quantitative framework, we discovered that the OPEN-GEM model and its underlying GTAP circularity database do not represent chemical recycling pathways at all. Consequently, the model cannot represent changing energy consumption patterns associated with scale-up of chemical recycling or the capital expenditures required. This means that the current modeling framework is completely blind to the competitiveness implications, trade-flow reconfigurations, and wider socio-economic impacts of scaling up chemical recycling within the Rhine-Ruhr chemical cluster. To support robust policy decisions within the TRANSIENCE project, this structural gap must be transparently addressed and for this reason chemical recycling should be included as a separate sector in the model.

Method and data

To assess the implications of circularity strategies for the competitiveness and decarbonisation of the European chemical industry, this study combines economic and energy-system modelling perspectives. In particular, the analysis focuses on the role of chemical recycling in the Rhine-Ruhr chemical cluster. Addressing this question requires an analytical framework capable of capturing both the economy-wide effects of changes in industrial production and trade patterns, as well as the associated impacts on energy demand, supply, investment, prices, and emissions.

For this purpose, the study employs the OPEN-GEM computable general equilibrium model and the OPEN-PROM energy system model. Particular emphasis is given to the treatment of recycling pathways within the modelling framework, as the current GTAP-CE database represents mechanical recycling but does not explicitly account for chemical recycling technologies. The following section describes the two models, outlines the proposed representation of chemical recycling as a dedicated economic sector, explains the soft-linking approach between the models, and presents the scenarios considered in the analysis.

OPEN-GEM

OPEN-GEM is a computable general equilibrium (CGE) framework based on the GTAP-CE database and documented in Deliverable D4.1. It represents the global economy in monetary terms and captures intersectoral production, consumption, and trade linkages across regions, with particular emphasis on energy-intensive and industrial value chains. The model is designed to assess how structural changes in production technologies and input use propagate through the economy, enabling the analysis of policy-relevant scenarios with a focus on macroeconomic performance, sectoral competitiveness, and international trade effects.

In the current GTAP-CE database (as used in OPEN-GEM), recycling is the main, and in practice the only explicitly represented, circular economy strategy that directly operationalises material circularity in the plastics sector. The framework captures circularity primarily through the reintroduction of post-use plastic waste into production as secondary material, thereby reducing the demand for virgin, fossil-based plastic production. Other circular economy strategies such as product redesign, reuse systems, demand reduction, or material substitution are not explicitly modelled as separate behavioural or technological options but may only be reflected indirectly through changes in demand or cost structures.

In general terms, recycling can be distinguished into mechanical recycling and chemical recycling, which have different implications for decarbonisation. Mechanical recycling involves the physical collection, sorting, and reprocessing of plastic waste into secondary polymers, typically requiring relatively lower energy input and directly displacing virgin plastic production, thereby reducing upstream petrochemical emissions. Chemical recycling, by contrast, breaks plastics down into monomers or hydrocarbon fuels through thermochemical or chemical processes, and its climate benefit depends strongly on energy intensity, process efficiency, and whether it displaces virgin feedstock or instead substitutes fossil fuels in energy use. In its current form, GTAP-CE represents only mechanical recycling, meaning circularity is captured through direct material substitution of virgin plastics with reprocessed secondary plastics, while chemical recycling pathways are not explicitly distinguished or modelled as a separate technology.

The transition towards a circular plastics economy is creating new industrial pathways that cannot be adequately represented through traditional recycling sectors. While mechanical recycling remains the dominant recycling route for high-quality and homogeneous plastic waste streams, it is unable to process a large share of post-consumer plastics such as multilayer films, flexible packaging, mixed plastics, and contaminated waste streams. Chemical recycling, particularly plastic pyrolysis, has emerged as a complementary technology capable of converting such waste into valuable hydrocarbon feedstocks.

The principal product of plastic pyrolysis is pyrolysis oil, which can be upgraded and used as a substitute for fossil-derived naphtha in steam crackers and petrochemical production. As a result, pyrolysis establishes a direct economic link between plastic waste management and the petrochemical value chain. This connection creates new interactions between waste markets, energy markets, refining activities, and plastics production

that are not captured in existing representations of mechanical recycling.

For this reason, chemical recycling should be represented as a dedicated industrial sector within General Equilibrium models.

Why Mechanical and Chemical Recycling Must Be Treated Separately

Although both technologies are classified as recycling activities, they produce fundamentally different outputs and follow different steps and processes (see Figures below). Mechanical recycling has as output recycled polymers and secondary plastic products with main competing sectors the primary vs secondary plastic products. Chemical recycling has as output pyrolysis oil, fuel gases, and hydrocarbon feedstocks with main competing sectors the oil, petrochemical feedstocks, and the virgin naphtha. Thus, mechanical recycling substitutes plastic materials directly, whereas chemical recycling substitutes petroleum-derived feedstocks. These are economically and technologically distinct activities.

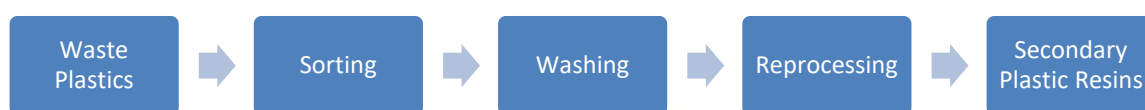


Figure 25. Mechanical Recycling



Figure 26. Chemical Recycling (Pyrolysis)

Pyrolysis Oil Creates a New Intermediate Commodity

The strongest argument for introducing a dedicated Chemical Recycling sector is the emergence of pyrolysis oil as a new commodity. Pyrolysis oil does not behave like secondary plastic resin, waste treatment services, and conventional recycled materials. Instead, it behaves like a liquid hydrocarbon feedstock that can enter existing refinery and petrochemical systems. After upgrading, pyrolysis oil may partially replace fossil naphtha used in steam crackers to produce ethylene and propylene. In a General Equilibrium framework, this introduces a new substitution relationship between fossil naphtha and pyrolysis oil which affects: Crude oil demand, Refinery output, Petrochemical production, Plastic production costs, Circular economy deployment. Without explicit representation, these substitution effects cannot be quantified.

OPEN-GEM Representation of Chemical Recycling

The key modelling innovation is the introduction of Chemical Recycling process as a separate commodity that can substitute petrochemicals that are used as intermediate product in the primary plastics sector. To investigate the role of circularity strategies in strengthening the resilience and competitiveness of German industry, the OPEN-GEM modelling framework was extended to explicitly represent chemical recycling within the plastics value chain. The new module introduces chemical recycling as a distinct industrial activity producing secondary chemical feedstocks that can substitute conventional fossil-based chemical intermediates in plastics manufacturing. A new sector is added to the OPEN-GEM: [IND36] - Chemical Recycling. The production structure and the demand structure should be defined for the technical representation of the sector. The modelling framework assumes that chemically recycled feedstocks are

produced domestically within Germany and compete directly with conventional chemical products supplied by the existing chemical industry. Consequently, chemical recycling not only affects the plastics sector but also influences upstream chemical production, capital allocation, trade flows, and production costs throughout the German economy. The introduction of this new sector makes it possible to evaluate the economy-wide and trade/ competitiveness implications of increased circularity and reduced dependence on virgin fossil-based feedstocks. Special attention is given to the interaction between chemical recycling and the primary plastics sector, as well as to the implications for industrial competitiveness under different assumptions regarding investment levels and oil prices.

OPEN-PROM

OPEN-PROM (Baka et al., 2026) is a global, open-source energy system simulation model based on the PROMETHEUS modelling framework and documented in Deliverable D4.6 of TRANSCIENCE (OPEN-PROM). The model simulates the evolution of energy demand, energy supply, technology deployment, and emissions under alternative socioeconomic, technological, and policy assumptions. As a recursive dynamic model, it represents year-by-year developments in the energy system while accounting for path dependencies and transition dynamics. In the context of this case study, OPEN-PROM receives key macroeconomic drivers from OPEN-GEM, including GDP, population, and sectoral industrial activity levels, which provide the socioeconomic context for projecting future energy demand and industrial development pathways.

OPEN-PROM provides a detailed representation of energy demand across industry, transport, and residential sectors, as well as energy supply, power generation, and fuel transformation technologies. The model explicitly captures interactions between energy consumption, fuel use, industrial production, and technology adoption, making it suitable for analysing industrial decarbonisation pathways, resource efficiency measures, energy transitions, and climate policy scenarios at both the European and global levels.

Particular attention is given to industrial energy use and the consumption of energy products as fuels and feedstocks in energy-intensive sectors. This allows the model to assess the implications of changes in industrial processes, fuel substitution, and circular economy strategies that affect energy demand and the use of fossil-based energy carriers. In this context, the model can be adapted to represent the introduction of secondary feedstocks that are classified as energy products, together with the associated energy requirements of recycling technologies, enabling the evaluation of their contribution to decarbonisation and reduced dependence on virgin fossil resources.

OPEN PROM Representation of Chemical Recycling

To investigate the role of chemical recycling in reducing fossil feedstock demand within the plastics value chain, the OPEN-PROM modelling framework was adapted to represent the use of plastic-waste-derived pyrolysis oil in petrochemical production. Chemical recycling is reflected through adjustments to existing feedstock and energy balances, allowing the model to capture its implications for resource use and energy consumption.

The representation focuses on the petrochemical sector, where naphtha serves as the primary feedstock for the production of chemical intermediates used in plastics manufacturing. The introduction of chemical recycling is modelled through the substitution of a share of the naphtha input with pyrolysis oil derived from plastic waste, reflecting the use of recycled feedstocks in steam crackers and petrochemical production pathways (Erkmen et al. 2023). In addition, the model accounts for the energy requirements associated with

the production of pyrolysis oil. The conversion of plastic waste into secondary feedstocks through pyrolysis requires additional electricity inputs, which are represented through an increase in the own energy consumption of the liquids sector. The additional electricity demand is assumed to be 0.023 Mtoe per Mtoe of pyrolysis oil produced, based on Stallkamp et al. (2024). This value is broadly consistent with current pyrolysis technologies, where a significant share of the process energy demand is satisfied internally through the combustion of process off-gases. The assumed electricity consumption therefore represents net external electricity demand, after accounting for process energy that is internally recovered from pyrolysis gases and other by-products. However, energy requirements can vary considerably across chemical recycling pathways and plant configurations. The selected parameter should therefore be interpreted as a stylised representation of a commercially relevant pyrolysis route rather than a universal characteristic of chemical recycling technologies.

This representation enables the assessment of how chemical recycling influences feedstock consumption, industrial energy demand, energy prices, and reliance on virgin fossil resources under alternative technology, market, and policy scenarios.

OPEN-GEM and OPEN-PROM soft link

The case study tests the applicability of two MIC3 components, OPEN-GEM and OPEN-PROM, to assess the competitiveness, resilience, and energy-system implications of chemical recycling. OPEN-GEM is used to evaluate the macroeconomic, trade, and competitiveness effects of introducing chemical recycling as a dedicated industrial sector, while OPEN-PROM assesses the implications for feedstock use, industrial energy demand, supply, prices and emissions. The models are linked through a baseline soft-link, as presented in Figure 27, whereby sectoral activity growth rates from OPEN-GEM are used to calibrate the reference energy-demand trajectory in OPEN-PROM ensuring consistency of energy system developments with socioeconomic evolution. Alternative circularity and oil-price scenarios are then explored within each modelling framework using harmonised assumptions on feedstock substitution and market conditions.

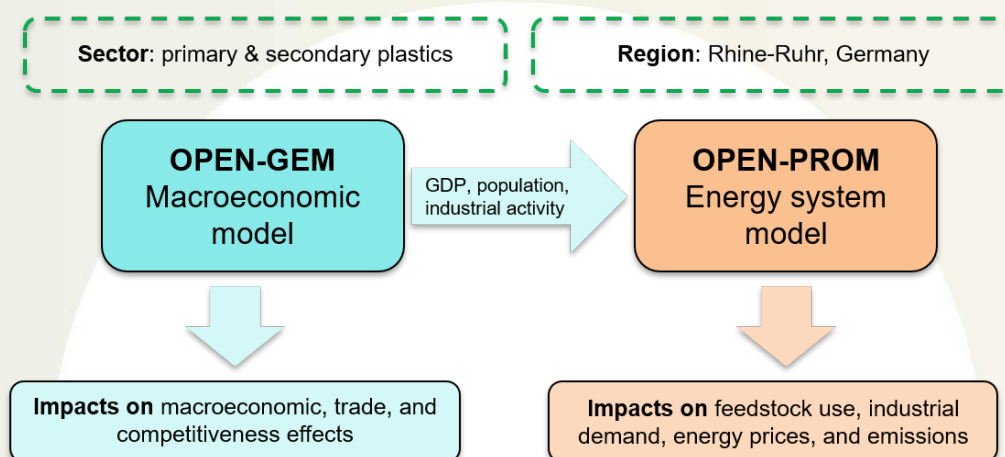


Figure 27. Schematic representation of OPEN-GEM and OPEN-PROM soft link

In the context of MIC3, this relationship will be bidirectional. Fuel mix, carbon prices, GHG targets, and emissions intensity will feed back into the OPEN-GEM macroeconomic framework, influencing production costs, competitiveness, investment decisions, and structural economic change. This integrated approach ensures that industrial transformation pathways are evaluated within realistic economic and energy system constraints, capturing the dynamic interactions between technological, energy, and macroeconomic developments.

Scenario Narratives & Results

To validate the applicability of the OPEN-GEM and OPEN-PROM modules for assessing the resilience, competitiveness, and decarbonisation implications of chemical recycling, dedicated scenarios were developed within each modelling framework. The following sections describe the respective scenario narratives and the main results from the modelling exercises.

OPEN-GEM

A baseline and four alternative scenarios were developed to assess the competitiveness and resilience implications of chemical recycling for German industries.

Baseline Scenario (Business-as-Usual)

The baseline assumes that no chemically recycled feedstocks are used in the production of primary plastics. The German plastics industry continues to rely exclusively on conventional chemical intermediates derived from fossil-based feedstocks. This scenario provides the reference against which all circularity scenarios are evaluated.

Circularity and High Oil price scenarios

In all circularity scenarios (Variants 1, 2, and 4, 5), chemically recycled feedstocks replace 50% of conventional chemical inputs used in the production process of primary plastics in the period 2030 - 2050. The high oil price scenario (Variant 3) is simulated for comparison purposes.

- **Variant 1 – CHM_REC** Chemical Recycling – No Additional Investment – Reference Oil Price
 - o 50% substitution of conventional chemicals by chemically recycled feedstocks. No additional investment in productive capacity.
 - o Oil prices remain at baseline levels.
- **Variant 2 – CHM_REC_INV** Chemical Recycling – Additional Investment – Reference Oil Price
 - o 50% substitution of conventional chemicals by chemically recycled feedstocks.
 - o Additional investment expands productive capacity in Germany.
 - o Oil prices remain at baseline levels.
- **Variant 3 – BASE_OIL** High Oil Price
 - o Oil prices are doubled relative to the baseline²

² A stylised sensitivity case in which oil prices are doubled relative to the baseline; intended for demonstration purposes rather than as a realistic projection.

- **Variant 4 – CHM_REC_OIL Chemical Recycling – No Additional Investment – High Oil Price**
 - o 50% substitution of conventional chemicals by chemically recycled feedstocks.
 - o No additional investment in productive capacity.
 - o Oil prices are doubled relative to the baseline.
- **Variant 5 – CHM_REC_INV_OIL: Chemical Recycling – Additional Investment – High Oil Price**
 - o 50% substitution of conventional chemicals by chemically recycled feedstocks.
 - o Additional investment expands productive capacity.
 - o Oil prices are doubled relative to the baseline.

Given the macro closure of the OPEN-GEM that total savings equals total investments among countries and sectors, the associated dual variable can be interpreted as the economy-wide return on savings, or interest rate, that equilibrates household savings with aggregate investment. An exogenous increase in investment demand creates excess demand for funds at the initial interest rate. To restore the savings-investment balance, the shadow price (interest rate) increases. Higher interest rates provide households with a stronger incentive to postpone current consumption and increase savings, since the return to savings becomes more attractive. As a result, household consumption tends to decline in the short run, while aggregate savings rise until sufficient financial resources are mobilised to finance the higher level of investment. Therefore, an investment expansion can crowd in savings through a higher equilibrium interest rate, reallocating resources from current consumption toward capital accumulation and future production capacity.

Results

The results demonstrate that the competitiveness effects of chemical recycling depend strongly on investment dynamics within the German economy.

In the scenarios without additional investments (CHM_REC and CHM_REC_OIL), the expansion of chemical recycling generates substantial additional demand for domestic capital and intermediate inputs. Because productive capacity remains at the Baseline level, this demand places pressure on German capital markets and increases capital and thus production costs across several sectors. As a result, domestic prices increase, export competitiveness weakens, and the trade balance deteriorates. These findings suggest that introducing chemical recycling without simultaneously expanding capacity can create economic and competitiveness trade offs despite the benefits associated with higher circularity.

In contrast, the scenarios with additional investments (CHM_REC_INV and CHM_REC_INV_OIL) show significantly more favourable outcomes. The expansion of productive capacity allows the German economy to accommodate the new demand generated by the chemical recycling sector without creating strong inflationary pressures. As a result, production costs remain relatively stable, the negative effects on trade performance are limited, and overall industrial competitiveness is largely preserved. The analysis therefore indicates that investments play a critical enabling role in achieving circularity objectives in the chemicals industry while maintaining competitiveness. Figure 28 presents the GDP impact in the German economy by comparing the different variant.

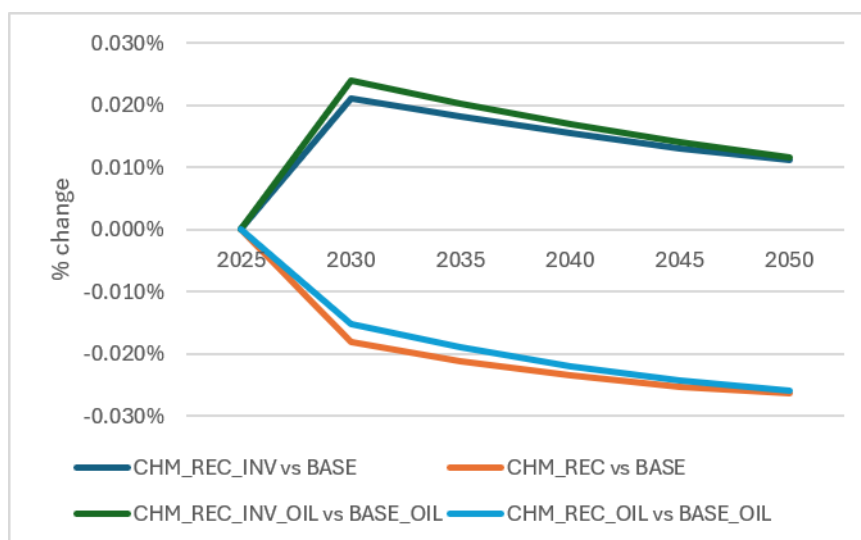


Figure 28. GDP impact by comparing different variants

The shift in demand from the petrochemical sector to domestically oriented chemical recycling activities stimulates wages, household income, and consumer spending. Under the assumption of full resource utilisation and the absence of additional investment, the resulting increase in aggregate demand would generate inflationary pressures, leading to higher product prices. Consequently, the trade balance may deteriorate in volume terms, but the terms of trade will be improved (the average price of exports increases, and the average price of imports remains unchanged - Figure 29). If additional investment is undertaken, capacity expansion would mitigate price pressures and alleviate the impact in terms of trade.

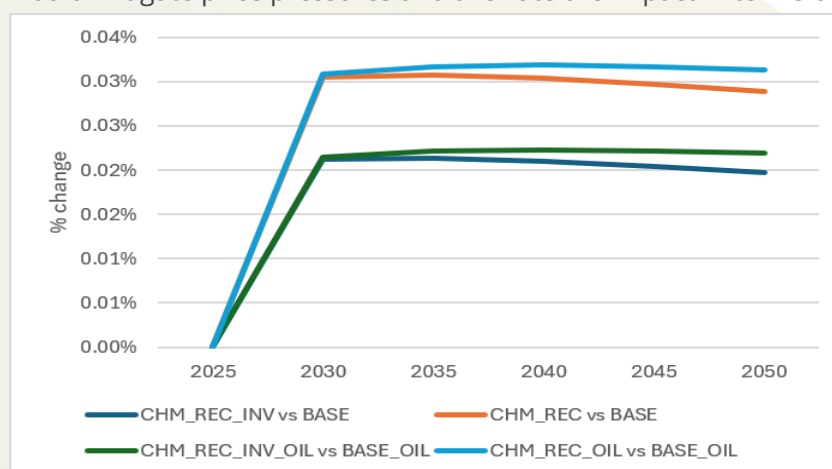


Figure 29. Average export price impact in Germany

At the sectoral level there is a substitution in the primary plastics sectors for the conventional chemicals with the chemically recycled feedstocks. This transition increases the demand for domestically produced products with an upward pressure in prices. On absence of additional investment this upward pressure will harm export-oriented sectors, such as equipment goods, having a negative impact in their production. Figure 30 to Figure 33 present the impact on production in the sectors with the highest impact on the variants simulated: primary plastic sector, other chemicals, chemical recycling, and equipment goods. The positive impact that arises from the re-allocation of demand to sectors with higher local content is partly alleviated if no additional investment occurs.

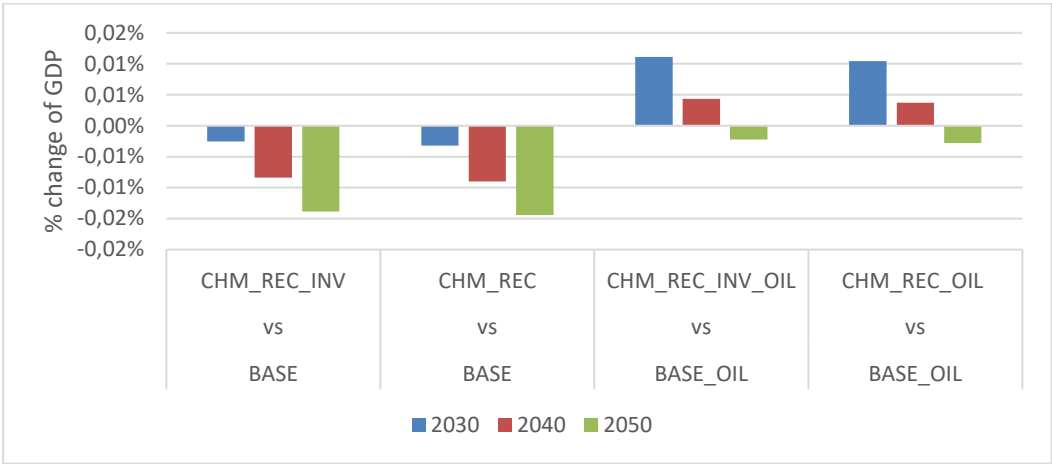


Figure 30. Primary plastics - sectoral production

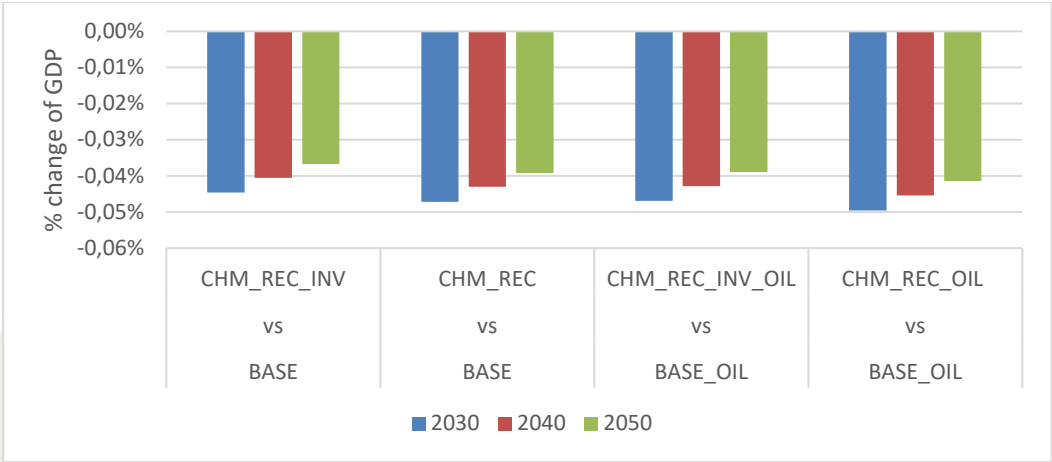


Figure 31. Other chemicals - sectoral production

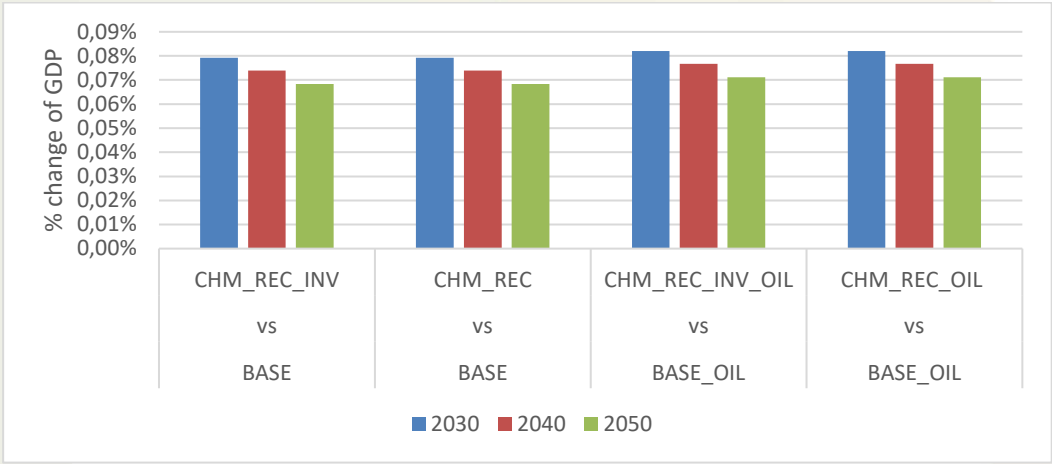


Figure 32. Chemical recycling - sectoral production

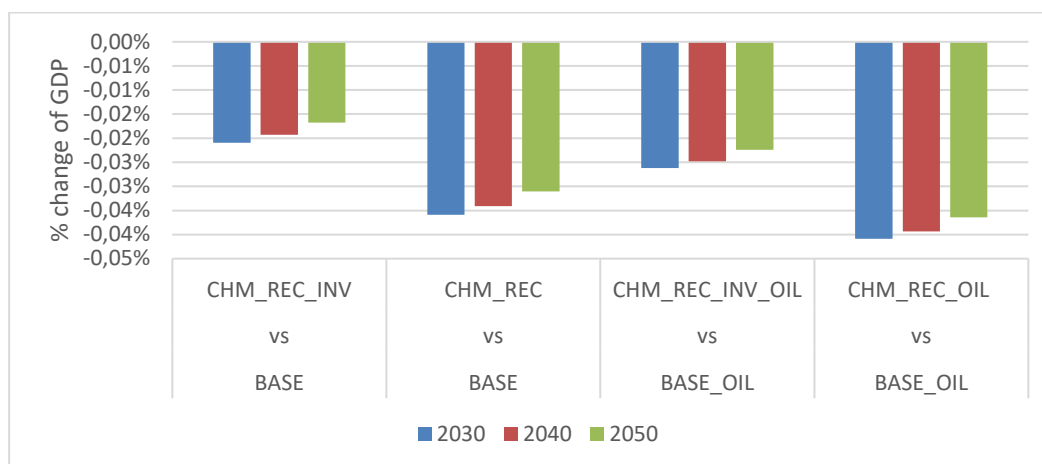


Figure 33. Equipment goods - sectoral production

The oil-price sensitivity analysis highlights an additional resilience benefit. Under higher oil prices, the production costs of conventional primary plastics increase substantially because of their reliance on fossil-based feedstocks. However, greater penetration of chemically recycled feedstocks reduces this dependence and lowers the exposure of the plastics value chain to (imported) fossil fuel price volatility. Consequently, the German primary plastics sector becomes comparatively more resilient and competitive under high oil-price conditions when chemical recycling is widely adopted.

OPEN-PROM

Baseline, Chemical Recycling, and High oil price scenarios

The scenario analysis is built around two policy pathways representing different levels of climate ambition. The first pathway corresponds to a National Policies Implemented (NPI) scenario, reflecting the continuation of current implemented energy and climate policies in Germany and the EU. The second pathway represents a more ambitious decarbonisation trajectory that is consistent with EU's Nationally Determined Contribution (NDC) and long-term net-zero climate target (LTT).

