

Prospective Life Cycle Assessment of the European PET Packaging Sector

Analyzing Environmental Impacts of Feedstock Substitution
under the Packaging and Packaging Waste Regulation for 2040

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Prospective Life Cycle Assessment of the European PET Packaging Sector: Analyzing Environmental Impacts of Feedstock Substitution under the Packaging and Packaging Waste Regulation for 2040

by

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Abstract

The EU Packaging and Packaging Waste Regulation (PPWR) sets recycled content targets for polyethylene terephthalate (PET) packaging at the product level for 2040 and enables future EU legislation on bio-based targets. However, its effect on the projected environmental impacts of the European PET packaging sector in 2040 remains unclear. This study addresses the research question: *“What magnitude and direction of change in projected environmental impacts of the European PET packaging sector is achievable through feedstock substitution in the context of the Packaging and Packaging Waste Regulation in 2040?”*

The research approach combines static prospective Material Flow Analysis (pMFA) with prospective Life Cycle Assessment (pLCA). Three foreground scenarios explore the Business-as-usual (BAU), PPWR recycled content targets (Scenario 1), and a potential Joint Target with bio-based-content targets (Scenario 2). The future PET packaging demand is represented by a packaging market mix. The pMFA uses data on projected feedstock shares from the Plastics Integrated Assessment (PLAIA), part of the Integrated Assessment Model (IAM) IMAGE, and is conducted in the *subSTance flow ANalysis* software. The pLCA adopts the ecoinvent v3.12 database modified using *premise*, applying the IAM IMAGE under three Shared Socioeconomic Pathway (SSP) scenarios based on SSP2 with medium emissions (SSP2-M), low emissions (SSP2-L), and very low high overshoot (SSP2-VLHO). The pLCA is performed in Activity Browser using the Environmental Footprint v3.1.

Results show that PPWR recycled content targets are highly environmentally beneficial, with Scenarios 1 and 2 reducing environmental impacts across all impact categories compared to BAU and achieving similar climate change impact reductions of -64% and -59%, respectively. Meeting the recycled content targets requires imports of recycled PET, indicating a risk of circularity leakage. A Joint Target, allowing bio-based feedstock to partially replace recycled feedstock, offers no additional advantage over recycled content targets, with Scenario 2 showing moderately higher environmental impacts than Scenario 1. The largest differences are observed in land use (-17 percentage points (pp)), terrestrial eutrophication, and particulate matter formation (both -10 pp), all relative to BAU. At the process level, energy production and manufacturing are the dominant contributors across most impact categories. At the life cycle stage level, PET polymer production and EoL management emerge as hotspots, with Bio-PET showing disproportionately high land use impacts in Scenario 2. The baseline assumes sugar beet as the biomass source for bioethanol and wood for terephthalic acid production. Sensitivity analysis with wheat for bioethanol production shows similar results.

Policy recommendations include scaling up recycling infrastructure to address the identified risk of circularity leakage and prioritizing demand reduction and reuse quotas. Main limitations include uncertainties resulting from reconciling multiple data sources in the pMFA, and the lack of prospective foreground unit process data for the chemical sector in the pLCA. Future research should develop and integrate such data, develop regional classification in IMAGE aligned with political entities, and evaluate the effects of the PPWR on further packaging materials to allow cross-sector assessment.

Keywords: Prospective Material Flow Analysis • Prospective Life Cycle Assessment • Integrated Assessment Models • PET packaging • Feedstock substitution • European Union • Packaging and Packaging Waste Regulation

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List of Abbreviations

Abbreviation	Full Term
ALCA	Attributional Life Cycle Assessment
BAU	Business-as-usual
Bio-PET	Bio-polyethylene terephthalate
Bio-TA	Bio- terephthalic acid
CE	Circular economy
CEU	Central Europe
CF	Characterization factor
CO ₂ e	Carbon Dioxide Equivalents
CS	Contact-sensitive
EF	Environmental flow
EoL	End-of-Life
EU	European Union
FU	Functional Unit
GHGs	Greenhouse gases
GLO	Global
GMST	Global mean surface temperature
IAM	Integrated Assessment Models
IAM-LCA	Integrated Assessment Models - Life Cycle Assessment
IMAGE	Integrated Model to Assess the Global Environment
kt	Kiloton
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
MFA	Material Flow Analysis
Mt	Megaton
Mt/yr	Megatons per year
PEF	Product Environmental Footprint
PET	Polyethylene terephthalate
PLAIA	Plastics Integrated Assessment
pLCA	Prospective Life Cycle Assessment
pMFA	Prospective Material Flow Analysis
pp	Percentage point
PPWR	Packaging and Packaging Waste Regulation
RCP	Representative Concentration Pathway
RER	Region Europe
RoW	Rest of the World
rBio-PET	Recycled Bio-polyethylene terephthalate
rPET	Recycled polyethylene terephthalate
SSP	Shared Socioeconomic Pathway
SSP2-M	Shared Socioeconomic Pathway 2 Medium Emissions
SSP2-L	Shared Socioeconomic Pathway 2 Low Emissions
SSP2-VLHO	Shared Socioeconomic Pathway 2 Very Low High Overshoot
STAN	Substance Flow Analysis
SM	Supplementary Material
TA	Terephthalic acid
TCs	Transfer coefficients
WEU	Western Europe

Introduction

1.1 Research problem

Plastics have brought many benefits to modern society due to their versatility, durability, light weight, and affordability, but today's plastics supply chains have significant environmental impacts at each life cycle stage (Bachmann et al., 2023; Houssini et al., 2025; Vanderreydt et al., 2021). Plastics risk human health and the environment through greenhouse gas (GHG) emissions and pollution on land and sea (Lebreton et al., 2017). Global plastic demand is projected to grow until 2050, increasing associated GHG emissions and environmental impacts. A transition toward circularity and net-zero requires global shifts from fossil to recycled and bio-based feedstocks, alongside renewable energy in supply chains, and demand reduction (Bachmann et al., 2023; Meys et al., 2021; Zheng and Suh, 2019).

In the European Union (EU), this transition is particularly urgent for packaging, the largest application of plastic consumption, and therefore a key leverage point (European Commission, Joint Research Centre, 2025). While essential for preserving and protecting goods, packaging generates substantial waste (Eurostat, 2025), and accounts for 31% of the total environmental impacts in the European plastic supply chain (Amadei et al., 2024). Key barriers to circularity are complexity, costs, and competitiveness, requiring harmonized and enforceable EU policy (Plastics Europe, n.d.).

An upcoming milestone in EU regulation is the Packaging and Packaging Waste Regulation (PPWR), which entered into force on 11 February 2025 and will become applicable and binding on 12 August 2026 (PPWR, 2025). The PPWR aims to reduce primary material use, promote circular economy (CE), and guide the sector towards net-zero by 2050 (European Union, n.d.). It requires all EU packaging to be recyclable by 2030, introduces mechanisms such as mandatory feedstock labelling, and sets targets for waste mitigation, reuse, recycling, and recycled content. For 2030 and 2040, the PPWR sets minimum recycled content targets on the product level depending on polymer and application. This content must be recovered from post-consumer plastic waste collected and recycled in the EU or in third countries with equivalent environmental standards (EUROPEN, 2024). The European Commission and Council (2022) assessed the recycled content targets at a multi-polymer level for 2030 and 2040, using scenario-based mass flow modelling with cost-benefit analysis, and selected environmental indicators such as GHG emissions and water use. It reports GHG reductions under a chemical and mechanical recycling mix, with further environmental benefits under a purely mechanical recycling scenario by 2040. In 2032, the Commission will review the 2030 targets and assess the feasibility of the 2040 targets.

A potential Joint Target, allowing bio-based feedstock to partially replace recycled feedstock, remains debated. While industry stakeholders from Plastics Europe (2023) advocate for it, the European Commission and Council (2022) found such a target not beneficial for 2030, as even doubling the bio-based share would contribute only marginally to achieving 30% GHG reduction. However, the PPWR foresees further review through the Commission of the “technological development and environmental performance of bio-based plastic packaging” (PPWR, 2025, p. 8).

The PPWR addresses polyethylene terephthalate (PET) with higher targets than other polymers, reflecting its high feasibility for mainstream feedstock substitution (PPWR, 2025). This likely stems from PET already being one of the most used and recycled polymer in packaging due to its comparably low cost, low energy consumption, simple mechanical recycling and the partly implemented deposit return systems for bottles (European Commission, Joint Research Centre, 2025; Plastics Recyclers Europe, 2022; Ren et al., 2024). Besides recycling, bio-polyethylene terephthalate (Bio-PET) offers a further substitution pathway for PET. It is a non-biodegradable “drop-in” polymer compatible with existing technology, and can be produced from multiple feedstocks (Ali et al., 2022; García-Velásquez and Van Der Meer, 2022; Ritzen et al., 2025). Attributional Life Cycle Assessments (ALCA) at the product level find lower fossil fuel use and GHG emissions for Bio-PET than for PET and recycled PET (rPET), but higher water demand, ecotoxicity and ozone depletion impacts (Benavides et al., 2018; Chen et al., 2016). Moreover, large-scale biomass deployment is projected to increase cropland expansion, intensification and deforestation by 2040 (Helm et al., 2025).

Although the PPWR will apply soon, the environmental impacts of recycled and bio-based feedstock substitution under the PPWR on the European PET packaging sector in 2040 have not yet been assessed. Assessing these environmental impacts more holistically across a broader range of categories than considered by the European Parliament and Council

(2022) can be supported by prospective Life Cycle Assessment (pLCA), which “models the product system at a future point in time relative to the time at which the study is conducted” (Arvidsson et al., 2024, p. 611). pLCA has been mainly applied to emerging technologies on the micro-scale (Nurdiawati et al., 2025; Thonemann et al., 2020). Extending its use to the macro-level, however, allows to capture effects across an entire sector, making it particularly relevant for policy assessments (Paris et al., 2026a). pLCA can be conducted on the macro-level when the system fulfills a “specific function representing the demand at the national, continental or global scale” (Paris et al., 2026a, p. 2).

One approach for macro-level pLCA is coupling it with Integrated Assessment Models (IAM), which apply possible future projections. However, IAMs have largely overlooked the importance of materials so far (Pauliuk et al., 2017). Currently, IAMs are unable to account for full supply chain effects and the potential benefits and drawbacks of CE policies (Magalar et al., 2026). Stegmann et al. (2022a) addressed this gap by developing the Plastics Integrated Assessment model (PLAIA) within the Integrated Model to Assess the Global Environment (IMAGE), projecting plastic production, waste, stocks, feedstocks, collection rates, End-of-Life (EoL) treatments and energy use from 2005 to 2100 for eight sectors across the IMAGE regions. Despite its advancements, PLAIA projects plastic on a material level and does not represent product-level demand, such as packaging, and its implications on a macro-level. Addressing these gaps requires connecting packaging end-use with intermediate supply chain stages (Magalar et al., 2026), and quantifying future material flows and assessing their environmental impacts.

1.2 Research gap

Following the classification by Miles (2017), the identified research gap is two-fold, comprising (1) a knowledge gap and (2) a methodological gap.

- 1) **The knowledge gap** arises from the lack of understanding of the future environmental impacts of the European PET packaging sector in 2040 and the effect of feedstock substitution under the PPWR. While the European Parliament and Council (2022) assessed feedstock substitution at a multi-polymer level and existing ALCAs focus on current PET packaging, the impacts of product-specific content targets at the macro-level remain unclear. Existing macro-level LCAs of the European PET supply chain lack a future projection (Amadei et al., 2024; European Commission, Joint Research Centre, 2025). PLAIA provides projections for the plastic sector but excludes packaging production, use and EoL (Stegmann et al., 2022a). Andreasi Bassi et al. (2022) applies pLCA to the European PET packaging sector but for an earlier timeframe and without focusing on feedstock substitution.
- 2) **The methodological gap** relates to the lacking material perspective in IAMs, which largely overlook climate change mitigation based on material efficiency and lack whole supply chain interactions. This hinders prospective CE analysis (Paris et al., 2026b; Pauliuk et al., 2017). Magalar et al. (2026) recommend including the missing material perspective through coupling IAMs with external models such as Material Flow Analysis (MFA) and LCA. However, integrated applications of static prospective MFA (pMFA) and IAM-pLCA remain scarce.

1.3 Research question

This research aims to assess the environmental impacts of the European PET packaging sector in 2040 and the effect of recycled and bio-based feedstock substitution on the sector's environmental impacts. It explores the degree of change that is realistically achievable through the different feedstock substitutions under business-as-usual (BAU) future developments, aiming to answer the following main research question:

“What magnitude and direction of change in projected environmental impacts of the European PET packaging sector is achievable through feedstock substitution in the context of the Packaging and Packaging Waste Regulation in 2040?”

The main research question can be split into three supporting sub-questions:

1. **What are the projected material flows of the European PET packaging sector in 2040 under different scenarios of feedstock substitution?**
2. **What are the projected environmental impacts of the European PET packaging sector in 2040 under the defined scenarios?**
3. **Which hotspots and trade-offs in environmental impacts between the scenarios can be identified?**

The research outcomes include projected material flows for 2040, an environmental impact assessment of the defined scenarios, and the identification of hotspots and trade-offs, enabling science-based policy recommendations.

Methods

The research approach combines a static pMFA and a pLCA. Figure 1 provides an overview of this approach, showing which method addresses each sub-question and how these build on one another to answer the main research question.

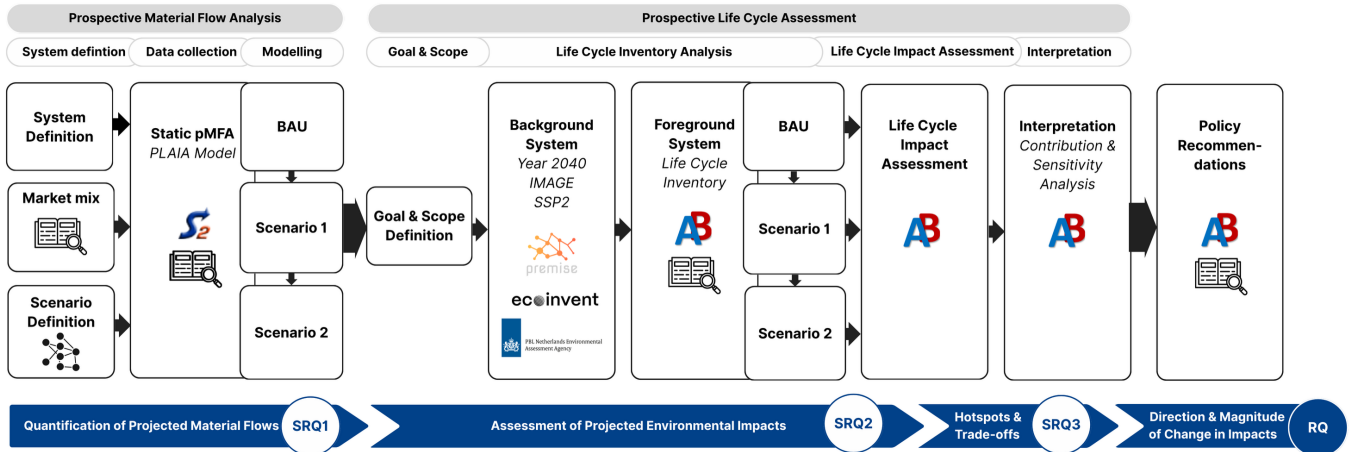


Figure 1: Overview of the research approach, combining pMFA and pLCA to address the study's research question. (Note: SRQ = sub-research question; RQ = research question).

