Circularity and greenhouse gas assessment of the plastic packaging and beverage carton system in the Netherlands until 2050

For a business-as-usual and a circular scenario

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Monitoring and Evaluation Circular Economy

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Management Samenvatting

Dit rapport bevat een circulariteits- en broeikasgasbeoordeling van het systeem van kunststof verpakkingen en drankkartons in Nederland tot 2050. Dit wordt gedaan door een business-as-usual (BAU) scenario en een circulair scenario te analyseren. Het rapport onderscheidt zeven verpakkingssoorten: flessen, vormvaste verpakkingen en flexibele verpakkingen in contactgevoelige toepassingen en in overige toepassingen, en daarnaast drankenkartons.

Voor de analyse is het Circular Industrial Transformation System (CITS)-model van TNO gebruikt. CITS is ontworpen om het gebruik van materialen te onderzoeken in de transitie naar een circulaire, duurzame en veerkrachtige economie, om beslissingen over circulaire economie (CE) strategieën en beleidsmaatregelen te ondersteunen. De analyse richt zich op broeikasgasuitstoot en circulariteit van het onderzochte systeem. Microplastics en de potentiële impact van bio-based plastics worden in dit rapport kwalitatief besproken.

We hebben de impact berekend tegen de achtergrond van twee energie scenario's. Het ene achtergrondscenario schetst een wereld die niet werkt aan het behalen van de klimaatdoelstellingen van Parijs, en daarom een op fossiele brandstoffen gerichte energiemix heeft, hierna "Fossiel" genoemd in de figuren. In het andere achtergrondscenario voldoen de lidstaten aan de 1,5-graden klimaatdoelstelling van het klimaatakkoord van Parijs, en nemen we aan dat de elektriciteitsmix groen wordt, hierna "Hernieuwbaar" genoemd.

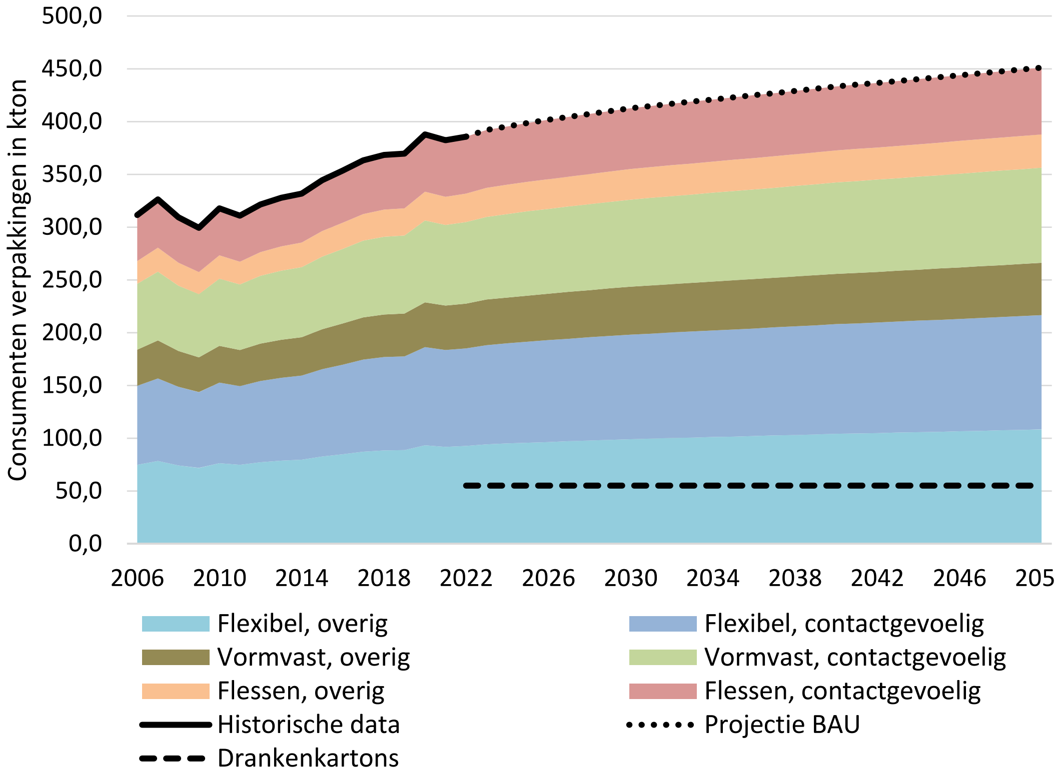
De netto broeikasgasemissies bestaan uit uitstoot bij het winnen van grondstoffen, het produceren van materialen en verpakkingen, de inzameling, sortering, en verwerking van het afval, en het transport. Daarnaast nemen we de vermeden impact door energieterugwinning en vermeden primaire materiaal productie door recyclaat als voordeel mee. De totale netto CO_2-eq emissies zijn afhankelijk van aannames over de duurzaamheid van de energiemix in de achtergrondscenario's.

Het BAU-scenario

Als referentie hebben we gebruik gemaakt van een versimpeld BAU-scenario waarin een voortzetting van historische verpakkingsconsumptiepatronen is aangenomen. Om de toekomstige volumes van de kunststofverpakkingsmarkt in Nederland te bepalen, hebben we de historische relatie tussen de marktomvang van kunststofverpakkingen, het BBP en de bevolkingsontwikkeling geanalyseerd. Hiermee hebben wij een lineair regressiemodel ontwikkeld om de toekomstige marktomvang voor kunststof verpakkingen te projecteren. De projecties zijn gebaseerd op BBP-projecties van OECD (1,18% groei per jaar tussen 2022 en 2050) en Eurostat bevolkingsgroeiprojecties (0,23% groei per jaar).

Daarnaast nemen we aan dat de huidige verwerkingssystemen voor verpakkingen hetzelfde zullen blijven tot 2050. Dit betekent bijvoorbeeld dat het aandeel verpakkingssoorten dat wordt verbrand en gerecycled gelijk blijft. In dit scenario wordt dus geen rekening houdt met

mogelijke toekomstige effecten van (aangekondigd) beleid. Alleen effecten van tijdens de geanalyseerde dataperiode (tot 2022) maken deel uit van dit scenario.
In het BAU-scenario stijgt de vraag naar plastic consumentenverpakkingen tot 451 kton in 2050. Wanneer een voortzetting van de historische consumptiepatronen wordt aangenomen, laat het BAU-scenario een stijging zien van 17% in de vraag naar kunststof verpakkingen door consumenten. De stijging is van 386 kton in 2022 tot 451 kton in 2050 (zie Figuur 1.1). Flexibele verpakkingen vormen het grootste deel, gevolgd door vormvaste verpakkingen en ten slotte flessen. In alle drie de categorieën is de contactgevoelige toepassing dominant. Vanwege een gebrek aan publieke historische data is in overleg met experts aangenomen dat de vraag naar drankkartons gelijk blijft op 55 kton tot 2050.



Figuur 1.1: Projectie van plastic consumentenverpakkingen & drankenkartons in het BAU-scenario

Momenteel is slechts een klein deel van de verpakkingen circulair en gaat 55% van de materialen verloren.
Zonder grote veranderingen in onze consumptie en afvalbeheer zou een BAU-systeem leiden tot materiaalverliezen door verbranding (met energieterugwinning) van 279 kton in 2050, ofwel 55% van de verpakkingen en drankenkartons. Bovendien wordt slechts een klein deel van het gerecyclede materiaal gebruikt voor nieuw verpakkingsmateriaal (ca. 7% in EU volgens PlasticsEurope). Dit komt doordat de kwaliteit van het recyclaat uit mechanische recycling gelimiteerd is door het ontwerp van de verpakkingen en het inzameling- en sorteersysteem. Bovendien zijn er beperkt goedgekeurde technologieën voor het maken van voedselveilig recyclaat volgens EFSA richtlijnen.

In het BAU-scenario stijgen de broeikasgasemissies van 1696 kton CO_2-eq. in 2022 tot 1901-1906 kton in 2050. De broeikasgasemissies van de hele levenscyclus van het Nederlandse verpakkingssysteem bedroegen 1696 kton CO_2-eq in 2022, wat zou kunnen

oplopen met 12% tot 1901-1906 kton CO_2-eq in 2050 (zie Figuur 1.2 en Figuur 1.3) afhankelijk van het achtergrondscenario.
De productie van primaire plastics en het terugwinnen van energie door verbranding leveren de grootste bijdrage aan de totale impact, gevolgd door de productie van de verpakkingen (zie Figuur 1.3). De inzameling, sortering en recycling hebben relatief lage impacts.

De impact van de teruggewonnen energie uit verbranding wordt gerekend als negatief: gelijk aan de impact van de op reguliere manier opgewekte energie die wordt vermeden. De regulier opgewekte energie in het BAU-scenario (fossiel) is op fossiele basis en heeft dus meer impact dan in het BAU-scenario (hernieuwbaar) waar het uit hernieuwbare bronnen komt. Hierdoor heeft binnen het gedefinieerde kunststofverpakkingen systeem het scenario met klimaatbeleid hogere netto broeikasgasemissies dan het BAU scenario zonder klimaatbeleid.