To assess the role of chemical recycling in reducing fossil feedstock consumption in the petrochemical sector, an additional chemical recycling scenario is developed for each policy pathway. In this scenario, plastic-waste-derived pyrolysis oil substitutes 50%³ of the naphtha demand in the German petrochemical sector throughout the analysis period. The selected substitution level represents a stylised high-circularity assumption designed to explore the implications of large-scale deployment of chemical recycling technologies in Germany rather than a projection of future market developments. The assumption is consistent with emerging chemical recycling pathways in which pyrolysis oil is upgraded and used as a feedstock for petrochemical production, reducing the need for virgin fossil-derived naphtha (Energy Live News, 2026; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2025).

³ The 50% substitution is assumed for all years of the analysis period for demonstration and sensitivity-analysis purposes and does not represent a realistic deployment trajectory

In addition, a high-oil-price variant is developed for each policy pathway. Under this variant, international crude oil prices are assumed to be twice as high as in the corresponding reference scenario during the period 2030–2050⁴. This assumption reflects increasing uncertainty in global oil markets, caused by potential geopolitical tensions and supply-side constraints, and allows the assessment of chemical recycling under conditions of substantially increased fossil feedstock costs.

It is worth noting that this assumption is intentionally stylised with the purpose to isolate and illustrate the potential impacts of chemical recycling on Germany's industrial sector, rather than to inform policy decisions or represent a realistic transition pathway.

The resulting scenario protocol combines two climate policy scenarios (NPI & NDC-LTT) with four technology-variants (reference, CR, HOP & CR-HOP) for each policy pathway resulting in eight scenarios in total. Climate policies are described below:

- **NPI:** The NPI scenario reflects the continuation of current and announced policies.
- **NDC-LTT:** NDC-LTT pathway consists of a more ambitious pathway, and it is aligned with Germany's climate commitments, achieving net-zero greenhouse gas emissions by 2045 and net-negative emissions by 2050 (German Federal Government, 2021).

The technology scenarios are briefly presented as follows. All the scenarios below are explored using both NPI and NDC-LTT climate variants:

- **Reference scenario:** No chemical recycling and reference oil prices.
- **Chemical Recycling (CR) scenario:** Pyrolysis oil substitutes 50% of naphtha demand in the German petrochemical sector.
- **High Oil Price (HOP) scenario:** Crude oil prices are assumed to be twice as high as in the reference scenario(s) over the period 2030–2050.
- **Chemical Recycling + High Oil Price (CR-HOP) scenario:** Combines the assumptions of the CR and HOP scenarios.

Table 5. OPEN-PROM scenario summary

Scenario	Climate Policy		Chemical Recycling		Oil Price	
	NPI	NDC-LTT	Not included	Included	Reference	High
NPI	x		x		x	
NPI-HOP	x		x			x
NPI-CR	x			x	x	
NPI-CR-HOP	x			x		x

⁴ A stylised sensitivity case in which oil prices are doubled relative to the reference scenario; intended for demonstration purposes rather than as a realistic projection.

Scenario	Climate Policy		Chemical Recycling		Oil Price	
	NPI	NDC-LTT	Not included	Included	Reference	High
NDC-LTT		x	x		x	
NDC-LTT-HOP		x	x			x
NDC-LTT-CR		x		x	x	
NDC-LTT-CR-HOP		x		x		x

This scenario design enables the assessment of the individual and combined effects of climate ambition, chemical recycling deployment, and fossil feedstock price developments on industrial energy demand, feedstock consumption, technology deployment, and carbon emissions.

Results

Impact on Emissions

Greenhouse gas emissions decline substantially across all scenarios between 2025 and 2050 (Figure 34). Under pathways aligned with NPI scenario, emissions in Germany are projected to decrease from approximately 600 MtCO₂e/yr in 2025 to around 200 MtCO₂e/yr in 2050, while the NDC-LTT-aligned pathways follows a steeper decarbonisation trajectory, reducing emissions to about 100 MtCO₂e/yr in 2045 and reaching net-negative emissions by 2050. The high oil price assumption leads to additional emission reductions relative to the corresponding reference technology pathways, with the effect being more pronounced under NPI than under NDC-LTT climate assumptions. This reflects the fact that the NDC-LTT pathway already achieves substantial emissions reductions through strong decarbonisation measures, leaving less scope for further abatement from higher oil prices. In contrast, the chemical recycling scenarios closely overlap with their respective reference pathways, indicating a limited impact on aggregate emissions over the modelling horizon. Consequently, the largest emission reductions are observed in the NDC-LTT combined CR-HOP scenario, although these reductions are driven primarily by the strong decarbonisation policies and the high oil price assumption rather than by chemical recycling.

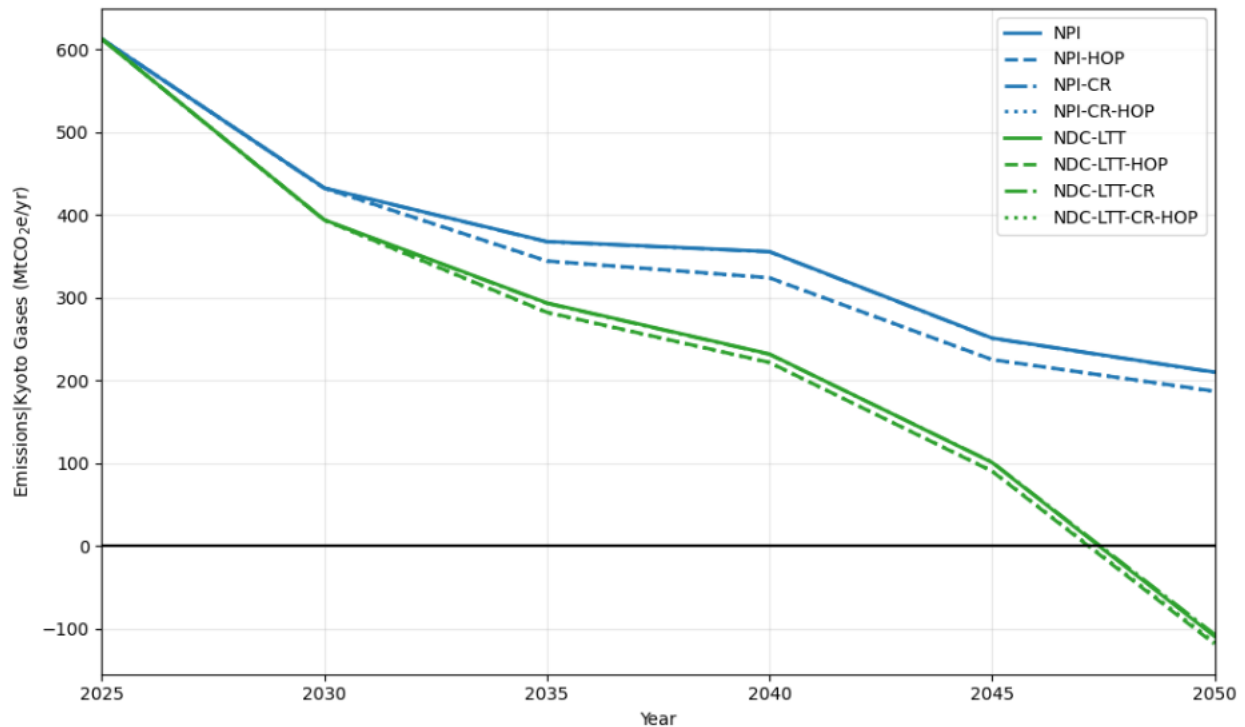


Figure 34. Greenhouse gas emissions (Kyoto gases) under the reference and alternative scenarios in Germany for the period 2025-2050

The industrial sector is critical in achieving Germany's long-term decarbonisation objectives, as shown in Figure 35 (left). The comparison between the NPI and NDC-LTT scenarios demonstrates that stronger climate action can lead to substantially lower industrial emissions by 2050. The pronounced difference between the two pathways highlights the importance of accelerating the transition of industrial energy systems and adopting low-carbon technologies across industrial activities.

The emissions reductions are closely linked to changes in the industrial energy mix, Figure 35 - right. While overall final energy demand in 2050 remains broadly similar in the two climate scenarios, the NDC-LTT pathway is characterised by a clear shift away from fossil fuels towards cleaner energy carriers. Electricity plays an increasingly dominant role, complemented by greater use of bioenergy and the emergence of hydrogen, while the contribution of natural gas and petroleum products declines. These structural changes illustrate how electrification and fuel switching can significantly reduce industrial emissions, making the sector a key contributor to Germany's transition towards climate neutrality.

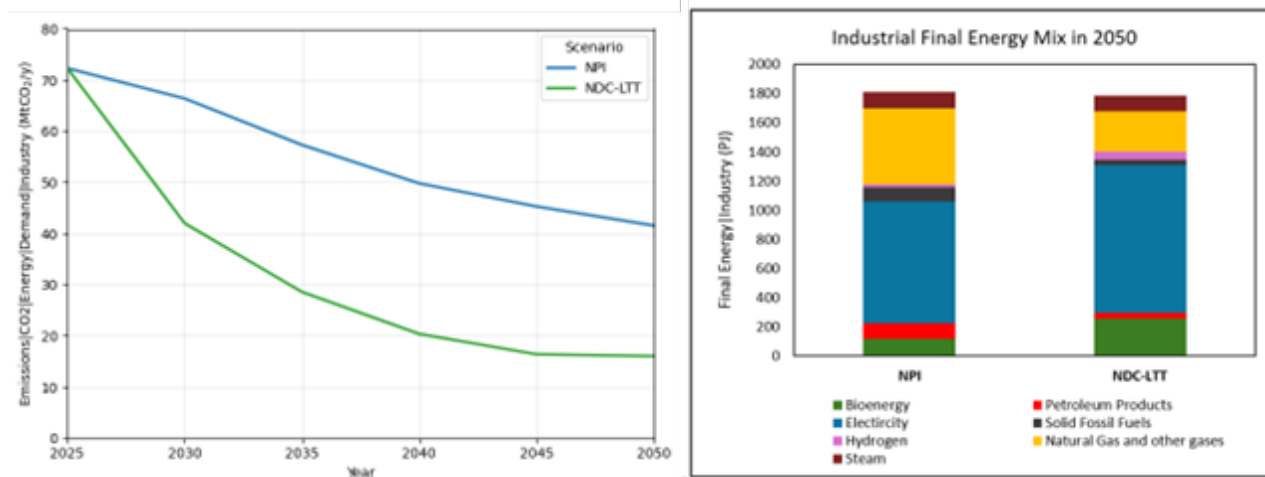


Figure 35. Energy-related emissions of the industrial sector (left) – Industrial Final Energy Mix in 2050 (right) for Germany for the reference scenarios NPI and NDC-LTT.

Impact of Chemical Recycling

Naphtha is predominantly used as a feedstock in the petrochemical industry for the production of olefins and other intermediate chemicals, which are subsequently converted into polymers, plastics, and a wide range of chemical products. Feedstock consumption of naphtha remains largely unchanged across the two reference scenarios (NPI and NDC-LTT), reflecting the continued demand for petrochemical products and the limited availability of alternative feedstocks in the reference pathways (Figure 36).

In the high oil price variants (NPI-HOP and NDC-LTT-HOP), where crude oil prices double over the period 2030–2050, naphtha demand declines as its cost increases in line with higher oil prices. The higher feedstock cost reduces the competitiveness of naphtha-based production routes and encourages the adoption of alternative feedstocks where available.

A much stronger reduction is observed in the chemical recycling scenarios, which assume the substitution of naphtha by pyrolysis oil. In these cases, pyrolysis oil replaces 50% of the naphtha feedstock used in the petrochemical sector, resulting in a corresponding reduction in final naphtha demand. This highlights the potential of chemically recycled feedstocks to reduce the sector's dependence on fossil-based inputs while maintaining the production of petrochemical intermediates and downstream products.

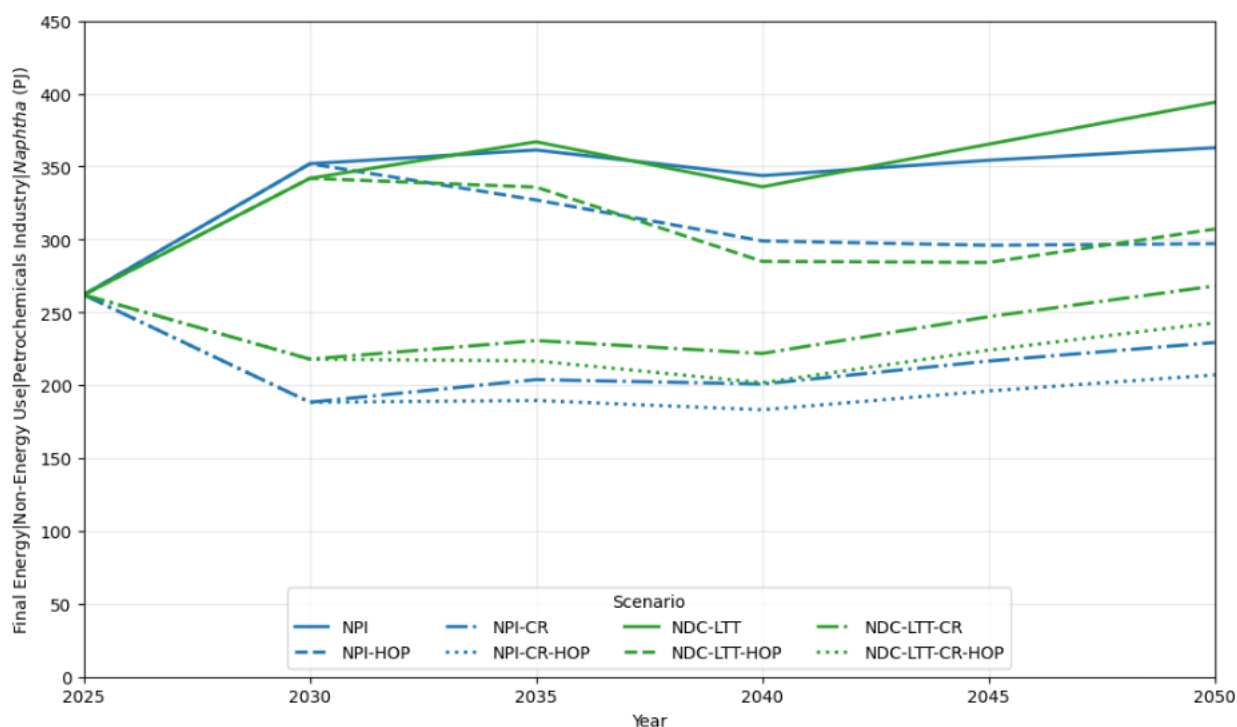


Figure 36. Final energy of naphtha for non-energy use in petrochemical industry for Germany for reference and alternative scenarios for the period 2025-2050

The production of pyrolysis oil leads to an increase in electricity consumption within the liquids supply sector, as each Mtoe of pyrolysis oil produced requires approximately 0.023 Mtoe of electricity (Stallkamp et al., 2024). Consequently, the additional electricity demand is directly linked to the volume of pyrolysis oil produced. As pyrolysis oil production increases to substitute larger quantities of naphtha, electricity consumption rises by the same amount. Therefore, scenarios with greater pyrolysis oil production exhibit higher electricity demand in the liquids supply sector, reflecting the energy requirements associated with the conversion and upgrading processes needed to produce this alternative feedstock (Figure 37).

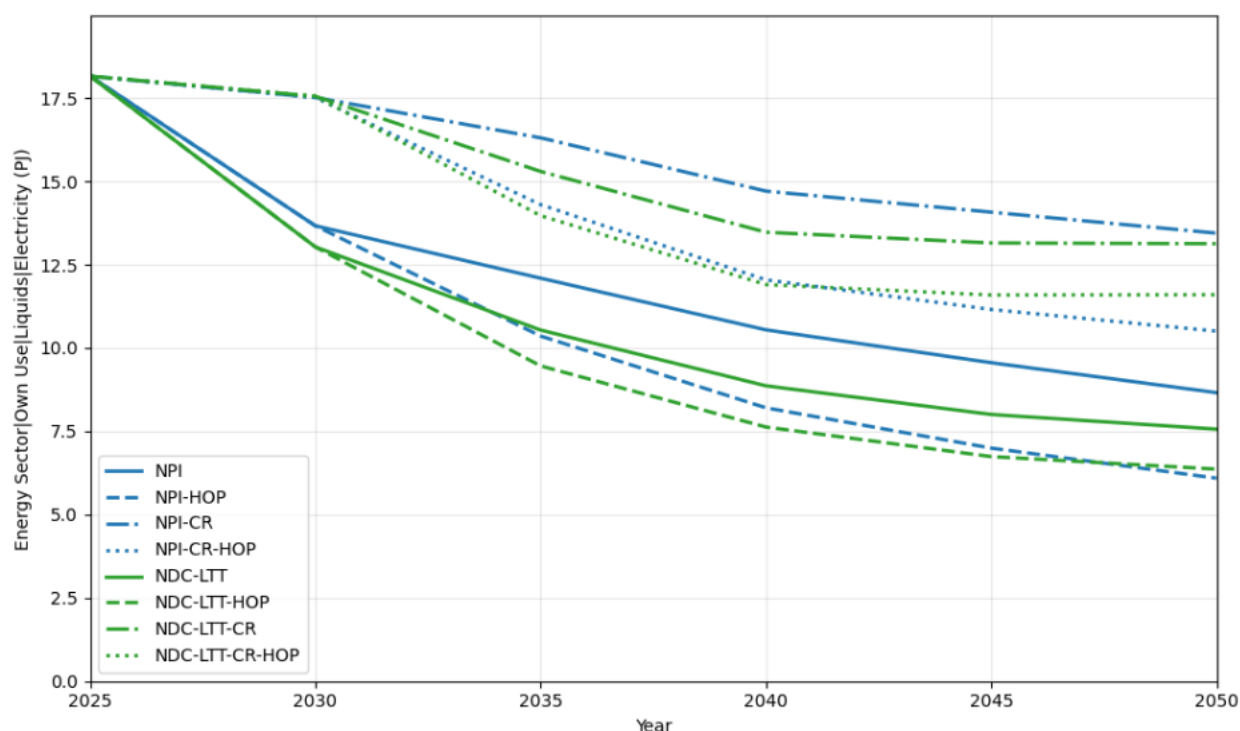


Figure 37. Electricity Consumption for Own Use in the Liquids Supply Sector across Reference and Alternative Scenarios in Germany, 2025–2050

Figure 38 shows the evolution of electricity prices under the reference and alternative scenarios in Germany. Electricity prices decline over time in all scenarios, reflecting the increasing deployment of low-cost renewable electricity (especially solar PV and wind power) and the broader transformation of the power sector. The decrease is particularly pronounced between 2025 and 2030 in the NDC-LTT scenarios, after which prices remain relatively stable through 2050. As a result, electricity prices are consistently lower in the NDC-LTT pathway than in the corresponding NPI scenarios.

The analysis also indicates that the chemical recycling (CR) scenarios have virtually no impact on electricity prices. The price trajectories of the NPI and NPI-CR scenarios are almost identical, while the same holds for the NDC-LTT and NDC-LTT-CR scenarios. This suggests that the additional electricity demand associated with pyrolysis oil production is too small relative to the overall electricity system to influence power market dynamics or generation costs.

Similarly, the high oil price (HOP) variants result in only marginal changes in electricity prices as oil is only marginally used for electricity generation in Germany. The limited differences between the reference and HOP scenarios indicate that electricity prices are driven primarily by developments within the power sector rather than changes in crude oil prices. Overall, the results show that neither the deployment of chemical recycling nor higher oil prices significantly affect the overall power sector dynamics and electricity price formation, which remains largely determined by the evolution of the electricity generation mix and the level of decarbonisation achieved in each pathway.

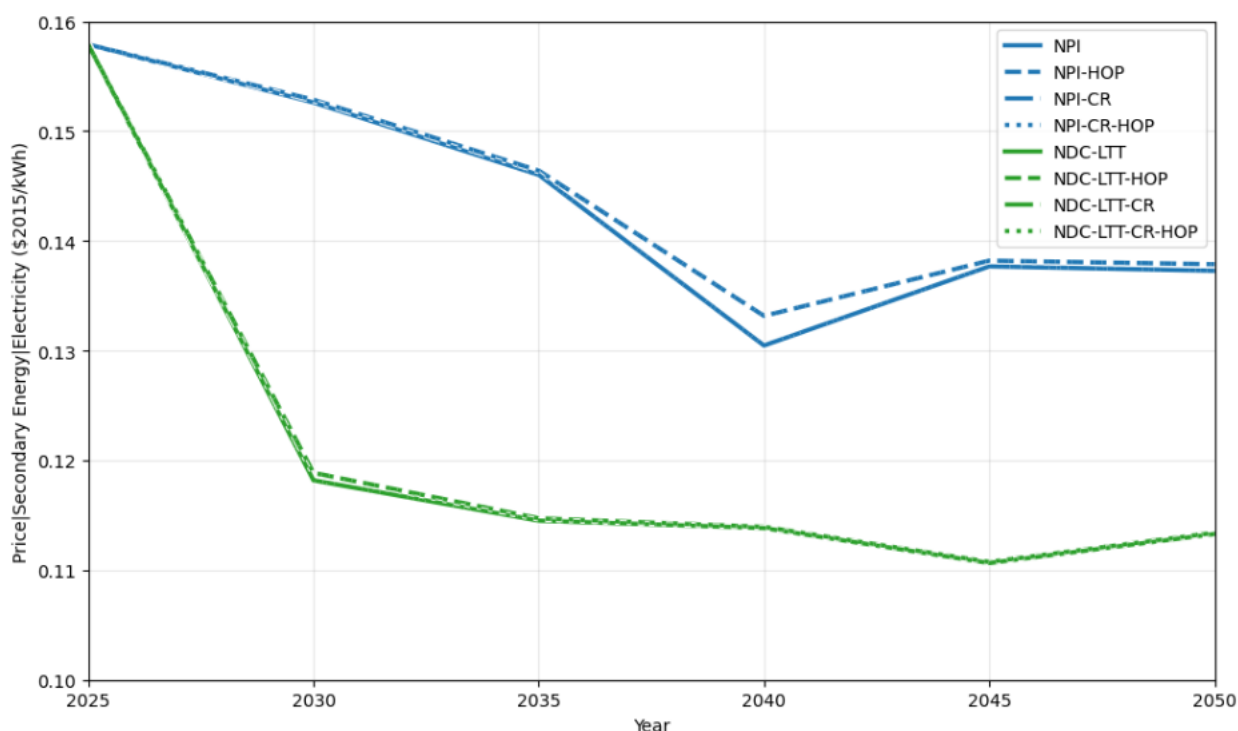


Figure 38. Electricity price of secondary energy under the reference and alternative scenarios in Germany for the period 2025-2050

Discussion

The combined OPEN-GEM and OPEN-PROM analyses provide a comprehensive assessment of the economic, competitiveness, and energy-system implications of large-scale chemical recycling deployment in Germany. The results show that chemical recycling can significantly reduce the petrochemical sector's reliance on fossil-based feedstocks by substituting naphtha with pyrolysis oil, thereby enhancing circularity and reducing exposure to fossil fuel price volatility.

From an economic perspective, the OPEN-GEM results demonstrate that the benefits of chemical recycling depend critically on accompanying investments. When chemical recycling is deployed without expanding productive capacity by crowding out investment in other sectors, increased demand for domestic capital and intermediate goods leads to higher production costs, reduced export in volume and improving terms of trade. In contrast, investment-led scenarios enable the economy to accommodate the additional demand generated by chemical recycling while minimising cost pressures and preserving industrial competitiveness. These findings highlight that investment in productive capacity is a key enabler for a successful circular transition.

From an energy-system perspective, the OPEN-PROM analysis shows that chemical recycling substantially reduces naphtha consumption but has only a limited effect on overall greenhouse gas emissions and energy prices. The production of pyrolysis oil increases electricity consumption in the liquids supply sector; however, the additional demand is small relative to the overall electricity system and therefore has a negligible impact on electricity prices. The analysis further demonstrates that ambitious climate policies remain the primary driver of long-term emissions reductions in the chemicals sector. The NDC-LTT pathway achieves significantly deeper decarbonisation through electrification, fuel switching, and the deployment of low-carbon energy carriers such as bioenergy and hydrogen, while chemical recycling mainly contributes

through reduced fossil feedstock requirements rather than direct emissions abatement.

The high-oil-price scenarios reveal an important resilience dimension. As conventional naphtha becomes more expensive, chemically recycled feedstocks become comparatively more attractive, reducing the vulnerability of the petrochemical value chain to fluctuations in fossil fuel markets. This strengthens the competitiveness of the plastics sector under adverse market conditions and reinforces the strategic value of domestic circular feedstock supply chains, reducing the sector's trade dependence and increasing its resilience.

Overall, the results indicate that chemical recycling should be regarded as a complementary strategy within a broader industrial transition. While it can improve resource circularity, enhance resilience, and reduce dependence on virgin fossil feedstocks, its economic benefits are maximised when supported by additional investment, and its contribution to climate mitigation is most effective when combined with ambitious decarbonisation policies and a rapidly evolving low-carbon energy system.

Limitations and future work within the MIC3 framework

The present analysis demonstrates the value of linking macroeconomic and energy-system perspectives through the MIC3 framework, but it also relies on several stylised assumptions. In particular, the 50% substitution of naphtha by pyrolysis oil is imposed exogenously and does not explicitly account for feedstock availability, waste collection and sorting constraints, technology deployment rates, investment requirements, or lifecycle environmental impacts.

A key advantage of MIC3 is that these limitations can be addressed by integrating the framework's additional modelling components. The material-flow models (EU-MFA and REMIND-MFA) can assess the availability of plastic waste and secondary feedstocks, while the industrial models (FORECAST-Sites and ITOM) can provide a more detailed representation of technology choices, production processes, investment needs, and sector-specific competitiveness effects. The P&S Database can further improve the representation of product demand and material requirements, and the LCA-TRANSIENCE module can evaluate the broader environmental implications of chemical recycling beyond greenhouse gas emissions.

Future work will therefore focus on exploiting the full capabilities of MIC3 by strengthening the integration between these perspectives, enabling a more comprehensive assessment of industrial decarbonisation pathways that jointly considers circularity, resource constraints, competitiveness, technology deployment, and environmental sustainability.

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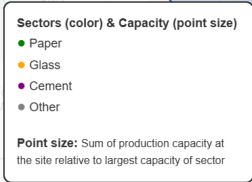
5 The Basque Country Case Study: Decarbonisation pathways for industry in the Basque Country

Introduction

The transformation of energy-intensive industry is one of the central challenges for achieving climate neutrality in Europe. Industrial plants often combine high energy demand, long investment cycles, site-specific process configurations and exposure to international competition. As a result, decarbonisation pathways cannot be assessed only at the level of national energy balances or generic technology lists. They require a representation of industrial sites, existing production capacities, process-specific technology options and the interaction between energy prices, CO₂ prices and investment timing.

The Basque Country provides a useful regional case study for this type of analysis. The region has a strong industrial structure and includes several energy-intensive activities that are relevant for industrial decarbonisation. For this case study, FORECAST-Sites is applied. FORECAST-Sites allows to model all energy-intensive industry branches (e.g. steel, chemicals, cement, glass, pulp & paper, ...) within one integrated framework, which is necessary for the industry structure in the Basque country allowing to better recognise energy-system integration. In the case study, we focus on three focal sectors: pulp and paper, glass and cement. These sectors were identified and selected in consultation with stakeholders as the most relevant for transformation and decarbonisation also showing highest impact on the energy-system, e.g. related to infrastructure requirements. Figure 39 shows the industrial sites of these sectors in the Basque Country considered. These sectors differ strongly in their process characteristics. Glass production is dominated by high temperature furnace technologies with high-quality requirements and increasing opportunities for hybrid or full electrification. Paper is defined by its substantial steam demand. Cement production includes both energy-related and process-related CO₂ emissions and therefore requires a broader technology portfolio including fuel switching, alternative calcination technologies, and carbon capture and storage.

This report uses the Basque Country case study to demonstrate potential application fields of the FORECAST-Sites model. The purpose is not to provide a final regional roadmap, but to show how a site-level modelling framework can be used to structure technology comparison, identify cost-optimal transformation pathways, and support discussions with regional stakeholders. The report therefore combines a transparent technology-screening step with an optimisation-based model application.



Method and data

The case study applies a two-step analytical approach. The first step is an abatement-cost comparison. It is intended as a transparent techno-economic screening exercise that helps to compare low-carbon technology options against a conventional reference technology. This step is deliberately simple: it clarifies which technologies are likely to be attractive under the assumed input data and which assumptions drive the results.

The second step is the application of FORECAST-Sites. In contrast to the static technology comparison, the model represents investment timing, existing process structures, and the interaction between technology choices in each site. It therefore allows the analysis to move from a marginal comparison of individual technologies to a pathway perspective in which reinvestment cycles, technology availability, energy-carrier prices, and CO₂ costs jointly determine the cost-optimal solution.