This study applies an EU-27 macro-level perspective. Corresponding system boundaries in the pMFA and functional unit (FU) in the pLCA allow for representing the entire European PET packaging demand in 2040. First, the scenario narratives and the plastic packaging market mix are defined. The pMFA is then carried out in the *subSTance flow Analysis* (STAN) software (Cencic and Rechberger, 2008) to quantify prospective material flows under the three defined scenarios. As MFA allows for the systematic accounting of flows and stocks of a material within an economic system defined by spatial and temporal boundaries (Brunner, 2004), it is well suited to answer the first sub-question on projected material flows. The pMFA results serve as input data for the pLCA (Jeswani et al., 2010). The pLCA, conducted in Activity Browser (AB) (Steubing et al., 2020) and adopting IAM-based future ecoinvent background data, assesses the future environmental impacts of the European PET packaging sector. pLCA is a suitable tool to assess the potential environmental impacts of product systems in future settings (Arvidsson et al., 2024; Guinée et al., 2018), making the characterization results of the three scenarios from the Life Cycle Impact Assessment (LCIA) well suited, to answer the second sub-question. Next, in the interpretation phase of the pLCA, hotspots and trade-offs between the scenarios are identified through contribution analysis at both the process and life cycle stage levels. This analytical approach quantifies the contribution of individual elements to the overall LCA results (Guinée, 2002), addressing the third sub-question. Finally, the results are interpreted to derive policy recommendations regarding the direction and magnitude of change in projected environmental impacts, thereby answering the main research question.

2.1 Scenarios

Three exploratory scenarios are defined to reflect the 2040 policy targets set by the PPWR and potential future legislation associated with the regulation (see Figure 2).

	BAU			Scenario 1 PPWR			Scenario 2 PPWR - Joint Target		
	Contact-sensitive PET packaging	Single-use PET bottles	Other PET packaging	Contact-sensitive PET packaging	Single-use PET bottles	Other PET packaging	Contact-sensitive PET packaging	Single-use PET bottles	Other PET packaging
Recycled feedstock	BAU projection (25.2%)			50%	65%	65%	50%	65%	65%
Bio-based feedstock (primary)	BAU projection (2.5%)			BAU projection (2.5%)			Bioeconomy projection (6.2%)		

Figure 2: Overview of the defined scenarios (BAU, Scenario 1: PPWR, and Scenario 2: PPWR – Joint Target) with key feedstock substitution shares.

A no-policy change scenario (BAU) is included to serve as baseline, against which the policy-driven scenarios can be compared. Scenario 1 explores the effect of recycled feedstock substitution as planned in the PPWR, and Scenario 2 a potential Joint Target combining recycled with bio-based feedstock substitution. This step-wise design allows the comparison of the degree of change achievable under BAU future developments through under each policy option (Adrianto et al., 2021; Bisinella et al., 2021). The three scenarios share the same societal and economic future developments based on Shared Socioeconomic Pathway (SSP) 2.

The **BAU** scenario applies a recycled feedstock substitution share of 25.2% based on the internal model provision, a bio-based feedstock substitution share of 2.5% (Stegmann et al., 2022a), and a recycling quota of around 50% (European Commission, Joint Research Centre, 2025).

Scenario 1 (PPWR) applies recycled feedstock substitution. This follows the recycled content targets set by the PPWR, requiring 50% for contact-sensitive (CS) PET packaging and 65% for single-use beverage PET bottles and other PET packaging for 2040 (Article 7). Bio-based feedstock substitution is 2.5% as in BAU. To account for the expected increase in demand for recycled feedstock, the scenario includes further PPWR target values, which influence the domestic provision of recycled feedstock. From 2030, the PPWR sets the recycling target of 55% for all plastic packaging (Article 52). Since a (higher) target for 2040 is not (yet) specified in the PPWR, the scenario fulfills the 55% target. Additionally, the scenario includes the PPWR's reuse target of 40% for beverages for 2040 (Article 29). Furthermore, the scenario applies the separate collection rate of 90% for single-use plastic beverage bottles (Article 50), which is a set policy target from 2029 onwards (PPWR, 2025), extended to all packaging as simplification. The recycled content targets increase the demand for recycled feedstock, increasing the provision in the demand-driven model. The increased separation rate and recycling quota also increase the provision, while the reuse target decreases it. For a causal loop diagram, illustrating these connections, see Supplementary material (SM) -S1.

Scenario 2 (PPWR - Joint Target) adopts the recycled feedstock substitution from Scenario 1 with all applied PPWR policy measures and combines it with bio-based feedstock substitution. This means a partial replacement of the recycled feedstock substitution. The biomass uptake in Scenario 2 increases from 2.5 % in BAU and Scenario 1 to 6.2 % (see Figure 2), increasing the share by about 148 %. This shift fully substitutes biomass imports with domestically produced biomass. Scenario 2 reflects a potential Joint Target under the PPWR legislation, allowing bio-based feedstock in both primary and recycled form to contribute toward recycled content targets (European Commission and Council, 2022). However, this has not yet been implemented in the current PPWR (PPWR, 2025). The Joint Target increases the demand for Bio-PET, which in turn raises its provision in this study due to the demand-driven model structure. Since the required rPET share under the PPWR could be replaced with Bio-PET under a Joint Target, rPET demand decreases while recycled Bio-PET (rBio-PET) provision increases (see SM-S1).

2.2 Plastic packaging market mix

The plastic packaging market mix is defined to represent the European PET packaging demand. It is based on Andreasi Bassi et al. (2022) and includes clear bottles, colored bottles, PET trays, PET strapping and PET film. These packaging types were grouped within the regulatory archetypes “contact-sensitive PET packaging”, “single-use beverage PET bottles” and “other PET packaging” applied by the PPWR, leading to the categories shown in Table 1. Separate beverage and non-beverage PET bottles categories were defined due to higher policy targets for single-use beverage PET bottles.

Table 1: Applied market mix of nine packaging archetypes throughout the study corresponding to regulatory archetypes of the PPWR.

Regulatory archetypes of PPWR	Recycled content targets	Included packaging types
Contact-sensitive PET packaging	50%	Contact-sensitive PET trays
		Contact-sensitive PET film
		Contact-sensitive clear non-beverage PET bottles
		Contact-sensitive colored non-beverage PET bottles
		Contact-sensitive reuse clear beverage PET bottles
		Contact-sensitive reuse colored beverage PET bottles
		Single-use clear beverage PET bottles
		Single-use colored beverage PET bottles
Other PET packaging	65%	PET strapping

2.3 Static pMFA

A static pMFA of the EU packaging sector at the polymer level of PET flows in 2040 was conducted under the three scenarios. A static prospective approach was required to assess the material flows as a snapshot in the future.

2.3.1 System definition

This pMFA analyzes primarily the material flows of PET. This necessarily requires quantifying upstream feedstock inputs from biomass, natural gas, oil, and coal. The spatial boundary is limited to the EU-27. Temporally, this study focuses on the year 2040, corresponding to the policy target year of the recycled content targets defined in the PPWR. It covers the provision of the nine PET packaging archetypes and their respective recycled content targets (see Section 2.2) across the five life cycle stages feedstocks, polymer production, manufacturing, use and EoL management (see SM1-S2). Figure 3 gives overview of the static pMFA model.

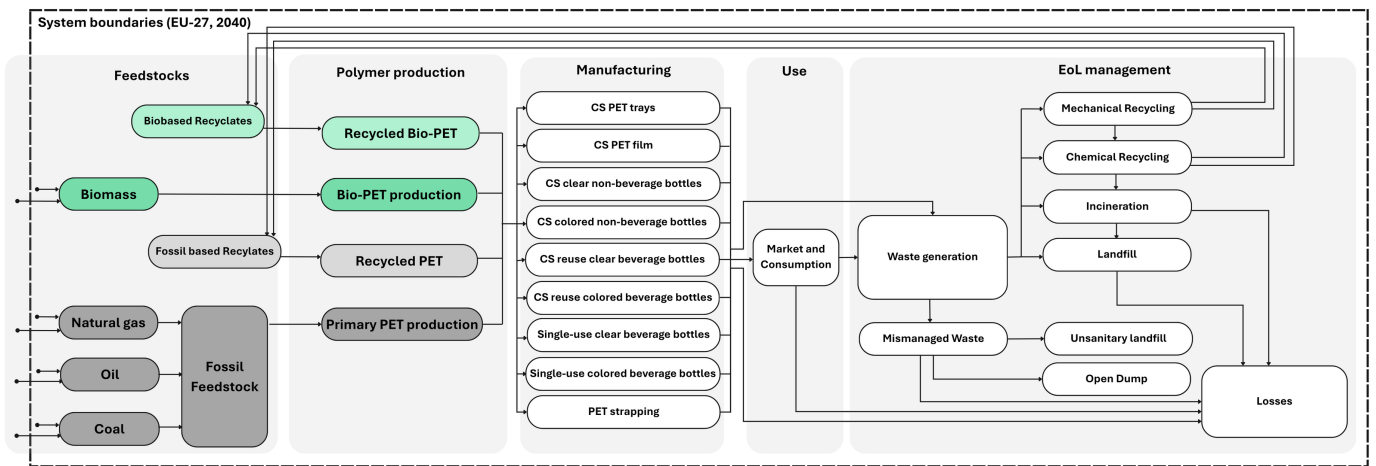


Figure 3: Simplified version of static pMFA model.

2.3.2 Model structure and calculation

The pMFA model applies a stock-flow logic as described by Brunner (2004). The system consists of a set of processes connected by material flows. Mass balance principles are applied to ensure that inputs, outputs and potential stocks are balanced within the defined system boundaries. Material shares, also referred to as transfer coefficients (TCs) (Brunner, 2004), are applied to account for the distribution of processes' outflows across different output flows. If available, these shares were based on data from PLAIA projections for CEU and WEU in 2040 (Stegmann et al., 2022b). Where no such share could be derived from PLAIA, shares from the European Commission, Joint Research Centre (2025) were used, assuming that these shares stay constant until 2040 (see SM1-S4 and SM2-I, II, VII, VIII, IX). This model is demand-driven, meaning that the demand for feedstocks determines their provision. The domestic EU feedstock provision was derived from PLAIA scenario output data (see SM2-III). Since the feedstock demand projected by Andreasi Bassi et al. (2022) is exceeding the EU production projected by PLAIA (Stegmann et al., 2022a), the model includes feedstock imports from non-EU countries. The required amounts of imports in megatons per year (Mt/yr) were calculated using Equation (1):

$$\text{Imports} = \text{Feedstock demand} - \text{Domestic EU production} \quad (1)$$

The import shares of the different feedstocks were calculated based on a market mix of the world without CEU and WEU, derived from PLAIA model output (see SM2-VI). Together, the EU production and the required imports give the total feedstock provision (see SM2-VI). Regarding the recycled material, this pMFA model reconciles the discrepancy between projected feedstock shares from PLAIA (Stegmann et al., 2022b), and the higher provision observed in this pMFA model. The latter results from the application of TCs derived from both PLAIA projected material flow amounts and current data from the European Commission, Joint Research Centre (2025). Consequently, this model projects a higher share of recycled feedstock provision than PLAIA. This can be largely attributed to the inclusion of consumption data in a demand-driven model, which increases the total feedstock amount in the system and, consequently, the amount of recycled feedstock. However, a limitation of the PLAIA model is that it underestimates the recycled feedstock provision (Stegmann et al., 2022a). To prevent potential overestimation in this model, further imports of recycled feedstocks beyond the

required amount to fulfill the PPWR's content targets are excluded, representing a conservative modelling choice. Adjusting the BAU scenario to Scenarios 1 and 2 required calculations (see SM2-VII, VIII, IX.).

In Scenario 1, several PPWR targets are applied. The reuse target of 40% for beverages is applied through an increased market share of the archetypes "CS reuse clear beverage PET bottles" and "CS reuse colored beverage PET bottles". The separation collection rate of 90% for single-use plastic beverage bottles is applied by changing the TC from around 63% to 90% in "Waste collection", based on the simplified assumption that this rate applies for all packaging. This automatically increases the recycling share from around 50% in BAU to around 71%, without changing further TCs. Therefore, the recycling target of 55% under the PPWR to all packaging archetypes is fulfilled and even exceeded.

In Scenario 2, the biomass uptake increases from 0.18 Mt/yr (2.5%) in BAU and Scenario 1 to 0.47 Mt/yr (6.2%). This fully replaces biomass imports with domestic production. This reduces the total recycled feedstock share from 4.32 Mt/yr (56.9%) to 3.86 Mt/yr (50.7%) and slightly increases the share of rBio-PET due to the higher Bio-PET production through a 148% increase in relevant TCs of fossil and bio-based recycling shares (see SM1-S4).

The static pMFA model was developed using the STAN software (Cencic and Rechberger, 2008), and results were visualized as Sankey diagrams using the *Material Flow Analysis Editor* (Structural Collective B.V., 2026) (see SM1-S5).

2.3.3 Data collection and assumptions

2.3.3.1 Data sources

Current materials shares were obtained from European Commission, Joint Research Centre (2022) and (2025). Projected feedstock production data and also partly TCs were derived from PLAIA using the scenario output data under the IMAGE SSP2 scenario in 2040 for the regions Central Europe (CEU) and Western Europe (WEU) (see SM1-S7) (Stegmann et al., 2022b). EU-27 PET data from PLAIA was derived by transforming the global plastic data in PJ/yr into Mt/yr by using the polymer-specific average lower heating value (LHV) for PET in GJ/t of 23.15, the global PET market share of 9% and a market share of packaging in 2040 of European production of 36.80% (see SM2-II) (Stegmann et al., 2022a). The PLAIA model estimates future demand data based on historical production data of upstream chemical production and assumes a logistic growth relationship between plastic production per capita and GDP per capita. However, this approach does not include recycled plastics in the demand projection, slightly underestimating the total plastic production and does not provide demand data on final plastic products. Because here a full life cycle approach is being followed, the future PET packaging demand was calculated using data from Andreasi Bassi et al. (2022) and the defined packaging market mix (see Section 2.2). On key discrepancy in the data is:

- Total Feedstock production in CEU and WEU in 2040: **5.24 Mt/yr** (Stegmann et al., 2022a).
- Total European PET packaging demand in 2040: 9.37 Mt/yr (considering BAU reuse quota of 5% for beverages), derived from Andreasi Bassi et al. (2022). In this model, this value is used as production input to packaging manufacturing processes, prior to accounting for pre-consumer losses, resulting in **9.25 Mt/yr**.

Since these amounts do not match and the EU demand for PET packaging is projected to exceed the EU production, this gap was covered by imports from non-EU countries (see Equation 1 in Section 2.3.2).

2.3.3.2 Assumptions

Several assumptions were required to close data gaps and were either partly based on grey literature or self-made.

General

- A constant global PET market share of 9% is assumed, and the market share of the EU packaging sector is assumed to be 36.80% in 2040 (Stegmann et al., 2022a).
- All consumed PET packaging in the EU-27 in 2040 is manufactured in the EU-27 and becomes waste after one year.
- The defined packaging market (see Section 2.2) covers 100% of the PET packaging demand of EU-27 in 2040.
 - 100% of PET trays are Contact-sensitive (CS).
 - 100% of PET film is CS.
 - 8% of clear and colored PET bottles are non-beverage (see SM1-S3).
 - 5% of clear and colored PET beverage bottles are reused (in BAU) (see SM1-S3).
 - An average of 20 reuse cycles per bottle is assumed in a steady-state reuse system.

- The PET packaging is assumed to consist of 100% PET, other potential ingredients (e.g., additives) are excluded.
- The calculated feedstock mix is equally applied to the different packaging types, depending on the market share of the packaging type, and does not distinguish potentially different feedstock shares within product groups.
- While feedstock imports are considered, trade of chemicals, plastic waste or final products along the supply chain is excluded.

Scenario 1: PPWR

- The increased recycled feedstock demand is met primarily through the higher domestic EU production, and rPET imports where necessary, assuming no global supply constraints.
- The increased recycled feedstock demand is met through rPET imports and not through rBio-PET imports.
- Recycled content shares are differentiated by packaging type (see Section 2.2.); non-recycled feedstock shares (coal, biomass, natural gas, oil) correspond to the BAU feedstock mix across all packaging types.