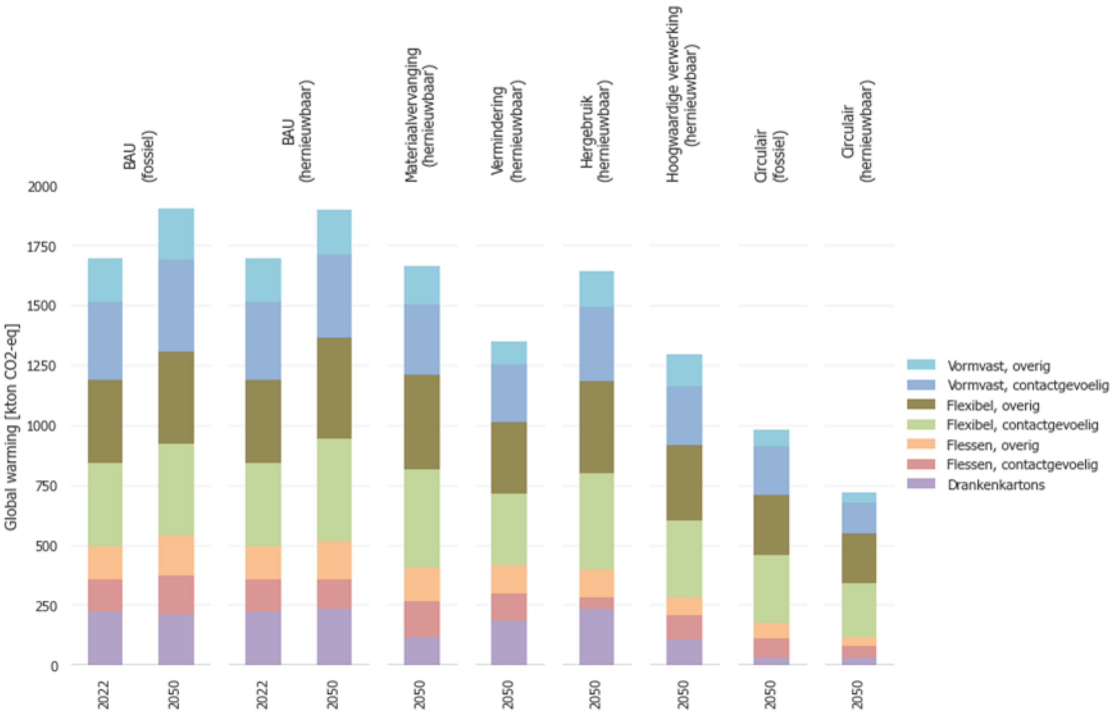
Kunststofverpakkingen zijn momenteel een van de belangrijkste bronnen van de directe uitstoot van microplastics naar het milieu: ongeveer 1,2 kiloton in Nederland in 2017. Dit is 25% van de totale directe uitstoot van microplastics. De rest van de microplastics komen voornamelijk uit autobanden (ca. 50%), textiel en landbouw.

Het Circulaire scenario

We hebben een circulair scenario gemaakt op basis van materiaalvervanging, vermindering, hergebruik en hoogwaardige verwerking.
Naast het BAU-scenario is een circulair toekomstscenario gemaakt, waarvoor via een literatuuronderzoek en een workshop met 9 experts aannames zijn gedefinieerd. Het doel was een optimistisch circulair scenario te ontwerpen, dat technisch haalbaar is volgens de huidige kennis. Dit scenario houdt rekening met upstream circulaire strategieën om de kringloop te verkleinen, waardoor de vraag naar materialen afneemt (weigeren, verminderen, vervangen van materialen). Daarnaast passen we strategieën toe om de materiaalkringloop te vertragen en producten langer in gebruik te houden (hergebruik, levensduurverlenging), en ook nog downstream strategieën (hoogwaardige verwerking) die betrekking hebben op het ontwerp van circulaire verpakkingen, en betere afvalinzameling, sortering en recycling. Deze strategieën worden afzonderlijk door het model doorgerekend en gecombineerd in het circulaire scenario.

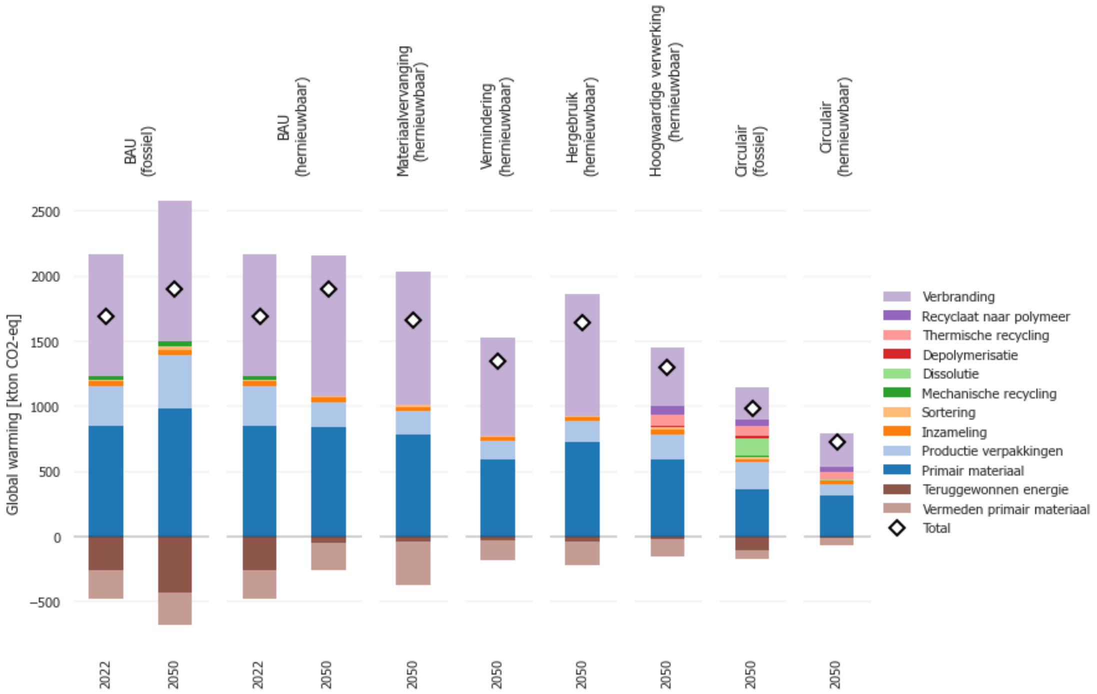
De vraag wordt verminderd door het elimineren van onnodige verpakkingen, het verminderen van de materiaalhoeveelheid per verpakking door slimmer ontwerp en het verminderen van lege ruimte. Ook materiaalvervanging binnen de systeemgrenzen van het model wordt meegenomen (bijvoorbeeld drankkartons die worden vervangen door kunststof flessen). Het model is op het moment niet in staat om vervanging met bijvoorbeeld bio-based kunststoffen, glas, textiel of metalen door te rekenen, omdat deze materialen buiten de scope van de verkregen data vallen. Verder speelt hergebruik voornamelijk een belangrijke rol bij drankflessen, maar tot op zekere hoogte ook bij andere verpakkingscategorieën.

Daarnaast worden opkomende recycling technologieën dissolutie, depolymerisatie, pyrolyse en vergassing geanalyseerd, waardoor hoogwaardige recyclaten ontstaan die geschikt zijn voor gebruik in verpakkingen, potentieel zelfs in contactgevoelige toepassingen (dit hangt af van goedkeuring door de Europese Commissie). We nemen aan dat door circulair productontwerp, meer gescheiden inzameling en verbeterde sortering een hogere zuiverheid in de gesorteerde stromen wordt bereikt dan in het BAU scenario. Dit betekent dat, naast chemisch gerecyclede kunststoffen, ook meer mechanisch gerecyclede kunststoffen weer in verpakkingstoepassing kunnen worden gebruikt, zij het niet in contactgevoelige toepassingen, tenzij ze via een statiegeldsysteem worden ingezameld (leidt tot schoner recyclaat).



Figuur 1.2: Broeikasgasemissies van het consumentenverpakkingssysteem per scenario, opgedeeld in de bijdrage per verpakkingstype.

Opmerking: Scenario's met (fossiel) nemen geen klimaatbeleid aan, wat resulteert in een elektriciteitsmix die gedomineerd wordt door fossiele grondstoffen (SSP2 base). Alle andere scenario's worden berekend met een hernieuwbare elektriciteitsmix die voldoet aan de Parijsdoelen van 1.5°C opwarming (SSP2 RCP19).