This sequencing is useful for stakeholder-oriented case studies. The abatement-cost comparison provides intuition and transparency. The model application then tests whether this intuition remains valid when sector-specific constraints, plant vintages, changing prices, and technology availability are considered simultaneously.

The energy-carrier price assumptions (Figure 40) are based on Eurostat energy price statistics for energy-intensive consumers and additional projections. The baseline assumptions include a constant electricity price of 70 €/MWh and a constant natural gas price of 46.1 €/MWh over the model horizon. Biomass remains in the range of approximately 38–41 €/MWh, while hydrogen prices decline from high (165 €/MWh) initial values towards lower long-term levels (120 €/MWh in 2030 and around 90 €/MWh from 2035 onwards).

Sensitivities with $\pm 30\%$ changes in electricity and gas prices over ten years are included. The CO₂ price is represented as a simple linear trajectory. It increases from 70 €/t CO₂ in 2025 to 200 €/t CO₂ in 2050. This assumption is important because CO₂ prices directly affect the cost competitiveness of fossil-based reference technologies and therefore influence the timing of fuel switching, electrification, and CCS investments.

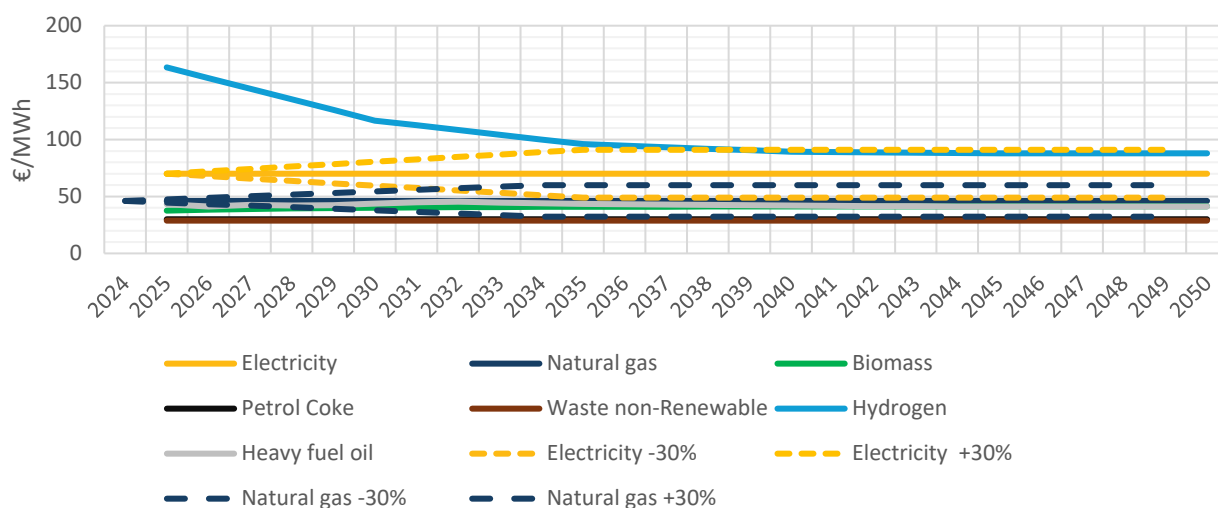


Figure 40. Energy carrier price assumptions used in the case study

Abatement-cost comparison

The simplified abatement-cost comparison evaluates the additional cost of a low-carbon technology relative to a fossil reference technology and divides this cost difference by the associated CO₂ emission reduction. It is therefore a marginal indicator that supports an initial ranking of technology options. In conceptual terms, the abatement cost is calculated as:

$$\text{Abatement cost} = \frac{\Delta \text{ cost}}{\Delta \text{ emissions}}$$

Δ cost: Difference of total production cost of climate friendly technology compared to reference technology

Δ emissions: Difference of CO₂ emissions

The model output includes investment pathways as well as energy demand and emission-related indicators. The results can therefore be used to discuss which technology options become cost-optimal, when reinvestments occur, and how the energy-carrier structure changes over time.

The numerator includes the difference in total production cost between the low-carbon option and the reference technology. This includes investment-related cost components, operation and maintenance, and energy costs. The denominator represents the avoided emissions relative to the reference case. A negative abatement cost indicates that the low-carbon option is less costly than the reference technology under the assumed price conditions.

The indicator is useful for communication, but it has limitations. It does not by itself represent plant vintages, technology availability, reinvestment timing, interactions between process units, or infrastructure constraints. These limitations motivate the second analytical step: the application of FORECAST-Sites.

FORECAST-Sites model application

FORECAST-Sites is applied as a site-level optimisation framework for industrial transformation pathways. The model minimises total cost across investment and operation decisions. The objective is the minimisation of investment costs plus discounted (8%) annual operation and maintenance costs, energy costs, and CO₂ costs. Figure 41 shows the structure of the model.

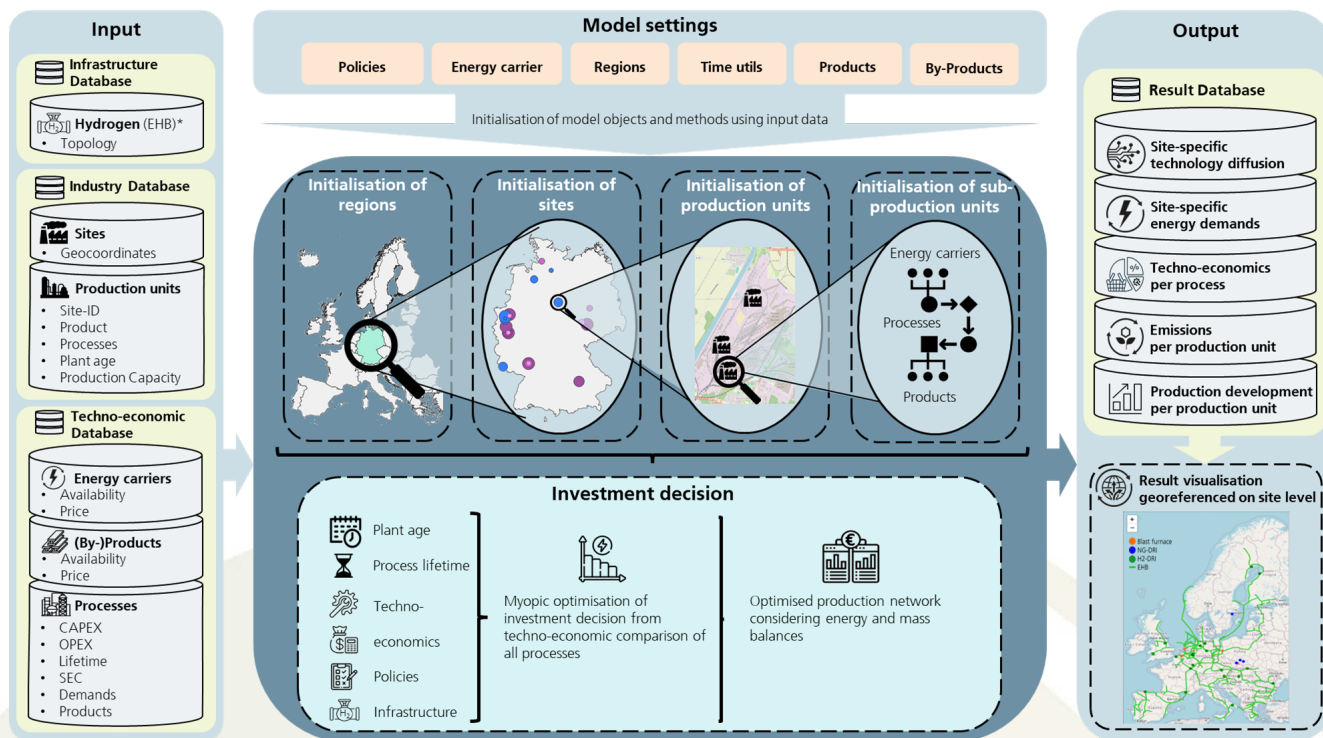


Figure 41. Schematic overview of FORECAST-Sites industry model

For this case study, the model is configured for the sector-specific characteristics of glass, paper, and cement production. The model can represent different process categories, technology options, energy-carrier requirements, technology availability years, lifetimes, capital expenditures, operating expenditures and emission factors or capture rates. This level of detail is important because decarbonisation options are highly sector specific.

Sector representation in FORECAST-Sites

The sector representation follows a process-based structure. Each sector is described through the relevant production steps, product categories, and technology options considered in the model. The following short descriptions summarise how glass, pulp and paper, and cement are represented in this case study.

Glass

Glass production is represented through furnace processes. Energy carriers are directly introduced into the process. Each product category has unique processes, reflecting that different glass products may have different technical and energy-demand characteristics.

The model distinguishes three glass product categories: flat glass, container glass, and special and other glass. For costs, only furnace costs are included. Operating expenditures are assumed to equal 5% of capital expenditures. For energy demand, only furnace energy demand is considered. Hybrid processes are derived

from regenerative furnace demand multiplied by an efficiency factor. Special and other glass is assumed to have 17% higher energy demand than flat glass. Table 6 shows the considered alternative technologies.

Table 6. Relevant considered technologies in the glass sector

Process	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5
Container glass	Regenerative Furnace	Hybrid Furnace (80% Elec.)	CCS post combustion	Electric Furnace	Recuperative Furnace
Flat glass	Regenerative Furnace	Hybrid Furnace (80% Elec.)	CCS post combustion	Electric Furnace	-
Special & other glass	Regenerative Furnace	Hybrid Furnace (80% Elec.)	CCS post combustion	Electric Furnace	-

Pulp & Paper

The pulp and paper sector is represented through pulp production, paper production, and separate steam generation. In the pulp stage, fibre input is converted into pulp output. Each pulp product has one unique pulp process. Steam is provided by a separate boiler or steam generation process. In the paper stage, an input mix of pulp products is converted into a specific paper grade. Each paper product has one unique paper process. As for pulp production, steam is provided by a separate boiler or steam generation process. This separation allows the model to analyse heat-supply technologies independently from the paper and pulp production steps.

Table 7. Relevant considered technologies in the pulp and paper sector

Process	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5
Mechanical pulp	Stone groundwood	-	-	-	CCS post combustion
Chemical pulp	Kraft Pulping	-	-	-	CCS post combustion
Recycled Pulp	Recycled Pulp	-	-	-	CCS post combustion
Graphic Paper	Graphic paper	-	-	-	CCS post combustion
Boards & Packaging	Boards & Packaging	-	-	-	CCS post combustion
Tissue	Tissue	-	-	-	CCS post combustion
Special & other Paper	Special & other Paper	-	-	-	CCS post combustion

Process	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5
Boiler/Steam	CHP	Biomass Boiler	NG/H ₂ /Electric Boiler	Heat Pump	CCS post combustion

Cement

Cement production is represented through a sequence of process modules. The model distinguishes calcinatory processes, rotary kiln processes, burner processes for the calcinator and the rotary kiln, and a proxy cement process. This structure allows the model to represent both energy-related emissions from fuels and process-related emissions from calcination. The proxy cement process is used to represent the choice between conventional cement and low-carbon cement. Decarbonisation options include alternative calcination technologies, fuel and burner switching, CCS and low-carbon cement production routes.

Table 8. Relevant considered technologies in the cement industry

Process	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5
Calcinator	Cyclone Calcinator	Leilac Calcinator	Leilac Calcinator	CCS post combustion	
Rotary kiln	Rotary kiln (short)	Rotary kiln (long)	Rotary kiln (long)	CCS post combustion	
Burner Calcinator	Hydrogen Burner	Electric Burner	Electric Burner	CCS post combustion	
Burner Rotary kiln	Hydrogen Burner	NG Burner	NG Burner	CCS post combustion	
Proxy Cement	Classic Cement	CO ₂ reduced Cement	CO ₂ reduced Cement	-	

Results

Glass sector

The first-step abatement-cost comparison (Figure 42 – container glass, Figure 43 – flat glass) indicates that hybrid electrification is highly attractive under the assumed energy and CO₂ price levels. Hybrid electrification is the most competitive technology and has abatement costs below 50 €/t CO₂. The reason is not only the direct substitution of natural gas by electricity, but also the efficiency gain of the hybrid furnace concept. Under the assumed prices, the combination of hybrid electrification and natural gas can even lead to negative abatement costs compared to the reference technology.

CO₂ Abatement Costs for Industrial Container glass production Reference Technology: Regenerative Furnace (100% NG)

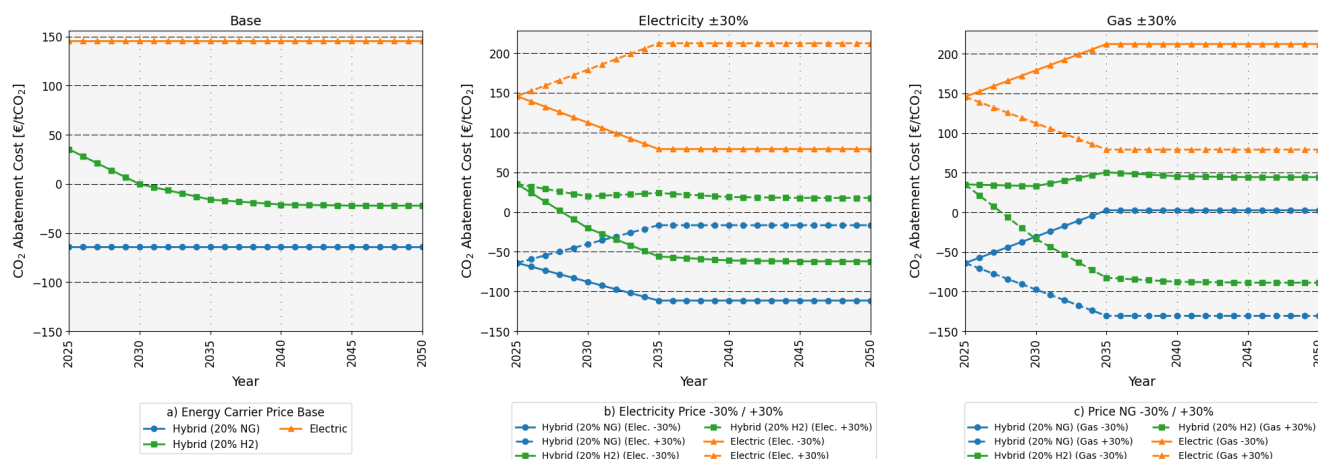


Figure 42. CO₂ abatement costs for container glass production

CO₂ Abatement Costs for Industrial Flat glass production Reference Technology: Regenerative Furnace (100% NG)

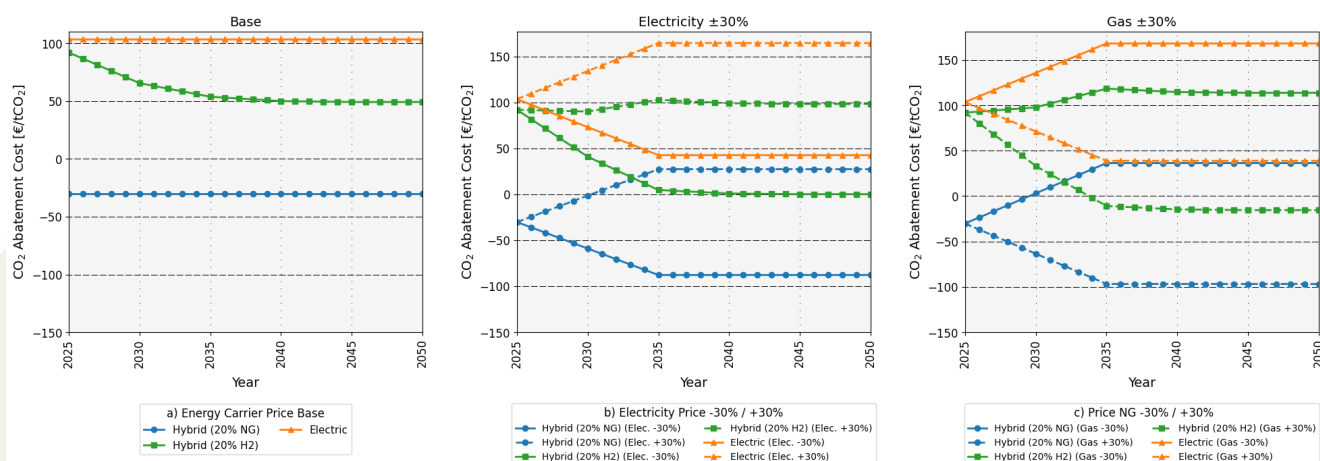


Figure 43. CO₂ abatement costs for flat glass production

The optimisation results support this conclusion. Hybrid electrification appears as an early cost-effective option in the base scenario. Because furnace lifetimes (15 years) are relatively short, the model also captures reinvestment cycles from 2030 and 2035 again before 2050 (see recurring investments in 2045 and 2050, Figure 44). Full electrification becomes more attractive in the long term, but its competitiveness depends on assumed technology maturity, capital cost, lifetime and the CO₂ price level. Full electrification becomes competitive at CO₂ prices above approximately 100 €/t CO₂. Furthermore, CCS becomes relevant from 2040 onwards to capture energy related, as well as process emissions. This reflects on the industries reaction to pressure from emission constraints to reaching net-zero targets until 2050. Implemented CCS results in a near CO₂ neutral glass production from 2040 onwards (Figure 45).

The model result for energy demand (Figure 46) shows a clear shift from natural gas towards electricity. Electricity demand increases from around 0.14 million GJ/a in 2025 to around 0.86 million GJ/a from 2040 onwards, while natural gas demand declines from around 1.59 million GJ/a in 2025 to around 0.17 million GJ/a from 2040 onwards. This confirms the role of hybrid electrification as the dominant transformation mechanism in the represented glass case.

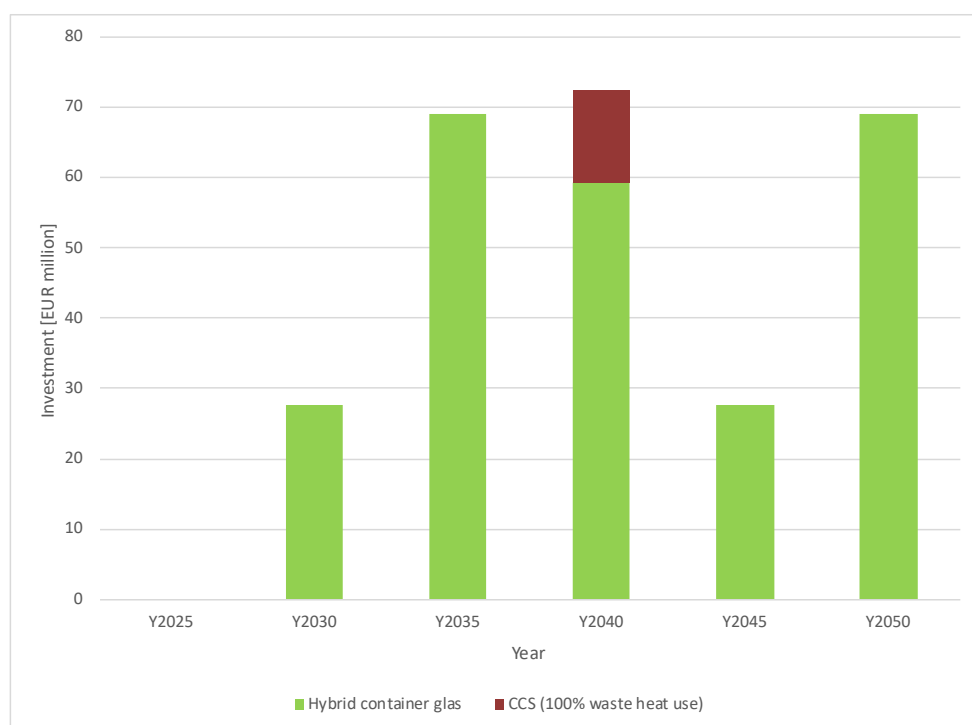


Figure 44. Investments until 2050 in the glass industry in the Basque country based on modelling results with FORECAST-Sites

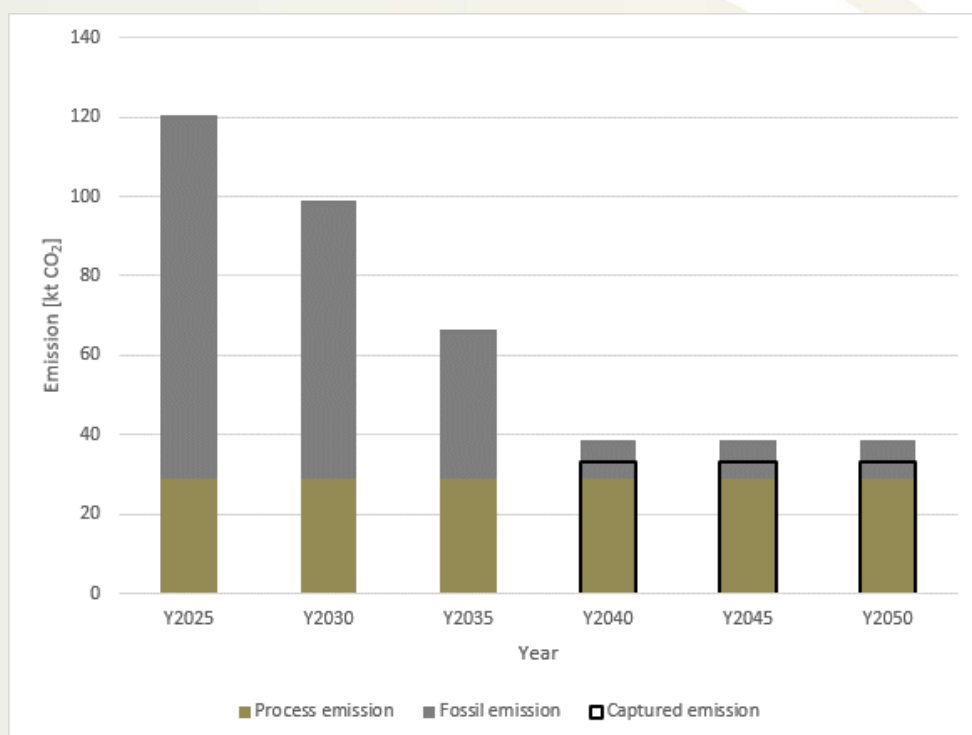


Figure 45. Emissions until 2050 in the glass industry in the Basque country based on modelling results with FORECAST-Sites

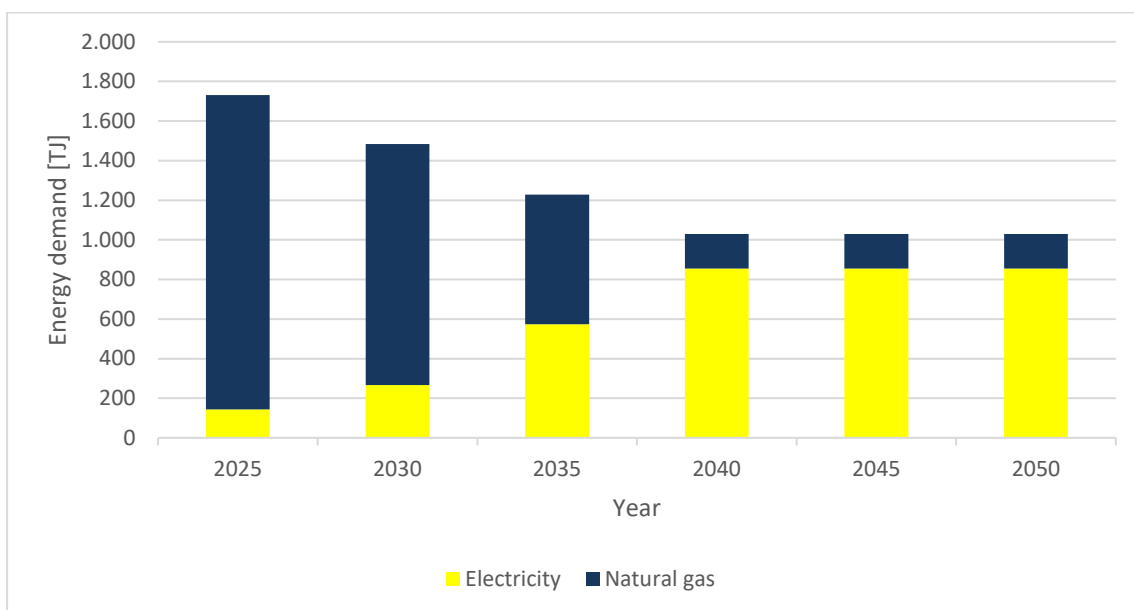


Figure 46. Energy demand until 2050 in the glass industry in the Basque country based on modelling results with FORECAST-Sites

Pulp & Paper

The first-step comparison and the model results both highlight the strategic importance of heat pumps. Heat pumps are identified as the most competitive technology for low-temperature steam, while biomass boilers become more cost-effective than biomass CHP after 2035 under the assumed energy price conditions. This can change depending on the electricity price.

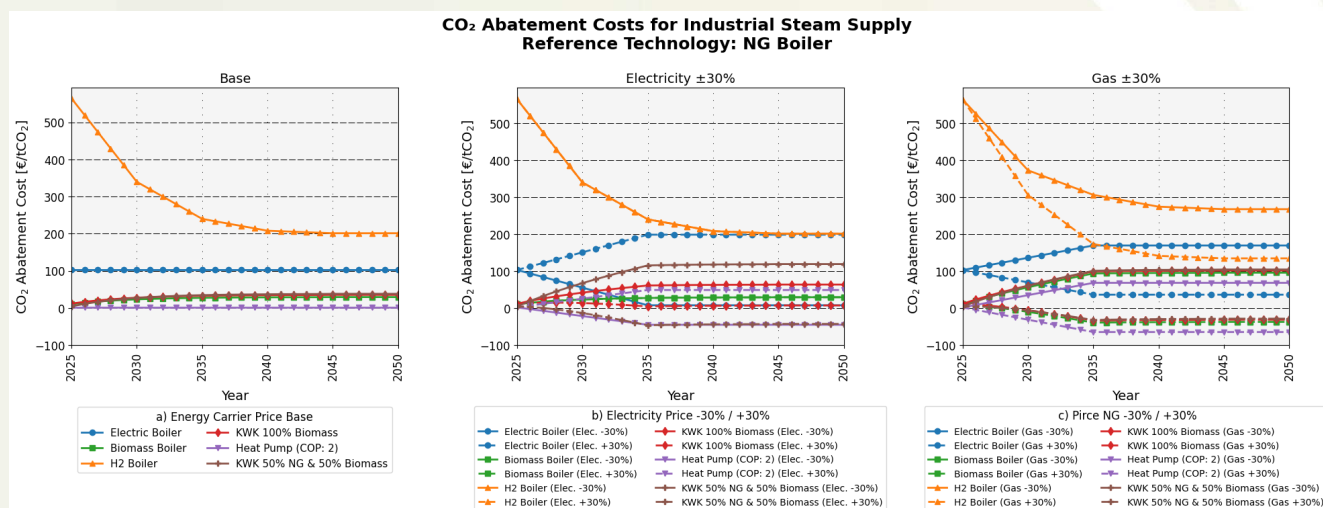


Figure 47. CO₂ abatement costs for steam supply in pulp and paper production

The model shows bulk investments around 2030 and 2035 (Figure 48). Heat pumps are deployed for low-temperature steam, while biomass CHP or biomass boilers cover higher-temperature steam demand. Emissions (Figure 49) decline primarily through the phase-out of natural gas and the shift towards electricity and biomass. Upstream emissions represent previously captured CO₂ from biomass, which lead to an overall carbon neutral emissions balance from 2030 onwards.

The resulting energy demand is shown in Figure 50. Natural gas demand declines from around 7.21 million GJ/a in 2025 to about 2.54 million GJ/a in 2030 and reaches zero from 2035 onwards in the displayed result. Electricity demand increases from about 4.17 million GJ/a in 2025 to about 7.81 million GJ/a from 2030 onwards. Biomass remains an important energy carrier, declining initially and then increasing to around 4.46 million GJ/a from 2035 onwards.