Scenario 2: PPWR - Joint Target

- All implemented policy measures in Scenario 1 remain in place; the key difference is that the recycled content targets may additionally be met through Bio-PET.
- The bio-based feedstock share increases from 2.5 % in BAU and Scenario 1 to 6.2 % in Scenario 2, based on the PLAIA's "Circular Bioeconomy" scenario applying a 30% subsidy on biomass use in the chemicals and plastics sector, implemented linearly between 2020 and 2030 (Stegmann et al., 2022b), serving as a proxy for the economic incentive under the Joint Target.
- A higher share of rBio-PET is subsequently assumed due to the increased Bio-PET provision.

Detailed explanation of these and additional assumptions regarding the applied market mix and those from Andreasi Bassi et al. (2022) and Stegmann et al. (2022a), are provided in SM1-S3.

2.4 pLCA

The study employs a pLCA on the macro-level aiming to represent the European PET packaging demand in 2040. This pLCA includes the goal and scope definition, inventory analysis, impact assessment and interpretation (Guinée, 2002).

2.4.1 Goal and scope definition

The goal of the pLCA is to estimate the future environmental impacts of the European PET packaging sector in 2040 in the BAU scenario, and to assess the impacts of recycled feedstock substitution in Scenario 1 and of the combined recycled and bio-based feedstock substitution in Scenario 2, enabling a comparison of their environmental performance. The model applies a cradle-to-grave system boundary. An attributional pLCA modelling approach for 2040 is applied, with IAMs integrated in the model foreground system (Paris et al., 2026a). ALCA assesses the impacts of the demand in a certain reference year as it is without any changes (Guinée et al., 2018). Unlike time-explicit pLCA, which considers multiple timesteps and accounts for the temporal distribution of processes, pLCA looks at a single, fixed future timestep (Müller et al., 2025). Table 2 presents the defined scope.

Table 2: Scope definition with a focus on the representativeness of the modelled system.

Dimension	Selected scope
Geographical	EU-27 (using the IMAGE regions WEU and CEU as proxies)
Temporal	2040
Technological	State of the art (2040) for background sectors (e.g., electricity and transport); limited prospective data for foreground chemical processes
Scenario type	Exploratory

The function of the system is to provide PET packaging consumption to the EU in 2040. Accordingly, the FU is defined as the total PET packaging demand in the EU in 2040 (see Table 3). The alternatives are the different scenarios as defined in Section 2.1. The reference flows correspond to the total mass of PET packaging placed on the EU market required to fulfil the demand in 2040, whose absolute quantity is determined in the pMFA (see Section 2.3).

Table 3: Function, FU, alternatives and reference flows.

Function	To provide PET packaging consumption to the EU in 2040
Functional Unit	Total PET packaging demand in the EU in 2040
Alternatives	BAU, Scenario 1: PPWR, Scenario 2: PPWR – Joint Target
Reference flow, BAU	9.25 Mt/yr of PET packaging placed on the EU market required to fulfil the demand in 2040
Reference flow, Scenario 1	7.51 Mt/yr of PET packaging placed on the EU market required to fulfil the demand in 2040
Reference flow, Scenario 2	7.51 Mt/yr of PET packaging placed on the EU market required to fulfil the demand in 2040

2.4.2 Life Cycle Inventory

The modeled system consists of a foreground and a background. The foreground entails processes of the European PET packaging sector across the defined packaging archetypes from cradle-to-grave (see SM1-S9). The background provides all remaining process inputs (Paris et al., 2026a). While all three scenarios constitute the foreground (see Section 2.1), they share the same background, built using the Python package *premise* (Sacchi et al., 2022) and the IAM IMAGE (PBL Netherlands Environmental Assessment Agency, 2014) under the SSP2 scenario. This future development matches the feedstock projections from PLAIA used in the pMFA (see Section 2.3.3).

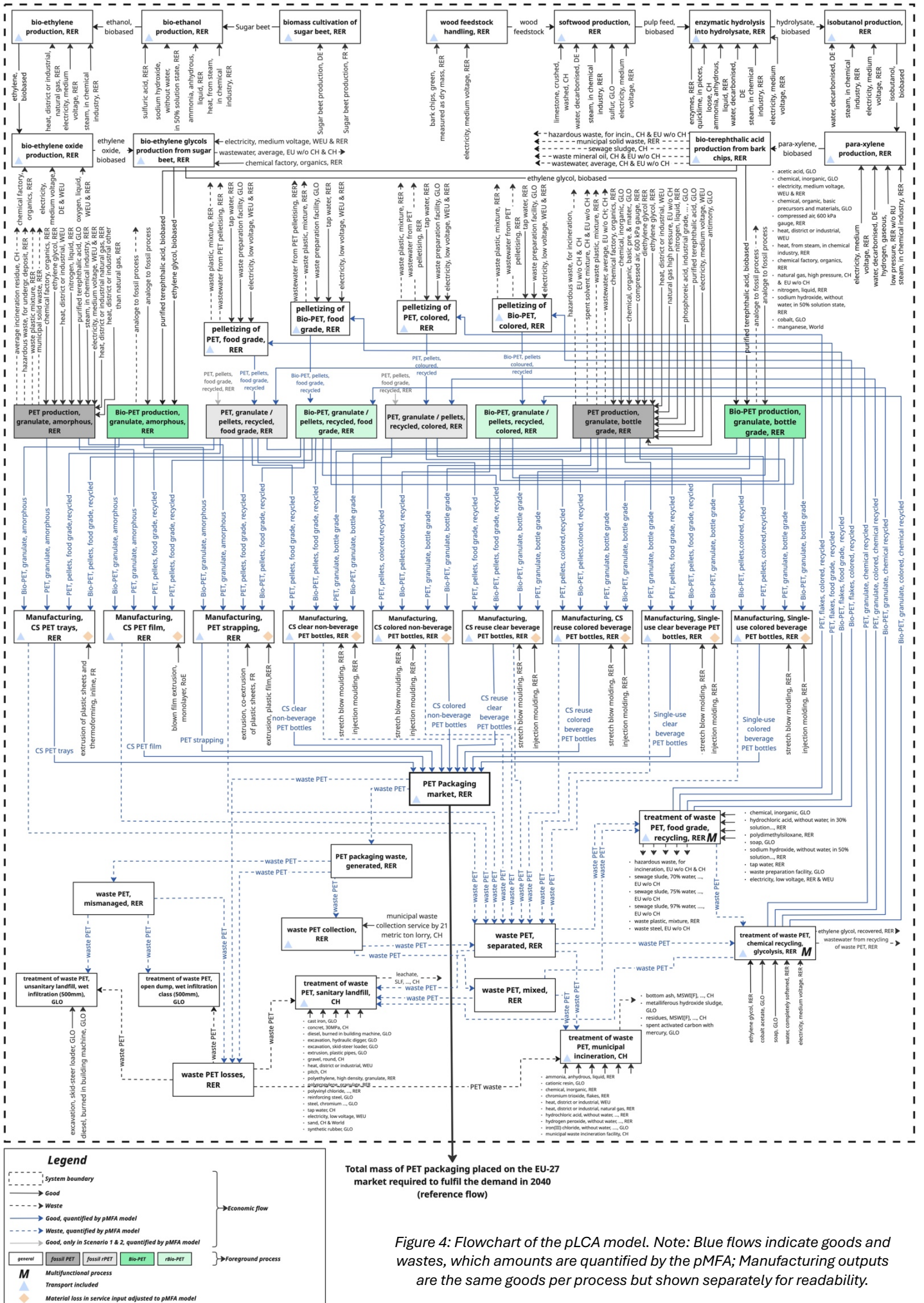
2.4.2.1 Foreground System

Figure 4 shows the flowchart of the pLCA model, covering the nine PET packaging archetypes from cradle-to-grave. It includes the life cycle stages feedstocks, polymer production, manufacturing, use and EoL management. The foreground system was modelled using background LCI data aiming to represent the EU-27, and therefore prioritizing European datasets (“RER”, “WEU”, and “CEU”). It was supplemented with Bio-PET upstream supply chain data from Ritzen et al. (2025) and chemical recycling (glycolysis) data from Golkaram & Heemskerk (2022). The pMFA results serve as input data for the LCI of the unit processes (see SM3-I; LCI data is provided in SM3-V, VI, and VII). The resulting pLCA model entails some simplifications (see SM1-S10).

Processes including transport are indicated with a triangle in Figure 4. Transport distances and underlying assumptions were kept constant across scenarios. A simplified proxy approach was applied to estimate the contribution of transport in polymer production and manufacturing, assuming all production facilities to be located in the geographical centre of the EU-27 (see SM1-S12.1). Freight transport was modelled per IMAGE region (CEU, WEU) using projected vehicle propulsion market mixes. For municipal waste collection, 20km distance and for transport to treatment facilities 200km distance were assumed, weighted by the number of EU Member States per region (see SM1-S12.2).

Multifunctional processes are characterized by multiple functional flows (Guinée, 2002). A functional flow can be either a good as output or a waste as input. Figure 4 indicates the multifunctional processes of the pLCA model with an “M”. In this study, the mechanical and chemical recycling processes are multifunctional and require the application of an allocation method, for which physical allocation was chosen, as it allocates impacts based on physical mass relationships between co-products, which is consistent with the study’s focus on material flows (see SM1-S14 for allocation factors).

A main modelling choice presents the selection of biomass for Bio-PET. It is a copolymer of monoethylene glycol and terephthalic acid (TA). Fully bio-based PET, where both components are bio-based, is not yet commercially available (García-Velásquez and Van Der Meer, 2022; Ritzen et al., 2025). Currently, only bio-based monoethylene glycol is commercially available (Bergsma et al., 2023), resulting in a 30% bio-based share when mixed with petrochemical TA (García-Velásquez and Van Der Meer, 2022). This study assumes 100% Bio-PET to be commercially available in the EU-27 by 2040. While bioethanol production is currently mainly based on imported biomasses such as sugarcane from India or Brazil (García-Velásquez and Van Der Meer, 2022), this study assumes biomass produced within the EU-27 to reflect a potential European bioeconomy. For bioethanol production, sugar beet from the region Europe (RER) is used as biomass, with LCI data sourced from Ritzen et al. (2025). Sugar beet was selected because of its common availability in Europe, energy-efficiency (Langeveld et al., 2014), and recommendation for large-scale use (García-Velásquez and Van Der Meer, 2022). For TA production, wood was selected following European Commission recommendations to use feedstocks of “second generation” to avoid food competition (European Commission, 2018; Molenvod et al., 2026). LCI data for TA production from wood was sourced from Ritzen et al. (2025), adjusted to RER and combined with the fossil background process. Since Bio-PET is a “drop-in” polymer, fossil processes can be adopted and adjusted (Ali et al., 2022). Detailed upstream supply chain flowcharts are provided in SM1-S11.



2.4.2.2 Background System

The background system was built using the Python *premise* (Sacchi et al., 2022), which modifies activities in the sectors electricity, steel and cement, fuels and road transport, affecting the plastic sector indirectly. For consistent comparison across the SSP scenarios, a superstructure database was developed (Steubing and De Koning, 2021). Figure 5 provides an overview of the workflow.

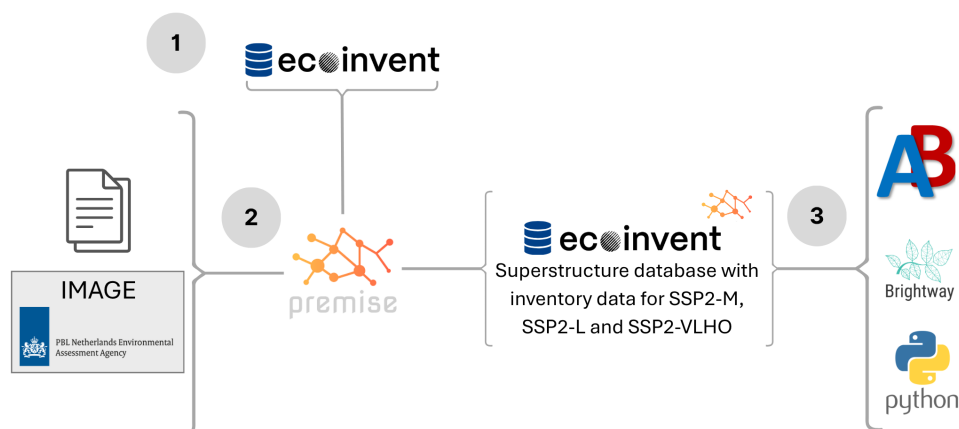


Figure 5: Workflow of scenario-based LCA modelling, adapted from Paul Scherrer Institut et al. (2025), adjusted for this study.

Firstly, the ecoinvent v3.12 cut-off database (Wernet et al., 2016), the latest version including new plastic processing data, was extracted from ecoquery (2025). Secondly, the ecoinvent database was modified using *premise* for the IAM IMAGE coupled with SSP2-M (Medium), SSP2-L (Low) and SSP2-VLHO (Very low high overshoot). SSP2 represents the “Middle-of-the-Road” pathway (O’Neill et al., 2017), and underlies the PLAIA model (Stegmann et al., 2022a). The SSP2-M was chosen as the baseline because it represents a medium emission scenario under Representative Concentration Pathway (RCP) 4.5. For sensitivity analysis, SSP2-L and SSP2-VLHO are used. IMAGE was selected because it integrates PLAIA (see SM1-S8). Its focus on climate-ecosystem interactions across land use, food, energy and climate makes it particularly suited for assessing environmental impacts related to Bio-PET (*premise dash*, n.d.). Thirdly, the modified ecoinvent database was implemented in AB (v3.0.0b202603241605), running on Brightway25 (v4.6) (Steubing et al., 2020). Table 4 details the projected global mean surface temperature (GMST) increase per SSP.

Table 4: Overview of selected SSPs (IPCC, 2023; Paul Scherrer Institut et al., 2025; *premise dash*, n.d.).

SSPs	Characteristic	GMST increase by 2040	GMST increase by 2100
SSP2-M	Without aggressive mitigation strategies	1.72°C	2.8 -3.0 °C
SSP2-L	Aggressive mitigation strategies, sustainable energy system	1.74°C	1.5-1.7 °C
SSP2-VLHO	Emissions temporally exceed limits, but are reduced to sustainable levels on the long term	1.82 °C	< 1.5 °C

2.4.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) is carried out in AB. The impact family Product Environmental Footprint (PEF) is selected and applied as EF v3.1 in AB because it is recommended by the European Commission (2021) and provides a comparable and standardized set of impact categories. The PEF method uses 16 midpoint impact categories (European Commission, 2021) (see SM1-S15 for impact categories with respective indicators, units and characterization models).

2.4.4 Interpretation

The interpretation of the pLCA allows the identification of hotspots and trade-offs. It entails the contribution and sensitivity analyses, and the consistency check (see SM1-16). Direct process contributions to impact categories are analyzed through grouping into energy production, transport, manufacturing, raw materials, waste treatment and others (see SM4-IV). Life cycle stage contribution analysis is conducted by dividing the system into the life cycle stages polymer production, manufacturing and use, and EoL management, whereby polymer production is further distinguished into PET, rPET, Bio-PET and rBio-PET (see SM1-S17). Sensitivity analyses on the LCI background are conducted with SSP2-L and -VLHO, and on the LCI foreground, by applying wheat as biomass source for bioethanol production based on LCI data from Ritzen et al. (2025) (see SM3-VIII-X).

2.5 Model alignment between pMFA and pLCA

Model alignment refers to the process of ensuring consistency between different models, so that outputs from one model can be correctly used as inputs in the other. In this study, model alignment was required due to data inconsistencies between ecoinvent 3.12 and the data sources used for the pMFA. This involved the bidirectional integration of data from one model into the other one and vice versa, which is detailed in the following sections. For information on how consistency with premise was ensured, see SM1-13.5.