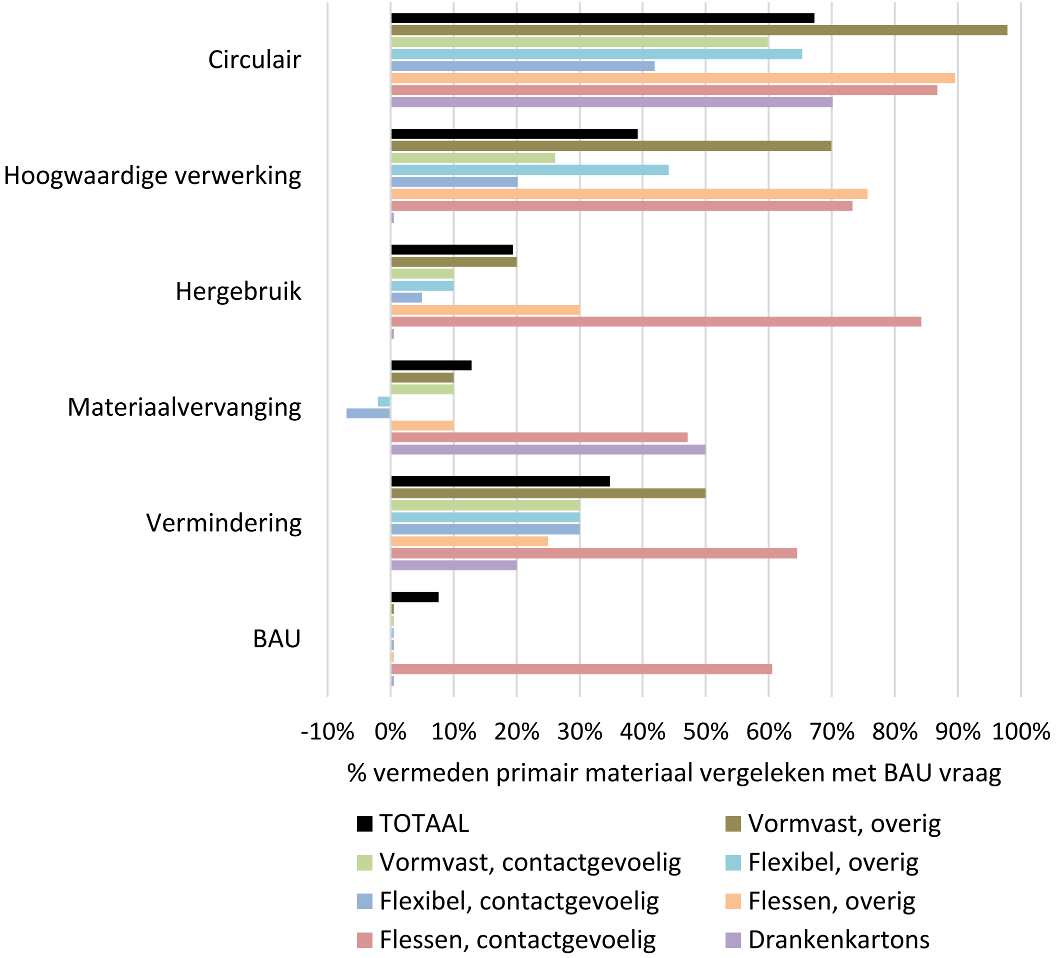


Figuur 1.3: Broeikasgasemissies van het consumentenverpakkingssysteem per scenario, opgedeeld in de bijdrage per processtap.

Opmerkingen: (1) Scenario's met (fossiel) nemen geen klimaatbeleid aan, wat resulteert in een elektriciteitsmix die gedomineerd wordt door fossiele grondstoffen (SSP2 base). Alle andere scenario's worden berekend met een hernieuwbare elektriciteitsmix die voldoet aan de Parijsdoelen van 1.5°C opwarming (SSP2 RCP19); (2) Gerecyclede producten die als grondstof worden gebruikt voor dezelfde verpakkingen laten de vraag naar primair materiaal voor deze verpakkingsgroep dalen; Gerecyclede producten en energie die buiten het systeem van de verpakkingen wordt gebruikt, worden apart weergeven als baten onder de X-as in Figuur 1.3 (vermeden primair materiaal en teruggewonnen energie); (3) Scenario’s en verpakkingssoorten, waar veel verbranding in plaatsvindt, presteren slechter bij aanname van een hernieuwbare energiemix, omdat energieterugwinning een lagere vermeden impact heeft aangezien er geen fossiele elektriciteit vermeden wordt, zoals BAU (hernieuwbaar), flexibel verpakkingen en drankenkartons; (4) Thermische recycling omvat pyrolyse en vergassing naar monomeren; (5) “Recyclaat naar polymeer” omvat alle omvormingsstappen die nodig zijn om polymeren te vormen uit recyclingproducten zoals nafta en monomeren.

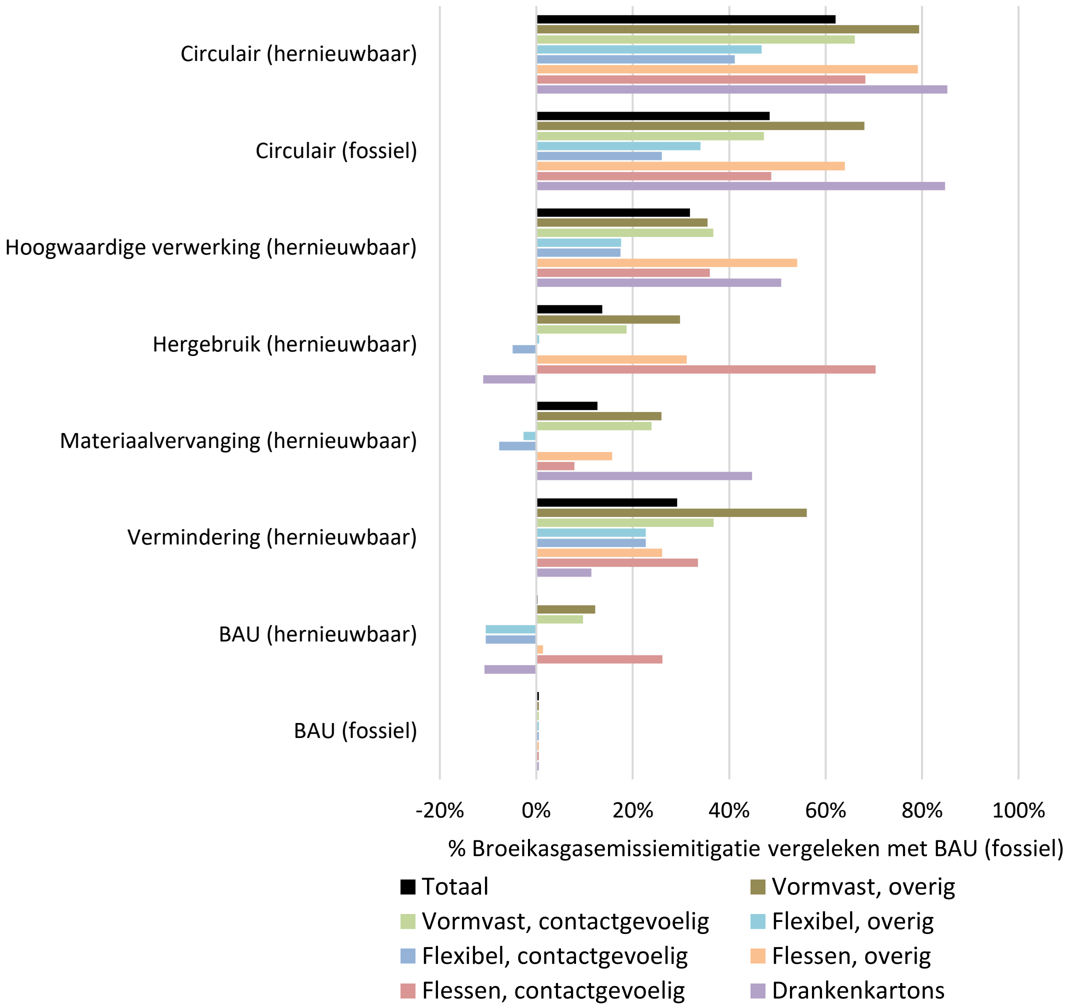
In het circulaire scenario, wordt in totaal 67% primair materiaal vermeden in 2050 (zie Figuur 1.4**).**
De afzonderlijke strategieën tellen door hun interacties niet direct op tot het totaaleffect van het circulaire scenario. We zien dat de potentie van de strategieën Vermindering (Refuse & Reduce), Materiaalvervanging, Hergebruik (levensduurverlenging) en Hoogwaardige verwerking (beter inzamelen, sorteren en recyclen) aanzienlijk varieert per type verpakking volgens de scenario-inschattingen van de experts. Het grootste effect is te zien in de scenario’s met Hoogwaardige verwerking en de Verminderings-maatregelen, waarin respectievelijk 39% en 35% primair materiaal wordt vermeden. Reduce maatregelen veroorzaken het grootste deel van het effect in het Vermindering scenario. Een voorbeeld hiervan is het lichter maken van verpakkingen door loze ruimte te verminderen. Experts voorzagen een kleiner potentieel voor Verminderings-maatregelen door het weigeren van verpakkingen, à 10%. In het Hergebruik scenario wordt circa 19% primair materiaal vermeden. In Materiaalvervanging is dit circa 13%, wat voornamelijk komt door het gebruik van meer lichtgewicht flexibele verpakkingen.

In totaal vermindert in het circulaire scenario met hernieuwbare energiemix de netto uitstoot van broeikasgassen met ongeveer 62% in verhouding tot de BAU-scenario's, tot **722 kton CO_2-eq in 2050** (zie Figuur 1.2, Figuur 1.3, en Figuur 1.5). Bij een hernieuwbare elektriciteits-mix, heeft Hoogwaardige verwerking (31%) en Vermindering (29%) de grootste potentie om broeikasgasemissies te verminderen, vergeleken met het BAU-scenario met fossiel energie mix. Hierna volgt Hergebruik met 14% en Materiaalvervanging met 13%.
In het Circulaire scenario zijn, net als in het BAU scenario, de meeste emissies afkomstig van de productie van primaire materialen (zie Figuur 1.3), gevolgd door verbranding. Productie van de verpakkingen komt op de derde plek, terwijl emissies van de recycling relatief klein zijn, zelfs als de mate en complexiteit van recycling hoog is (zoals in scenario Hoogwaardige verwerking en Circulair).