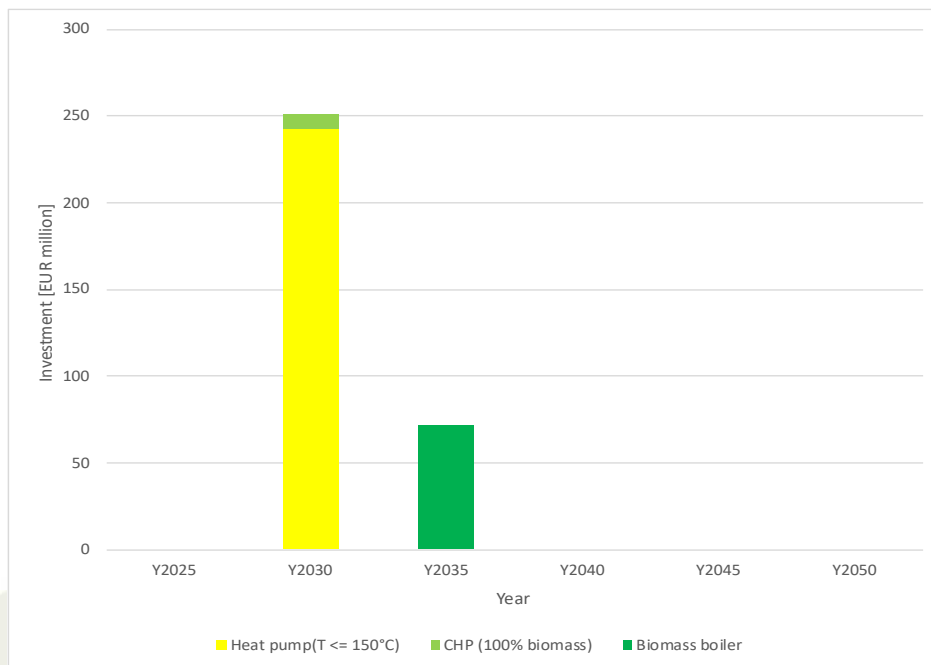


Figure 48. Investments until 2050 in the pulp and paper industry in the Basque country based on modelling results with FORECAST-Sites

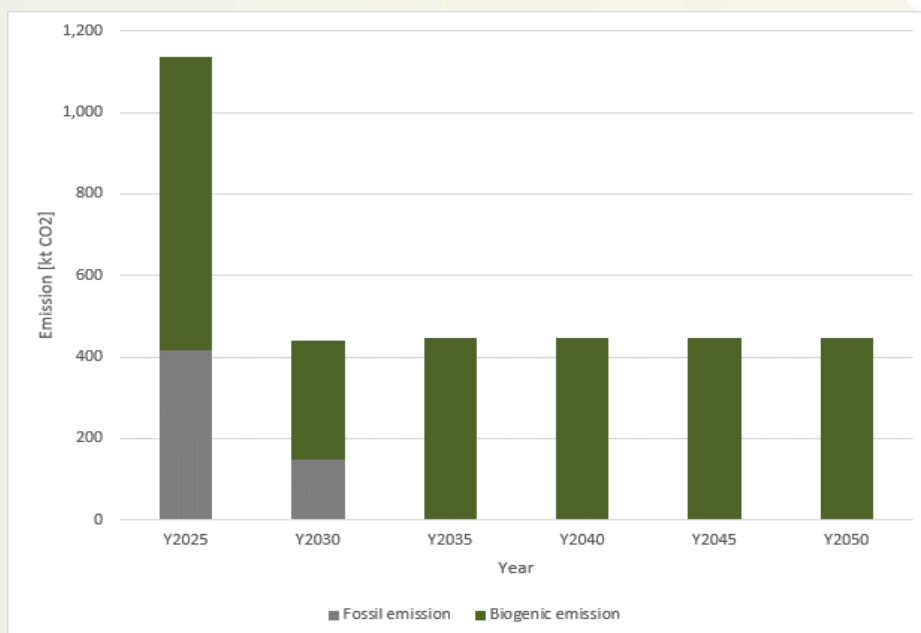


Figure 49. Emissions until 2050 in the pulp and paper industry in the Basque country based on modelling results with FORECAST-Sites

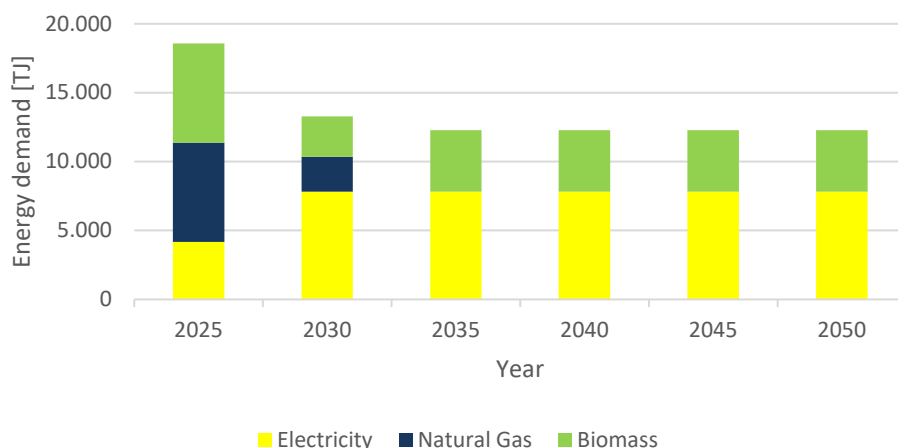


Figure 50. Energy demand until 2050 in the pulp and paper industry in the Basque country based on modelling results with FORECAST-Sites

The case study also illustrates an important modelling issue. Heat pumps can be cost-attractive, but their practical deployment depends on local conditions achievable coefficients of performance, integration into process heat systems, technology readiness for higher temperature levels, and skilled workforce for their installation. Capturing local conditions (such as detailed knowledge per industry site on existing grid capacity) and feasibility for integration could be considered in the model, but sufficient information on those aspects remains scarce while technology readiness has to be projected by assumptions. Cement

The cement production requires a portfolio approach. Fuel switching can reduce energy-related emissions, but process emissions from calcination require complementary options such as Leilac calcination technology and CCS. The combination of different technologies is difficult to consider in the simplified approach of CO₂ abatement cost curves. Figure 51 shows the abatement cost for two key strategies: A separated calcination which allows the capture of the process related emissions as nearly pure CO₂ stream (Leilac calcinator + CCS) compared to the post combustion capture (cyclone-calcinator + CCS). We see an advantage of the Leilac technology independent of the electricity and CO₂ price.

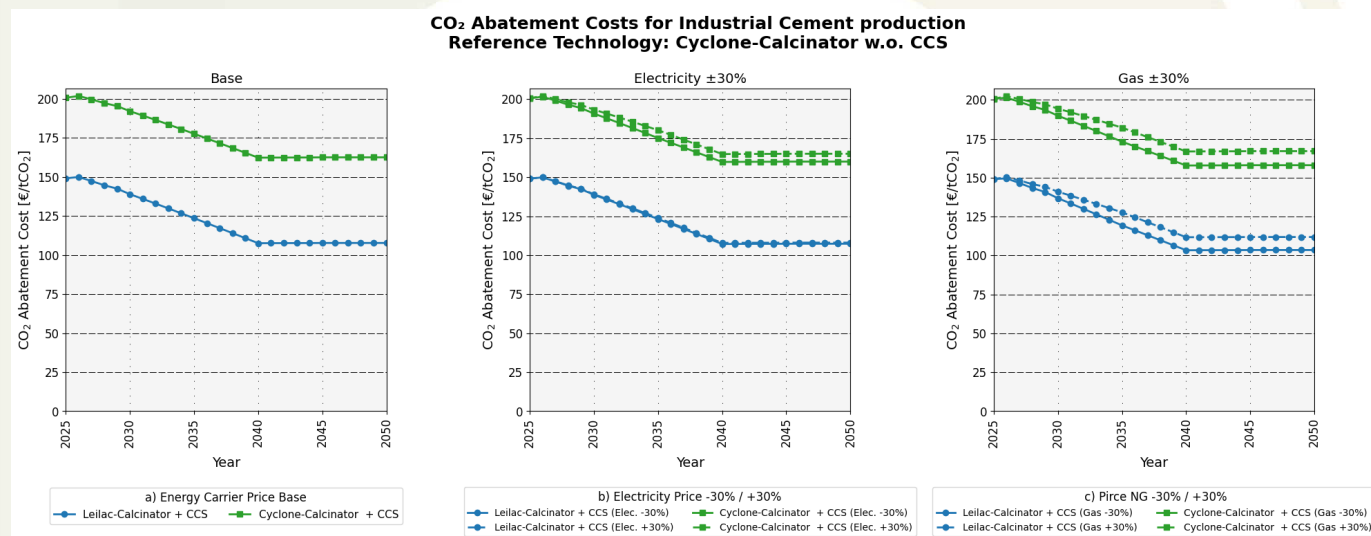


Figure 51. CO₂ abatement costs cement production

When modelling the plants, the model first invests around 2030 in a new burner and switches the fuel mix towards biomass and natural gas. Around 2035, the pathway includes investment in Leilac calcination technology. Around 2040, post-combustion CCS is added to further reduce remaining process and energy-related emissions. A burner renewal is shown around 2050 while keeping the prior energy-carrier mix. The investments are shown in Figure 52.

Emission reductions occur in three stages (Figure 53): first through the replacement of the conventional fossil-based and emission-intensive fuel mix by switching to fuels from biogenic origin. Fossil energy emissions are mitigated while process-related emissions from the calcination process still remain. Second, the implementation of the Leilac technology allows to already capture a major share of the process-related emissions. Finally, CCS contributes to also capturing energy emissions from the use of biomass. Biomass-related upstream emissions are shown in Figure 53, however they should be interpreted as climate-neutral and previously captured CO₂. Thus, they contribute to achieve overall negative emissions when captured.

The energy-carrier structure changes substantially (Figure 54). Waste from non-renewable fuels (Waste non-RES), other renewables and petrol coke are used in 2025 but disappear in the subsequent displayed years resulting from fuel switch towards biomass. Biomass becomes the dominant fuel from 2030 onwards and increases further from 2040. Natural gas appears as a complementary fuel carrier from 2030 onwards. Electricity demand increases in 2040 as result from the implementation of CCS.

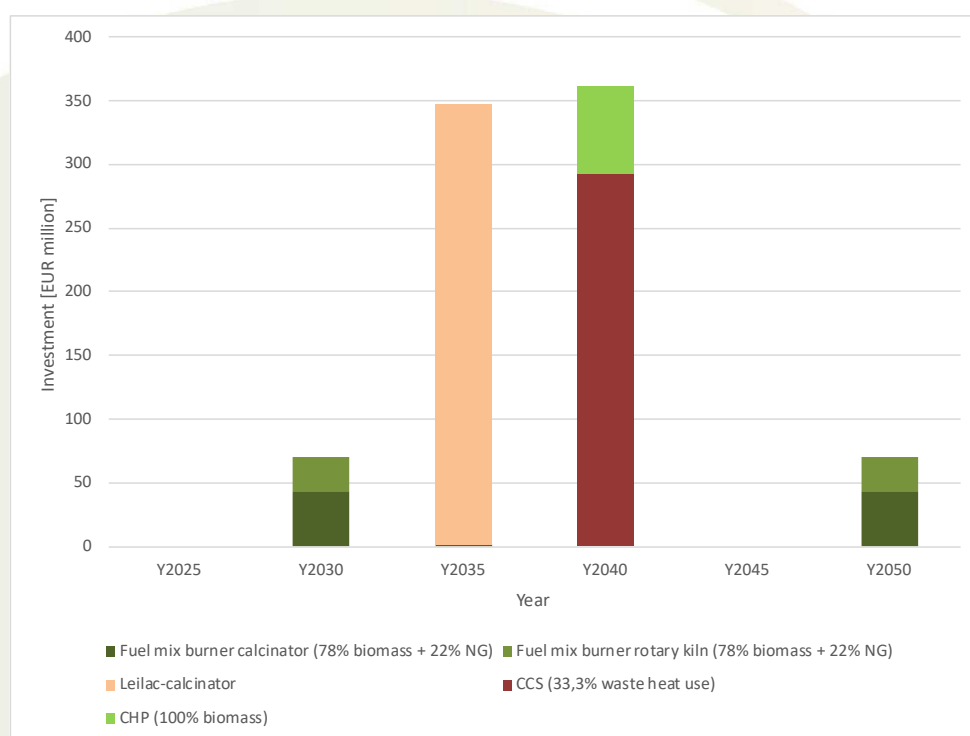


Figure 52. Investments until 2050 in the cement industry in the Basque country based on modelling results with FORECAST-Sites

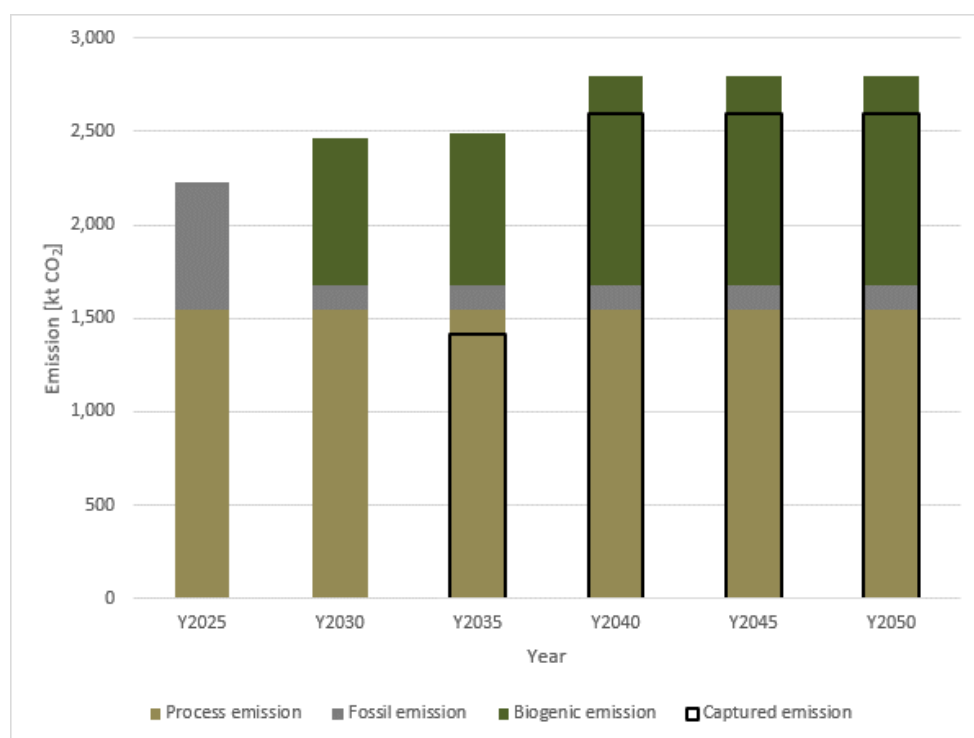


Figure 53. Emissions until 2050 in the cement industry in the Basque country based on modelling results with FORECAST-Sites

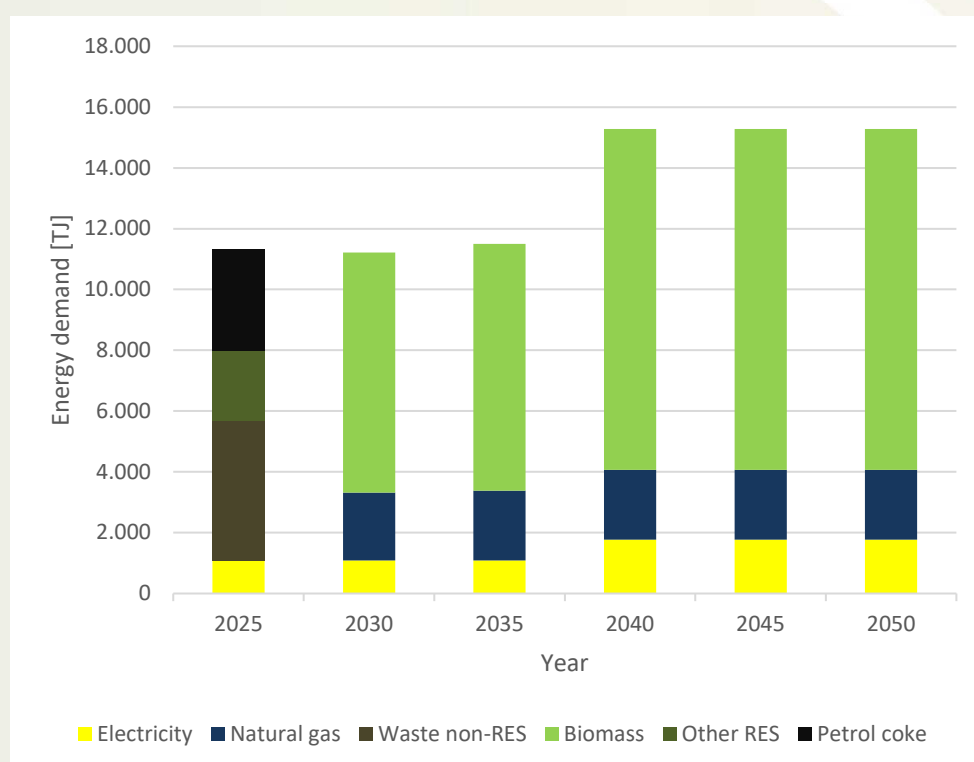


Figure 54. Energy demand until 2050 in the cement industry in the Basque country based on modelling results with FORECAST-Sites

Discussion

The case study demonstrates the value of combining a simple abatement-cost screening with a site-level optimisation model. The abatement-cost step is useful because it is transparent and easy to communicate. It helps to explain why certain technologies appear attractive under the assumed energy and CO₂ prices. For example, the strong performance of hybrid electrification in glass and heat pumps in paper can be understood directly from their energy efficiency and cost structure. However, the optimisation step is needed to turn this technology intuition into a time-dependent transition pathway. Industrial sites do not invest continuously. They invest when existing equipment reach relevant decision points like the end of their lifetime, when technologies become available, and when price signals make alternatives attractive. FORECAST-Sites is therefore useful because it links cost competitiveness with investment timing, process requirements, and technology availability.

The three sectors show different decarbonisation logics. Glass production is dominated by furnace substitution and can move strongly towards hybrid electrification. Paper production is dominated by steam supply and therefore combines heat pumps, biomass, and boiler or CHP choices. Cement production requires a portfolio approach because fuel switching alone cannot eliminate process emissions. Electricity becomes increasingly important in all sectors, but for different reasons. In glass, electricity substitutes part of furnace heat input. In the paper sector, electricity enables heat pumps and electric steam technologies. In cement, electricity demand rises in connection with new process configurations and carbon capture options. This implies that regional electricity infrastructure and prices can become decisive boundary conditions for industrial transformation. Biomass is another recurring option, particularly in paper and cement. The model results show that biomass can become highly attractive from a cost perspective. This is an important result, but also a warning sign. Without explicit sustainability, availability or competing-use constraints, a cost-minimising model may overuse biomass. Future applications should therefore analyse biomass potential limits or scenario-based biomass restrictions as unavailability of biomass might restrict decarbonisation options.

The Basque Country case study shows several potential application fields of FORECAST-Sites. First, it can be used for technology screening at regional or sectoral level. Second, it can support the development of investment pathways for industrial sites by connecting technology costs with reinvestment timing. Third, it can identify infrastructure-relevant signals, such as increasing electricity demand, possible CO₂ capture requirements or future hydrogen demand and/or constraints in biomass supply. Fourth, it can support decision-making by providing an explicit and transparent structure for discussing assumptions and model results. The model is particularly useful when the research question is not only which technology has the lowest standalone cost, but when and under which conditions a technology becomes part of a cost-optimal site pathway. This is relevant for policy analysis, industrial strategy, regional infrastructure planning, and the evaluation of technology support instruments.

Modelling results identify several methodological challenges. These include flexible fuel switching (e.g. example between hydrogen and natural gas) flexible operation under electricity markets with high temporal resolution, and the need of a more specific representation of infrastructure capacities and costs for CO₂, electricity and hydrogen. In addition, the case study suggests further refinement needs for sector-specific parameters. In paper production, heat pump deployment is sensitive to the coefficient of performance and local process integration conditions. In cement production, biomass availability and sustainable fuel-mix constraints are central. In glass production, the future maturity, cost, and lifetime of full electric furnaces

strongly influence the long-term result.

The results should therefore be interpreted as first model-based insights rather than as final investment recommendations. The value of the case study lies in demonstrating how the model can structure regional analysis, reveal key assumptions and identify where additional data collection or stakeholder validation is required.

6 The Silesia Case Study: Mapping European Decarbonisation Pathways and the Regional Impacts of Carbon Infrastructure Bottlenecks with ITOM-Cement

Introduction

This study presents the application and validation of the ITOM-Cement model (Industrial Technology Optimisation Model for Cement), a high-resolution, site-specific optimisation model covering the EU27+3⁵ region. As ITOM-Cement was newly developed in the TRANSIENCE project, applying it to a full regional case study provides the necessary framework to test and validate the model's core mechanics. To showcase the model's functionality, the transformation of the European and Polish cement sector, with a specific focus on the highly industrialised Silesian region, is utilised as a core case study context. Cement contributes roughly 13% of Poland's industrial emissions (Bukowiński, 2024). Although Silesia itself hosts only one integrated cement plant, with several others located in adjacent regions, the sector serves as an ideal proxy for decentralised heavy industry. Its combination of unavoidable process emissions, high capital costs, and strict dependence on national transport and feedstock networks makes it a valuable exemplar for how regional industrial clusters adapt under tight infrastructure constraints.

Poland represents one of eleven macro-regions explicitly defined within the model, allowing for a detailed exploration of how localised infrastructure bottlenecks interact with overarching European climate mandates.

Context of the Polish Industrial Transformation

The decarbonisation of the Polish industrial sector has rapidly evolved from a secondary policy issue into a critical national priority. However, this transformation remains largely reactive to European Union regulatory mandates rather than being driven by a proactive domestic strategy. Historically, Polish industrial policy heavily prioritised short-term energy security and coal-based competitiveness, with carbon mitigation only entering strategic national frameworks after 2009.

Today, the macro-level transition is guided by the National Energy and Climate Plan (*National Energy and Climate Plan - Ministry of Climate and Environment - Gov.Pl Website, 2024*), which targets a 34% to 53% reduction in greenhouse gas (GHG) emissions compared to 1990 levels and a renewable electricity share exceeding 50% by 2030. Despite these high-level ambitions, a stark structural disparity exists between sectors. While the domestic power sector achieved a 24% decline in emissions between 2019 and 2024, industrial emissions fell by only 6%—a reduction primarily triggered by production cutbacks during recent energy crises rather than structural, planned capital investments towards cleaner technologies.

Today the Polish industrial transformation is constrained by several systemic boundary conditions, including limited national grid flexibility, and the absence of a sustained surplus of low-cost, zero-emission electricity. In hubs like Silesia, this transition is further complicated by the socio-economic necessity of balancing radical emissions reductions with a just transition for mining-dependent communities (European Commission,

⁵ EU27 + UK, CH and NO

2022). While major utilities have pledged climate neutrality by 2040, heavy manufacturing sectors continue to grapple with high capital intensity and the preservation of legacy, asset-heavy processes to safeguard regional employment. Ultimately, the Polish transition reflects a strategic clash between a conservative model focused on traditional energy security and an ambitious modernisation path aligned with the EU's "Fit for 55" package ('Fit for 55', 2021).

Stakeholder Insights: The March 2026 TRANSCIENCE Workshop

To anchor these systemic complexities within an empirical framework, this study integrates insights from the TRANSCIENCE regional stakeholder workshop held in Silesia in March 2026. A primary conclusion of the expert panel was that a Business-as-Usual (BAU) trajectory would rapidly undermine regional industrial competitiveness due to escalating EU Emissions Trading System (ETS) costs. Consequently, stakeholders recommended adopting a "Systemic Modernisation" scenario as the analytical baseline, emphasising an optimised sequence that prioritises aggressive energy efficiency measures followed by a phased deployment of deep decarbonisation technologies.

The workshop identified CO₂ transport and storage infrastructure as a "Priority I" critical investment and a definitive hard constraint for regional industry. Experts emphasised that without an operational, integrated carbon logistics network, deep decarbonisation in hard-to-abate sectors is physically impossible. This is particularly true for the cement industry, where carbon capture and storage (CCS) is a prerequisite to mitigate unavoidable process emissions given the lack of other mitigation options.

Furthermore, the workshop highlighted that the sustainable potential of biomass is frequently overestimated in broad, macro-level policy documents. Participants cautioned that due to restricted regional availability and lower thermodynamic efficiency in high-temperature applications, biomass must be treated as a secondary energy carrier rather than a primary decarbonisation solution. Within an optimisation modelling framework, biomass must be explicitly constrained as a scarce resource with an uncertain or declining supply chain.

Research Questions

Using the ITOM-Cement framework applied to this dual-scenario structure, this study addresses the following core research questions:

- What does an ambitious transformation pathway for the European cement industry look like under an efficient CO₂ infrastructure rollout? What absolute emission reductions can be achieved, what capital investments are required, and how does the industrial energy mix evolve through 2050?
- How does this industrial transformation pathway structurally adapt if the development of CO₂ transport and storage infrastructure, alongside biogenic and waste supply chains, is significantly delayed or geographically restricted within specific European regions like Poland?

Method and data

Model description

The quantitative analysis in this case study was conducted with the Industry Transformation Optimisation Model (ITOM) model, the core mathematical architecture and validation of which are detailed in deliverable D4.4 (Bussmann et al., 2024). As this study serves to showcase the model functionalities, this section outlines only the structural refinements, sectoral expansions, and data updates integrated since the initial model release.

Demand Section Refinement and Clinker Balance

To align the model with real-world data availability and ensure cross-model coherence, the demand module was simplified by removing the explicit downstream concrete application pathways within the building sector. Instead, the model is now driven by an exogenously specified, region-specific cement demand. Figure 55 gives an overview on the updated representation of the cement value chain in the model.

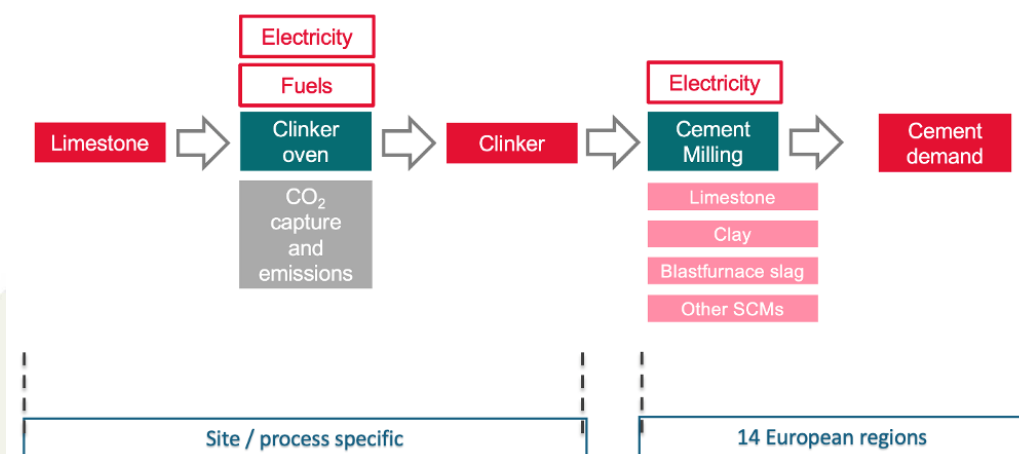


Figure 55. Representation of the cement production system in the ITOM-Cement model. On the left side the site-specific covering of the clinker production and on the right side the aggregated production of cement in 14 European regions from clinker and supplementary cementitious materials.

To satisfy this localised demand, the model selects from a portfolio of standard cement types characterised by distinct material compositions. The maximum availability and maximum blending limits of alternative Supplementary Cementitious Materials (SCMs), such as calcined clay and limestone, are exogenously defined based on established literature and scenario-specific narratives (*Cement Europe's Net Zero Roadmap*, 2024; Verein Deutscher Zementwerke, VDZ, Hrsg., 2020). The regional availability of ground blast furnace slag from the steel industry can furthermore be included from modelling results of ITOM Steel. Consequently, the residual material volume required to bridge any deficit between SCM availability and the aggregate cement demand must be met endogenously through the production of primary clinker. Figure 56 shows how the SCM availability evolves.

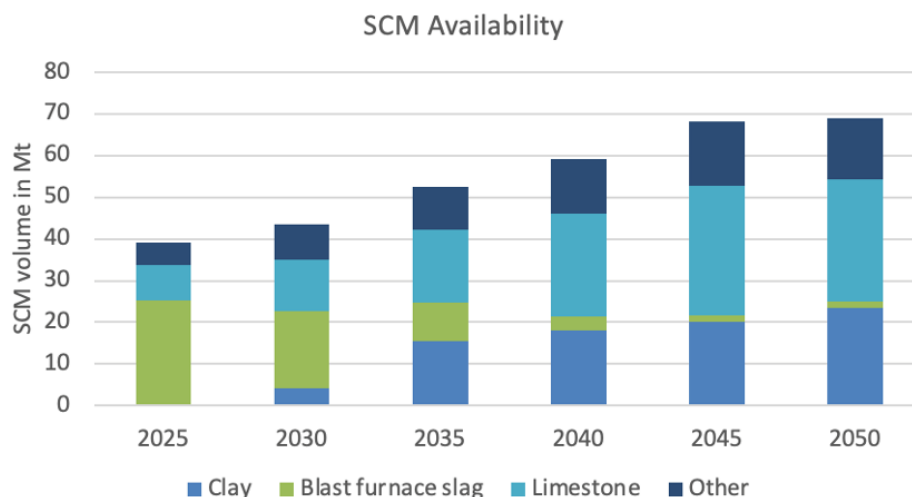


Figure 56. Availability of SCMs over the modelled period.