Domestic production and imports: In the pMFA, feedstock supply distinguishes domestic EU production and imports to align the consumption data (Andreasi Bassi et al., 2022) with the production data (Stegmann et al., 2022a). The pLCA simplifies this by using the total fossil or bio-based inputs only, disregarding geographic and feedstock source shares (see SM1-S13.2). While the pMFA includes biomass imports in BAU and Scenario 1, the pLCA represents all biomass inputs through domestic EU supply chains. Scenario 2 eliminates this discrepancy by adopting domestic EU biomass provision from the PLAIA's "Circular Bioeconomy" scenario. The RER market process for recycled PET pellets was used as a proxy for non-EU imports in Scenarios 1 and 2 (see grey arrows in Figure 4).

Waste losses: To allow the use of the pMFA results, "collection processes" were established (see SM1-13.1), including the "losses" sink in the pMFA represented by "waste PET losses [RER]" in the pLCA. Based on European Commission, Joint Research Centre (2025), 33% of losses are recollected, while the other share is polluted into the environment. Due to missing environmental flows (EFs) in ecoinvent biosphere, only the recollected share was modelled to represent the EoL treatment of losses and was proportionally allocated to incineration, sanitary landfill, open dump and unsanitary landfill, depending on their distribution within each scenario (see black arrows from losses in Figure 4, and SM3-III). The recollected share serves thus as a proxy to include these losses in the EoL treatment, while the proportional distribution reflects the assumed fate of PET waste across both managed and mismanaged pathways along the supply chain, including incomplete collection and informal disposal.

Material losses: Manufacturing service inputs (see Figure 4) are applied based on Andreasi Bassi et al. (2022) and TNO (2024). Their LCI data in ecoinvent v3.12 differ from the projected manufacturing losses in the pMFA model (~1.16% of output), which are based on shares from the European Commission, Joint Research Centre (2025). To ensure consistency, the manufacturing losses derived from the pMFA model are applied to pLCA manufacturing service inputs (see SM1-S13.3). Several adjustments were made to avoid double counting. The incineration process adopted from the background includes bottom ash and other residues as outputs. Consequently, waste PET flows to losses and sanitary landfill derived from the pMFA were excluded. Similarly, the sanitary landfill process accounts for leachate, making an additional waste PET output to losses redundant. Material losses in pelletizing, chemical recycling and mechanical recycling processes, adopted from the background system were incorporated into the pMFA model and the pLCA processes were scaled accordingly (see SM1-S13.4). As the mechanical recycling process adopted from the background already includes waste plastic mixture and waste for incineration, the corresponding pMFA-derived flows to sanitary landfill and incineration were excluded.

3.1 Prospective material flows

The first sub-question “*What are the projected material flows of the European PET packaging sector in 2040 under different scenarios of feedstock substitution?*” is addressed by the prospective materials flows from the pMFA across the three scenarios (see SM1-S6). The following sections explain the main trends identified in the pMFA results.

3.1.1 BAU

Fossil feedstock reliance: The BAU scenario projects a total feedstock demand of 9.37 Mt/yr. As visualized in Figure 6, it is dominated by 6.24 Mt/yr non-recycled feedstocks, in particular by oil (4.69 Mt/yr), while natural gas (0.67 Mt/yr), coal (0.65 Mt/yr), and biomass (0.23 Mt/yr) play a minor role.

Dominance of PET: Consequently, the resulting polymer provision is dominated by 6.01 Mt/yr PET, with recycled feedstock covering a smaller share (2.36 Mt/yr rPET, and 0.76 Mt/yr rBio-PET), and a very small Bio-PET share (0.23 Mt/yr).

Import dependence: Around a quarter of the total feedstock demand relies on imports (2.34 Mt/yr), again dominated by oil (1.5 Mt/yr), while the majority is covered by domestic EU production (7.03 Mt/yr).

High demand and low reuse: The total PET packaging demand in BAU is 9.37 Mt/yr, considering a 5% reuse share in beverage product groups. In BAU, 9.25 Mt/yr of PET packaging is placed on the EU-27 market in 2040. For the applied packaging archetype shares see SM1-S2.

High waste generation: After use, 8.82 Mt/yr of PET packaging waste is generated. Of this, the majority is collected (8.12 Mt/yr), with 5.15 Mt/yr as separately collected and 2.97 Mt/yr as mixed waste. From uncollected waste, 0.52 Mt/yr is mismanaged.

High amounts incinerated and landfilled: Incineration treats a combined 2.9 Mt/yr and sanitary landfills receive a combined 1.4 Mt/yr.

Moderate recycling: Mechanical recycling processes 4 Mt/yr of separated waste and 0.002 Mt/yr mixed waste. It passes 0.87 Mt/yr on to chemical recycling, which additionally receives 0.037 Mt/yr of separated waste. Combined, the closed-loop recycling output is 2.36 Mt/yr rPET and 0.76 Mt/yr rBio-PET.

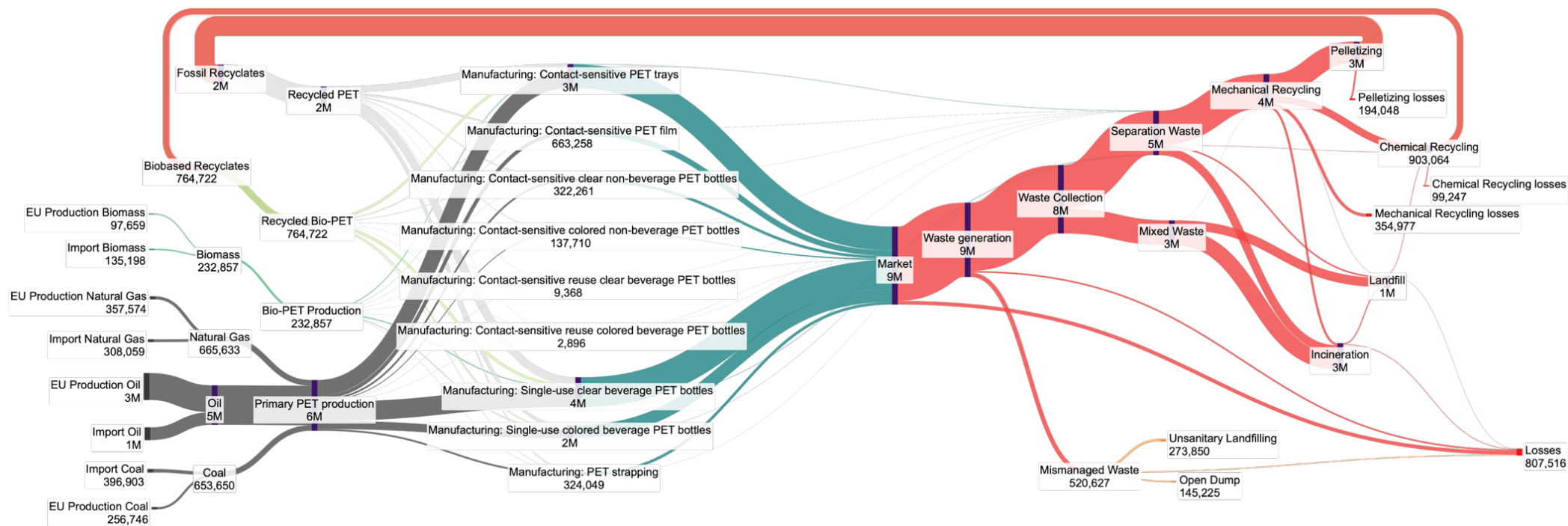


Figure 6: pMFA results of the European PET Packaging Sector, BAU in 2040, in kt/yr. Note: units are mixed (kiloton (kt) and megaton (Mt)) due to software limitations; values ≥ 1 Mt are displayed as “M”; proportions remain accurate; Colors indicate the different life cycle stages: dark grey = PET polymer production, light grey = rPET polymer production, dark green = Bio-PET production, light green = rBio-PET polymer production, petrol blue = packaging manufacturing, red = EoL management.

3.1.2 PPWR

Demand reduction: Scenario 1 projects a reduced total feedstock demand of 7.61 Mt/yr, driven by the applied 40% reuse share in beverage product groups. As a result, 7.51 Mt/yr of PET packaging is placed on the EU-27 market.

Decreasing fossil feedstock reliance: The feedstock demand in Scenario 1 shifts significantly from fossil to recycled feedstocks (see Figure 7). Non-recycled feedstocks drop to 3.28 Mt/yr and remain dominated by oil (2.1 Mt/yr). Notably, oil imports are eliminated entirely, and 1.09 Mt/yr of potential domestic oil production remains unused.

Required imports of rPET: While most recycled feedstock demand is met domestically (2.78 Mt/yr rPET and 0.88 Mt/yr rBio-PET), 0.67 Mt/yr rPET imports are required.

Dominance of rPET: The polymer provision is now dominated by rPET (3.45 Mt/yr), alongside primary PET (3.09 Mt/yr), followed by rBio-PET (0.88 Mt/yr), and Bio-PET (0.19 Mt/yr).

Packaging waste reduction: Packaging waste generation falls to 7.16 Mt/yr.

Increased separation collection: The applied 90% separation collection rate raises separately collected waste to 5.93 Mt/yr, while mixed waste drops to just 0.66 Mt/yr.

Less incinerated and landfilled material: As a result, incineration falls significantly to 1.7 Mt/yr (from 2.9 Mt/yr in BAU) and sanitary landfilling to 0.6 Mt/yr (from 1.4 Mt/yr in BAU).

Increased recycling: The higher separation collection rate leads to higher inputs into the recycling processes. The closed-loop recycling output is 2.78 Mt/yr rPET and 0.88 Mt/yr rBio-PET.

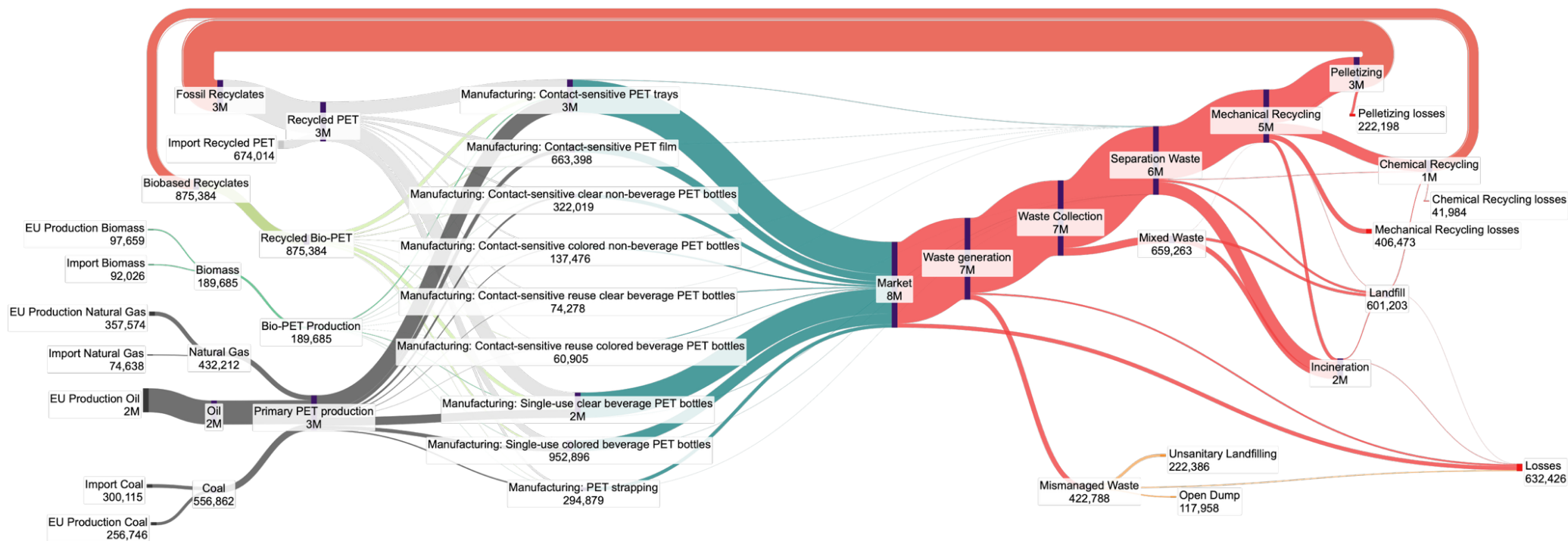


Figure 7: pMFA results of the European PET Packaging Sector, Scenario 1 in 2040, in kt/yr. Note: units are mixed (kt and Mt) due to software limitations; values ≥ 1 Mt are displayed as “M”; proportions remain accurate; Colors indicate the different life cycle stages: dark grey = PET polymer production, light grey = rPET polymer production, dark green = Bio-PET production, light green = rBio-PET polymer production, petrol blue = packaging manufacturing, red = EoL management.

3.1.3 PPWR - Joint Target

Demand reduction: As in Scenario 1, the total feedstock demand in Scenario 2 drops to 7.61 Mt/yr, and 7.51 Mt/yr of PET packaging is placed on the EU-27 market in 2040 (see Figure 8).

Increased biomass uptake: The feedstock provision is characterized by increased biomass uptake (0.47 Mt/yr) and a subsequently slightly increased rBio-PET share through domestic production with no assumed imports. Consequently, the polymer provision shifts modestly towards bio-based feedstocks, with 0.47 Mt/yr Bio-PET and 0.9 Mt/yr rBio-PET. However, PET (3.28 Mt/yr) and rPET (2.96 Mt/yr) still dominate the overall provision.

Dominance of rPET: Recycled feedstocks slightly dominate the demand with 3.86 Mt/yr (2.96 Mt/yr rPET and 0.9 Mt/yr rBio-PET), and non-recycled feedstocks account for 3.75 Mt/yr (2.23 Mt/yr oil, 0.59 Mt/yr coal, 0.47 Mt/yr biomass, and 0.46 Mt/yr natural gas).

Required rPET imports: To fulfill the recycled content targets in Scenario 2, rPET imports are required, accounting for 0.29 Mt/yr.

Packaging waste reduction: Packaging waste generation falls to 7.16 Mt/yr, as in Scenario 1, resulting in similar EoL material flows across both scenarios.

Increased recycling (compared to BAU): The closed-loop recycling output reaches 2.66 Mt/yr rPET, entirely provided by mechanical recycling and pelletizing, and 0.9 Mt/yr rBio-PET (0.04 Mt/yr from mechanical recycling and pelletizing, and 0.86 Mt/yr from chemical recycling).

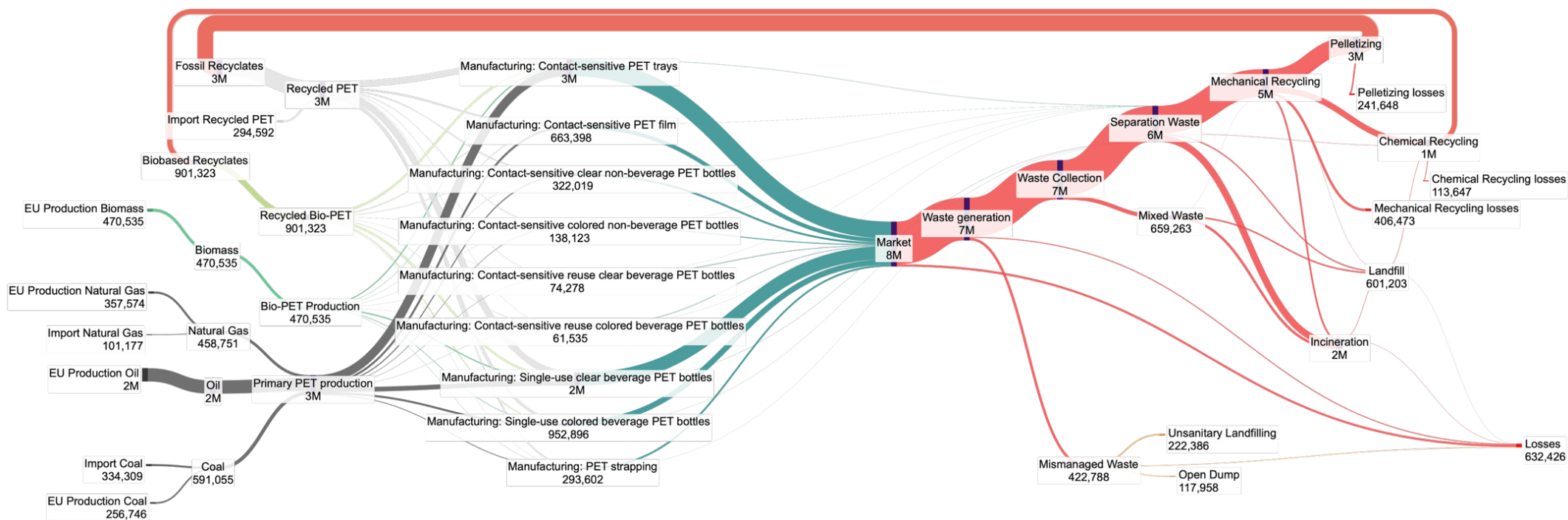


Figure 8: pMFA results of the European PET Packaging Sector, Scenario 2 in 2040, in kt/yr. Note: units are mixed (kt and Mt) due to software limitations; values ≥ 1 Mt are displayed as “M”; proportions remain accurate; Colors indicate the different life cycle stages: dark grey = PET polymer production, light grey = rPET polymer production, dark green = Bio-PET production, light green = rBio-PET polymer production, petrol blue = packaging manufacturing, red = EoL management.