Figuur 1.4: Percentage vermeden primair materiaal per verpakkingstype en scenario in 2050, in verhouding tot de totale vraag naar primair materiaal in het BAU-scenario.

Opmerkingen: (1) In deze figuur wordt aangenomen dat mechanisch gerecyclede producten (zonder statiegeldsysteem) uit contactgevoelige toepassingen worden gebruikt als grondstof voor andere verpakkingstoepassingen. Hierdoor presteert bijvoorbeeld 'Vormvast, overig' zeer goed omdat het recyclaat overneemt van 'Vormvast, contactgevoelig'; (2) 'Flessen, contactgevoelig' presteren slechter in het 'Materiaalvervanging'-scenario vergeleken met BAU, omdat het volume flessen is vergroot om drankkartons te vervangen.



Figuur 1.5: Mitigatie van broeikasgasemissies vergeleken met het BAU (base) scenario, per verpakkingstype en scenario

Opmerkingen: (1) Scenario's met (base) nemen geen klimaatbeleid aan, wat resulteert in een elektriciteitsmix die gedomineerd wordt door fossiele grondstoffen (SSP2 base). Alle andere scenario's worden berekend met een hernieuwbare elektriciteitsmix die voldoet aan de Parijsdoelen van 1.5°C opwarming (SSP2 RCP19); (2) Sommige verpakkingssoorten waarbij veel verbranding in plaatsvindt (zoals drankenkartons en flexibel), kunnen slechter presteren bij aanname van een hernieuwbare energiemix, omdat energieterugwinning een lagere vermeden impact heeft aangezien er geen fossiele elektriciteit vermeden wordt.

Het effect van de circulaire strategieën verschilt tussen de verpakkingssoorten.
Het vermeden primair materiaal in het circulaire scenario varieert aanzienlijk per verpakkingssoort, van 42% voor contactgevoelige flexibele verpakkingen tot 98% voor niet-contactgevoelige vormvaste verpakkingen (zie Figuur 1.4). De reductie van de netto broeikasgasemissies vergeleken met het BAU scenario met fossiele energiemix varieert van 38% voor contactgevoelige flexibele producten tot 85% voor drankkartons (zie Figuur 1.5).

We zien in Figuur 1.4 en Figuur 1.5 dat het potentieel van de strategieën Vermindering, Materiaalvervanging, Hergebruik en Hoogwaardige verwerking aanzienlijk varieert tussen de verpakkingssoorten. In Hergebruik wordt, met 19%, minder primair materiaal vermeden dan in Vermindering en Hoogwaardige verwerking, maar dit scenario is wel het meest effectief voor contactgevoelige flessen (85% primair materiaal vermeden). Het effect van Vermindering is het hoogst voor niet-contactgevoelige vormvaste verpakkingen, waar door experts de grootste potentie voor reductie zagen. Materiaalvervanging wordt het sterkst toegepast op drankenkartons, die worden in het Circulair Scenario vervangen door flexibele verpakkingen en flessen, respectievelijk om het gewicht te verminderen en hergebruik te stimuleren. Hoogwaardige verwerking door verbeterde inzameling, sortering en recycling heeft de grootste impact voor overige flessen (76%) en overige vormvaste verpakkingen (70%). Overige verpakkingen presteren beter dan hun contactgevoelige tegenhangers omdat we ervan uitgaan dat zij gebruik kunnen maken van recyclaat afkomstig uit contactgevoelige toepassingen. Conform EFSA-richtlijnen nemen wij aan dat het recyclaat van mechanische recycling niet toegepast wordt in contactgevoelige verpakkingen. Uitzondering hierop is recyclaat van afval afkomstig is van een mono-inzamelsysteem zoals statiegeld.

Het reductiepotentieel voor flexibele verpakkingen (voor zowel vermeden primair materiaal, als voor broeikasgasemissies) in het Hoogwaardige verwerking-scenario is beperkt doordat een groot deel ervan in gemengde gesorteerde stromen terechtkomt (Film en Mix), die in dit scenario in grotere mate door pyrolyse en vergassing worden behandeld. Beide technologieën bieden recyclaat van primaire kwaliteit, maar ten koste van een lager polymeer-rendement ten opzichte van mechanische recycling.

Er zijn compromissen tussen recyclaat kwaliteit, recyclaat kwantiteit, en broeikasgasemissies. Hoewel thermische recyclingtechnologieën zoals pyrolyse en vergassing leiden tot recyclaat van hogere kwaliteit, presteren ze slechter als het gaat om materiaalefficiëntie en broeikasgasemissies dan bijvoorbeeld mechanische recycling. Voor dissolutie is veel elektriciteit nodig vergeleken met conventionele mechanische recycling. De impact hiervan is verwaarloosbaar wanneer er sprake is van een hernieuwbare elektriciteitsmix, maar is significant wanneer fossiele energie wordt gebruikt (zieFiguur 1.3).

Het circulaire scenario in dit rapport bekeek slechts één potentiële technologiecombinatie voor afval recycling, waarbij de nadruk lag op hoogwaardige recycling waarmee nieuwe verpakkingen gemaakt kunnen worden. Uiteindelijk dient er een geoptimaliseerde combinatie van mechanische en chemische recyclingtechnologieën te worden gevonden, die voor elke toepassing de juiste materiaalkwaliteit biedt en die kunststoffen die door herhaalde mechanische recycling degraderen weer bruikbaar maakt.

Zelfs in het circulaire scenario blijft er met 149 kton nog steeds een substantiële vraag naar primair plastic voor consumentenverpakkingen bestaan, die vooral gebruikt wordt voor flexibele verpakkingen en contactgevoelige toepassingen.
Als het streven is om fossielvrij te zijn in 2050, dan dienen niet-fossiele bronnen gebruikt worden om te voldoen aan deze vraag. Hiervoor kan men gebruik maken van kunststofafval uit andere sectoren, van biomassa, of van nieuwe technologieën voor het afvangen en gebruik van CO_2.

Bio-based plastics kunnen broeikasgasemissies reduceren, maar hebben neveneffecten en moeten concurreren om een beperkte hoeveelheid beschikbare biomassa. Biomassa als grondstof zou een belangrijke rol kunnen spelen bij het terugdringen van fossiele grondstoffen en broeikasgasemissies van de plasticsector. Uit levenscyclusanalyses blijkt dat bio-based kunststoffen doorgaans een lagere uitstoot van broeikasgassen hebben dan fossiele kunststoffen, maar aanzienlijk grotere gevolgen hebben in andere milieucategorieën, zoals landgebruik of verzuring. Deze impacts kunnen worden teruggedrongen door bio-based kunststoffen circulair te maken en afvalstromen als grondstof te gebruiken, bijvoorbeeld reststromen uit landbouw en bosbeheer, en groenafval van huishoudens en industrie. Het potentieel van biomassa uit afval en residuen is echter beperkt. Om hiervan gebruik te maken, moet nog wel rekening worden gehouden met competitie om deze grondstoffen tussen regio's, maar ook tussen sectoren zoals verwarming.

Betere data en een uitgebreidere scenario analyse zijn nodig om besluitvorming te ondersteunen.
Deze analyse werd gedaan op basis van de huidige publiek beschikbare data en aannames door experts. Consistente databronnen met betrekking tot materiaalstromen vormt de basis van circulariteitsonderzoek. Betere en meer gedetailleerde dataverzameling en open-source beschikbaarheid zijn van cruciaal belang voor uitgebreidere analyses in de toekomst. Niettemin bieden de modelresultaten een eerste kwantificering van de impact van het verpakkingssysteem, hetgeen ons in de circulaire transitie helpt bij het evalueren van de uitdagingen die voor ons liggen, en de strategieën die we kunnen toepassen.

Langetermijnbeoordelingen zoals deze kunnen geen toekomstige ontwikkelingen voorspellen, maar verschaffen informatie over de potentiële impact van verschillende toekomstige paden. Deze evaluatie bekeek onderzocht één pad naar circulariteit, gebaseerd op de inbreng van experts. Een uitgebreidere analyse maakt het mogelijk om verschillende potentiële toekomsten beter in kaart te brengen en naast elkaar te leggen. Hiermee kunnen afwegingen bloot worden gelegd, bijvoorbeeld tussen een systeem dat wordt gedomineerd door mechanische recycling of door chemische recycling. Daarnaast moeten andere impactcategorieën geanalyseerd worden, om af te kunnen wegen tussen broeikasgasemissies en andere factoren zoals verzuring, fijnstof uitstoot of landgebruik.