Geospatial Clustering of Carbon Transport and Storage Costs

The CCS module was significantly expanded from its baseline framework to better account for geographical, infrastructure, and economic constraints. The updated model explicitly covers three distinct carbon sequestration sinks: the North offshore cluster, the South offshore cluster, and an Onshore storage cluster.

The underlying economic parameters are derived from a high-resolution geospatial dataset developed by the Clean Air Task Force (Sievert et al., 2025), which specifies site-specific transport and storage costs for every active European production facility. This dataset considers multi-modal logistics, including pipeline, rail, barge, and maritime shipping pathways. To preserve computational tractability within the overarching optimisation framework, this granular dataset was aggregated and simplified via a multi-step clustering approach:

- **Disaggregation by Sink:** Individual storage locations are mapped and assigned to one of the three primary macro-hubs (North, South, Onshore).
- **K-Means Cost Clustering:** A **k-means clustering algorithm is applied to the individual marginal transport and storage cost curves of all production facilities designated to a specific hub. The choice of k remains flexible to accommodate varying research objectives, model complexity, and granularity requirements. In this study we use a $k=11$, yielding 11 archetypal, stepwise cost curves for each macro storage hub.**
- **Site-Specific Allocation:** Individual production facilities are then mapped to one or two of these representative cost curves, depending on country-specific regulatory and geological assumptions regarding the near- and long-term viability of onshore storage.

Revised Alternative Fuel Module

Decarbonisation of the thermal energy supply has been refined by upgrading the alternative fuel pathways, focusing on solid biomass and biogenic waste fractions.

To accurately capture the energy penalties of low-carbon fuel switching, the model now includes an endogenous investment pathway for upstream alternative fuel pre-treatment infrastructure (specifically drying and grinding). The expansion rate of this infrastructure is bounded by exogenous maximum diffusion constraints, which mirror real-world supply chain construction lags and biomass value chain maturity in the cement sector.

The model explicitly differentiates between *renewable waste* and *solid biomass*, as these fuel streams exhibit distinct physical properties and require different shares of low-grade process heat for thermal drying prior to kiln injection. The regional availability potentials and underlying primary supply costs for both fuel categories are parameterised using the European Commission's ENSPRESO database (Ruiz et al., 2019). For this analysis, the high-availability scenario was selected. Notably, because the absolute thermal energy demand of the cement sector utilises only a minor fraction of the aggregate European biomass potential, choice of alternative availability scenarios does not introduce systemic resource constraints within the model, we rather add additional availability constraints according to scenario narratives to not let the model tend unrealistically into biobased fuels.

To safeguard thermodynamic realism, the revised fuel module introduces a strict differentiation between high-calorific and low-calorific alternative fuels. Because maintaining the high clinker burning temperatures inside the kiln requires a stable flame profile, fuels are explicitly categorised to prevent technically unfeasible thermal substitutions at the main burner:

- High-Calorific Fuels: Pet coke, hard coal, and non-renewable waste.
- Low-Calorific Fuels: Lignite, solid biomass, and renewable waste.

A technical constraint is enforced requiring a minimum thermal energy share of 30% from high-calorific fuels at the main burner, ensuring that the modelled optimisation adheres to the physical operational realities of modern cement kilns.

Case Study Implementation and Scenario Design

A prominent point of friction identified during the stakeholder consultations was a deep scepticism among regional actors toward highly ambitious, top-down decarbonisation timelines. Notably, localised CO₂ transport infrastructure is virtually absent from current discussions between infrastructure providers and policymakers, and the utilisation of domestic onshore storage is not viewed as a viable political or social option by regional stakeholders.

To reflect this discrepancy between European-level mandates and regional implementation realities, this study implements a two-scenario modelling architecture within ITOM-Cement across its EU27+3 site-specific framework:

Ambitious Transformation Baseline Scenario: This pathway assumes a rapid, optimised transformation of the European cement industry driven by a strong EU ETS carbon price regime with prices increasing to 311 €/t in 2050. It assumes that necessary CO₂ transport and storage infrastructure is deployed on schedule and that sufficient biomass supply chains are established to satisfy industrial process heat requirements.

Delayed Regional Infrastructure Scenario: While maintaining identical EU ETS carbon price incentives, this scenario integrates the sceptical assessment of regional stakeholders regarding implementation barriers in Poland. Specifically, it completely deactivates the availability of onshore CO₂ storage within the Polish model region and shifts the CO₂ logistics pathways away from cost-effective pipeline networks toward alternative, higher-cost transport modes, specifically rail and barge, capturing the realistic impact of localised infrastructure bottlenecks and long project lead times.

Structurally, the ITOM-Cement framework is built on a site-specific asset foundation, capturing individual plant capacities, kiln types, and localised technical characteristics. However, because the model operates as a macro-level system optimiser designed to minimise the total system costs, outputs are evaluated at the national level rather than simulating independent corporate decision-making at single sites.

The parameterisation of the Delayed Regional Infrastructure Scenario bridges this macro-optimisation with subnational qualitative insights, gathered during the stakeholder workshop with the Silesian industrial cluster. Regional actors emphasised that the decisive bottlenecks for local heavy industry are not individual site limitations, but systemic national framework conditions, namely the absence of a centralised CO₂ transport strategy, regulatory barriers to onshore storage, and intense competition for national biogenic feedstocks. To reflect these subnational concerns, we operationalised these stakeholder insights into national-level boundary conditions (deactivating pipeline transport, omitting domestic storage sinks, and constraining national biomass), thereby capturing how localised infrastructure delays propagate across national industrial transitions.

Boundary conditions and assumptions

To validate the applicability and structural resilience of the ITOM-Cement model, the tool is deployed to evaluate two distinct industrial transformation pathways. Rather than serving as a direct policy forecast, the primary objective of this dual-scenario approach is to test the model's capacity to simulate complex industrial optimisation behaviour under varying degrees of infrastructure readiness and localised constraints. Because ITOM-Cement operates as a standalone sectoral model, consistent exogenous macroeconomic and climate policy boundary conditions must be established to ensure comparative validity.

Across both scenarios, the underlying production volumes that the model must satisfy act as the foundational material driver. Regional cement production volumes are assumed to remain relatively stable until 2035. For the 2035–2050 period, demand trajectories are adapted from the *GExit* project projections (Jakob et al., 2023). These trajectories explicitly incorporate progressive material efficiency assumptions resulting in a net decline in absolute cement demand over the latter half of the modelling horizon, as summarised in Table 7.

Table 9. Cement production volumes

Model Region	2025	2030	2035	2040	2045	2050
BeNeLux	6,36	6,36	6,35	6,03	5,7	5,37
CH	5,24	5,23	5,23	4,97	4,69	4,42
DE	27,68	27,65	27,61	26,23	24,8	23,35
EU_Baltic	2,46	2,45	2,45	2,33	2,2	2,07
EU_MidEast	20,49	20,46	20,43	19,42	18,35	17,28
EU_North	6,23	6,22	6,21	5,9	5,58	5,26
EU_SouthEast	20,44	20,41	20,38	19,37	18,31	17,24
EU_SouthWest	23,91	23,88	23,85	22,66	21,42	20,17
FR	14,39	14,37	14,35	13,63	12,89	12,14

Model Region	2025	2030	2035	2040	2045	2050
IE	5,78	5,77	5,76	5,47	5,17	4,87
IT	16,22	16,2	16,18	15,37	14,53	13,68
NO	2,2	2,2	2,19	2,09	1,97	1,86
PL	13	12,98	12,96	12,32	11,64	10,96
UK	8,54	8,53	8,52	8,1	7,65	7,21
Total	172,94	172,71	172,47	163,89	154,9	145,88

To drive the decarbonisation within these production targets, energy price trajectories and ETS carbon price pathways are drawn from the Horizon Europe *IAM Compact* project (Holtz et al., 2025). These price pathways represent output variables generated by the GCAM (Global Change Analysis Model) integrated assessment model, ensuring coherent systemic linkages between broader energy-economy dynamics and the localised cement sector.

Table 10. ETS certificate price as the main driver for both modelled scenarios

	Unit	2030	2035	2040	2045	2050
ETS CO₂ certificate price	€/ t CO ₂	176	234	239	273	311

Specifically, the EU ETS carbon price serves as the central economic mechanism for decarbonisation, following a steep escalation path that reaches key regulatory landmarks of €176/t CO₂ by 2030 and €311/t CO₂ by 2050 (Table 10). The exogenous price trajectories from the *IAM Compact* project are applied to core energy carriers, specifically electricity and fossil fuels (e.g., hard coal, pet coke). Other energy carriers, including biomass, renewable waste, and non-renewable waste, rely on baseline technoeconomic data inherent to the internal ITOM database.

To test how the cement production system behaves when critical decarbonisation pathways are constrained, a second scenario the **Delayed Regional Infrastructure Scenario** is modelled. This scenario maintains identical overarching European macroeconomic drivers, including the baseline cement demand, the EU ETS price trajectory, and energy prices. However, it alters localised supply chain and carbon management infrastructure availability within the Polish model regions by integrating refined, sceptical regional assumptions on carbon management logistics: Domestic onshore CO₂ storage is entirely deactivated as an available model option for Poland. Furthermore, cost-effective CO₂ transport pipelines are omitted from the regional technology portfolio. Instead, carbon transport logistics are restricted to alternative, multi-modal transport pathways—specifically rail and barge networks—triggering higher site-specific marginal transport costs and representing significant project implementation bottlenecks.

Results

Main results for the EU27 ambitious baseline scenario

The emissions trajectory for the European cement industry under the ambitious transformation baseline scenario is illustrated in Figure 57. The emissions profile is differentiated by source type (fossil, process, and biogenic) alongside the volumes mitigated via CCS. The solid line denotes the resulting net emissions balance.

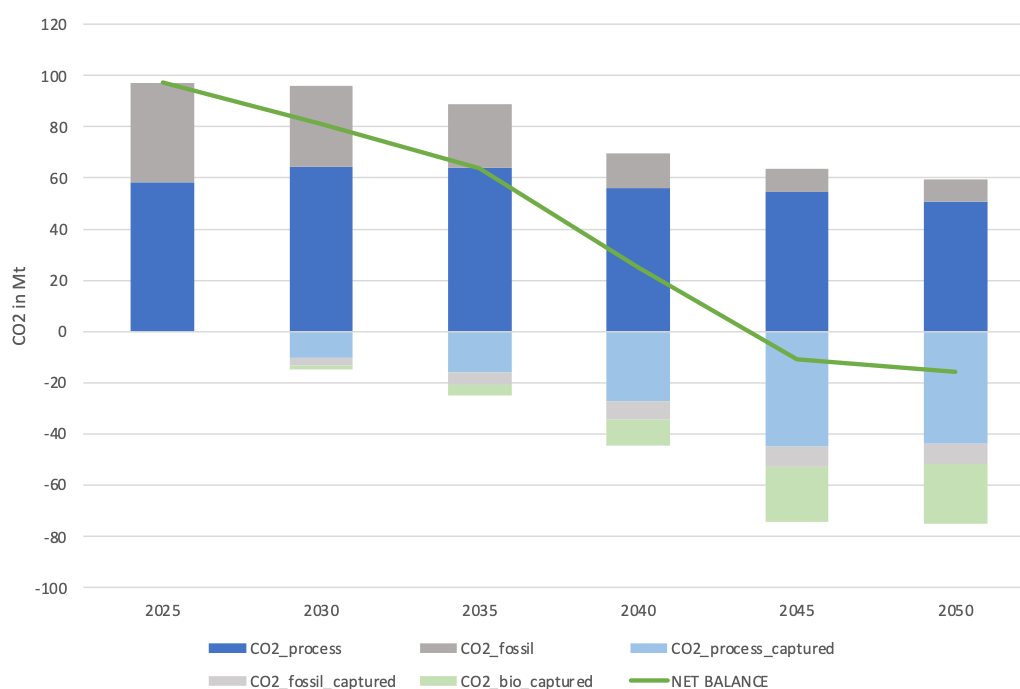


Figure 57. EU27 emissions trajectory by source type of the baseline scenario

Under prevailing emissions accounting frameworks, biogenic emissions are exclusively recorded when captured, as they are omitted from the positive emission accounts. Consequently, the combustion of biogenic fuels coupled with carbon capture functions as Bioenergy with Carbon Capture and Storage (BECCS), generating net-negative emissions. Driven by the EU ETS carbon price trajectory detailed in the methodology the sector undergoes a deep defossilisation. Overall, total net emissions decline significantly from 97 Mt CO₂ in 2025 to reach a net-negative balance of -16 Mt CO₂ by 2050.

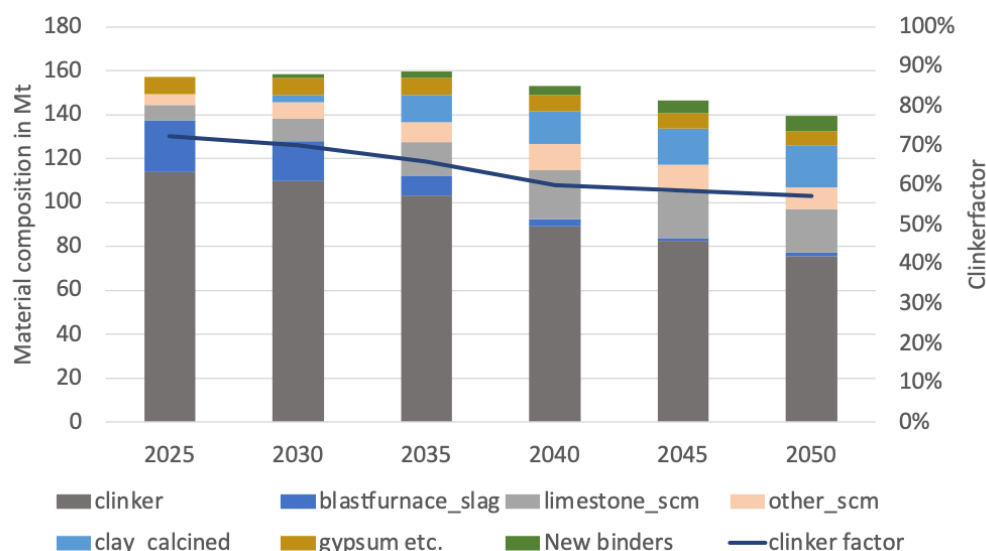


Figure 58. Evolution of cement composition. Left axis: EU27 material composition of cement in Mt. Right axis: Clinker factor in %.

Figure 58 details the structural shift in European cement composition over the transition period. The average clinker factor decreases markedly from over 72% in 2025 to a more diversified cement mix with a 57% clinker share by 2050. Ground Granulated Blast-Furnace Slag, that was historically and initially the primary Supplementary Cementitious Material (SCM), is gradually phased out. This decline directly reflects the broader decarbonisation of the steel sector and the subsequent decommissioning of traditional blast furnaces. To compensate for this deficit, the industry primarily substitutes slag with limestone and calcined clay, alongside a minor share of novel binders that commercialise in later timesteps. Conversely, the market shares of gypsum and alternative SCMs remain virtually constant; this behaviour is governed by exogenous model constraints reflecting maximum permissible blending limits in standard cement specifications. Driven by both a declining clinker factor and changing demand dynamics, total EU27 clinker production falls from 125 Mt in 2025 to 76 Mt by 2050.

The evolving energy mix of the European cement industry is presented in Figure 59. Induced by the high EU ETS price, the sector transitions away from conventional fossil fuels and non-renewable waste toward a fuel mix dominated by renewable waste, a residual share of non-renewable waste, and electricity. Conventional fossil fuels are entirely phased out after 2035.

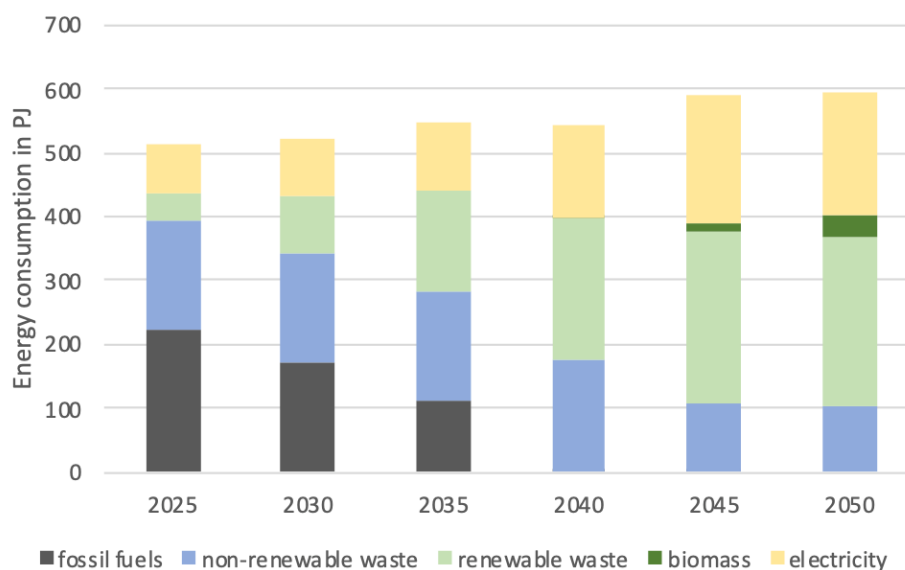


Figure 59. EU27 energy consumption in the baseline scenario

Despite the contraction in absolute cement and clinker production volumes, aggregate energy consumption increases by approximately 15%, rising from 512 PJ in 2025 to 594 PJ in 2050. This net increase is driven by the significant energy penalty associated with CCS operations, as well as the thermal energy required for drying and pre-treating biogenic and renewable fuels. Notably, the electricity consumption component more than doubles within this total, climbing from 80 PJ in 2025 to 192 PJ in 2050.

The deployment and technological transformation of clinker production capacities are depicted in Figure 60. In the initial timestep (2025), the entire kiln fleet operates without carbon capture capabilities.

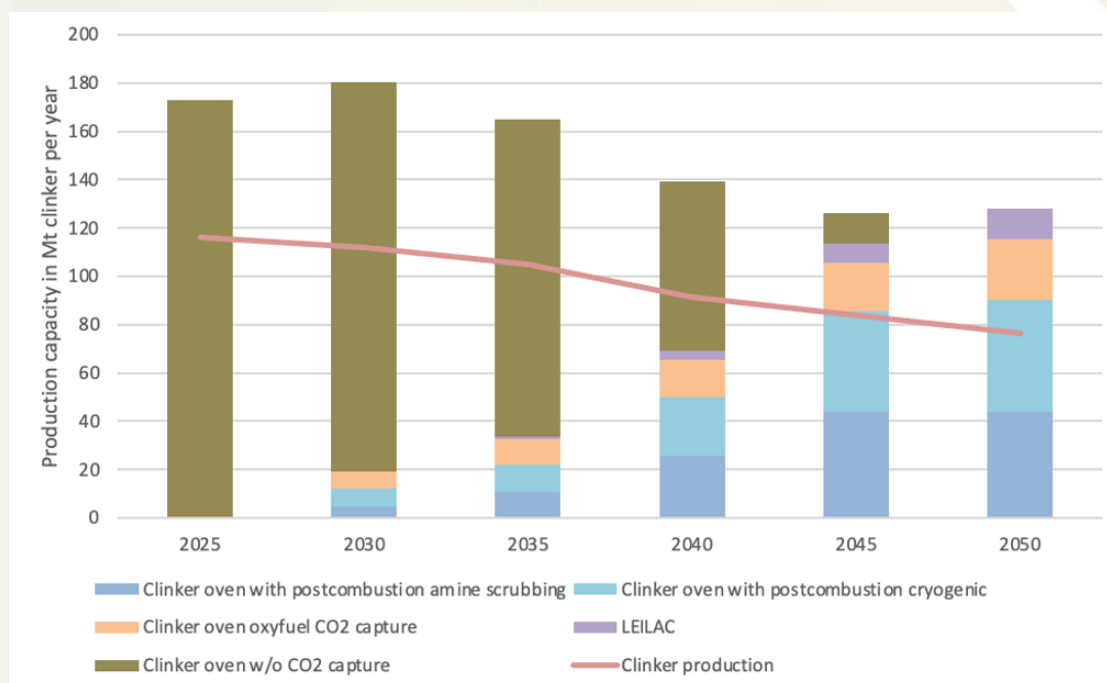


Figure 60. Evolution of EU wide installed clinker production capacity by kiln/capture type

Beginning in 2030 CO₂ capture technologies are progressively phased into operation. The early wave of deployment is heavily dominated by post-combustion technologies owing to their suitability for retrofitting existing kiln infrastructure. This phase is subsequently followed by the introduction of oxyfuel kilns featuring fully integrated carbon capture. It should be noted that the deployment velocity of these low-carbon configurations was regulated by exogenous maximum diffusion rates within the model, reflecting the industry's realistic supply chain, installation, and financing constraints. By 2050 the structural transition is complete: 100% of the active clinker production capacity is equipped with carbon capture, utilised via either integrated or post-combustion setups.

Figure 61 illustrates the total volume of captured CO₂ directed to permanent storage, disaggregated by three geographical storage clusters defined in the model: North, South, and Onshore.

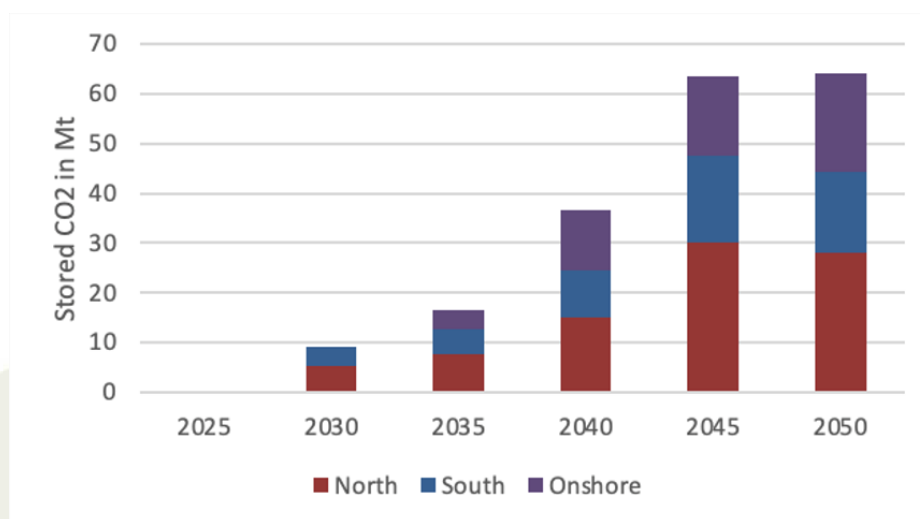


Figure 61. Stored CO₂ from the European cement sector differentiated by storage cluster.

Sequestration activities commence in the 2030 timestep with an aggregate volume of 9 Mt CO₂, distributed between the North and South offshore clusters. Onshore storage infrastructure registers a minor share starting in 2035. By the 2045 and 2050 timesteps, total sequestered volumes plateau at a system maximum of 64 Mt CO₂. Within this final decade, however, a distinct structural shift occurs volumes migrate away from offshore sites toward increased onshore utilisation, driven by the progressive regulatory approval and development of onshore storage projects across a broader set of European member states.

Influence of delayed infrastructure development

To assess the economic implications of regional infrastructure bottlenecks, Figure 62 illustrates the evolution of marginal cement production costs (€/t) from 2025 to 2050. The analysis compares the baseline and delayed infrastructure scenarios for the Polish model region (solid lines) against the volume-weighted EU mean marginal production costs (dashed lines).

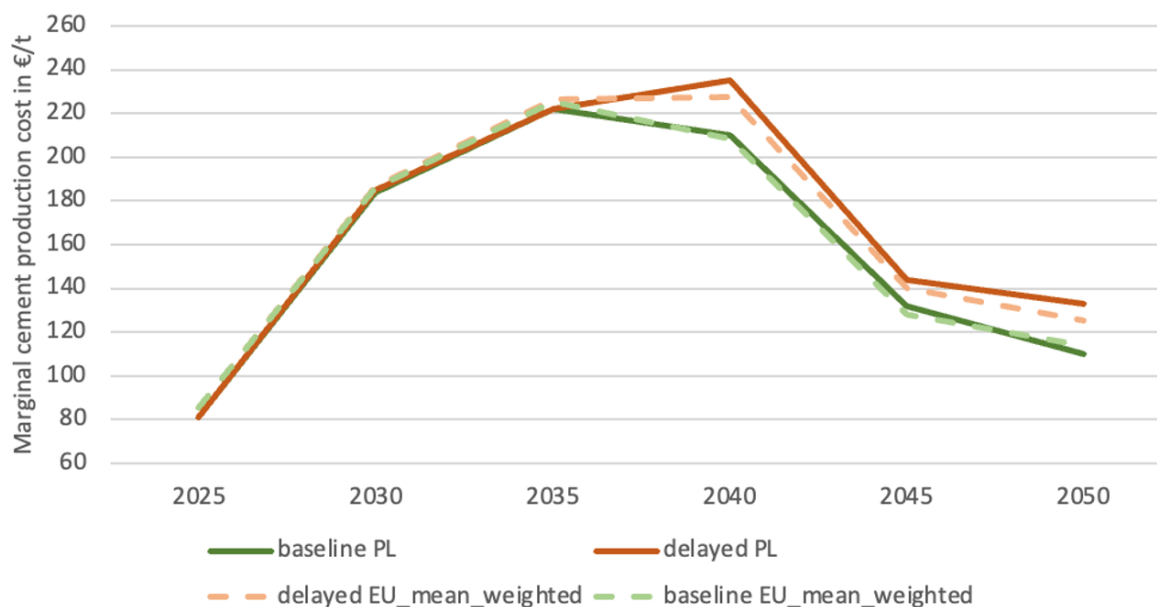


Figure 62. Marginal cement production cost in the EU and Poland for the baseline and the delayed scenario. Dotted lines show the EU mean marginal production cost weighted by the regional production volumes. Solid lines show the marginal production cost for Poland

Between 2025 and 2035, marginal production costs follow an identical upward trajectory across both scenarios and regions. During this initial phase, costs increase sharply from approximately €80/t in 2025 to peak at roughly €220/t by 2035. This parallel cost escalation is directly driven by the rapidly increasing EU ETS carbon price regime, which places a heavy financial penalty on unabated fossil fuel combustion and process emissions.

Because the deployment of carbon capture technologies is bounded by realistic industrial diffusion limits during this first decade, the entire European sector passes through a period of high carbon exposure. Crucially, the marginal production costs for Poland (solid green and orange lines) track in line with the weighted EU average (dashed green and orange lines), indicating that Poland maintains its relative cost competitiveness during the early phases of the carbon price incline.

A stark divergence between the two scenarios occurs after 2035. In the *Ambitious Transformation Baseline Scenario* (green lines), marginal production costs across both the EU and Poland begin a steady decline, dropping from the ~€220/t peak down to approximately €110/t by 2050.

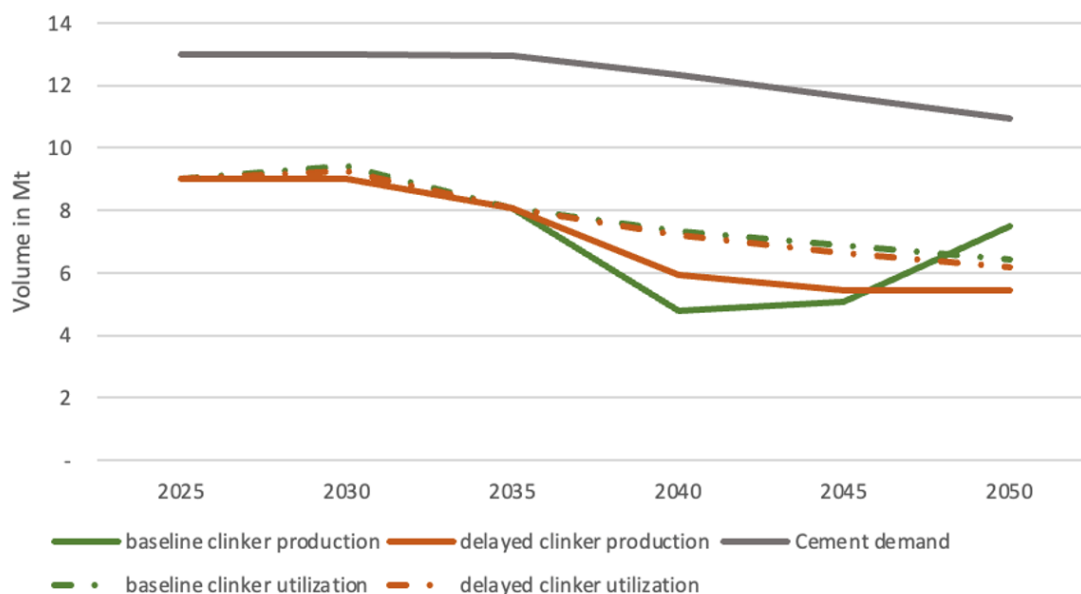


Figure 63. Cement demand, clinker production, and clinker utilisation trajectories in Poland

To uncover the operational mechanisms driving the divergent regional cost curves, Figure 63 illustrates the trajectories of absolute cement demand, clinker production, and internal clinker utilisation (measured in million tonnes, Mt) within the Polish model region across both scenarios.