3.1.4 Comparison of scenarios

In BAU, most of the feedstock demand is met through domestic production, while a significant dependence on imports might exist in 2040 (see Figure 9). The overall feedstock demand decreases from 9.37 Mt/yr in BAU to 7.61 Mt/yr in Scenarios 1 and 2 due to higher reuse quotas under the PPWR, which also reduces imports from non-EU countries. A key distinction between BAU and Scenario 1 is the domestic oil production, which reduces from 3.19 Mt/yr in BAU to 2.1 Mt/yr in Scenario 1, with oil imports eliminated. Scenario 2 shows a similar pattern, with oil production at 2.23 Mt/yr and no oil imports. In Scenario 1, rPET supply increases from 2.36 Mt/yr in BAU to 2.78 Mt/yr through the PPWR measures. However, imports of rPET are required to fulfill the recycled content targets. Scenario 2 is characterized by biomass more than doubling from 0.23 Mt/yr in BAU and 0.19 Mt/yr in Scenario 1 to 0.47 Mt/yr, and by an increased rBio-PET share of 0.88 Mt/yr in Scenario 1 to 0.9 Mt/yr in Scenario 2.

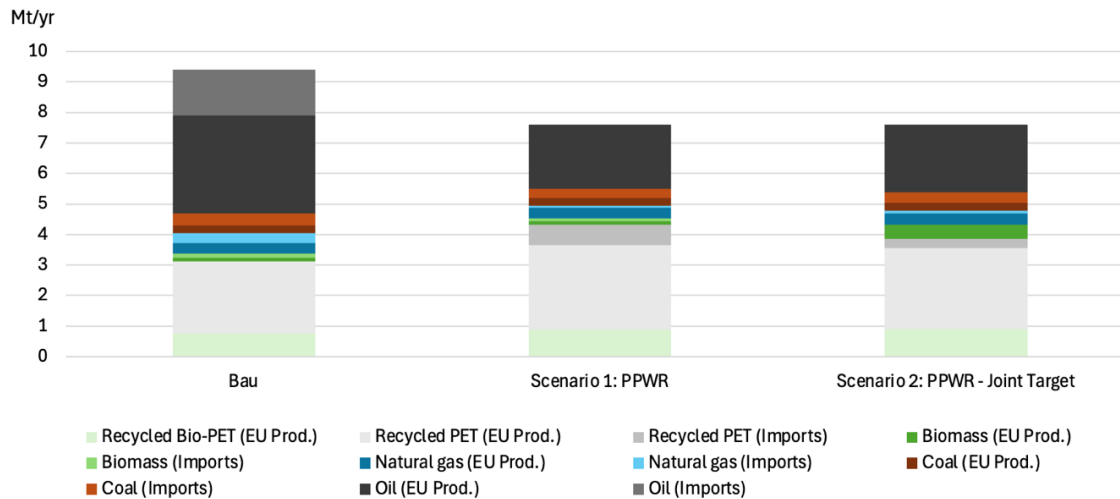


Figure 9: Comparison of absolute amounts (in Mt/yr) of feedstock sources (rBio-PET, rPET, Biomass, Coal, Natural gas and Oil) across the scenarios, covering domestic EU production and required imports to fulfill the demand.

The feedstock inputs result in the polymer production shares shown in Figure 10. In BAU, polymer shares consist of 64% PET, 2.5% Bio-PET, 25% rPET and 8% rBio-PET. In Scenario 1, the rPET share increases to 45% and the rBio-PET share to 11.6%, reducing required fossil feedstocks. In Scenario 2, the Bio-PET share rises to about 6%, slightly increasing the rBio-PET share. Since the Bio-PET share accounts for the content target in Scenario 2, the PET share slightly increases in Scenario 2 compared to Scenario 1.

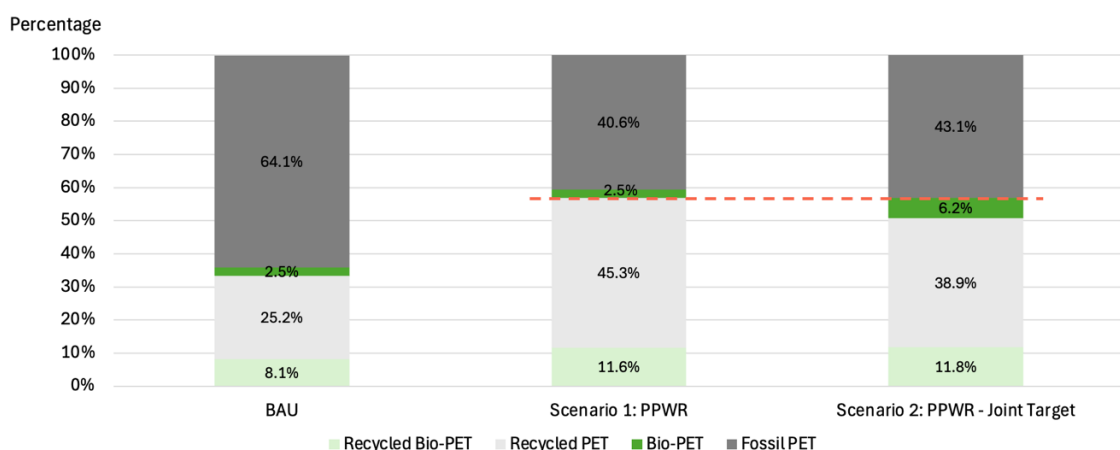


Figure 10: Comparison of polymer production shares across the three scenarios (in %). Note: the red line marks the percentual share of the PPWR's recycled content targets, fulfilled by rPET and rBio-PET under Scenario 1 and rPET, rBio-PET and Bio-PET in Scenario 2.

Figure 11 shows the EoL options across all scenarios. Since the total PET amount placed on the market is higher in BAU (9.25 Mt/yr) than in Scenario 1 and 2 (7.51 Mt/yr), all EoL amounts are generally higher in BAU, most notably incineration. Scenarios 1 and 2 are broadly similar in their EoL management, with Scenario 1 showing slightly higher amounts of rPET.

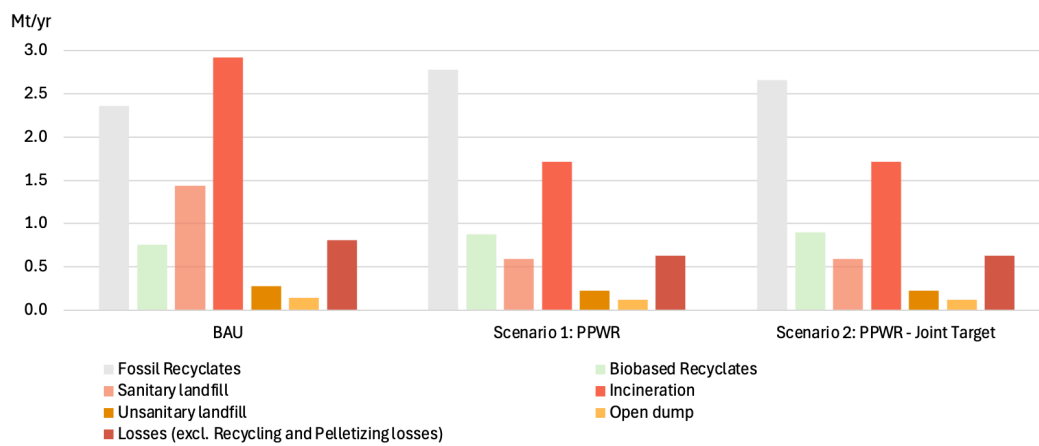


Figure 11: Comparison of EoL management across the three scenarios (in Mt/yr).

3.2 Prospective environmental impacts

3.2.1 Characterization results

The second sub-question “What are the projected environmental impacts of the European PET packaging sector in 2040 under the defined scenarios?” is answered through the pLCA of the three scenarios under SSP2-M (for absolute results presented in table form and ranked results as a bar chart see SM1-S19.1). Figure 12 shows the ranked characterization results in a heatmap, comparing the three scenarios under SSP2-M.

BAU achieves the highest impacts across all impact categories, both Scenarios 1 and 2 reduce impacts considerably compared to BAU, and Scenario 1 achieves the lowest impacts consistently across all impact categories. Ranked to the highest impacts in BAU, Scenario 1 reduces climate change impacts by -64% and Scenario 2 by -59%.

In Scenario 1, the largest reductions compared to BAU are found in material resources (-82%), followed by ozone depletion (-73%), energy resources (-72%), freshwater eutrophication, ionizing radiation, photochemical oxidant formation (all -69%), acidification (-68%), land use (-66%), and water use (-65%).

In Scenario 2, the largest reductions relative to BAU can be found in material resources (-78%), ozone depletion (-70%), energy resources (-67%), ionizing radiation (-66%), freshwater eutrophication, and photochemical oxidant formation (both -62%), water use (-61%), and acidification (-60%). Land use in Scenario 2 shows the smallest reduction, at -49%.

The reduction gap between Scenario 1 and 2 is most pronounced in land use, where Scenario 2 shows a 17 percentage points (pp) lower reduction relative to BAU. It is followed by particulate matter formation and terrestrial eutrophication, with 10 pp lower reductions, and carcinogenic and non-carcinogenic human toxicity, with 6 pp lower reductions, all relative to BAU.

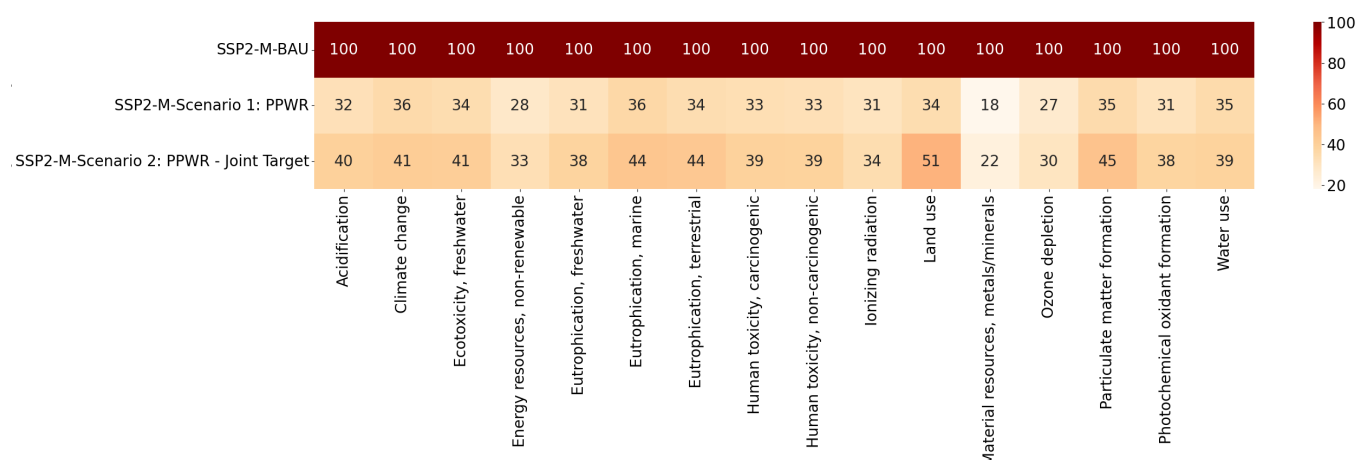


Figure 12: Comparative heatmap of ranked characterization results of BAU, Scenario 1 and Scenario 2 under SSP2-M conditions. Note: results are scaled to the highest score within each impact category. For example, in acidification, Scenario 1 has 32% of impacts relative to the highest impact in BAU (=100%).

3.2.2 Hotspots and trade-offs

The third sub-question “Which hotspots and trade-offs in environmental impacts between the scenarios can be identified?” is addressed by the contribution analysis results of EFs, direct process contributions and life cycle stages.

3.2.2.1 Environmental flow contribution

Figure 13 presents the EF contributions to the impact categories climate change, freshwater ecotoxicity, terrestrial eutrophication and land use.

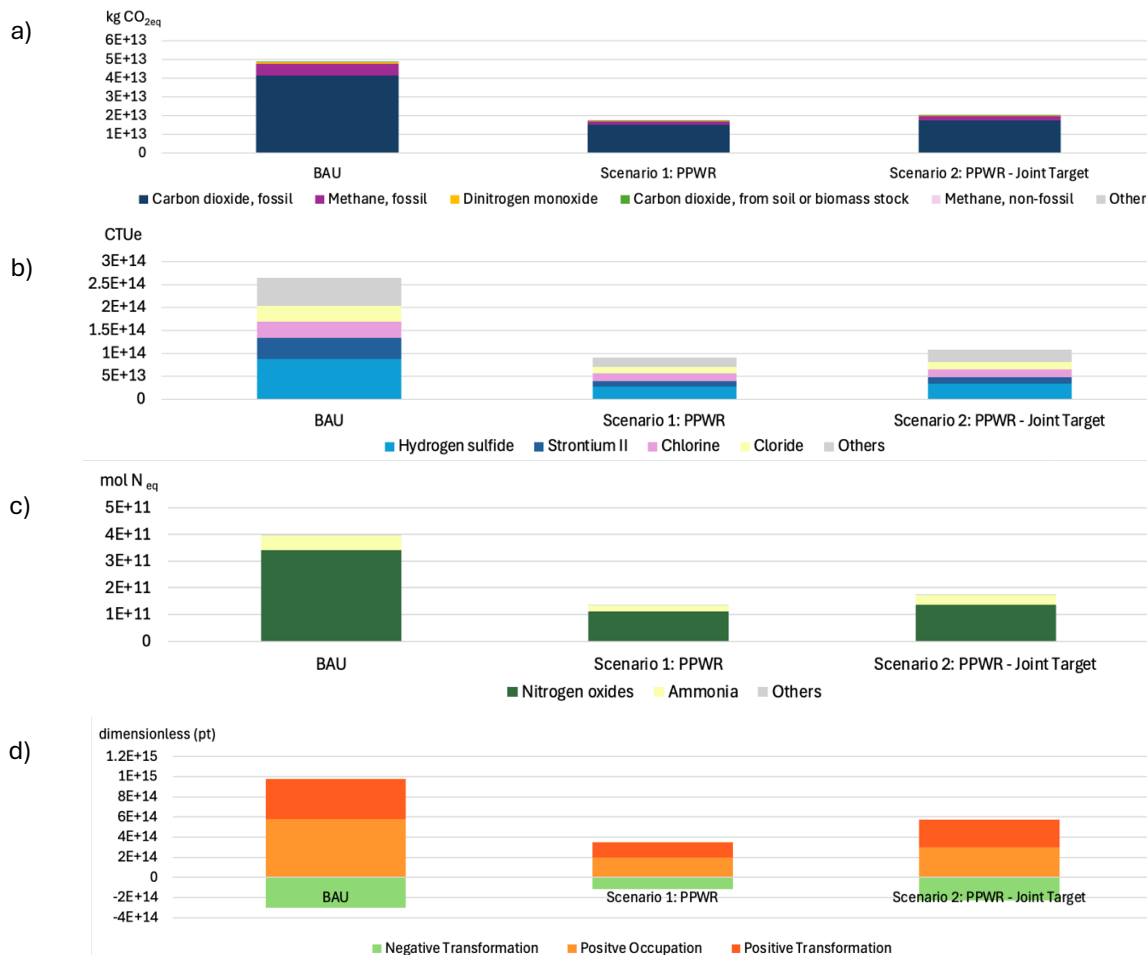


Figure 13: Environmental flow contribution in the impact categories (a) climate change, (b) freshwater ecotoxicity (c) terrestrial eutrophication and (d) land use.