Contents

Appendices

Abbreviations

ABBREVIATION	Definition
BAU	Business as usual
CAGR	Compound Annual Growth Rate
CITS	Circular Industrial Transformation System
DKR	Classification of sorted waste streams introduced by Deutsche Gesellschaft für Kreislaufwirtschaft und Rohstoffe
GHG	Greenhouse gas
GWP	Global Warming Potential
ICER	integrated circular economy report published by PBL
LCA	Life Cycle Assessment
MFA	Material flow analysis
MSW	Municipal solid waste
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
PMD	Separate collection system (Plastic verpakkingen, metalen verpakkingen, en drankpakken)
PPWR	Proposal for a Revision of EU Legislation on Packaging and Packaging Waste
RWS	Rijkswaterstaat
SSP	Shared socioeconomic pathways (scenarios used in climate modelling)

1 Introduction

Every two years PBL writes the integrated circular economy report (ICER) (PBL 2023) for the Dutch government. This report assesses the progress in the Netherlands regarding the transition towards a circular economy. In the future, this report should provide more insights into the transition for different product groups, one of them is packaging. TNO was asked to provide a circularity and environmental assessment (focus Greenhouse gas emissions) of the current consumer packaging system in the Netherlands, for a business as usual (BAU) scenario, and a circular scenario until 2050. We do so for seven packaging types:

- Plastic bottles in contact-sensitive applications
- Plastic bottles in other applications
- Rigid plastic packaging in contact-sensitive applications
- Rigid plastic packaging in other applications
- Flexible plastic packaging in contact-sensitive applications
- Flexible plastic packaging in other applications
- Beverage cartons

For this purpose, TNO's Circular Industrial Transformation System (CITS) model was deployed. CITS was designed to explore the role of materials in the transition towards a circular, carbon neutral and resilient economy, to support informed decisions on strategies and policy measures.

In our analysis of the model results for the seven packaging types, we focus on the global warming impact and the avoided primary material demand. Microplastics and the potential impact of bio-based plastics are addressed qualitatively in this report.

This report serves as background information for a common publication with Rijksinstituut voor Volksgezondheid en Milieu (RIVM), Rijkswaterstaat (RWS), and Utrecht University, namely *"Productgroepanalyse kunststofverpakkingen en drankenkartons"*, which includes key results of this report.

2 Method

2.1 The CITS model

CITS can analyze circular strategies and their effects and consequences for the resource and product demand as well as the energy and climate transition in industry in European countries. The CITS model forecasts and analyzes future product, material and energy demands, product stocks, waste volumes, material compositions and environmental impacts as a result of circular (R-strategies), energy and climate developments. CITS consists of three modules: (1) dynamic stock modelling, (2) material flow analysis (MFA), and (3) impact & circularity assessment (see Figure 2.1). CITS is linked to TNO's Plastic Recycling Impact Scenario Model (PRISM) which assesses the costs and environmental impacts for 25 polymers and 11 different waste treatment technologies, including various chemical recycling technologies. The environmental impact assessment of the recycling technologies in PRISM is based on the LCA matrix model (A. E. Schwarz et al. 2021).

Based on historic production data and product lifetime distributions, the CITS model calculates the annual product stocks, production, and waste generation, structured in product groups and sectors. In this part of the model, we can introduce upstream R-strategies such as refuse and reduce. The MFA module uses product composition databases to determine the amount and type of materials in these products and then defines the material flows according to historic and current data and assumptions. In this part of the model, we can introduce downstream R-strategies such as refurbish, recycle and recover. The impact assessment module quantifies the environmental impact of each process in the product life cycle, using 18 impact categories. The impact assessment module is based on Sacchi et al.'s (2022) prospective environmental impact assessment method (premise)[1]. It uses data from life cycle assessments, which is adapted per country and year according to scenario inputs on the respective energy mixes, supplied by integrated assessment models (IAM) such as PBL's IMAGE model. These scenarios form the background scenarios upon which the effect of R-strategies on systemic impact are compared.

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[1] PREMISE (2022) Documentation 1.3.0 – in a nutshell https://premise.readthedocs.io/en/latest/introduction.html#workflow

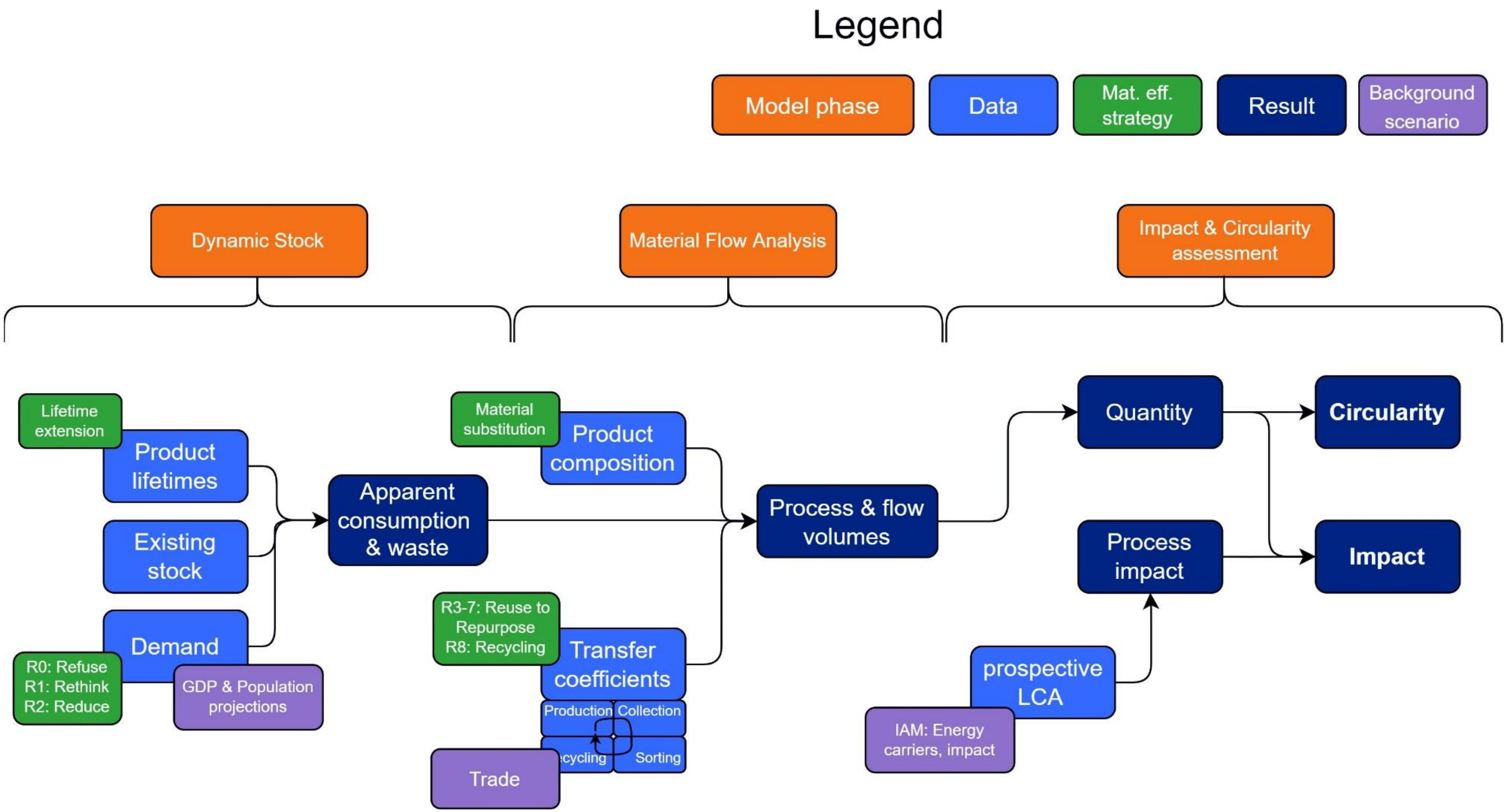

Figure 2.1: The CITS model structure.

2.2 Approach

2.2.1 Data collection

As part of the common publication “Productgroepanalyse kunststofverpakkingen en drankenkartons” to which also this report contributes, RWS compiled data on the Dutch packaging market via expert interviews, workshops and literature review. Since the available data was too aggregated and not sufficient to provide a product group specific environmental impact assessment of the entire value chain, TNO added to this through own literature search with the goal to (a) find data on packaging type specific material flows in the Netherlands and (b) Life cycle assessment data for missing process steps.

2.2.2 Scenario development

We distinguish between (1) foreground scenarios which provide assumptions on the future development of the consumer packaging system and (2) background scenarios, which cover external developments affecting consumer packaging, such as socioeconomic trends and changes in the energy system.

Foreground scenario

This research focused on the design and implementation of two custom foreground scenarios for the future consumer packaging system: a Business-As-Usual (BAU) and a circular scenario. The scenario assumptions have been defined via a literature review as well as via a workshop with nine packaging experts from research, industry, and government agencies. The resulting circular scenario assumptions have then been presented to further stakeholder groups (begeleidingscommissie / monitoring committee of the report *“Productgroepanalyse kunststofverpakkingen en drankenkartons”,* Transition Agenda CE – Plastics) whose feedback has been incorporated.

The BAU scenario is a simple projection of the current packaging system to 2050, while the circular scenario aims at an optimistic – but technically feasible – scenario that can highlight the potential of circular strategies. PBL defined four scenario “buttons” that have been considered when designing the circular scenario: Material substitution, feedstock reduction (e.g., via refuse, reduce, rethink), high quality processing (e.g., via chemical recycling, better collection & sorting) and lifetime extension (i.e., reuse of packaging).