Up to the 2035 timestep, clinker production and domestic utilisation track nearly symmetrically across both scenarios, remaining steady at approximately 9 Mt to satisfy a stable regional cement demand of 13 Mt. The gap between clinker utilisation and total cement demand represents the baseline incorporation of standard SCMs.

Between 2035 and 2040, a major structural shift occurs as the EU ETS price rises toward its €176/t landmark. In the *Ambitious Transformation Baseline Scenario*, domestic clinker production drops precipitously from 8 Mt in 2035 to its lowest point of 4.8 Mt in 2040 (solid green line). However, internal clinker utilisation remains significantly higher at 7.3 Mt (dashed green line). This wide deficit indicates that the optimisation model prefers to import clinker from other EU regions rather than continuing inefficient, carbon-exposed domestic production while local CCS infrastructure is still expanding.

In contrast, under the *Delayed Regional Infrastructure Scenario*, domestic clinker production drops less severely, reaching 6 Mt in 2040 (solid orange line), indicating that the production stays localised despite a rising exposure to rising ETS cost. Because the lack of localised pipelines and onshore storage heavily penalises the downstream logistics of carbon management in Poland, the systemic cost of integrating the region into the wider low-carbon EU supply chain shifts. However, it is more cost-effective for the model to sustain a higher volume of carbon-exposed domestic production rather than relying as heavily on imports. This suboptimal economic lock-in directly drives the steep marginal production cost premium observed in Poland during this decade.

In the final decade of the modelling horizon (2045–2050), the two pathways diverge radically, establishing the physical operational landscape that directly dictates the industry's late-stage capital expenditure. Under the delayed infrastructure pathway, domestic clinker production completely flattens, locking in at exactly 5.4 Mt between 2045 and 2050. Bound by high multi-modal logistics costs (rail/barge) for its residual captured emissions, the regional industry reaches an operational optimisation ceiling. Under a €311/t

carbon price, expanding or shifting domestic clinker capacity becomes economically unviable, freezing the sector's operational state. Conversely, the baseline scenario exhibits an extraordinary operational inversion by 2050. Enabled by a mature, cost-effective regional pipeline network and onshore storage hubs, domestic clinker production in Poland rebounds sharply, surging from 5.1 Mt in 2045 to 7.5 Mt by 2050. Under this optimised baseline environment, Poland transforms from a net clinker importer back into a highly competitive production centre. By 2050, domestic production exceeds domestic utilisation (~6.4 Mt), allowing the optimised Polish cement sector to leverage its infrastructure advantage and act as a net exporter of low-carbon clinker to the broader European market.

Cumulative Capital Expenditure and Technology Asset Shifts

To examine the physical asset transformations enabling these operational strategies, Figure 64 illustrates the cumulative capital investment (CAPEX) in kiln infrastructure and post-combustion carbon capture systems within Poland.

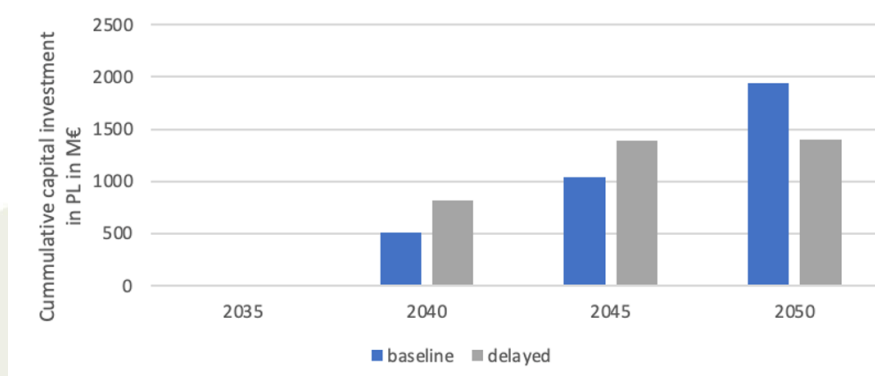


Figure 64. Cumulative capital investment in kiln and post-combustion CCS technology in Poland

Up to 2035, zero asset-level capital expenditure occurs across both scenarios as the pre-existing kiln fleet continues operating without carbon capture retrofits. However, a distinct investment paradox emerges during the 2040–2045 transition decade. By 2040, cumulative investment under the *Delayed Regional Infrastructure Scenario* (grey bar) reaches 820 M€, 60% higher than the 510 M€ spent in the *Ambitious Transformation Baseline Scenario* (blue bar). This premium persists into 2045, with the delayed pathway accumulating nearly 1400 M€ compared to roughly 1050 M€ in the baseline.

This front-loading directly explains the operational trends identified in the previous section. Because the delayed scenario lacks low-cost pipelines and onshore CO₂ storage, the model cannot easily substitute local production with cheaper low-carbon imports. To sustain the higher domestic clinker production required to meet demand under a steep 176€/t carbon price, the Polish cement sector is forced to aggressively front-load capital to retrofit localised kiln assets with post-combustion CCS, despite relying on highly sub-optimal downstream logistics (rail and barge).

By the 2050 horizon, as the EU ETS price reaches 311€/t, this investment paradigm reverses. In the baseline scenario, cumulative CAPEX surges to approximately 1950 M€ by 2050, representing the late-stage deployment of clinker production systems (such as integrated oxyfuel kilns) unlocked by a mature regional pipeline network. This investment directly powers Poland's operational resurgence into a competitive net exporter.

Conversely, cumulative investment in the delayed infrastructure scenario completely plateaus between 2045 and 2050, remaining frozen at roughly 1400 M€. This highlights the ultimate systemic risk of permanent infrastructure bottlenecks; when lack of pipelines locks in high multi-modal logistics costs, further capital investment in capture technology ceases to be economically viable. The sector hits a technical stagnation ceiling, capping domestic production and cementing the region's cost penalty.

Discussion

This study presented the new developments and EU wide as well as localised application of the ITOM-Cement model, demonstrating its capacity to evaluate complex industrial system behaviour under stringent ETS, energy cost, and technology rollout constraints. By introducing advanced modelling features, e.g. the revised CO₂ transport and storage section, ITOM-Cement provides a robust tool for analysing the decarbonisation pathways of the European cement industry.

RQ1: The Ambitious Baseline Pathway

To answer the research questions stated in the introduction we modelled the *Ambitious baseline scenario*. Under an idealised infrastructure rollout, an ambitious transformation pathway for the European cement industry across the EU relies on swift, high-capital technical adaptation driven by the EU ETS price. The model demonstrates that absolute European process and fossil emissions can be abated, provided that cost-effective carbon pipeline networks are available by 2040. To achieve deep defossilisation, massive capital investments are required to systematically deploy new clinker kiln technologies and post-combustion CCS facilities. The overarching European energy mix shifts fundamentally: coal is displaced entirely by biomass and renewable waste fractions, while a steady baseline of high-calorific non-renewable waste is maintained. Crucially, this transformation triggers a massive shift toward electrification, with total European electricity demand more than doubling to electricity extensive carbon capture operations.

RQ2: Regional Structural Adaptations Under Infrastructure Delays.

When critical CO₂ transport networks, storage sinks, and biogenic supply chains are delayed or geographically restricted, as tested in the Polish model regions, the industrial transformation path is drastically altered. Because trade conditions remain unconstrained across both scenarios, the model's structural adaptation is purely economic. Instead of utilising early low-carbon imports to avoid compliance costs, the infrastructure bottleneck forces Poland to sustain higher domestic clinker production in the mid-horizon. This operational lock-in forces a massive, front-loading of capital investment into localised post-combustion carbon capture retrofits. Ultimately, however, high multi-modal logistics costs (rail/barge) cap further expansion, resulting in a complete CAPEX and production plateau after 2045, technical stagnation, and a persistent regional cost penalty by 2050.

Limitations

While the ITOM-Cement application successfully isolates the impact of infrastructure availability on sectoral optimisation, several key limitations must be acknowledged when interpreting these results.

The model operates under fixed exogenous cement demand trajectories derived from the *GExit* project. It does not account for downstream economic feedback, where the significant marginal production cost premiums observed in the delayed scenario (e.g., the €23/t penalty) would realistically depress cement demand, drive material substitution, or trigger local construction market contraction.

Due to limited project capacity to model a wider matrix of paths, this study explored only two extreme infrastructure configurations (an idealised rollout versus a highly restrictive, localised delay). In reality, a multitude of intermediate timeline configurations, phased rollouts, or partial pipeline network expansions are possible, which would yield a more nuanced cost and investment spectrum over the 2025–2050 horizon.

The sceptical infrastructure assumptions were applied exclusively to the Polish model regions. It would be highly valuable to model a broader lag in carbon infrastructure development across multiple European nations simultaneously. A wider regional bottleneck of this nature would alter inter-regional clinker trade dynamics, potentially eliminating Poland's ability to rely on net imports during its transition decades and shifting the overall European supply equilibrium.

The model's macroeconomic baseline is tightly coupled to a single, specific data source—the Horizon Europe *IAM Compact* project framework and its GCAM-derived energy and carbon price pathways. Consequently, the absolute cost curves and timeline transitions are highly sensitive to these specific exogenous price projections.

While the model explicitly tracks shifting SCM availabilities and handles unconstrained inter-regional trade for clinker, it does not fully model a highly competitive, cross-border market for alternative raw materials (like calcined clays or imported slag). As clinker utilisation falls across Europe, regional competition for high-quality SCMs might intensify, which could introduce additional cost variables not captured in the current sectoral framework.

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7 The Port of Rotterdam Case Study: Exploring future environmental burdens and trade-offs of decarbonisation pathways in the chemical sector

Introduction

The Port of Rotterdam is one of Europe's largest industrial and petrochemical clusters and plays a key role in the production, import, conversion, and distribution of fuels, chemicals, and materials (Schneider et al., 2025). As such, it is an important cluster for studying industrial decarbonisation pathways, the circular economy, and the future role of alternative feedstocks, electrification, and carbon capture and storage (CCS) (Port of Rotterdam, 2026). Various MIC3 models represent such transition pathways in terms of technology deployment, material flows, energy demand, and costs. More specifically, the ITOM model (Wuppertal Institute, 2025) provides an optimisation problem that optimises (part of) the chemical cluster for the Port of Rotterdam. However, these MIC3 models (such as ITOM) do not directly quantify full life cycle environmental burdens, meaning that potentially important environmental trade-offs, co-benefits, geopolitical dependencies, and potential burden shifting to other regions remain unclear. For this reason, environmental life cycle assessment (LCA) is required (Hellweg & i Canals, 2014), which needs to be coupled to the various MIC3 modules. Here, the main research question of this case study is: How can local industrial transition pathways for the Port of Rotterdam be coupled with environmental life cycle assessment to assess the broader environmental burdens of such (low carbon) industrial energy transitions?

This case study focuses on translating energy model outputs from various MIC3 models for the Port of Rotterdam into life cycle inventories to quantify overall environmental burdens of industrial decarbonisation pathways. In particular, IAMC-style outputs from models such as OPEN-PROM, FORECAST, and ITOM are used to describe technology-specific production volumes, energy requirements, material inputs, and final product demand. These outputs are then linked to background life cycle inventory databases (those provided by ecoinvent (Wernet et al., 2016) and premise (Sacchi et al., 2022)) to quantify environmental impacts beyond the direct system boundary of the Port of Rotterdam.

The environmental LCA module is particularly relevant for this case study because it complements the strengths of the other MIC3 modules. While other MIC3 modules, such as ITOM, describe how the Port of Rotterdam's industrial system may evolve in terms of technologies, energy use, material flows, and costs, they do not quantify the wider environmental implications associated with these industrial pathways. This is especially important for the Port of Rotterdam, where decarbonisation strategies such as electrification, hydrogen, biomass, circular feedstocks, and CCS affect global supply chains and can introduce environmental trade-offs throughout multiple environmental impact categories. The environmental LCA module therefore helps identify not only climate benefits, but also environmental co-benefits and burden shifting beyond the boundaries of industrial clusters.

Method and data

In this chapter, we first briefly discuss the set-up of the stakeholder workshop at the Port of Rotterdam. Next, we dive into the modelling work to answer the main research question, which is sub-divided into the Goal and Scope, Functional Unit and System Boundaries, Life Cycle Inventory Modelling, Modified background LCA databases and scenario packages, and Life Cycle Impact Assessment.

Stakeholder workshop at the Port of Rotterdam

The TRANSCIENCE consortium organised a workshop at the Rotterdam to identify the most relevant research questions for the Port of Rotterdam authority. During the workshop, participants discussed ongoing decarbonisation challenges, future development pathways, and sustainability priorities for the Rotterdam industrial cluster. These discussions identified a key knowledge gap: while many industrial transition studies focus primarily on carbon dioxide or greenhouse gas (GHG) emissions, much less is known about the broader environmental implications of large-scale decarbonisation strategies of their industrial cluster. Consequently, stakeholders expressed interest in understanding potential environmental trade-offs, co-benefits, and burden shifting associated with alternative decarbonisation pathways for the chemical sector in the Port of Rotterdam.

Modelling of research questions

Figure 65 illustrates an overview of the Methods and Data used for the case study to evaluate the above research question. The environmental LCA module relies on life cycle inventory data from ecoinvent 3.12 (Wernet et al., 2016), which is a static representation of the global economy. Ecoinvent serves as the background database and provides geographically and technologically differentiated data/inventories for, among others, energy, materials, transport, waste management, and industrial processes across global supply chains. However, such conventional background LCA databases represent a snapshot of the current economy and therefore do not capture future technological and structural changes. However, for the case study of the Port of Rotterdam, we are particularly interested in future defossilisation pathways of the chemical industry. Thus, we should consider a future decarbonisation scenario of the Port of Rotterdam and the background global and European economy. This implies that we need to modify the background LCA database to be more consistent with potential future global economies.

To address this limitation, prospective modified background LCA databases can be generated using the open-source framework *premise* (Sacchi et al., 2022). *Premise* modifies background LCA databases from ecoinvent based on external scenario information, such as those from Integrated Assessment Model (IAM) pathways, like REMIND, by updating technology market shares, process efficiencies, emissions, and supply mixes across various sectors, such as electricity, fuels, transport, steel, and cement. In addition, *premise* has been enhanced to integrate scenario outputs from other TRANSCIENCE/MIC3 modules, including OPEN-PROM, ITOM, and FORECAST, thereby enabling a more consistent coupling between industrial transformation pathways and background life cycle inventories.

Subsequently, the *pathways* framework (Sacchi & Hahn-Menacho, 2024) is used to quantify the environmental impacts of entire industrial transformation pathways, allowing the assessment of environmental trade-offs and co-benefits across a broad range of impact categories beyond climate change impacts. Finally, the resulting prospective databases and energy system transformation were transferred to the Brightway ecosystem (Mutel, 2017) to calculate environmental impacts of individual technologies and products.

Next, since the framework applies an LCA approach to entire energy system transformation scenarios, we structure the Methods and Data into the Goal and Scope, Functional unit and system boundaries, life cycle inventory modelling, and environmental impact assessment.

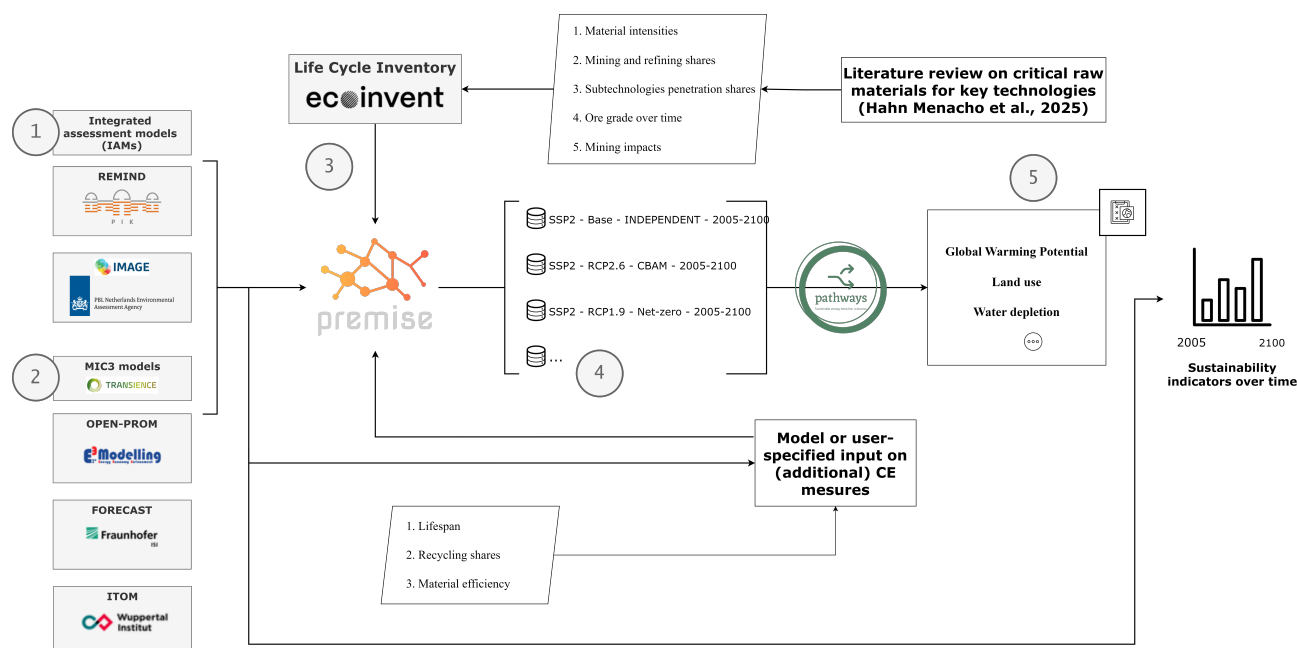


Figure 65. Overview of the environmental LCA module and connections between energy system, integrated assessment, material flow, and industrial models. The figure is based on the work of (Hahn Menacho et al., (2025) and has been modified to make it representative for MIC3. The figure is reproduced from D4.7. CE = circular economy

Goal and scope

This case study applies the environmental LCA module developed within the TRANSIENCE project, as part of the MIC3 framework. The goal is to assess the environmental burdens, trade-offs, and co-benefits of industrial decarbonisation pathways for the chemical sector in the Port of Rotterdam. The chemical sector was selected because it is a major contributor to industrial emissions, is central to distinct value chains, and faces multiple competing decarbonisation pathways. This complexity makes it an ideal test case for demonstrating how the TRANSIENCE environmental LCA module can quantify environmental trade-offs and co-benefits while avoiding burden shifting. As such, our assessment evaluates broader environmental impacts such as resource use, human toxicity, ecosystem quality, and other burdens that may arise from feedstock shifts, electrification, hydrogen use, recycling, carbon capture, and changes in import dependencies.

The LCA module is designed as a flexible and transparent framework that can integrate outputs from other MIC3 modules, including local industrial transformation models and energy system scenarios. In this case study, outputs from the ITOM, OPEN-PROM, and FORECAST models are used to represent alternative transformation pathways for the Port of Rotterdam chemical cluster (see Table 12). These model outputs describe technology deployment, production volumes, material flows, energy inputs, and final product demand over time. The LCA module then translates these pathways into life cycle inventories and an assessment of environmental burdens.

Overall, an attributional LCA perspective is adopted, using ecoinvent v3.12 (Wernet et al., 2016) as a source of background database using the system model “allocation, cut-off by classification”. The assessment is implemented using the open-source Brightway framework (Mutel, 2017), while prospective modifications to background processes are introduced using *premise* (Sacchi et al., 2022).

Functional unit and system boundaries

The functional unit is defined as the annual production of all final-demand chemical products supplied by the Port of Rotterdam chemical sector in a given model year, i.e. '1 year of chemical production in the Port of Rotterdam system'. Final-demand products include explicitly demanded outputs, such as polymers and chemical products represented in the industrial transformation model. Intermediate products and by-products are not treated as independent functional units but are used to construct upstream supply chains and market mixes within the modified LCA databases. This distinction is key to avoid potential double counting, since intermediates may already be consumed in the production of final products. An overview of chemical products, as part of the functional unit, is provided in Table 11. Imports are considered in the market mix of intermediate products; however, we do not consider any credits for intermediates that are exported.

Table 11. Mapping between final-demand products from the Port of Rotterdam chemical-sector model and the corresponding foreground life cycle inventory (LCI) activities used in the environmental assessment. Retrofit activities represent improved versions of existing production technologies, while lignin-based polyols represent bio-based production routes using lignin-derived feedstocks

Final product	Production technology	Ecoinvent activity	Reference product
MDI	MDI_default	MDI production	methylene diisocyanate diphenyl
PBR	PBR	PBR production	styrene butadiene rubber, solution polymerised
PET	polyethylene_terephthalate_(PET)_default	PET production	polyethylene terephthalate, granulate, amorphous
Polypropylene	polypropylene_(PP)_default	PPP production	polypropylene, granulate
Nylon 6.6	nylon_6_6_default	nylon 6-6 production	nylon 6-6
Polyols	polyol_default	PEP production	polyether polyols, long chain
Polyols	retrofit_polyol_BAT	PEP production, retrofit	polyether polyols, long chain
Polyols	polyol_from_lignin	PEP production, from lignin	polyol
PLA	PLA_from_sugar	PLA production	polylactic acid
PBS	polybutylene_succinate_(PBS)	PBS production	polybutylene succinate
PMMA	PMMA_default	PMMA production	polymethyl methacrylate

The system boundaries include the foreground industrial transformation pathways represented by the Port of Rotterdam model (from ITOM) and the associated upstream and downstream life cycle processes represented in the background LCA databases. This allows the assessment to capture environmental burdens that occur outside the direct geographical boundary of the Port, including upstream energy supply, feedstock production, material imports, waste treatment, and technology supply chains. The use phase and end-of-life treatment of the produced polymers (here indicated as ‘final’ products) are excluded, as a substantial share of these products is exported and their final applications, locations, and disposal routes are unknown.

Table 12. Description of data used in the environmental LCA module and for the case study in the Port of Rotterdam. This table is reproduced from D4.7 but has been adapted for the PoR case study

Data type	Description	Source(s)
Background LCA database	The ecoinvent v3.12 database is used as a source of background, representing the global economy of year ~2025.	(Wernet et al., 2016)
Integrated assessment model (IAM) scenarios	IAM scenarios modify the entire background LCA database first, ensuring that the future economy changes not only in Europe but also globally.	(Baumstark et al., 2021)
Energy system scenarios from OPEN-PROM	Energy system model output from OPEN-PROM. Country- and continent-specific electricity and hydrogen mixes are used to modify them in the background LCA database.	(E3Modelling, 2025)
Industrial energy transformation scenarios from ITOM	Module output from ITOM. Data used for the European steel industry.	(Scholz et al., 2025; Wuppertal Institute, 2025)
Industrial energy transformation scenarios from FORECAST	Module output from FORECAST. Currently, country-specific (preliminary) data are provided and used for the ammonia and methanol industry in Europe.	(Marius Neuwirth, 2024; Neuwirth et al., 2024)
Cluster energy transformation for the Port of Rotterdam from ITOM	Data for the Port of Rotterdam cluster have been obtained from ITOM using one energy system transformation scenario.	(Schneider et al., 2025; Wuppertal Institute, 2025)
Additional circular economy measures	The possible option to apply user-specific modifications in the background LCA database, considering primary vs. secondary shares of metals.	n.a.

Life cycle inventory modelling

The model outputs of the MIC3 models used (see Table 12) are first converted into an IAMC-style format, including information on region, product, technology, year, output value, and unit. For the Port of Rotterdam, energy system model outputs are classified into final polymer outputs, intermediates and by-products, material inputs, energy inputs, and CO₂-related accounting flows. Production volumes are then used to construct product-specific market mixes for each relevant (intermediate) product, region, and year in the Port of Rotterdam. These market mixes represent the contribution of different technologies to the supply of a given product, such as ethylene, benzene, toluene, p-xylene, and propylene. Those market mixes

are essential for producing the various polymers listed in Table 12.

Technology inventories are developed by linking model variables to life cycle inventory datasets (see Table 11). Where possible, foreground technology inventories are either (i) constructed from the available model data on material inputs, energy inputs, product outputs, by-products, and emissions, or (ii) linked to existing ecoinvent datasets that are regionalised to be better representable for the Netherlands. Background processes are linked to ecoinvent 3.12, and prospective LCA background databases are generated with *premise*. CO₂-related accounting variables, such as ETS allowances or avoided-incineration credits, are treated separately and are not mapped to conventional LCI datasets unless explicitly required.

Modified background LCA databases and scenario packages

The environmental LCA module builds on open-source tools such as *premise* (Sacchi et al., 2022), which modifies background LCA databases according to future energy and industrial scenarios, and the *pathways* tool (Sacchi & Hahn-Menacho, 2024), which enables the assessment of entire energy transformation pathways. This allows the Port of Rotterdam case study to evaluate how environmental impacts change under future background conditions, such as electricity system decarbonisation, changing fuel mixes, and evolving material supply chains.

First, the transformation was based on the REMIND ‘SSP2-NDC scenario’ (Baumstark et al., 2021) – i.e., a relatively conservative climate pathway combining Shared Socioeconomic Pathway 2 (SSP2) (Fricko et al., 2017) with countries’ Nationally Determined Contributions (NDCs) under the Paris Agreement. It was complemented with several external scenario packages developed within the TRANSIENCE project (Table 14). The REMIND pathway provides an overview of global socio-economic and energy system developments, while OPEN-PROM updates electricity and hydrogen supply mixes for many countries worldwide. In addition, ITOM modifies the European steel sector, and FORECAST introduces country-specific ammonia and methanol markets across Europe.

Finally, the ITOM-PetChem module integrates chemical-sector transformation pathways specifically for the Port of Rotterdam. The latter includes changes in precursor market mixes and the final energy demand associated with polymer production. Together, these scenario packages create a prospective background database that combines global energy system developments with detailed sectoral and regional industrial transition pathways relevant for the Port of Rotterdam.

In addition to changes in energy systems and production technologies, a novel element of the environmental LCA module is integrating and adapting evolving material supply chains. As industrial decarbonisation may increase the use of recycled materials, future changes in the balance between primary and secondary material production should be reflected in the background database where possible.

Shares of primary versus secondary metals and integration in LCA

To potentially represent future developments in material circularity and recycling within the prospective LCA framework, data was collected for primary and secondary metal supply shares. The objective was to move beyond the static recycling assumptions represented in current life cycle inventory databases and introduce metal-specific projections of future metal recycling assumptions. The resulting dataset provides primary and secondary supply shares for a broad range of metals and metal intermediates under alternative 2050 circularity scenarios. Those assumptions are presented in Table 13.

The development of the dataset followed a four-step approach. First, current primary and secondary supply

shares were established for all relevant metals and intermediates. Secondary supply shares were derived by systematically identifying recycling and waste treatment activities that generate secondary metal outputs and linking these outputs to the corresponding market datasets. The aggregated contribution of all recycling routes was used to determine the secondary share of supply, while the remaining fraction was attributed to primary production.

Second, future recycling potentials were derived through reviewing scientific and grey literature. Data sources included reports from the International Energy Agency (IEA), OECD Global Material Resources Outlook, International Resource Panel (IRP), European Commission Joint Research Centre (JRC), and metal-specific material flow analysis studies. The collected evidence included projected recycling rates, scrap availability, secondary production potentials, and circularity indicators. Because future projections are not available for every individual metal product in the life cycle inventory database, metals were grouped into broader material families that share similar recycling characteristics and supply-chain structures.

Third, future secondary supply shares were estimated for three scenarios representing different levels of circular economy development. The conservative scenario assumes gradual improvements in collection and recycling systems, resulting in modest increases in secondary production. The circular scenario represents substantial improvements in material recovery, recycling infrastructure, and product circularity. The optimistic scenario assumes widespread deployment of advanced recycling technologies and high collection efficiencies, approaching estimated technical recycling limits. Here, we tested the optimistic scenario for the case study. For each material family, projected secondary supply shares were translated into corresponding primary supply shares while ensuring that the combined shares sum to '1'.