Climate change is mainly driven by fossil carbon dioxide, with smaller contributions from fossil methane. Freshwater ecotoxicity is mainly influenced by hydrogen sulfide, with smaller contributions from strontium II, chlorine and chloride. For terrestrial eutrophication, nitrogen oxides contribute the most, followed by ammonia impacts. Land use is dominated by positive occupation and transformation, with BAU showing the highest overall impacts. Negative transformation impacts are also the highest in BAU, which includes for example deforestation. Across the four categories, Scenarios 1 and 2 reduce impacts significantly compared to BAU, with Scenario 2 showing slightly higher impacts than Scenario 1, particularly in terrestrial eutrophication and land use. Overall, the relative contributions are similar across the scenarios.

3.2.2.2 Direct process contribution

Figure 14 presents the direct process contributions under SSP2-M grouped into energy, transport, manufacturing (covering polymer and packaging production), raw materials, waste treatment and others (see SM4-IX for grouping). Overall, energy production and manufacturing emerge as dominant contributors at the process level. Differences in the relative direct process contribution between the scenarios are minor.

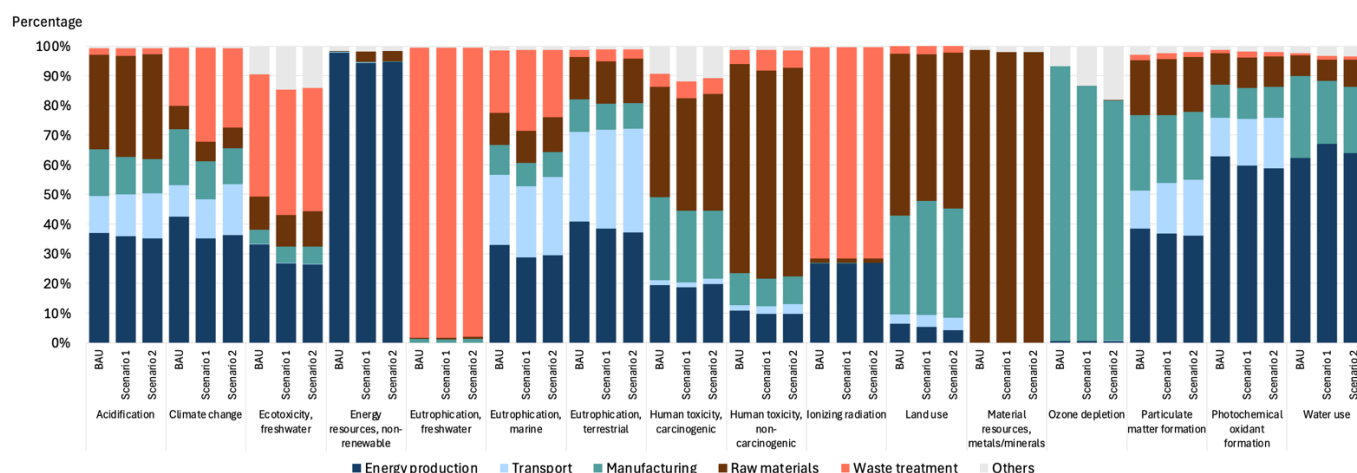


Figure 14: Direct process contribution under SSP2-M, grouped into energy, transport, manufacturing, raw materials, waste treatment and others (see SM4-IX for grouping).

Acidification is primarily driven by energy production, raw materials, and manufacturing. The highest impacts within energy production are associated with diesel burned in diesel machines (3-5%). Regarding raw materials, the highest contributions are driven by smelting of copper concentrate (6-7%). In terms of manufacturing contributions, impacts from reformat production (8% in BAU, 6% in Scenario 1, and 5% in Scenario 2) are most pronounced. Climate change is dominated by energy production, largely due to natural gas venting from petroleum (11%, 9%, and 9%), and by waste treatment, particularly incineration (14%, 23%, and 19%). As the overall climate change impacts decrease in Scenario 1 and 2 (see Figure 13a), the relative contribution of incineration grows. Transport, manufacturing and raw materials remain marginal contributors.

Freshwater ecotoxicity impacts are dominated by waste treatment and energy production. Within waste treatment, the wastewater market (4.8-6%) and treatment of sulfidic tailings from copper mine operation (5-6%) contribute moderately. Regarding energy production, high contributions from water discharge from petroleum and natural gas extraction (21%, 17%, and 16%) and methanol production from coal gasification (7%, and 5% in Scenario 1 and 2) can be found. Energy resources are almost entirely determined by energy production, with the highest contributions from petroleum and gas production onshore. Freshwater eutrophication impacts are almost entirely driven by waste treatment due to high contributions from treatment of spoil from hard coal mining in surface landfill (26-27%), treatment from spoil and coal lignite mining in surface landfill (17-18%), and treatment of sulfidic tailings from copper mine operation tailings impoundment in Serbia, Armenia and Montenegro (12%) and China (9%). These processes were grouped under waste treatment, though these are also closely linked to raw materials. Marine eutrophication is mainly driven by waste treatment, with the highest contributions from the sanitary landfill foreground process (8%, 9%, and 7%), and energy production, with the highest impacts from diesel burned in building machines (8%, 8%, and 9%). Terrestrial eutrophication shows large contributions from energy production, with the highest contributions from burned diesel in building machines (9%, 11%, and 12%), likely related to construction work, alongside sea transport.

Carcinogenic human toxicity impacts can be largely associated with raw materials and manufacturing. Raw material contributions are mainly driven by smelting of copper concentrate (9-10%). Manufacturing impacts are influenced by chlor-alkali electrolysis (6-7%). Non-carcinogenic human toxicity is more strongly linked to raw materials due to smelting of copper concentrate sulfide ore in Chile (23-24%) and RoW (4%). Ionizing radiation is driven by waste treatment due to high contributions from tailing from uranium milling (66% across all scenarios), and by energy production, dominated by the disposal of spent nuclear fuel (11%). Land use is primarily driven by manufacturing due high impacts from road construction (19%, 24%, and 26%), which is included in this group (see SM4-IX), and raw materials, particularly softwood production from spruce (20%, 19%, and 24%) and pine (12%, 12%, and 14%). As expected, material resource use is almost entirely linked to raw materials, with the highest contributions from stibnite mine operation and beneficiation (44%, 33%, and 32%). Ozone depletion is determined by purified TA production in RoW (75%, 70%, and 70%) and RER (18%, 16%, and 15%), as well as the foreground process of Bio-TA production (4%, 5%, and 12%). The growing contribution of Bio-TA production, particularly in Scenario 2, reflects the higher Bio-PET production assumed in the scenario design.

Particulate matter formation is associated to a mix of energy production and manufacturing. Energy production is dominated by burned diesel in building machines (10%, 11%, and 12%). Manufacturing impacts are associated with road construction (9%, 7%, and 6%) and reformation production (7%, 8%, and 10%). Photochemical oxidant formation is strongly influenced by energy production due to natural gas venting (41%, 37%, and 36%) and diesel burned in building machines (5%, 6%, and 7%), with minor contributions from manufacturing and raw materials. Water use is primarily driven by energy production, particularly electricity production in Norway (18%, 16%, and 16%) and RoW (15%, 27%, and 23%), and manufacturing, specifically injection molding (8%, 5%, and 5%) and stretch blow molding (8%, 6%, and 5%).

3.2.2.3 Life cycle stage contribution

Figure 15 shows the life cycle stage contributions of polymer production (PET, rPET, Bio-PET and rBio-PET), manufacturing of packaging and use, and EoL under SSP2-M (see SM1-S17 for life cycle stage definitions). While the manufacturing group in Figure 14 also includes polymer production, manufacturing in Figure 15 represents only packaging manufacturing.

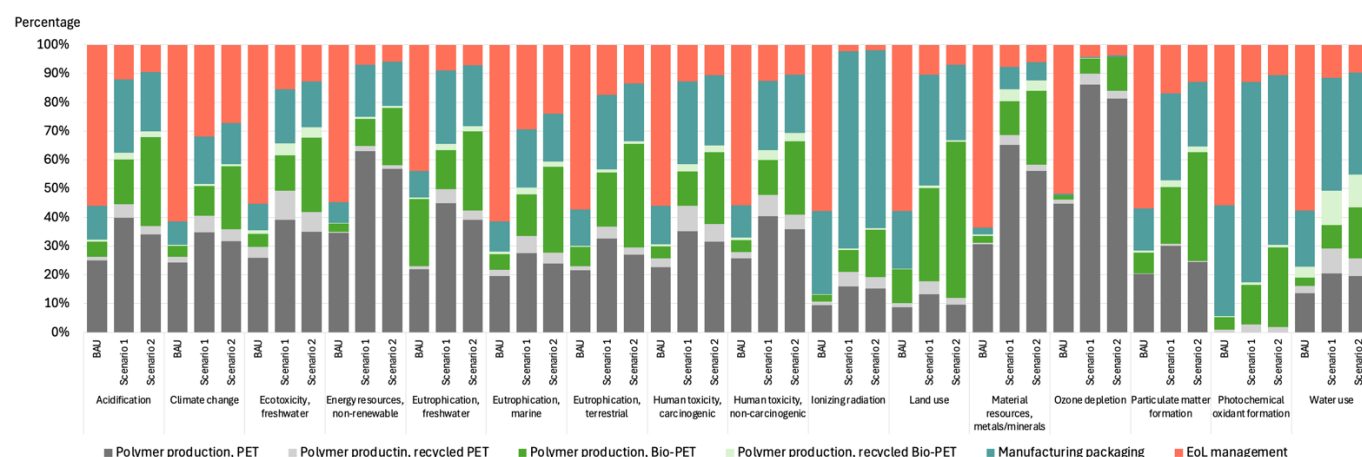


Figure 15: Life cycle stage contribution under SSP2-M, grouped into Polymer production (PET, rPET, Bio-PET, rBio-PET), Manufacturing & Use and EoL (see SM1-S17 for life cycle stage definitions).

PET production and EoL management emerge as dominant hotspots. EoL management contributions are stronger in BAU than in Scenarios 1 and 2, which might be due to higher incineration volumes (see Figure 11). PET production contributions increase relatively in Scenario 1 and 2 due to lower EoL contributions, particularly in the impact categories energy resources, and ozone depletion. rPET and rBio-PET contributions are negligible across all impact categories. Its largest but still small contributions can be found in Scenarios 1 and 2 in freshwater ecotoxicity, carcinogenic and non-carcinogenic human toxicity, and water use. Despite its small material share (2.5% in Scenario 1, and 6.2% in Scenario 2) in the pMFA, Bio-PET shows disproportionately relevant contributions in Scenarios 1 and 2, with higher contributions in Scenario 2. Largest contributions can be observed in land use, followed by particulate matter formation, terrestrial eutrophication, freshwater eutrophication, and energy resources. Packaging manufacturing contributes moderately across most impact categories, with the highest contributions in Scenario 1 and 2 in ionizing radiation, photochemical oxidant formation, and smaller but relevant contributions in land use and water use.

3.2.3 Sensitivity analysis

To test the sensitivity of the results, analyses are conducted on both the background and the foreground system. For the background, SSP2-L and SSP2-VLHO are applied as alternatives to the selected baseline SSP2-M. For the foreground, wheat is used as an alternative biomass for bioethanol production, while all other foreground processes, including wood for TA production, are kept constant (see SM1-S19). This sensitivity analysis was selected because Bio-PET polymer production contributes relatively strongly compared to its small share in the pMFA (2.5% in BAU and Scenario 1, and 6.2% in Scenario 2) (see Figure 15). The biomass selection presented a main modelling choice and Ritzen et al. (2025) reported lower land use impacts for sugar beet than for wheat, making it interesting for testing the sensitivity of the results to this assumption.

3.2.3.1 Background system

Figure 16 shows the characterization results of BAU, Scenario 1 and 2 across SSP2-M, -L and -VLHO when ranked per SSP separately. Overall, the results are highly consistent, indicating that the choice of SSP2 type has only a minor influence on the results. The direct process and life cycle stage contributions under SSP2-L and -VLHO show also similar results as under -M (see SM1-S19.2). This is expected since all three are SSP2 variants that shift impact levels uniformly, leaving relative differences between scenarios unchanged.

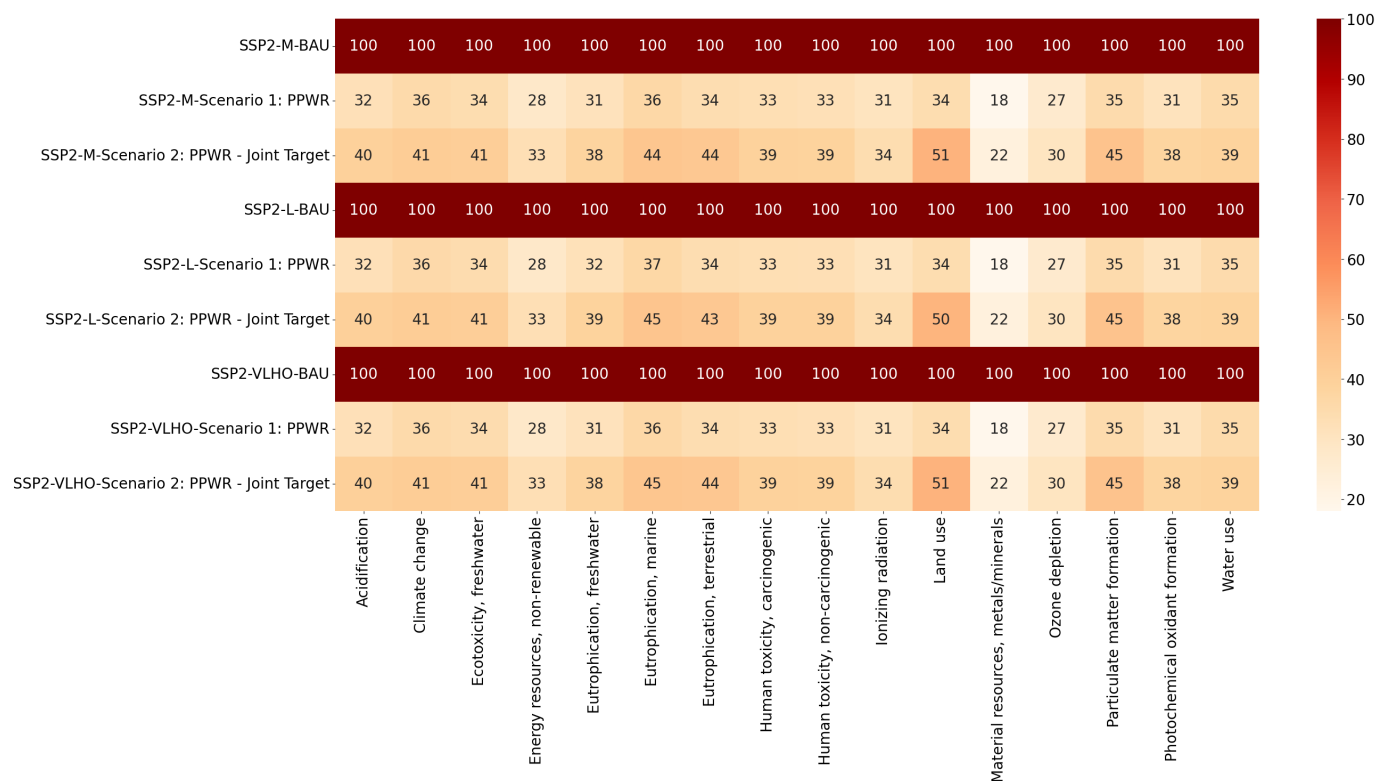


Figure 16: Comparative heatmap of ranked characterization results under SSP2-M, -L and -VLHO. Note: results are scaled to the highest score within each impact category separately for each SSP, resulting in three independent scaling groups in the figure.