Background scenario

The background scenarios regarding changes in the energy system originated from PREMISE, a Prospective Lifecycle Assessment (PLCA) library written in Python (Sacchi et al. 2022). PREMISE is capable extrapolating an ecoinvent database with life cycle assessment (LCA) data towards the future according to predefined or user-defined scenarios. The predefined scenarios use the results from Integrated Assessment Models (IAMs) for selected scenarios, namely the shared socioeconomic pathways (SSP) (O’Neill et al. 2017; Riahi et al. 2017). Currently, PREMISE supports scenarios from both IMAGE (Stehfest et al. 2014), and REMIND (Gong et al. 2023). These databases then cover the entire background system of a given LCA model. By creating a timeseries of these scenarios databases, that scenario can serve as the foundation of a changing system over time. Two predefined scenarios covered the background system in this project: a scenario without climate policy, reaching a change in temperature of 3.5 °C in 2100 and a scenario following the Paris Climate Agreement, reaching a temperature change of 1.2-1.4 °C in 2100. Both of these scenario results originate from the IMAGE IAM and are called SSP2-Base and SSP2-RCP19 respectively.

Socioeconomic projections on GDP and population development were taken from OECD (OECD 2023) and Eurostat (Eurostat 2023b).

2.2.3 Indicators

In this study we compare the scenarios in terms of their avoided primary material demand and their global warming potential (Greenhouse-gas-emissions in kton CO_2 equivalents).

The global warming potential is calculated with the ReCiPe 2016 method, version 1.03 (Huijbregts et al. 2017), see chapter 2.4.3.

We measure circularity as the percentage of avoided primary packaging material (e.g., plastics, cardboard) in relation to total packaging demand in the BAU scenario (see section 3.1). This indicator allows for accounting for all circular strategies, including refuse and reduce. However, it does not consider recycled packaging that is used in other sectors. We thus only consider strategies that actually reduce the primary material use for packaging as contributing to packaging circularity.

2.3 The analysed packaging system

We model the entire life cycle of consumer plastic packaging and beverage cartons (see Figure 2.2). This includes the extraction of fossil resources, the upstream chemical processing of these resources into of feedstocks (e.g., naphtha) and intermediates (e.g., ethylene, propylene), the plastic polymer production, and the transformation of the materials (forming) into packaging products.

After the use phase, we model the different collection systems for packaging, their sorting and eventual treatment by different recycling technologies and incineration with energy recovery. The recycling technologies feedback the recycled outputs to the plastic production system in different formats (oil, gas, monomers, flakes), depending on the technology, or alternatively offer the output as resource for other industry sectors, which is included as a benefit. We assume that all consumer packaging consumed in the Netherlands will also be collected and treated in the Netherlands. While the Netherlands also exports plastic waste to other countries (Plastic Soup Foundation 2022), this assumption allows us to provide a (theoretical) assessment of the total life cycle impact of plastic waste consumed in the Netherlands if treated within its borders.

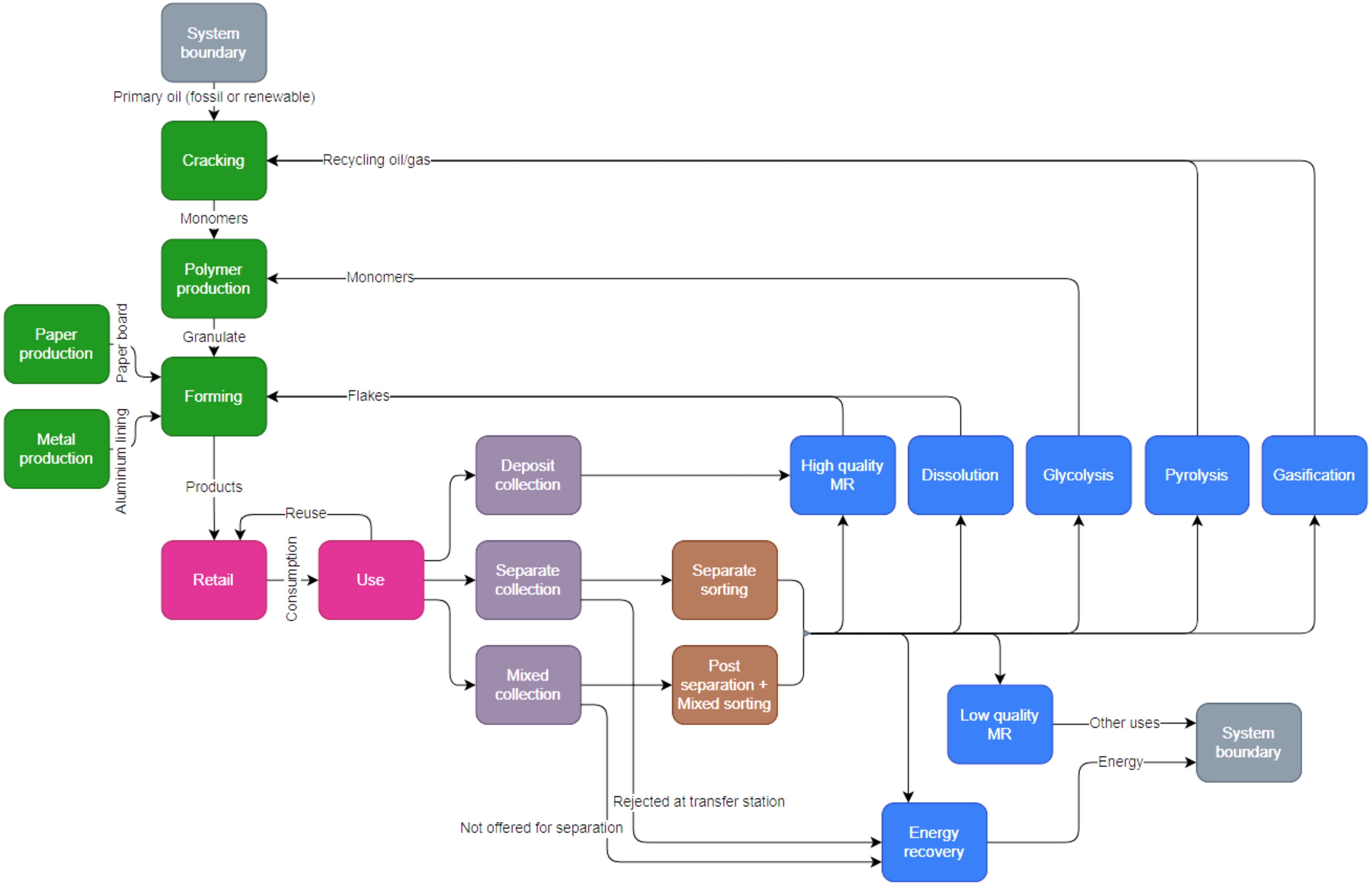

Figure 2.2: The analyzed packaging system, or scope of the Material Flow Analysis

2.4 Data inventory

2.4.1 Packaging types

As part of the common report *"Productgroepanalyse kunststofverpakkingen en drankenkartons", RWS* provided the distribution of plastic packaging types (rigid, flexible) over contact-sensitive (e.g., food packaging) and other applications (see Table 2.1).

Table 2.1: Distribution of the consumer plastic packaging types as provided by RWS.

	Rigids	*Flexibles*	*Total*
Contact-sensitive	34%	24%	58%
Other	18%	24%	42%

However, market contacts of RWS could not provide how these packaging types behave in the collection, sorting, and recycling system, e.g., how many of these packaging types end up in sorted streams or as recycled products. To fill this gap, we made use of packaging flow data from Brouwer et al. (2019, 2018), who detail the material composition and the flows of different packaging types with a high resolution through the Dutch collection and sorting system. We allocated their more detailed packaging types (e.g., PET beverage bottle, PET trays, PE film) to the product categories provided by RWS. This allocation can be seen in Appendix a: Allocation of product categories.

We chose to separate bottles from other rigid packages in this study, as we expect that the role of some circular strategies differs between bottles and other rigids, e.g., deposit system and reuse are more widely applied to bottles than to other rigids. Using the data from Brouwer et al. (2019), this split could be implemented (see Table 2.4).

It must be noted that this approach of linking the RWS assumptions with the data from Brouwer et al. (2019) is a major limitation of this work since not one consistent data-source was used. Additionally, Brouwer et al. (2019) describe the 2017 situation, and therefore is not fully up-to-date. This had to be done as there is very limited public information on the detailed flows of waste types in our collection and sorting systems. Nevertheless, this approach provides a first packaging type specific impact assessment which can be updated with better data in the future.

2.4.2 Current packaging waste management data

Material composition

The material composition of the packaging categories was derived from Brouwer et al. (2018, 2019), see Table 2.2. By multiplying the material compositions of the specific packaging types from Brouwer et al. (2018, 2019) with the respective waste volumes, an average (weighed) material composition was calculated, aggregated to the product categories from RWS (see Table 2.1 and chapter 2.4.1). The material composition of beverage cartons was not included and assumed to be 25% PE, 70% Paper and 5% Metal (Aluminium) (Afvalfonds Verpakkingen 2023b).

Table 2.2: The material composition of the packaging categories

Packaging type	PET	PP	PE	PS	PVC	paper	metal	glass	Other plastics
Bottles - contact sensitive	79%	3%	17%	-	-	1%	-	-	-
Bottles - other	29%	24%	45%	-	-	1%	-	-	1%
Flex - contact sensitive	37%	27%	9%	8%	3%	2%	-	-	14%
Flex - other	37%	27%	9%	8%	3%	2%	-	-	14%
Rigid - contact sensitive	1%	20%	57%	-	1%	1%	1%	-	18%
Rigid - other	1%	20%	57%	-	1%	1%	1%	-	18%
Beverage cartons	-	-	25%	-	-	70%	5%	-	-

Consumption

Table 2.3 shows the consumption of consumer plastic packaging for a business as usual (BAU) scenario (see chapter 3.1 for the calculation method). In absence of publicly available historic data on beverage cartons, we assumed after consultation with experts that the beverage cartons demand stays constant at 55kt between 2022 and 2050.