Table 13. Assumed shares of secondary material supply in 2050 for different material families under conservative, baseline, and optimistic circularity scenarios. Values were compiled from various literature sources, including the International Energy Agency (IEA), Joint Research Centre (JRC), International Copper Association (ICA), and Van der Voet et al. (2019). The shares represent the contribution of secondary (recycled) material production to total material supply in 2050 and are used to evaluate the sensitivity of prospective LCA results to future circularity assumptions

Material family	Conservative (2050)	Baseline (2050)	Optimistic (2050)
Aluminium	45%	60%	70%
Copper	25%	35%	45%
Cobalt	20%	30%	40%
Nickel	20%	25%	30%
Lithium	20%	25%	30%
Graphite	10%	15%	20%
Lead	65%	77%	85%
Zinc	10%	13%	20%
Rare earth elements	2%	5%	10%

Material family	Conservative (2050)	Baseline (2050)	Optimistic (2050)
Precious metals	10%	20%	30%
Platinum group metals (PGMs)	15%	25%	35%
Other base metals	5%	10%	15%
Non-metal mineral feedstocks	0%	0%	0%

Finally, the scenario-specific assumptions were mapped to all relevant metal products and intermediates represented in the LCA database. The resulting dataset provides internally consistent projections of primary and secondary metal supply mixes for 2050 and can be integrated directly into prospective life cycle inventory databases. Compared with static recycling assumptions, the approach enables a more realistic representation of future material circularity and resource recovery, which is particularly important for assessing emerging energy technologies that rely heavily on recycled metals and critical raw materials.

A limitation of the approach is that most published studies report end-of-life recycling rates, scrap availability, or material recovery potentials rather than the exact secondary market shares required for life cycle inventory modelling. Consequently, future primary and secondary supply shares were derived through the synthesis and interpretation of multiple evidence sources. The resulting projections are therefore best interpreted as scenario-based representations of plausible future developments rather than precise forecasts. Nevertheless, the methodology provides a transparent, reproducible, and easily updateable framework for incorporating future metal circularity into prospective LCA.

However, this introduces an unavoidable uncertainty, as future recycling rates and secondary supply shares depend not only on recycling technologies but also on the evolution of material demand and stock accumulation. The resulting scenarios should therefore be interpreted as exploratory representations of future recycling pathways rather than precise predictions of future primary and secondary metal production shares.

Table 14. Overview of the scenario packages integrated into the prospective ecoinvent database using *premise* for the 2050 Port of Rotterdam case study. The transformation combines the global REMIND SSP2-NDC pathway with sector-specific scenario outputs from TRANSIENCE/MIC3 modules, including OPEN-PROM, ITOM (European system), FORECAST, and the Port of Rotterdam ITOM model. Together, these modifications provide a more consistent representation of future developments in the European electricity sector, steel industry, ammonia and methanol production, and the chemical sector of the Port of Rotterdam

Scenario package	Scenario label	Model	Scope	Role in premise transformation
REMIND pathway	SSP2-NDC	REMIND	Global	Provides the overarching IAM background pathway used by premise.
datapackage_open_prom.json	NDC-EI	OPEN-PROM	Global	Updates worldwide electricity and hydrogen mixes for a large set of countries.

Scenario package	Scenario label	Model	Scope	Role in premise transformation
datapackage_edm_i.json	CBAM	ITOM	Europe	Modifies the European steel sector representation.
datapackage_forecast.json	fc_nz	FORECAST	EU country-specific	Adds country-specific low-carbon ammonia and methanol markets in Europe.
datapackage_itom_por.json	CL	ITOM Port of Rotterdam	Netherlands/ Port of Rotterdam	Integrates the Port of Rotterdam chemical-sector transformation pathway, including market mixes of precursors and the final energy demand of polymers.

Energy system transformation scenario assessed: Carbon Looping (CL)

For the chemical sector in the Port of Rotterdam, the first scenario that we have analysed (and received from ITOM) is called the Carbon Looping (CL) scenario (Scholz et al., 2025; Wuppertal Institute, 2025). This scenario represents a deep decarbonisation pathway for the chemical industry that aims to substantially reduce GHG emissions while maintaining the production of key chemical products. However, at this stage, the scenario should be considered exemplary, as the modelling teams for ITOM and LCA are still improving the models and their coupling. The scenario is based on replacing fossil carbon feedstocks with circular, low-carbon carbon sources, combined with extensive electrification, carbon capture and storage (CCS), biomass feedstocks, plastic waste recycling, and renewable hydrogen production. The underlying objective is to progressively close the carbon cycle within the chemical sector and reduce dependence on virgin fossil resources.

Within the CL scenario, fossil naphtha and natural gas are gradually substituted by a portfolio of alternative carbon sources, including biomass-derived feedstocks, recycled plastics, captured carbon dioxide, and synthetic intermediates produced from renewable electricity and hydrogen. Methanol plays a key role as a platform chemical, acting as an intermediate to produce olefins, aromatics, and polymers through technologies such as Methanol-to-Olefins (MTO) and Methanol-to-Aromatics (MTA).

The scenario further assumes large-scale deployment of renewable electricity and low-carbon hydrogen to decarbonise process energy demand and enable the production of synthetic feedstocks. Carbon capture technologies are applied to unavoidable process emissions, while captured carbon is either permanently stored or reused as a feedstock for chemical production. Consequently, the chemical sector evolves from a predominantly fossil-based system towards a more circular carbon system in which carbon molecules are reused multiple times throughout value chains before final storage or release.

For the Port of Rotterdam case study, the CL scenario is implemented through the ITOM industrial transformation model (Wuppertal Institute, 2025) and integrated into the prospective LCA framework via *premise*. The scenario modifies the production routes and market shares of major chemical intermediates and polymers, including methanol, olefins, aromatics, polyols, PET, PMMA, PLA, PBS, and other petrochemical products (see Figure 66 for the annual production volumes of final product polymers).

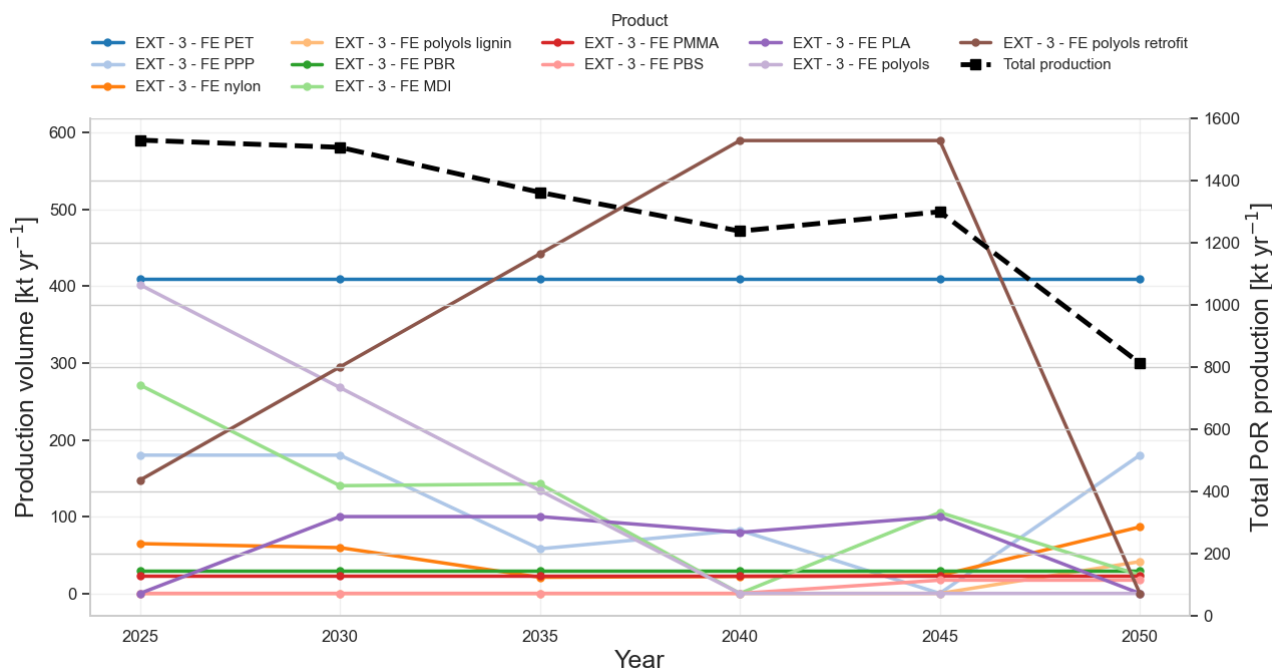


Figure 66. Development of annual production volumes of final chemical products in the Port of Rotterdam chemical sector under the CL pathway. Values represent modelled annual production volumes (kiloton year⁻¹) derived from the ITOM industrial transformation model

Figure 66 illustrates the evolution of final chemical product production in the Port of Rotterdam under the CL scenario between 2025 and 2050. PET remains the largest product throughout the period with a stable production volume of approximately 410 kt year⁻¹, while PMMA, PBS, and PBR production remain relatively constant. The most pronounced transformation occurs in the polyols sector, where conventional polyol production is gradually phased out and replaced by retrofit-based production routes, which become the dominant source of polyols after 2040, alongside a smaller contribution from lignin-based polyols. PLA emerges as an increasingly important bio-based polymer, while polypropylene production recovers towards 2050 after an initial decline. Overall, the scenario shows a substantial restructuring of the chemical product portfolio and production technologies, with the total production volume declining from approximately 1.5 Mt year⁻¹ in 2025 to around 0.8 Mt year⁻¹ in 2050.

It is worth noting that polymer production decreases substantially towards 2050 because the CL scenario assumes a transition away from fossil feedstocks. The resulting bio-based and synthetic feedstock production routes are more energy-intensive, making production in the Port of Rotterdam less economically attractive than in regions with lower renewable electricity prices. Consequently, a substantial share of polymer production relocates to other European regions and to locations outside Europe that produce renewable feedstocks, effectively shifting part of the associated environmental burdens along the supply chain to other world regions.

This CL scenario enables assessment of environmental trade-offs and co-benefits associated with the transition from fossil-based production to circular and low-carbon chemical value chains, considering not only climate change impacts but also resource use, toxicity, critical material requirements, and other environmental indicators throughout the entire life cycle. In the future, more emphasis will be placed on scenarios for the Port of Rotterdam that include the imports of low-carbon fuels and feedstock. However, the current CL scenario is already useful for analysis to test model linkages and provide preliminary results.

Life cycle impact assessment

Our functional unit, the annual production of a set of polymers in the Port of Rotterdam, is assessed across a broad set of environmental impact categories to identify potential trade-offs and co-benefits associated with industrial decarbonisation pathways. In addition to climate change impacts (using the IPCC 2021 factors, including those related to short-lived climate forcers and biogenic CO₂), the assessment covers human toxicity, particulate matter formation, acidification, freshwater ecotoxicity, terrestrial eutrophication, and mineral and metal resource depletion. These are assessed using the Develop Environmental Footprint (v3.1) (European Commission, 2022) life cycle impact assessment method. An overview is provided below.

Table 15. Overview of environmental impact categories considered for the life cycle impact assessment

Impact category	Method	Indicator	Unit
Climate change	IPCC 2021 (incl. biogenic CO ₂ and short-lived climate forcers)	Global warming potential (GWP100)	kg CO ₂ -eq.
Climate change	EF v3.1	Global warming potential (GWP100)	kg CO ₂ -eq.
Human toxicity (carcinogenic)	EF v3.1	Comparative Toxic Unit for humans (CTUh)	CTUh
Particulate matter formation	EF v3.1	Impact on human health	disease incidences
Acidification	EF v3.1	Accumulated Exceedance (AE)	mol H ⁺ -eq
Freshwater ecotoxicity	EF v3.1	Comparative Toxic Unit for ecosystems (CTUe)	CTUe
Terrestrial eutrophication	EF v3.1	Accumulated Exceedance (AE)	mol N-eq
Mineral and metal resource depletion	EF v3.1	Abiotic Depletion Potential (ADP), ultimate reserves	kg Sb-eq
Copper extraction	RELICS	Primary and secondary copper extraction demand	kg Cu
Lithium extraction	RELICS	Primary and secondary lithium extraction demand	kg Li
Nickel extraction	RELICS	Primary and secondary nickel extraction demand	kg Ni
Cobalt extraction	RELICS	Primary and secondary cobalt extraction demand	kg Co
Iridium extraction	RELICS	Primary and secondary iridium extraction demand	kg Ir
Dysprosium extraction	RELICS	Primary and secondary dysprosium extraction demand	kg Dy
Palladium extraction	RELICS	Primary and secondary palladium extraction demand	kg Pd

Impact category	Method	Indicator	Unit
Titanium extraction	RELICS	Primary and secondary titanium extraction demand	kg Ti

To further evaluate dependencies on critical materials required for, for example, increased electrification, hydrogen production, catalysts, and low-carbon industrial infrastructure, specific material extraction indicators are included for copper, lithium, nickel, cobalt, iridium, dysprosium, palladium, and titanium. This broad impact coverage is important because strategies that reduce GHG emissions may simultaneously increase other environmental burdens, such as reliance on critical raw materials. Note, however, that we could widen the selection of environmental impact categories later into the project.

Results

Environmental impacts of the Port of Rotterdam chemical-sector transformation pathway

Figure 67 to Figure 70 present the environmental impacts associated with the annual production portfolio of the Port of Rotterdam chemical sector between 2025 and 2050 under the 'CL' scenario. In those figures, the x-axis shows the assessment year, while the y-axis represents the total annual environmental burden associated with the production of all final-demand chemical products in the system (i.e., the functional unit used). The stacked bar segments indicate the contribution of individual polymers/products, including methylene diphenyl diisocyanate (MDI), polybutadiene rubber (PBR), polyethylene terephthalate (PET), polylactic acid (PLA), poly(methyl methacrylate) (PMMA), polypropylene (PP), nylon 6.6, and various polyol production routes. Total values are shown above each bar. Additional figures, normalised per kilogram of product produced, are provided in the Appendix.

Overall, the results indicate that environmental burdens evolve substantially over time as production volumes, feedstock production mixes, and the background global economy change. Throughout most environmental impact categories, PET and polyol production routes are the largest contributors, while the relative importance of other products varies by category. This demonstrates that climate mitigation strategies can lead to different environmental outcomes throughout various environmental impact categories and, as such, highlights the importance of evaluating industrial transformation pathways beyond GHG emissions. Next, we will discuss the environmental burdens for the selected impact categories one by one.

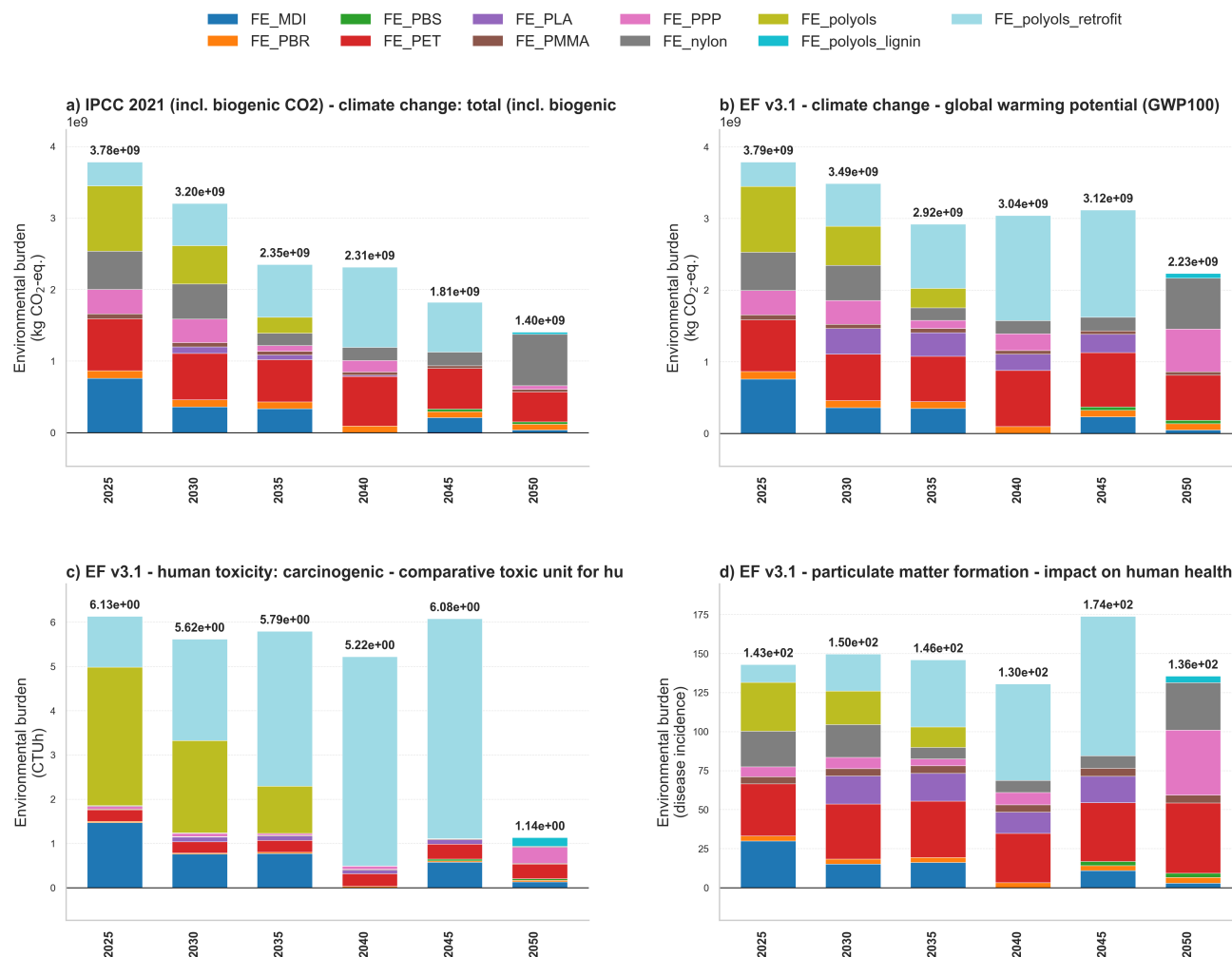


Figure 67. Annual environmental burdens of the Port of Rotterdam chemical sector under the CL scenario between 2025 and 2050 for (a) climate change (IPCC 2021, including biogenic CO₂), (b) climate change (EF v3.1), (c) human toxicity (carcinogenic effects), and (d) particulate matter formation. Stacked bars represent total sector-level impacts, with individual segments showing the contribution of major chemical products and production pathways, including PET, MDI, PMMA, polypropylene (PPP), nylon 6.6, PLA, polyols, lignin-based polyols, and retrofit polyol production. Values above the bars indicate the total annual environmental burden for each year

Climate change, toxicity, and particulate matter formation

Climate change

Figure 67 a and b present climate change impacts calculated using the IPCC 2021 and EF v3.1 methods, respectively. Both methods show similar trends, with total impacts on climate change decreasing from approximately 3.8 Mt CO₂-eq. year⁻¹ in 2025 to approximately 1.4–2.2 Mt CO₂-eq. year⁻¹ in 2050. The main difference between the two methods is that the IPCC 2021 indicator accounts for biogenic CO₂ uptake and temporary storage in chemical products, whereas the EF v3.1 indicator excludes biogenic carbon storage effects. Both indicators are reported because the climate benefits of biogenic feedstocks depend strongly on the duration of carbon storage within polymer products and their end-of-life treatment. However, many polymer products have relatively short lifetimes and eventually release the stored biogenic carbon back to the atmosphere through incineration, degradation, or other waste-management pathways. Consequently,

the EF v3.1 climate change impact results can be interpreted as a more conservative estimate of long-term climate mitigation benefits, while the IPCC 2021 results illustrate the potential contribution of temporary biogenic carbon storage.

Overall, the strongest reduction on climate change impacts occurs between 2025 and 2045 and is mainly driven by decreasing contributions from MDI, PET, conventional polyols, and nylon production. These reductions reflect both industrial process changes, changing polymer supply, and the progressive decarbonisation of electricity, hydrogen, and material supply chains represented in the prospective background databases. It is worth noting that the total production volume of polymers is much lower in 2050 (as shown in Figure 66).

Although climate impacts decrease substantially, they are not eliminated entirely. PET production remains a major contributor throughout the assessment period, while retrofit polyol production contributes significantly between 2035 and 2045. These findings imply that even ambitious industrial transformation pathways continue to generate residual life cycle GHG emissions that require further climate mitigation and/or compensation via carbon dioxide removal technologies (Terlouw et al., 2021).

Human toxicity

Figure 67 c shows human toxicity impacts. Total impacts remain relatively stable between 2025 and 2045 before declining sharply in 2050 due to less polymer production. A notable observation is the prominent contribution of the polyol production pathways to several environmental impact categories, which account for the majority of total human toxicity impacts throughout the period. MDI and PET production also contribute substantially but to a lesser extent.

Particulate matter formation

Figure 67 d shows the evolution of particulate matter formation impacts. Total impacts remain relatively stable throughout the assessment period. PET production represents an important contributor across all years, while the contribution of conventional polyol production declines over time.

By 2050, impacts decrease compared to 2025. This reduction is primarily driven by lower overall production, and as such, lower contributions from MDI, PET, and conventional polyol production, but also reflects improvements in upstream electricity generation and industrial supply chains. Nevertheless, alternative polyol routes remain an important source of particulate matter impacts, indicating that decarbonised production pathways do not automatically eliminate air-pollution-related burdens.

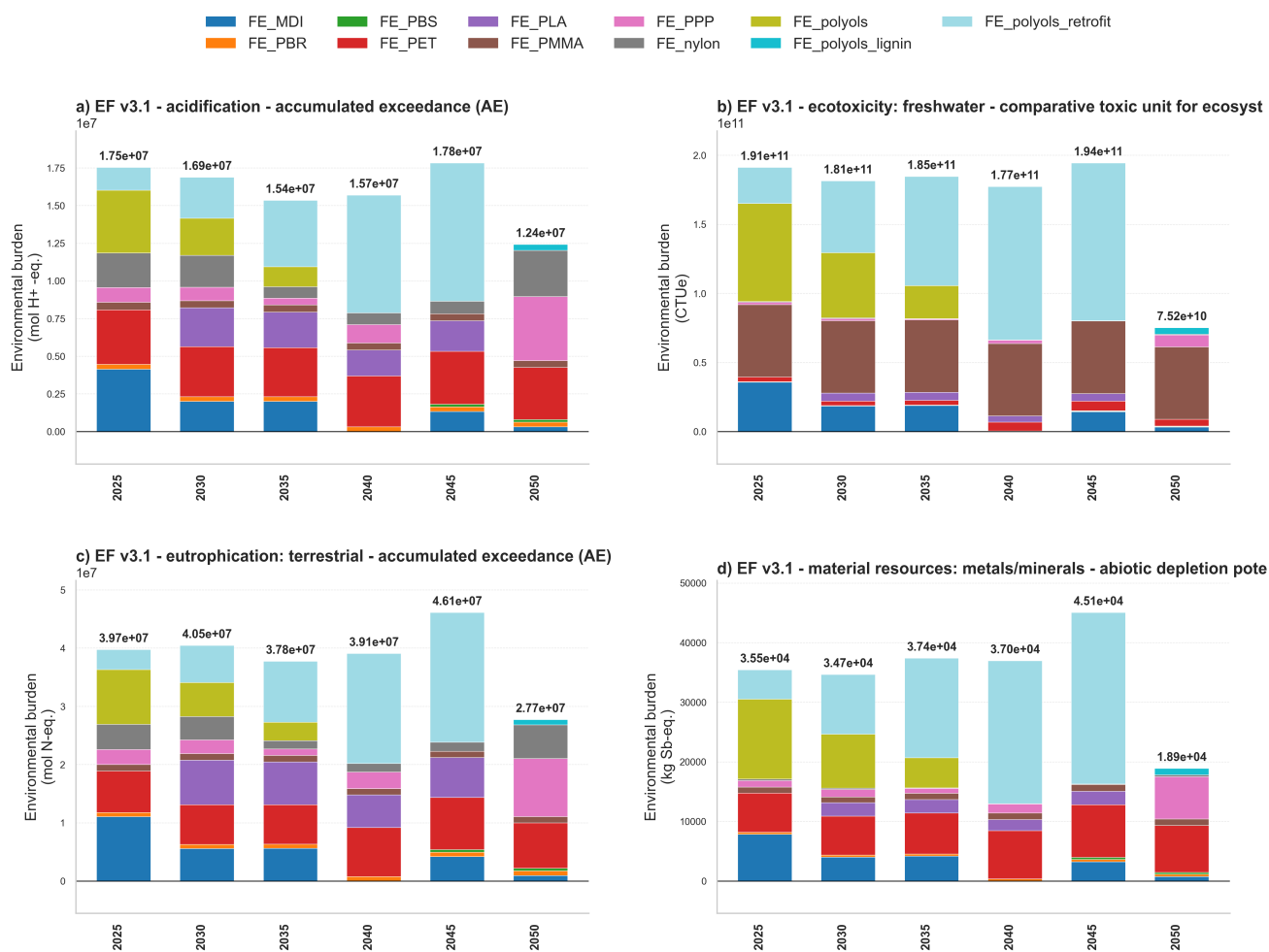


Figure 68. Annual environmental burdens of the Port of Rotterdam chemical sector under the CL scenario between 2025 and 2050 for (a) acidification, (b) freshwater ecotoxicity, (c) terrestrial eutrophication, and (d) material resource depletion. Stacked bars represent total sector-level impacts, while colours indicate contributions from individual chemical products and production routes. Values above the freshwater ecotoxicity bars indicate total annual impacts

Air pollution and ecosystem-related impacts

Acidification

Figure 68 a presents acidification impact. Similar to particulate matter formation, total impacts remain within a relatively narrow range throughout the period. Polyol production dominates acidification impacts in most years, with an increasingly large share of the retrofit route towards 2040–2045. By 2050, total acidification impacts decline substantially, driven by reductions in most product systems despite increasing contributions from polypropylene and nylon production.

Freshwater ecotoxicity

Freshwater ecotoxicity results (Figure 68 b) show substantially different behaviour. Total impacts remain high throughout the assessment period and peak around 194 CTUe year⁻¹ in 2045 before declining sharply to approximately 75 CTUe year⁻¹ in 2050.

Unlike the previous impact categories, PMMA production dominates freshwater ecotoxicity across most years, contributing roughly one-third of total impacts. The pronounced reduction in 2050 is associated with a strong decrease in polymer supply and in impacts from both PMMA and retrofit polyol production.

Terrestrial eutrophication

Figure 68 c presents terrestrial eutrophication impacts. Total burdens remain relatively constant between 2025 and 2040, increase to a maximum around 2045, and subsequently decline in 2050. The dominant contributors shift considerably over time. Conventional polyol production contributes significantly in 2025, whereas retrofit polyol production becomes the largest contributor from 2040 onwards. PET production remains important throughout the assessment period.

Mineral and metal resource depletion

Figure 68 d presents abiotic depletion of metals and minerals. Resource depletion increases between 2025 and 2045 before declining in 2050.

Retrofit polyol production is the largest contributor from 2035 onwards and accounts for a substantial fraction of total resource depletion impacts. PET production remains the second most important contributor throughout the assessment period. The results suggest that the transition towards low-carbon chemical production may increase demand for resource-intensive technologies and infrastructure, creating potential trade-offs between climate mitigation and material resource consumption.