Figure 17 presents the characterization results of the three scenarios across SSP2-M, -L and -VLHO ranked together. Under SSP2-M, the three scenarios achieve lower ionizing radiation (-25% in BAU), land use (-4% in BAU), and water use (-5% in BAU) than under SSP2-L. In contrast, under SSP2-L, compared to SSP2-M, the scenarios achieve lower acidification (-5% in BAU), climate change (-3% in BAU), freshwater eutrophication (-19% in BAU) and slightly lower non-carcinogenic human toxicity (-3%), marine and terrestrial eutrophication (both -2% in BAU), particulate matter formation and photochemical oxidant formation impacts (both -1% in BAU). Under SSP2-VLHO, also compared to SSP2-M, the scenarios show slightly higher ionizing radiation (+2% in BAU), and slightly lower impacts (-1% in BAU) across many impact categories.

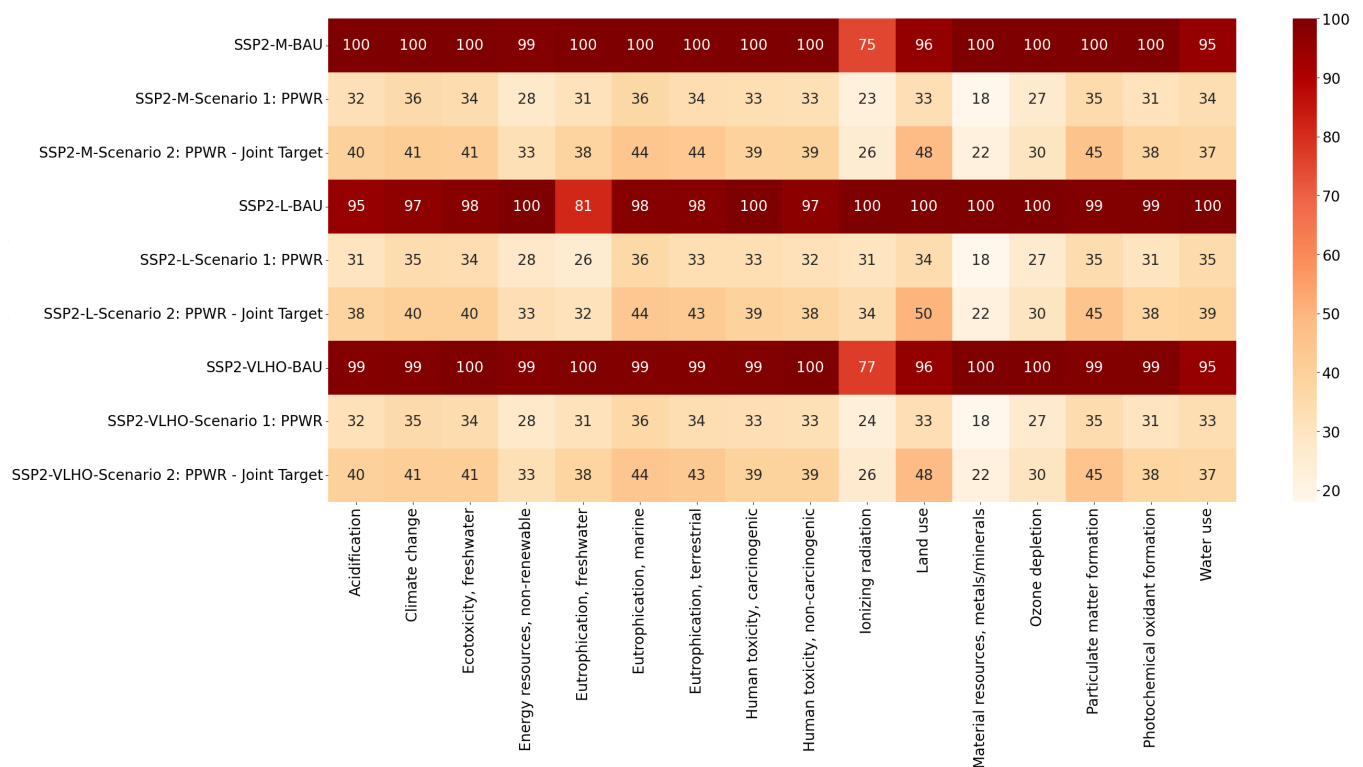


Figure 17: Comparative heatmap of ranked characterization results under SSP2-M, -L and -VLHO. Note: results are scaled to the highest score within each impact category for all SSP together, resulting in one combined scaling group in the figure.

3.2.3.2 Foreground system

The characterization results of the three scenarios across SSP2-M, -L and -VLHO, using wheat instead of sugar beet as biomass source for bioethanol production, lead to the same results as presented for the baseline in Figure 16. Only very small, negligible differences occur under SSP2-L (see SM1-S19.3). This indicates that the choice of biomass for the bioethanol production has only minor influence.

4.1 Key Findings

4.1.1 Prospective material flows

The first sub-question “*What are the projected material flows of the European PET packaging sector in 2040 under different scenarios of feedstock substitution?*” was answered through the projected material flows in the European PET packaging sector in 2040 (see Figure 6, Figure 7 and Figure 8). The pMFA allows us to understand the polymer shares of PET, Bio-PET, rPET and rBio-PET at a macro-level under the PPWR’s content targets. Additionally, the results give insights into future import dependencies. In BAU, most of the feedstock demand can be met through domestic production. However, results indicate that a significant import dependence on fossil feedstocks, particularly oil, might exist in 2040. Although the implemented reuse quotas decrease the packaging demand in Scenario 1 and 2, rPET imports are required to fulfill the recycled content targets under the PPWR. Nonetheless, the demand reductions and increased recycling in Scenarios 1 and 2 significantly reduce the amounts of waste generated, incinerated and landfilled compared to the BAU.

4.1.2 Prospective environmental impacts

The second sub-question “*What are the projected environmental impacts of the European PET packaging sector in 2040 under the defined scenarios?*” was addressed through the environmental impact assessment of the three scenarios, showing that Scenarios 1 and 2 achieve strong environmental improvements compared to BAU by 2040, with climate change impact reductions of -64% and -59% respectively (see Figure 12). Scenario 1 consistently achieves the lowest impacts across all impact categories, with the largest reductions in material resources (-82%), ozone depletion (-73%), and energy resources (-72%). Scenario 2 shows moderately higher environmental impacts than Scenario 1, most notably in land use (-17pp), terrestrial eutrophication, and particulate matter formation (both -10pp), all relative to BAU.

This third sub question “*Which hotspots and trade-offs in environmental impacts between the scenarios can be identified?*” was investigated through the direct process and life cycle stage contribution analyses (see Figure 14, and Figure 15). At the process level, energy production and manufacturing are the dominant contributors across most impact categories. Despite slowly declining fossil fuel dependence and intensity in energy use under SSP2 (O’Neill et al., 2017), energy production remains a significant contributor across several impact categories. This may indicate that decarbonization under SSP2 is insufficient to strongly reduce these impacts, or that fossil-related burdens may be partially replaced by those from renewables. Raw materials drive mainly acidification, carcinogenic and non-carcinogenic human toxicity, while waste treatment dominates freshwater eutrophication, freshwater ecotoxicity, and ionizing radiation. At the life cycle stage level, PET polymer production and EoL management emerge as hotspots, with EoL contributions being more substantial in BAU due to greater amounts of incinerated and landfilled material. Bio-PET shows disproportionately high contributions, particularly in land use under Scenario 2 despite its small material share. Sensitivity analysis confirmed that the choice of biomass for bioethanol production has only minor influence on the environmental effects at the macro-level. rPET and rBio-PET show small contributions, supporting the conclusion that it is beneficial to use secondary material. Overall, the findings indicate that recycled content targets under the PPWR are highly environmentally beneficial, while a Joint Target (allowing bio-based feedstock to partially replace recycled feedstock) offers no additional advantage over recycled content targets.

4.2 Implications

4.2.1 Scientific contribution

This study improves the understanding of the effect of feedstock substitution under the PPWR on prospective environmental impacts of the European PET packaging sector. To the best of my knowledge, it is the first study assessing the effect of content targets on the product-level for PET packaging under the PPWR on the European macro-level. Therefore, comparable studies remain limited. The identified import dependence in the pMFA model aligns with projections from Plastics Europe (n.d.) that European plastics will develop into an import market. The pLCA focusing on the European PET packaging sector from Andreasi Bassi et al. (2022) is only partly comparable to this study due to differing methodological approaches (consequential compared to attributional), its focus (waste management rather

than feedstock substitution), background database (ecoinvent 3.5 versus 3.12), and time horizon (2020-2030 instead of 2040). However, the finding that reducing PET packaging demand significantly lowers environmental impact aligns with the findings of this study. The impact assessment of the European Commission and Council (2022) finds the recycled content targets for 2030 (measure 35em) and 2040 (measure 35eh) beneficial, but not the Joint Target for 2030 (measure w). These results are in line with the findings of this study for 2040. Methodologically, this study extends the EU assessment, which only assessed a few selected environmental indicators (e.g., GHG emissions, water use). By applying a pLCA covering 16 impact categories, this study offers a more detailed environmental impact assessment and allows the identification of trade-offs and hotspots between policy options. In addition, this study provides specific results for the PET sector, complementing the more aggregated multi-polymer perspective of the EU impact assessment.

At the intersection of materials, circular economy and IAMs, this study contributes to closing the recognized methodological gap of the currently lacking material perspective in IAMs, namely the limited representation of material flows as well as the lack of whole supply chain interactions (Magalar et al., 2026; Pauliuk et al., 2017). Linking IAMs with MFA models has been proposed as one way of addressing these shortcomings, enabling material-balanced analysis through multi-scale coupling (Magalar et al., 2026). This means, for example, the combination of micro-level product data with macro-level sector data to improve data on the material content of products at a regional scale. Moreover, integrating all life cycle stages and interlinkages of material flows between the life cycle stages in models, connecting the end-use sector with intermediate supply chains, has been highlighted as a further way to strengthen such models (Magalar et al., 2026). This study implements both recommendations by coupling IAMs with pMFA and pLCA for the European PET packaging sector and covering the entire packaging life cycle. As a result, this study improves prospective data on material contents of PET packaging in the EU-27 and demonstrates a practical example of multi-scale coupling by combining the material content of packaging products with sector-wide material flows. The novel integration of IAMs, static pMFA and LCA extends existing modelling approaches and shows a possible way to address the currently lacking material perspective in IAMs and to provide prospective projections for material systems. At the same time, this study identified practical challenges when linking static pMFA with pLCA (see 4.3.3 Model alignment). Despite these constraints, the combination of models provides a useful approach for the environmental assessment of materials systems until materials and CE measures are more comprehensively represented in mainstream IAMs. This study builds on the IAM PLAIA, which is limited by its reliance on production data, assuming production data to represent demand. Stegmann et al. (2022a) highlighted the need for incorporating country-specific consumption data. By integrating European consumption data from Andreasi Bassi et al. (2022) and accounting for imports from non-EU countries based on PLAIA data, this study overcomes this limitation.

This study contributes to the field of IAM-pLCA on the macro-level by demonstrating how CE policies can be modelled. Paris et al. (2026a) called for strengthening policy relevance in this niche to enable more effective policy design. This study evaluated the PPWR and represented circularity measures such as increased reuse of PET bottles and higher recycling rates in Scenarios 1 and 2.

Furthermore, Paris et al. (2026a) have identified pitfalls and challenges in the field of pLCA on the macro-level, of which this study resolves some but also leaves others unaddressed. Looking at systems scaling, this model used the pMFA results as input data into the LCI unit processes, scaling processes proportionately to material quantities. Therefore, this study assumes a linear relationship between scale and unit process performance, disregarding scale-dependent changes, such as potential increased recycling efficiency at higher throughput, and thereby falls into this pitfall. In terms of internal consistency, this study aligned the pMFA and pLCA model as closely as possible by ensuring mass balance, matching for example material losses (see 4.3.3 Model alignment), and applying the same IMAGE SSP2 background scenarios in both models. This study does not address the temporal distribution pitfall, as the pLCA represents only the single target year 2040 and does not distinguish when processes occur across lifecycle stages. However, the relevance of this limitation is likely lower for packaging than for products with longer lifetimes. Common pitfalls in the literature include the insufficient definition of the FU, system boundaries and multifunctionality, as well as a lack of transparency and reproducibility. This study addresses both by providing transparent definitions and ensuring reproducibility through detailed supplementary materials (see SM1-4). In addition, addressing the common pitfall of narrowly focusing on climate change impacts, this study covers 16 impact categories, enabling a detailed hotspot and trade-off analysis.

Since existing IAM-pLCA studies are thematically often limited to the sectors electricity, transport, space heating, and cement, reflecting the sectors directly modified by *premise*, this study broadens the thematic scope of macro-level IAM-pLCA research (Paris et al., 2026a; Sacchi et al., 2022). Paris et al. (2026a) have called for broadening the thematic scope by including consumer goods which are relevant for sustainability transitions. While the analysis remains subject to limitations regarding the availability of prospective data for the chemical sector (see 4.3.2 pLCA model), this study demonstrates the applicability of the macro-level IAM-pLCA beyond the mainstream sectors and extends the application to the plastic packaging sector. This was only possible because the IAM community itself had already moved beyond the standard sectors, with PLAIA (Stegmann et al., 2022a) providing a foundation for the plastic sector on which this study could build. This study does not contribute to scenario diversity, as it focuses solely on SSP2 (see limitation in Section 4.3.4). Extending the analysis to other SSPs was not feasible, as the underlying PLAIA model is based on SSP2, which formed the foundation for the pMFA and pLCA model.

Overall, this study contributed scientifically to the field of Industrial Ecology by advancing and linking methodological approaches within pLCA. Specifically, it (1) links IAM-pLCA with static pMFA, (2) demonstrates the evaluation of material circularity policies in IAM-pLCA, and (3) explores IAM-pLCA on a macro-level beyond the mainstream sectors (Jeswani et al., 2010; Magalar et al., 2026; Paris et al., 2026a).

4.2.2 Societal relevance

From a societal perspective, promoting plastic circularity in order to reduce the fossil fuel dependence and environmental impacts from plastic packaging in the EU remains a key policy challenge (Hsu et al., 2021; Plastics Europe, n.d.). This study gives insights into whether the set recycled and potential bio-based content targets under the PPWR for 2040 translate into actual environmental improvements and where potential challenges may arise.

The results suggest that implementing the PPWR's recycled content targets for 2040, combined with measures that increase the availability of rPET, is highly environmentally beneficial. It achieves substantial reductions across all impact categories compared to BAU (see Figure 12). The robustness of this finding is supported by its consistency across all impact categories, its alignment with findings from European Commission and Council (2022), and its confirmation under sensitivity analysis using SSP-L and -VLHO. However, it should also be acknowledged that the derived material flows from the pMFA model are limited by partly assumed constant material shares until 2040 (see limitations in Section 4.3.3), and that this study conducted only a limited sensitivity analysis (see Section 3.2.3). This suggests that the reported findings should be interpreted as indicative of directional trends, consistent with the study's focus on the magnitude and direction of change in environmental impacts.

Scenario 1 applied several PPWR targets. It meets the recycled content targets for different packaging types (see Section 2.2), increased reuse, and increased collection efficiency (see 2.1 Scenarios), with the recycling rate increasing from 50% to 71%, thereby even exceeding the PPWR target of 55% for packaging. The environmental impact reduction in Scenario 1 can be mainly associated with the reduced primary PET demand, increased rPET use and overall demand reduction.