Table 2.3: Total Business as usual consumption of consumer plastic packaging (excluding beverage cartons) in key years; see also Figure 4.1 in chapter 4.1)

Year	*Total consumption*
2020	387.8
2022	385.7
2030	412.7
2040	433.2
2050	451

The consumption is split between the packaging types using the numbers provided by RWS, see Table 2.1. The rigids are further divided into bottles and other rigids, according to the shares from Brouwer et al. (2019), see chapter 2.4.1. The final % share is multiplied with the packaging consumption number from Table 2.4. The beverage cartons volume is kept at 55 kton.

Table 2.4: Calculation example (for 2022) of the waste volumes of the packaging categories

Scenario	*Year*	*Product*	*Shares (inc. bottles) wrt. total consumption (RWS)*	*Bottles in total rigids (Brouwer et al. 2019)*	*Final %*	*Final volume*
base	2022	Bottles, contact-sensitive		27%	14%	54.2
base	2022	Bottles, other		14%	7%	28.1
base	2022	Rigids, contact-sensitive	34%		20%	77.4
base	2022	Rigids, other	18%		11%	41.0
base	2022	Flexibles, contact-sensitive	24%		24%	92.6
base	2022	Flexibles, other	24%		24%	92.6
base	2022	Beverage cartons				55.0

Collection

Around 28 tonnes of large PET bottles (>0.5 L) for beverages were collected via a deposit system in 2017, representing 86% of all collected large beverage PET bottles (M. Brouwer et al. 2019). In 2022, also 58% of small PET bottles (≤0.5L) for beverages were collected through a deposit system (Afvalfonds Verpakkingen 2023a). We assume that these PET bottles from the deposit system have no sorting losses. For all other packaging types, data from Brouwer et al. (2019) is used to determine the relative distribution between separate collection (PMD) and collection with municipal solid waste (MSW). Table 2.5 shows the resulting average shares of the collection methods by packaging type.

Table 2.5: Shares of the collection methods by packaging type

Packaging type	*Collected in PMD*	*Collected in MSW*	*Collected in the deposit system*
Bottles, contact-sensitive	22%	7%	71%
Bottles, other	73%	27%	0%
Rigids	60%	40%	0%
Flexibles	48%	52%	0%
Beverage cartons	49%	51%	0%

Overall, 81% of the packaging waste collected through MSW is directly sent to energy recovery, and only 19% is sent to material recovery facilities (M. Brouwer et al. 2019). According to RWS, 9% of the separately collected packaging waste (PMD) is rejected at the transfer station and sent to incineration. All subsequent recovery & sorting losses are sent to energy recovery. Figure 4.3 in section 4.2 shows the material flows of consumer plastic packaging and beverage cartons in 2022, including collection and sorting as described here.

Sorting

Yields of the sorting steps are taken from M. Brouwer et al. (2019). They are differentiated between MSW (recovery and sorting) and PMD (sorting) yields, and per product category. The product types of M. Brouwer et al. (2019) are aggregated into the 7 product categories used in this report (see Appendix a: Allocation of product categories). The yields are aggregated into weighed averages to fit the product categorization of this report, while also considering the material compositions provided by Brouwer et al. (2018). This provides a final table for each of the products and materials, defining the shares collected with MSW, PMD, and deposit system, and the efficiencies from the collection to the sorting, and from the sorting to the final sorted bales. In Table 2.6 we provide an example for this. The table shows the fraction of PET inside Bottles, contact sensitive that ends up in each of the sorted DKR bales after sorting.

Table 2.6: Transfer coefficients for PET inside Contact-sensitive bottles. Determine the share of material flowing from the PMD collection to each of the sorted DKR bales.

Target DKR sorted bale	*Share of PET sent to bale (weight %)*
PET	82.3%
PET trays	3.5%
PE	0.0%
PP	0.3%
Film	0.2%
Mix	8.1%
Beverage cartons	0.4%
Residues	5.2%
Total	100%

Recycling

The collected packaging waste is sorted into eight sorting streams. Table 2.7 shows the allocation of these sorting streams to recycling technologies for 2022 and the BAU scenario. We assume that only recycled PET bottles from the deposit system will be used in packaging again (closed loop), all other recyclates have a lower quality and are used as feedstock for different sectors, such as in roadside poles. Currently, only 9% of plastics in the Netherlands is made from recycled material (Bergsma et al. 2022). Within the European Union, plastic packaging had a 6.6% recyclate content in 2020 (PlasticsEurope 2022). Packaging specific numbers are not available for the Netherlands. Therefore, we work with the simplified assumption that all recyclate from deposit-collected PET bottles will be used for new PET bottles. This is likely rather reflecting its use potential as a high quality recyclate. In reality, a part of this recyclate is probably being used for PET trays or textiles (SYSTEMIQ 2023). Moreover, already today plastic foils are recycled into plastic bags, or HDPE and PP bottles into bottles and other rigids in non-contact-sensitive applications. However, without quantitative data available, this could not be integrated into the model.

Table 2.7: The sorted streams and their allocation to recycling technologies in 2022 and the BAU scenario.

DKR stream	*Recycling technology in baseline situation*
PET bottles (deposit)	Mechanical recycling PET HQ
PET trays	Mechanical recycling PET
PET	Mechanical recycling PET
PP	Mechanical recycling PO
PE	Mechanical recycling PO
Film	Mechanical recycling PO
Mix	Mechanical recycling PO
Beverage cartons	Paper recycling

The yields of the mechanical recycling technologies, and the chemical and thermal recycling technologies that will be applied in the circular scenarios are displayed in Table 2.8. For mechanical recycling, we assumed the yield to depend on the behaviour of the materials in a sink-float separation (M. T. Brouwer et al. 2018). We assume the floating fraction is the product of recycling for polyolefins, and the sinking fraction is the product of recycling for PET. For high quality PET recycling we assume that less of the paper ends up in the granulate, making it of a higher quality. The remaining fraction is assumed to be incinerated along with the process residues. This is a simplification. In theory, a very low-quality by-product could potentially be made from the remaining fraction.

Table 2.8: Yields of recycling technologies

Recycling technology	*Product of recycling*	*PET*	*PP*	*PE*	*PS*	*PVC*	*paper*
Mechanical recycling for PET	low quality granulates	99%	2%	1%	83%	80%	5%
Mechanical recycling for PET HQ	high quality granulates	99%	2%	1%	83%	80%	1%
Mechanical recycling for PO, PP and PE	low quality granulates	1%	98%	99%	17%	20%	0%
Paper recycling	low quality recycled paper	0.0%	0.0%	0.0%	0.0%	0.0%	97.0%
Dissolution	High quality granulates	95.0%	95.0%	95.0%	95.0%	95.0%	0.0%
Gasification	recovered aliphates	32.9%	45.1%	45.1%	48.6%	20.3%	25.0%
Glycolysis	recovered monomer	95.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pyrolysis to naphtha	pyrolysis oil	39.0%	76.5%	84.8%	93.5%	17.7%	0.0%

The yields of further processing of the recycled oil, gas and monomers of the chemical and thermal recycling technology products are shown in Table 2.9.

Table 2.9: Yields of the processing steps of refining recycled oil and monomers to polymers.

Processing step	*Product*	*Yield*
Plastic production	Primary feedstock	100.0%
Cracker	Monomers	50.6%
(re)Polymerisation	Granulate	99.0%
Hydrotreatment	Pyrolysis oil treated for cracking	100.0%

2.4.3 Impact assessment

The impact assessment was conducted with the ReCiPe 2016 method, version 1.03 (Huijbregts et al. 2017). The technology data for the recycling technologies was taken from TNO's PRISM model (see chapter 2.1). Other data was taken from the ecoinvent 3.9.1 database (cut-off) or external literature sources. The Dutch electricity mix was applied for the waste treatment, but European or global energy mix for production processes. Depending on packaging type, different forming technologies are applied for producing the required packages. Table 10 shows which technologies are used for which packaging type in the model.

Table 2.10: Overview of the applied forming technologies per packaging type.

Activity	*PET Bottle*	*Bottles, contact-sensitive*	*Bottles, other*	*Flex, contact-sensitive*[2]	*Flex, othter*[2]	*Rigid, contact-sensitive*	*Rigid, other*
blow moulding	1	0.56	0.56			0.56	0.9
thermoforming, with calendering		0.44	0.44			0.44	
injection moulding							0.1
laminating service, foil, with acrylic binder				0.22	0.22		
extrusion, plastic film				0.8	0.8		

Substitution factor for recycled materials

We include a benefit for recycled materials that are offered to other sectors outside our system boundaries, using a substitution factor that reflects the quality of the recycled output. For polyethylenes and mixed polyolefins we chose a 50% substitution factor, and for PET and PP a 75% substitution factor (Huysveld et al. 2022; L. Rigamonti et al. 2014). For all

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[2] Flexibles include a laminating step which has a functional unit of 1 sqm, which is adjusted to kg in the ratios. Therefore, the technology shares add up to more than 1 in this category, this is by design.

closed-loop applications, namely recycled plastics being used in packaging again, we assume a 1:1 substitution, implicitly assuming that they are mixed with virgin or chemically recycled materials where needed or that they are applied in packaging with lower quality requirements.