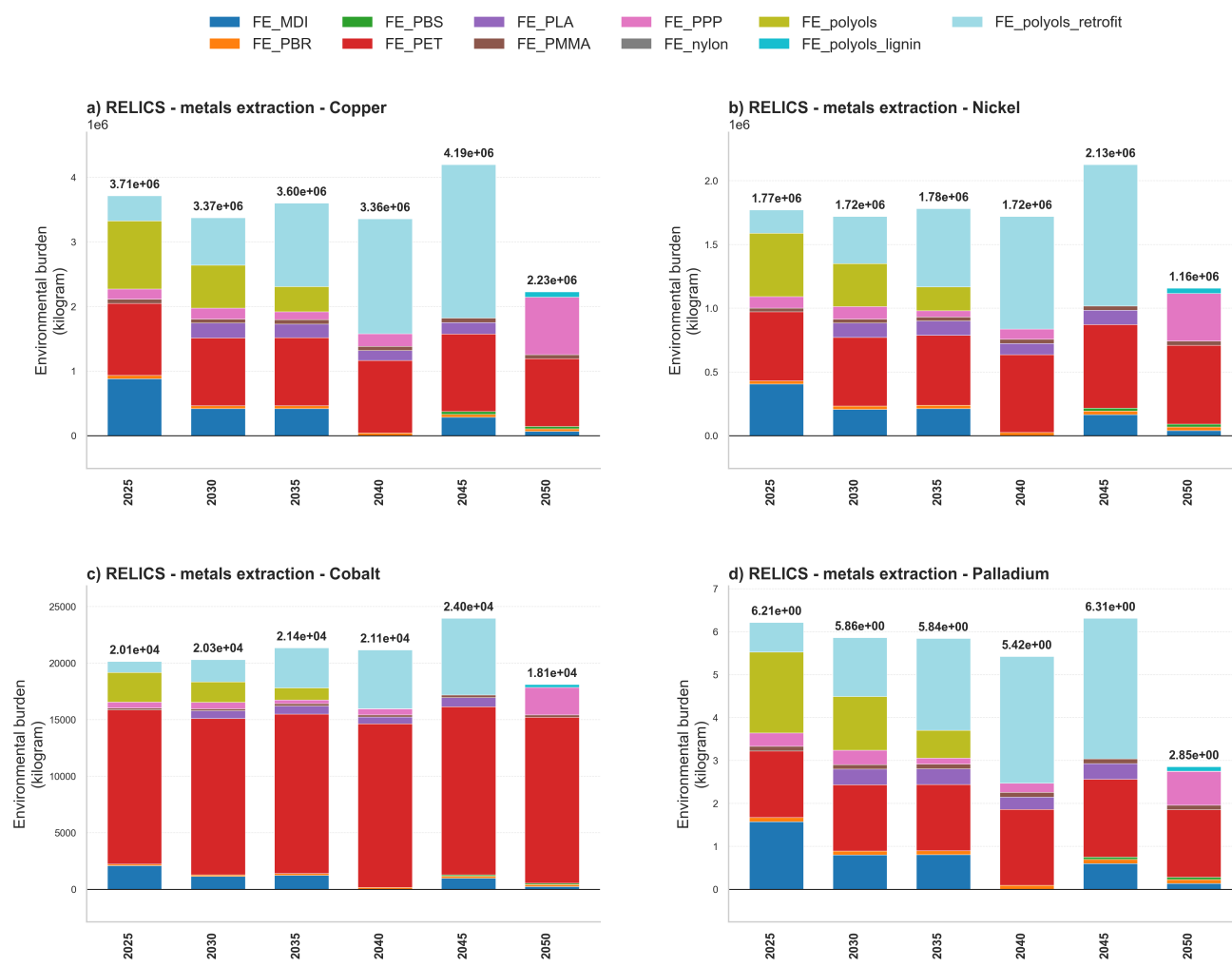


Figure 69. Annual extraction requirements of selected energy-transition and battery-related metals associated with the Port of Rotterdam chemical sector under the CL scenario between 2025 and 2050: (a) copper, (b) nickel, (c) cobalt, and (d) palladium. Stacked bars show the contribution of individual chemical products and production pathways to the total metal extraction burden, highlighting trade-offs on (critical) raw materials associated with industrial decarbonisation

(Critical) material requirements

Figure 69 and Figure 70 present the extraction requirements of selected critical and strategic materials. The results provide insights into potential supply-chain dependencies associated with the chemical-sector transition.

Nickel and copper

Nickel and copper (Figure 69 a and Figure 69 b) extraction increase moderately until 2045 before declining in 2050. PET production is consistently the largest contributor, while retrofit polyol production becomes increasingly important over time.

Lithium and cobalt

Lithium extraction (Figure 70 b) increases strongly between 2025 and 2045, rising by more than an order of magnitude. This increase is primarily driven by PET production and retrofit polyol pathways. Cobalt

extraction (Figure 69 c) shows a similar pattern, although the relative increase is smaller. These trends are consistent with increasing deployment of battery storage and electrification technologies throughout upstream supply chains.

Palladium

Palladium extraction (Figure 69 d) remains relatively stable throughout the assessment period. PET production and retrofit polyol pathways dominate total demand. Compared with lithium and dysprosium, changes over time are less pronounced, indicating a weaker dependence on future technology deployment.

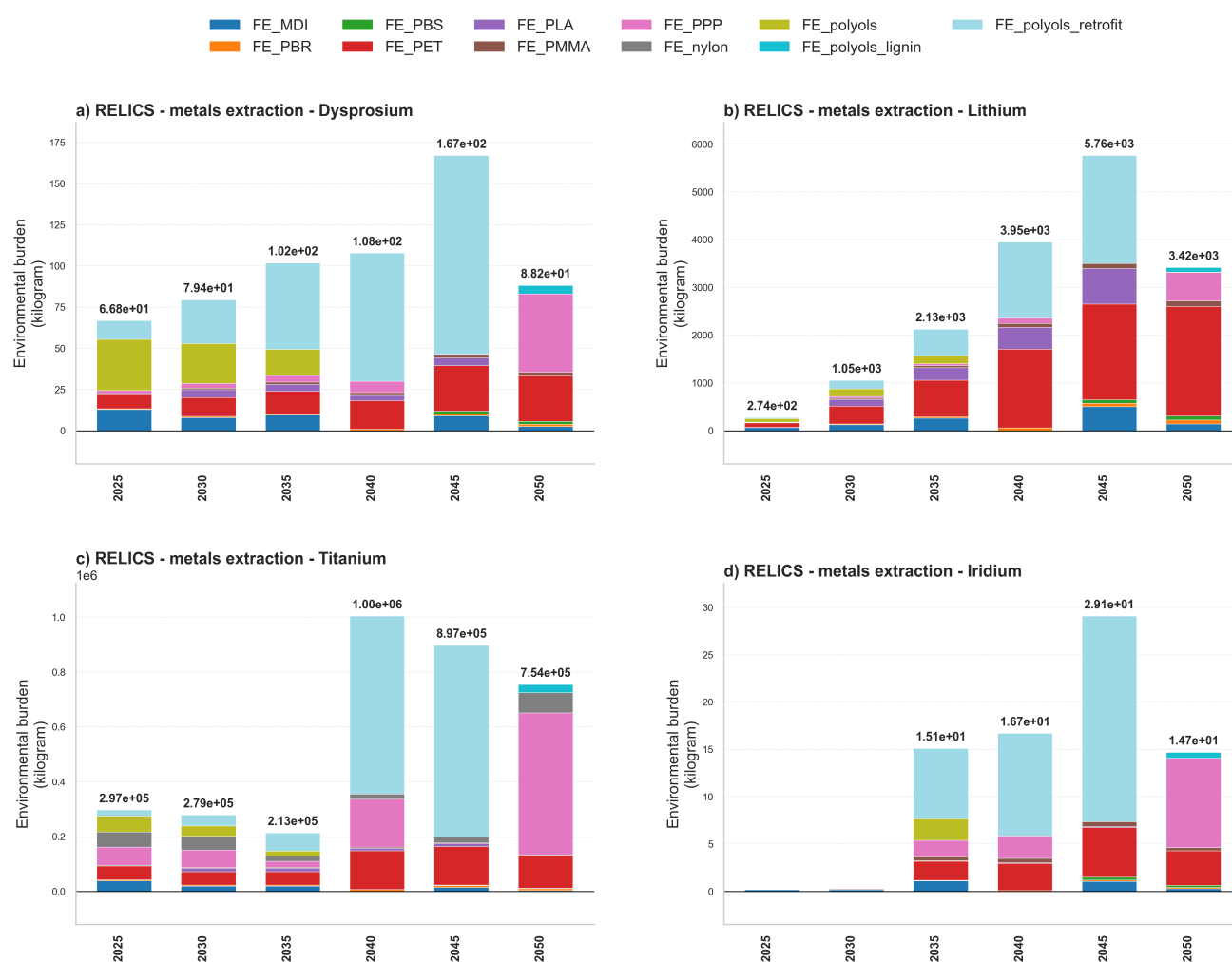


Figure 70. Annual extraction requirements of selected strategic and scarce metals associated with the Port of Rotterdam chemical sector under the CL scenario between 2025 and 2050: (a) dysprosium, (b) lithium, (c) titanium, and (d) iridium. Stacked bars represent the contribution of individual chemical products and production pathways to total metal extraction, illustrating potential resource dependencies emerging from low-carbon industrial transformation pathways

Dysprosium

Dysprosium extraction (Figure 70 a) increases steadily until 2045 and is largely associated with retrofit polyol production and PET production. Since dysprosium is commonly used in permanent magnets for high-efficiency electric motors and wind turbines, the observed increase reflects growing dependence on renewable electricity systems.

Titanium

Titanium extraction peaks (Figure 70 c) around 2040–2045 and remains elevated in 2050. Unlike most other critical materials, polypropylene production becomes the dominant contributor in 2050.

Iridium

Iridium extraction (Figure 70 d) exhibits one of the strongest relative increases among all assessed materials, particularly between 2035 and 2045. Retrofit polyol production is the dominant contributor. Given the importance of iridium for proton exchange membrane (PEM) electrolyzers, these results indicate a potential critical-material bottleneck associated with hydrogen-based industrial decarbonisation pathways.

Overall findings

Substantial reductions in climate change impacts are achieved between 2025 and 2050. However, these reductions are accompanied by increasing impacts in various other environmental dimensions, mainly (critical) material extraction. In particular, retrofit polyol production emerges as a recurring hotspot across many indicators, while PET production remains a dominant contributor throughout the assessment period. These preliminary results therefore demonstrate that evaluating industrial decarbonisation solely on the basis of GHG emissions is likely to overlook important environmental trade-offs, resource dependencies, and potential burden shifting along global supply chains.

Discussion

This case study demonstrates the potential of the MIC3 environmental LCA module to evaluate industrial decarbonisation pathways beyond life cycle GHG emissions. For the Port of Rotterdam, chemical sector, the Carbon Looping (CL) scenario shows substantial reductions in climate change impacts between 2025 and 2050, largely driven by electricity-system decarbonisation, increasing circularity, and the deployment of low-carbon production technologies. At the same time, the results reveal that environmental trade-offs may emerge in other environmental impact categories, especially material resource depletion and the extraction of critical raw materials such as lithium, iridium, and dysprosium. These findings highlight the importance of assessing industrial transformation pathways from a life cycle perspective rather than focusing solely on (direct) CO₂ emissions.

To directly answer the research question, *“How can local industrial transition pathways for the Port of Rotterdam be coupled with environmental life cycle assessment to assess the broader environmental burdens of such (low-carbon) industrial energy transitions?”*, the results show that this can be achieved by translating model outputs – such as production volumes, technology deployment, market mixes, energy demand, and material flows – into new and updated market mixes in the background LCA databases as well as life cycle inventories that are subsequently linked to prospective background LCA databases. This coupling enables quantification of the environmental implications of industrial transformation pathways across entire supply chains, including upstream energy production, feedstock supply, material extraction, and infrastructure requirements. The Port of Rotterdam case study demonstrates that such an integrated approach can capture not only climate-change mitigation benefits, but also broader environmental trade-offs, co-benefits, and potential burden shifting across regions and supply chains. Consequently, the environmental LCA framework provides a robust methodology for evaluating whether industrial decarbonisation strategies contribute to broader sustainability objectives beyond GHG reductions alone.

However, the results presented should be considered preliminary and serve primarily to illustrate the capabilities of the MIC3 environmental assessment framework. Several methodological developments are still required before robust policy conclusions can be drawn. First, the assessment is based on a single industrial transformation pathway (i.e., Carbon Looping, CL) and a single background scenario (SSP2-NDC, based on official national climate action plans). At present, the different MIC3 model scenarios are not yet fully harmonised, and interactions between model assumptions require further validation. In future work, the OPEN-PROM model could directly provide the overarching energy-system pathway, thereby reducing dependence on external IAM scenarios (currently the one from REMIND) and improving consistency across the framework.

Second, the coupling between the ITOM model outputs for the Port of Rotterdam and the life cycle inventory database remains an important area for further development. The mapping between model variables, production technologies, market mixes, and life cycle inventories has been established through a first systematic matching procedure, but additional expert validation is required to ensure consistency and completeness. This is particularly relevant for novel production routes, circular material pathways, and intermediate chemical products that are not directly represented in existing background LCA databases.

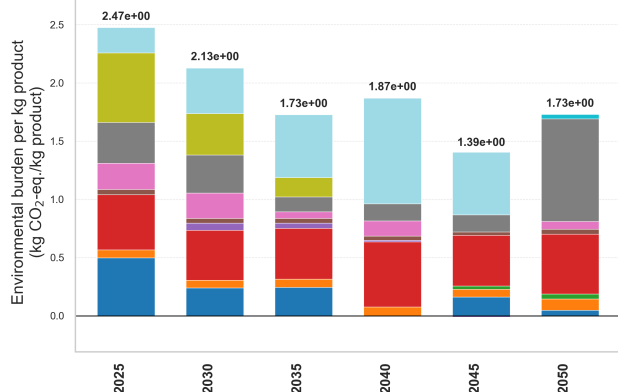
Third, the representation of future material supply chains remains simplified. Changes in primary versus secondary material production shares were incorporated using external literature sources and expert assumptions. While this provides a first indication of future resource requirements, a more consistent approach would directly link to material flow analysis (MFA) results from the MIC3 framework. If available, this would enable dynamic modelling of recycling rates, secondary material availability, and circular economy strategies across sectors and regions.

Despite these limitations, the case study of the Port of Rotterdam illustrates the strength of combining (industrial) energy transformation models with (prospective) LCA. The current LCA module enables the quantification of not only climate benefits but also broader environmental implications, including burden shifting across impact categories, supply chain dependencies, and critical material requirements. Furthermore, the modular structure of the environmental LCA module enables straightforward application to other industrial clusters and regions. Consequently, once additional validation and harmonisation efforts have been completed, the framework can support the environmental assessment of industrial transformation pathways and clusters throughout Europe (like the Rhine-Ruhr area or Basque Country) and, as such, will provide decision-makers with a more comprehensive understanding of the sustainability implications of industrial decarbonisation pathways.

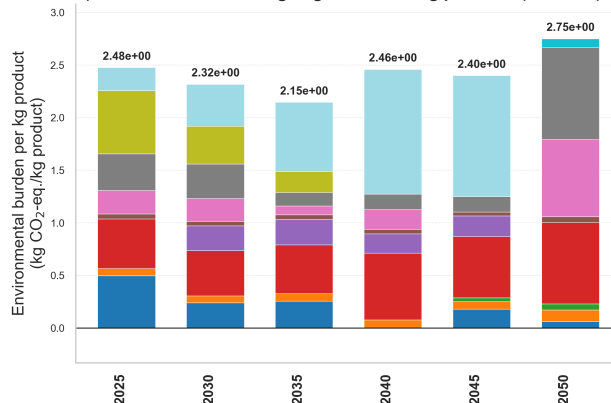
Appendix – additional figures normalised per kilogram of product produced



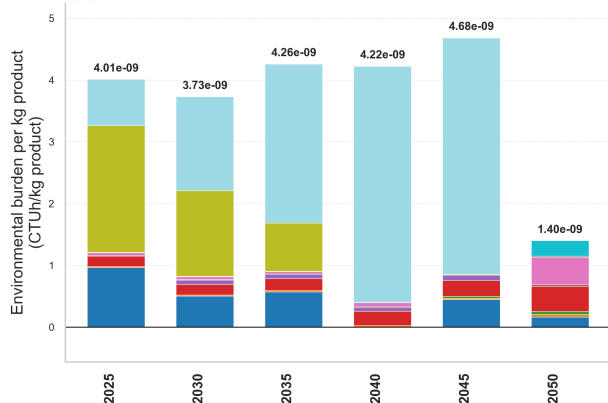
a) IPCC 2021 (incl. biogenic CO₂) - climate change: total (incl. biogenic)



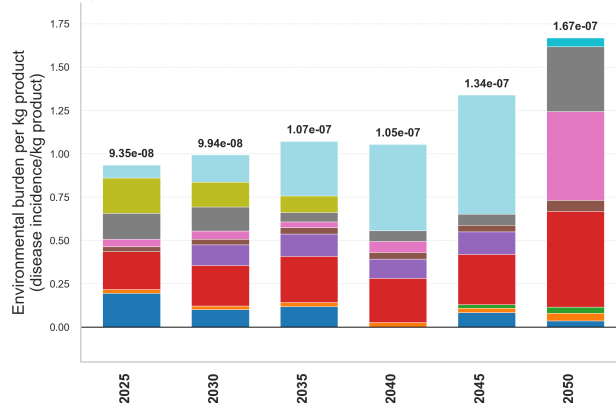
b) EF v3.1 - climate change - global warming potential (GWP100)



c) EF v3.1 - human toxicity: carcinogenic - comparative toxic unit for hu
1e-9

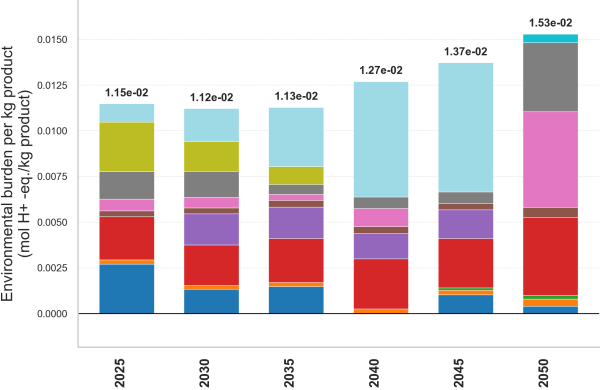


d) EF v3.1 - particulate matter formation - impact on human health
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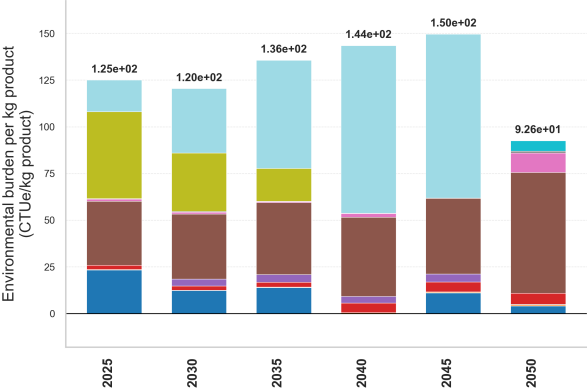




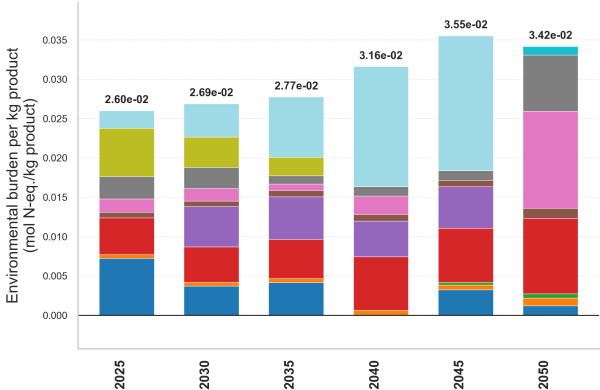
a) EF v3.1 - acidification - accumulated exceedance (AE)



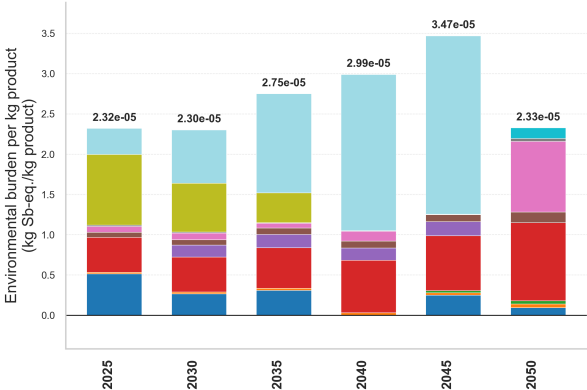
b) EF v3.1 - ecotoxicity: freshwater - comparative toxic unit for ecosystem

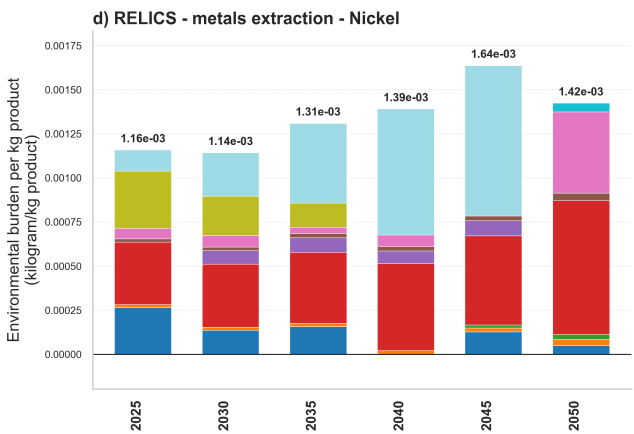
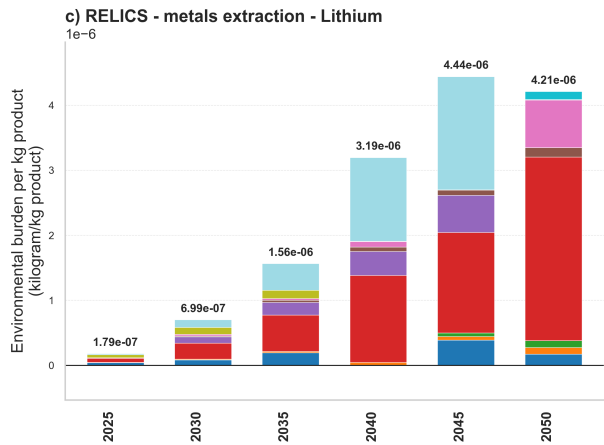
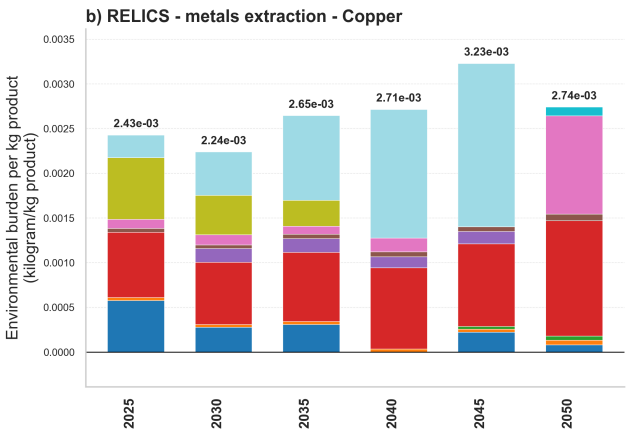
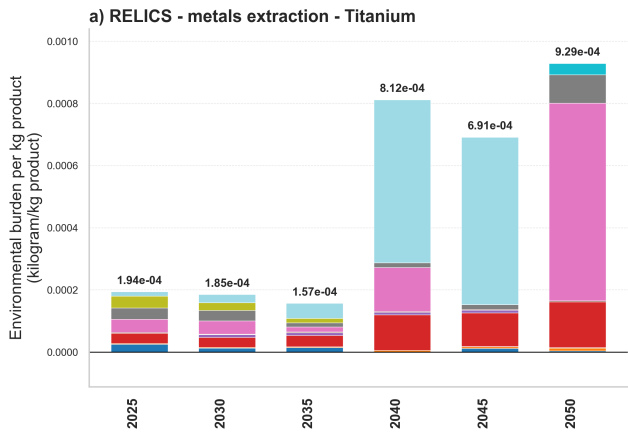


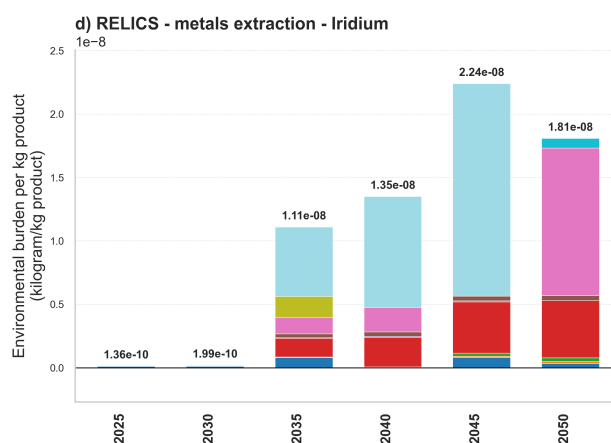
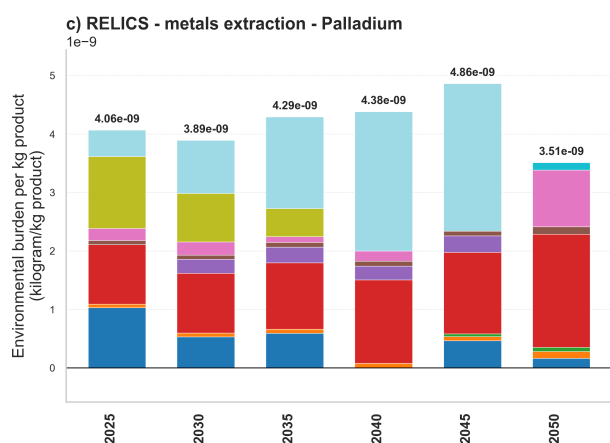
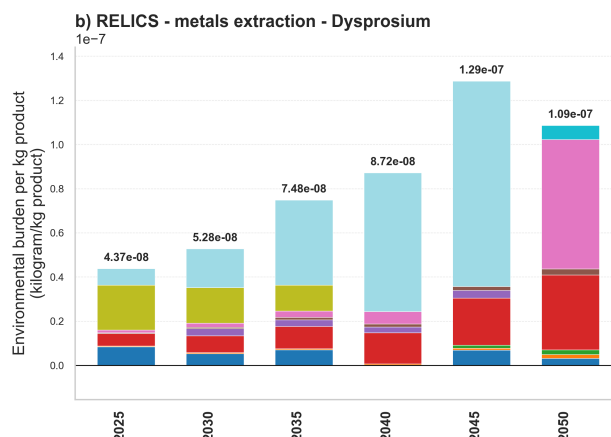
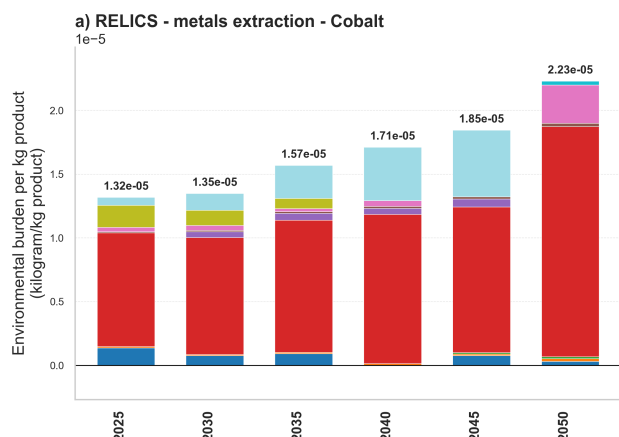
c) EF v3.1 - eutrophication: terrestrial - accumulated exceedance (AE)



d) EF v3.1 - material resources: metals/minerals - abiotic depletion pote







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8 Conclusions

This deliverable presented five case studies that were developed to test and validate individual modules of the MIC3 framework within the TRANSIENCE project. Covering perspectives ranging from material flows and trade to industrial transformation, energy systems, socioeconomic and environmental impacts, the case studies demonstrate the analytical capabilities currently available within the emerging MIC3 modelling framework. The applications address stakeholder-relevant research questions concerning circularity and decarbonisation, while simultaneously serving as practical validation exercises for the underlying modules.

Overall, the case studies confirm that the individual modules are capable of addressing the specific research questions they were matched with. The material flow and trade modules were successfully applied to investigate the effects of circular economy strategies for passenger cars and plastics packaging on trade dependencies and thus, industrial resilience. The macroeconomic and energy system modules demonstrated their applicability for assessing competitiveness implications in the chemicals sector. The FORECAST-Sites model proved effective in analysing site-level industrial decarbonisation pathways and investment decisions, while ITOM cement illustrated how sector-specific industrial transformation questions can be addressed. Finally, the LCA module demonstrated the feasibility of linking industrial transformation pathways for the chemicals sector with broader environmental and sustainability assessments that extend beyond greenhouse gas emissions. Together, these applications provide confidence that the individual modules can generate relevant insights within their respective domains.

At the same time, the case studies highlight important limitations. In several applications, results depend strongly on scenario assumptions and on the system boundaries of the respective modelling approach. Moreover, the modules are currently unable to capture interactions between socioeconomic aspects, material flows, industrial production, energy system, and environmental impacts. The case studies therefore underline the importance of moving beyond standalone modules towards a more integrated modelling framework that combines their complementary strengths. This observation is consistent across all case studies and represents a central motivation for the continued development of MIC3.

Additionally, the case studies highlight the value of stakeholder engagement. Across the case studies, stakeholder workshops helped to identify relevant research questions, refine assumptions, and assess plausibility of modelling results. The case studies therefore not only tested technical model functionality but also provided an opportunity to evaluate the relevance and usability of model outputs from the perspective of potential users. This contributes to the broader TRANSIENCE objective of developing modelling tools that are scientifically robust while remaining applicable to decision making processes at the EU, national, and even local levels.

The project will now focus on strengthening the linkages between modules and progressing towards the integrated MIC3 framework that consistently captures all complex interactions between macroeconomic modelling, material flow analysis, energy system modelling, industrial decarbonisation pathways, and LCA environmental assessment. Insights gained through the case studies will inform model improvements, harmonisation of assumptions, and the development of interfaces between the different modules to reliably capture all the above interactions. In this way, the lessons learned through the present deliverable provide an important foundation for the subsequent development, integration, and application of MIC3.