Another important implication for the recycled content targets is that the pMFA results indicate a risk of circularity leakage, showing that rPET imports are required to meet the increased demand under the PPWR (see Figure 7). This raises questions about the robustness of the EU-27 circular economy in 2040. While the PPWR requires imported recycled content to originate from third countries with equivalent environmental standards (EUROPEN, 2024), this requirement does not address potential rPET supply constraints itself. As producers strive to meet the targets, competition for available rPET increases. This is especially critical for food-grade pellets since contamination reduces rPET feedstock purity (Hadley, 2022). This also calls into question the overall environmental benefit, as increased EU imports could, in a situation of limited global rPET supply, reduce the ability of non-EU countries to meet their own recycled content targets. This suggests that if the EU aims to achieve self-sufficiency in rPET, while meeting the recycled content targets under the PPWR, a substantial expansion of domestic recycling infrastructure will be required. In this context, upscaling recycling infrastructure capacity and quotas across Member States, while reducing national disparities, emerges as a future policy challenge, given that recycling performance varies significantly across the EU and is projected to continue diverging until 2030 (Scrioșteanu and Criveanu, 2024).

In contrast, the results do not support the implementation of a Joint Target under the PPWR for 2040. The pLCA shows that Scenario 1 achieves consistently lower impacts across all impact categories than Scenario 2 (see Figure 12),

indicating that a shift in policy from recycled content targets towards a Joint Target does not appear environmentally beneficial. The robustness of this finding is supported by its consistency across all impact categories, and its confirmation under the foreground sensitivity analysis using wheat instead of sugar beet for bioethanol production, indicating only limited sensitivity to the choice of biomass for bioethanol production. However, as noted above, this sensitivity analysis remained limited in scope. Moreover, the results demonstrate that demand reductions significantly reduce environmental impacts. The environmental impacts of Scenarios 1 and 2 are lower than BAU levels (see Figure 12), which can be mainly associated with the demand reduction resulting from higher reuse quotas.

The PPWR seeks to reduce packaging waste generated per capita by 15% in 2040 compared to 2018 levels (173.5 kg/yr per capita), of which approximately 20% consists of plastic (Eurostat, 2025; Eurostat News, 2025). Applying the European PET share in plastic packaging of 19.5% (European Commission, Joint Research Centre, 2025) yields a target amount of 6.7 kg/yr for PET. Based on population projections for 2040 (Eurostat, 2026), the modelled PET packaging waste generation (8.82 Mt/yr in BAU and 7.16 Mt/yr in Scenarios 1 and 2) corresponds to 19.6 kg/yr and 15.9 kg/yr per capita, respectively. This reflects a reduction of 19% in PET packaging waste generation between BAU and Scenarios 1 and 2. Notably the PPWR aims for an absolute reduction in packaging waste, which is exceeded in all modelled scenarios. This reflects the assumption of continued PET demand growth, combined with the study's focus on feedstock substitution and increased reuse rather than on broader waste prevention measures or absolute modelled demand reduction in Scenarios 1 and 2. This suggests that the modelled feedstock substitution and current reuse targets alone, under growing demand, are insufficient to meet the PPWR's waste reduction target, highlighting the importance of further measures such as waste prevention, lightweighting, and more ambitious reuse targets. Furthermore, the PPWR seeks to guide the sector towards net-zero by 2050, supporting the European Green Deal (European Union, n.d.). While the results indicate strong mitigation by 2040 (-64% in Scenario 1, and -59% in Scenario 2), additional efforts beyond 2040 will be needed to achieve the net-zero objective in 2050.

4.3 Limitations

4.3.1 pMFA model

The pMFA model faces uncertainty from the combination of several data sources. The implementation of feedstock imports based on non-EU production reconciles the discrepancy between available PET production and consumption data, but risks misrepresenting future feedstock shares. Future economic interactions might not be accurately represented through the exclusion of chemicals and plastic waste along the supply chain. Applied demand projections based on an annual growth rate are uncertain due to the unknown real future growth rate, the PPWR's requirement to reduce packaging through lighter designs (PPWR, 2025), and potential shifts between packaging groups. Moreover, future material competition with other industries and technical limitations for higher recycled content targets add uncertainty (European Commission and Council, 2022). Prospective data for 2040 was very limitedly available, which introduces uncertainty in TCs, which represent e.g., collection, recycling or separation quotas. These were largely derived from the European Commission, Joint Research Centre (2022, 2025), assumed to remain constant until 2040, risking the misrepresentation of future developments. Additionally, the limited data availability required many assumptions, including high uncertainties, which were transparently reported to ensure reproducibility (see Section 2.3.3.2).

4.3.2 pLCA model

The pLCA model is limited by the absence of prospective data for the chemical processes, as *premise* modifies only certain sectors, lacking the chemical sector (Sacchi et al., 2022). Electricity and transport are the most relevant modified sectors for this study, because transport is modeled as input in the foreground and electricity is an input across multiple life cycle stages. However, these affect the plastic sector only indirectly. Potential future advancements in the chemical upstream supply chains of PET production are not represented in this study. Future net-zero pathways in the chemical sector are complex, depending on available renewable energy, biomass and recycling rates (Zibunas et al., 2022).

To assess bioeconomy strategies such as Bio-PET, the inclusion of biogenic carbon is of significant interest, however, the accounting of biogenic carbon in LCA is a debated topic in research (Bishop et al., 2021; Füchsl et al., 2025). The LCIA of scenarios relying heavily on biogenic carbon can be challenging, as standard characterization factors might not fully capture environmental impacts of these flows. The *premise_gwp* extension, a supplementary Python package for pLCA using Brightway, provides additional characterization factors (CFs) for biogenic carbon as well as hydrogen uptake and

release flows. Its integration was considered for this study, however, it does not yet support ecoinvent 3.12 (GitHub, n.d.; Sacchi, 2025). Therefore, this study excludes further assessments of biogenic carbon.

Further limitations arise from missing EFs and CFs. For instance, this study applies EFs to mechanical recycling due to the adoption of a background process but lacks EFs for chemical recycling, risking misrepresenting impacts of chemical recycling. In addition, plastic-related environmental risks might not be fully reflected due to missing CFs for micro- and macroplastics in marine and terrestrial environments (Maga et al., 2022). As a result, potential differences between scenarios regarding plastic littering into the environment are not captured in this study. EFs lacking CFs are provided in SM4-XXV-XXVII and SM4-XXXI-XXXIII.

4.3.3 Model alignment

Linking pMFA with pLCA introduced several practical constraints, requiring iterative adjustments to ensure consistency (see Section 2.5). Thus, differentiating material losses from the pMFA data sources and ecoinvent in the pLCA across recycling and manufacturing processes required alignment. This indicates that while static pMFA and pLCA are integrable, consistency requires iterative model development. This process involves incorporating data from one model into the other bidirectionally to achieve the most consistent alignment possible. For example, manufacturing losses from the pMFA were implemented into the pLCA, while recycling and pelletizing losses indicated in ecoinvent were integrated into the pMFA to ensure mass balance.

Another key limitation is that material losses quantified in the pMFA model could not be fully integrated into the pLCA model. The exact fate of plastic losses is uncertain, making their environmental impacts difficult to quantify. Due to missing EFs for plastic littering in the biosphere database the uncollected share polluted into soil and water could not be modelled. Therefore, only the recollected share was included and hereby used as a proxy to allocate the material proportionally to the EoL treatment options incineration, sanitary landfill, open dump and unsanitary landfill (see Section 2.5). This approach was preferred over treating the recollected share as purely collected waste and allocating losses only to incineration and landfill, as this would neglect the mismanaged fraction, which better reflects the uncertainty in the fate of plastic losses.

Adopted from PLAIA, the pMFA model assumes that all plastic waste is treated in its producing region, therefore the pLCA accounts for all EoL impacts within the EU, neglecting potential plastic waste exports. Projection of future plastic waste trade is complex and highly dependent on developments in international trade regulations (Li et al., 2025; Zhao et al., 2022). Although the EU is expected to expand domestic recycling and EoL management, it will likely continue to dominate cross-regional plastic waste trade, exporting plastics to countries with less advanced EoL infrastructure, increasing environmental risks (Liu et al., 2022).

4.3.4 IAMs

This study applies IMAGE, which can be categorized as a mainstream IAM (De Bortoli et al., 2025), meaning that its underlying assumptions such as its sectoral perspective, narrow focus on climate change or economic paradigms, risk excluding possible future developments (Paris et al., 2026b). As only SSP2 is applied due to its consistency with PLAIA, only BAU future developments are represented. While IAMs can affect the robustness and relevance of pLCA results (De Bortoli et al., 2025), IAMs remain widely used for their standardization advantages (Mendoza Beltran et al., 2020). Currently, no alternative data source adequately covers the global scope and technical details required for pLCA databases (Paris et al., 2026b).

This study used the IMAGE regions WEU and CEU as EU-27 proxies, limiting the regional representativeness. IMAGE classifies regions based on location and socio-economic properties (Sacchi et al., 2022) (see SM1-S7). Potential EU enlargement, through e.g., Albania and Ukraine, were excluded due to uncertain EU membership timing up to 2040 (European Union, n.d.). More broadly, this reflects the limited alignment of regional definitions of IAM-based pLCA databases with political entities. Future geopolitical developments may further reduce this representativeness. Additionally, the lower regional resolution of IMAGE compared to ecoinvent may introduce inconsistencies during IAM-LCA coupling (Sacchi et al., 2022; Steubing et al., 2023).

4.3.5 Representativeness of scenarios for the PPWR

Data limitations in the pMFA and pLCA are the dominant source of uncertainty in the scenario results, as the pLCA results are primarily driven by the material quantities derived from the pMFA. Specifically, restricted prospective data availability limits the pMFA, while the absence of prospective chemical process data limits the pLCA. A further, though more moderate, source of uncertainty arises from the limited regional representativeness through applied IMAGE regions and model alignment constraints. Together, these limitations influence the scenarios' representativeness in capturing the key effects of feedstock substitution under the PPWR.

The scenarios are exploratory and thus only provide a snapshot of possible futures and capture only a part of the PPWR's scope. Scenarios 1 and 2 were designed to assess the recycled content targets and policy measures intended to increase the availability of rPET, and thus do not represent all set PPWR targets, such as lightweighting, labelling requirements or substance restrictions. Furthermore, several simplifications further limit the scenarios' representativeness. For example, all PET trays are assumed to be CS, not distinguishing between PET trays for transport and not applying the 70% reuse target for PET trays for transport in 2040 (Article 29) (PPWR, 2025). This likely overestimates PET trays demand and its environmental impacts in Scenarios 1 and 2, though the overall effect on the results is expected to be minor.

In Scenario 1, rPET availability relies partly on simplifying assumptions. It increases through the applied 40% reuse target for beverages, and an assumed 90% separate collection rate, which is applied for all packaging, representing a simplifying assumption based on the PPWR target for single-use beverage bottles. This contributes to an increase in the overall recycling rate to 71% in Scenario 1 compared to 50% in BAU, thereby meeting and exceeding the PPWR's overall recycling target of 55% for all packaging types. Potential supply constraints are neglected, assuming that the increased rPET demand is met by domestic EU production and by imports where necessary.

Scenario 2 partly substitutes recycled content targets with biobased feedstock, but this rests on uncertain policy assumptions. The bio-based share increases from 2.5% in BAU and Scenario 1 to 6.2% (see 2.1 Scenarios), which is based on the assumption that a 30% subsidy on biomass use in the chemicals and plastics sector linearly implemented between 2020-2030 adequately represents the economic incentive under a Joint Target. Furthermore, since it assumes that bio-based feedstock replaces recycled feedstock, the fossil PET share consequently slightly increases (see Figure 10). However, the actual policy design under a potential Joint Target, including the biomass share and economic incentives, remains unknown due to ongoing political discussion and the European Commission's review (PPWR, 2025).

Overall, the scenarios provide sufficient resolution to assess the direction and magnitude of change in projected environmental impacts achievable through feedstock substitution under the PPWR, thereby addressing the main research question.

Conclusions and Recommendations

This study assessed prospective environmental impacts of the European PET packaging sector in 2040 and the degree of change that is achievable through feedstock substitution under the PPWR. Three prospective scenarios Business-as-usual (BAU), PPWR recycled content targets (Scenario 1) and a potential Joint Target with bio-based content targets (Scenario 2) were explored. These were assessed by combining pMFA and pLCA on the EU-27 macro-level, allowing the environmental assessment of the future material flows.

In BAU, although most feedstock demand can be met through domestic production, a significant import dependence will exist in 2040. In Scenario 1 and 2, despite increased reuse reducing overall packaging demand, rPET imports would be required to fulfill the PPWR's recycled content targets unless domestic recycling capacity is scaled up, indicating a risk for circularity leakage. Demand reductions and increased recycling in Scenarios 1 and 2 significantly reduce the amounts incinerated compared to the BAU.

BAU consistently achieves the highest environmental impacts, while Scenarios 1 and 2 reduce impacts across all categories compared to BAU, with climate change impacts decreasing by -64% and -59% respectively. Scenario 1 achieves consistently the lowest impacts, with the strongest reductions in material resources (-82%), ozone depletion (-73%), and energy resources (-72%). Scenario 2 shows moderately higher environmental impacts than Scenario 1, most notably in land use (-17pp), terrestrial eutrophication, and particulate matter formation (both -10pp), all relative to BAU. Across most categories, impacts are dominated at the process level by energy production and manufacturing. At the life cycle stage level, PET polymer production and EoL management emerge as hotspots, with the latter particularly pronounced in BAU due to greater amounts of incinerated and landfilled material. Bio-PET shows despite its small material share disproportionately high contributions, specifically in land use under Scenario 2. rPET and rBio-PET show only small contributions, supporting the conclusion that it is beneficial to use secondary material.

The main research question *“What magnitude and direction of change in projected environmental impacts of the European PET packaging sector is achievable through feedstock substitution in the context of the Packaging and Packaging Waste Regulation in 2040?”* can be answered by finding that recycled feedstock substitution under the PPWR significantly reduces the prospective environmental impacts, while the combination of recycled and bio-based feedstock substitution under a Joint Target offers no additional advantage over recycled feedstock targets.

This study advances the field of Industrial Ecology methodologically by linking IAM-pLCA with static pMFA, demonstrating the evaluation of material circularity policies, and broadening the thematic scope of IAM-pLCA on a macro-level.

Policymakers should address the identified risk of circularity leakage by expanding recycling infrastructure to support domestic rPET supply in line with the 2040 recycled content targets. Material amounts are identified as determining factor influencing environmental impacts, highlighting the importance of demand reductions and reuse quotas.

Considering prior discussed limitations, this study identifies several directions for future research. First, this study does not represent future developments in the chemical sector. Future research should therefore prioritize the development of prospective data for chemical processes, such as PET polymer production, as a prerequisite for their integration into macro-level pLCA models. Second, the regional classification in IMAGE is currently not aligned with political entities such as the EU-27, requiring the use of larger regions as proxies. Addressing this depends on the IAM community developing finer regional resolutions aligned with geopolitical boundaries, which would improve regional representativeness in pLCA-based policy evaluation. Third, the identified practical constraints when linking static pMFA and pLCA models suggest that future studies should address potential data inconsistencies early in the model development phase through bidirectional alignment to ensure consistency between the models. Fourth, future research on pLCA of the PET packaging sector is needed to allow direct comparison with this study, as current studies differ in system boundaries and time horizons. Finally, research on the PPWR's effects on other packaging sectors (e.g., other polymers, cardboard) is recommended to allow cross-sector assessment and support a more holistic policy evaluation.

Statement on the use of AI

This study made use of AI to compare textual descriptions of LCI background processes from ecoinvent to understand their characteristics and differences, assist with finding the correct category in Zotero for references, and assist with text refinement, including shortening, grammar and spelling. AI was not used to generate scientific findings.

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