For paper recovered from beverage cartons we assume a substitution of sulphate pulp with a substitution factor of 80%, in line with literature (Gala, Raugei, and Fullana-i-Palmer 2015; Lucia Rigamonti, Grosso, and Sunseri 2009; Villanueva and Wenzel 2007).

LCA Modelling framework in CITS

The CITS framework can track materials through society over the course of a product's lifetime through its material flow analysis (MFA). All impacts that directly relate to the materials covered by the MFA of CITS (so far: plastics and metals) are calculated as the material flows through the different stages of the lifecycle. The impacts of materials and processes that are not specifically tracked in CITS are calculated outside the MFA. In this way, we can still provide the entire impact of a product or process. In short, this means that the impact for a given product is the tracked material impact + the untracked material impact.

For this reason, the CITS model needs to separate the specifically tracked materials from all other processes of the LCA model. Furthermore, the LCA models need to be separated between the different life cycle stages defined in the CITS framework. This allows the CITS framework to address and calculate the associated impacts of materials as they flow through the different stages. Using Brightway2 (Mutel 2017), CITS checks each LCA model from databases such as ecoinvent (ecoinvent 2023) for tracked materials, and does so using the classifications present in these database. Ecoinvent includes sectors, ISIC Classifications, ISIC Sectors, CPC Classifications, and more. Using these classifications, for every exchange in an LCA model, primary materials, transforming activities, waste activities, and other types of exchanges in a LCA model can be separated. The result is a LCA model broken up in its parts throughout the lifecycle. These LCA models serve as the basis for modular and scenario adjusted LCA modelling. By complementing these LCA models with results from the aforementioned PREMISE library (see section 2.2.2), CITS can create and utilise "modular" LCA models over time, for different scenarios. Currently, this method is limited to the use of primary materials and transforming activities, due to it being in active development.

3 Scenarios

3.1 Business as usual (BAU)

We opted for a simple BAU scenario in which we assumed a continuation of historic packaging consumption patterns. Moreover, we assumed that the current waste management system for packaging will stay constant until 2050, e.g., the share of packaging types being incinerated and recycled will stay the same as today in the BAU scenario.

Plastic packaging projection

To determine the future volumes of the plastic packaging market in the Netherlands, we analysed the historic relationship between the plastic packaging market size and GDP and population development. This information was used to develop a linear regression model for projecting the future plastic packaging market. Data on the historic Dutch plastic packaging market was taken from Afvalfonds Verpakkingen (2023) and Eurostat (2023). GDP and population projections were taken from OECD (GDP growth of 1,18% between 2022 and 2050) and Eurostat (Population growth of 0.23% per year between 2022 and 2050) (Eurostat 2023b; OECD 2023).

We assume a logistic growth relationship between plastic packaging consumption per capita and GDP per capita. We selected the formula below since it proved to best match historical developments and expected behaviour, i.e., that plastic demand levels off with higher GDP per capita. Our regression analysis found that an alpha of 0,055 and a beta of 23602 to best reproduce the historic data of the Netherlands.

$$\text{Plastic packaging demand} = \alpha \cdot e^{\frac{-\beta}{\text{GDP/capita}}} \cdot \text{population}$$

The data of Afvalfonds Verpakkingen (2023) and Eurostat (2023) is covering the entire packaging market (incl. business to business). We assume that a fixed share of 70% of the total packaging market is for consumer packaging, which is the focus of this report. This percentage was provided by RWS based on experts they consulted. Moreover, we assume that the shares of plastic packaging types provided by RWS (Table 2.1) will stay constant in the BAU scenario.

Beverage carton projection

For beverage cartons, no historic time series of the market size were publicly available. Hence, it was not feasible to create a projection model as was done for the plastic packaging market. KIDV reports a market reduction of beverage cartons from 70 kton in 2013 to 55 kton in 2020 (KIDV (Netherlands Institute for Sustainable Packaging) 2022). According to experts this number stayed roughly the same in recent years and no increase in market size is expected.

Impact assessment

We assessed the impact of the BAU scenario with a baseline background scenario that continues to have a fossil-focused energy mix, referring to a world that does not work towards meeting the Paris climate targets (SSP2 Base). For comparison, we also run the BAU scenario with a greener energy mix, namely the SSP2_RCP19 background scenario, which meets the 1.5 climate target of the Paris climate agreement. Both electricity mixes can be found in the premise database (https://premisedash-6f5a0259c487.herokuapp.com/) and in Appendix B.

3.2 Circular scenario

We describe an optimistic, but technically feasible circular scenario for plastic packaging and beverage cartons. The scenario covers the upstream R-strategies, i.e., Material substitution, Refuse & Reduce and Reuse, as well as well as the downstream R-strategies Recycle and Recover. Since we see strong differences in circular strategies between bottles and other rigid packaging, we further disaggregated the packaging categories from five to seven types. The circular scenario is run in conjunction with a green energy mix, namely the SSP2_RCP19 background scenario, which meets the 1.5 climate target of the Paris climate agreement. As sensitivity, we also show the results of the circular scenario with a fossil-focused electricity mix. Combinations of the measures described in these sections, lead to the scenarios Material Substitution, Refuse & reduce, Reuse and High-quality processing. These combinations are shown in Table 3.4. The scenario assumptions have been developed in a workshop with nine experts from research, industry, and government agencies.

3.2.1 Upstream measures: Refuse, Reduce, Material substitution, Reuse

Refuse

Refuse refers to avoiding a product or its function altogether. Some unnecessary packaging can be eliminated, e.g., secondary packaging and overwraps or packaging that does not fulfil any customer needs but only marketing purposes. More water bottles can be avoided by drinking from the tap and reducing small portion packaging of e.g., readily cut vegetables, could also contribute to refuse (but might have negative trade-offs with food waste). The experts assumed moderate decreases of mostly 10% can be achieved by refuse throughout most packaging categories (see Table 3.1).

Reduce

The experts we consulted saw a strong potential for reducing the material intensity of many packaging types, especially in non-contact-sensitive rigid packaging (see Table 3.1). Substantial amounts of empty space in packaging could be reduced, something that might also be incentivized by upcoming legislation (European Commission 2022). Moreover, using concentrates could contribute to reducing the packaging material, for example for juices or detergents. Lastly, the experts observed a continuous improvement in packaging design, leading to a weight reduction of ca 1% per year.

Material substitution

Moreover, the experts expect that circularity, reuse, and weight reduction goals as e.g., laid out in the proposal for a revision of EU legislation on Packaging and Packaging Waste (European Commission 2022) will lead to the **substitution** of some packaging types.

In our circular scenario we assume that 30% of beverage cartons will be substituted by bottles to enable reuse. Literature provides varying estimates of the weight of a plastic bottle that provides the same service as a beverage carton, ranging from similar weights to significantly higher numbers. Since we aim for reusable plastic bottles, we assume that a plastic bottle will have 30% higher weight than a beverage carton, leading to a total increase of the plastic beverage bottle category of 34%[3].

Moreover, we assume that another 20% of beverage cartons will be replaced by flexible plastic packaging for weight reduction purposes. According to consulted experts, flexible pouches will have a ca. 60% lower weight than beverage cartons. However, this switch will face technical challenges and has the disadvantage that flexible pouches need more space and thus a higher transport volume.

Similarly, we assume that 10% of rigids will be substituted by flexible packaging to reduce the material use of packaging (e.g., meat packed in foils instead of rigid trays). For non-contact-sensitive bottles we assume that 5% will be substituted by flexible plastic packaging and 5% by other packaging materials such as cardboard boxes. Together, these material substitutions will increase contact-sensitive flexibles by 7% and other flexibles by 2% (see Table 3.1).

Table 3.1: Circular scenario assumptions for Refuse, reduce, and reuse by packaging category by 2050.

	Refuse	*Substitution*	*Reduce*	*Reuse*
	% change	% change	% change	% share
Bottles - cont. sens.	-10%	+34%	0	60%
Rigid – cont. sens.	-10%	-10%	-20%	10%
Bottles - Other	0%	-10%	-25%	30%
Rigid - Other	-10%	-10%	-40%	20%
Flexible – cont. sens.	-10%	+7%	-20%	5%
Flexible - Other	-10%	+2%	-20%	10%
Beverage cartons	-10%	-50%	-10%	0%

Reuse

The potential of **reuse** varies substantially between the product categories. Reuse will most likely be incentivized by upcoming legislation such as the PPWR directive. The highest potential lies with contact-sensitive bottles (60%), where commercial reuse systems are already in place in countries like Germany. The reuse numbers in Table 3.1 already implicitly include losses in the reuse system, meaning more bottles are collected for reuse, but only 60% end up being reused. The rest will be recycled or incinerated along with the other products. Other contact-sensitive rigids face hygienic issues in reuse, only allowing for 10% reuse in our circular scenario. This 10% focus on packages for dry food, refill systems on the go, or refill at home from concentrated products. Bottles and rigids in other applications face fewer hygienic issues, but still logistic issues, leading to assumptions of 30% reuse for bottles

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[3] This was calculated by taking 30% of the original beverage carton demand (0,3 * 55 = 16,5 kton), multiplying it with the material substitution factor (1,3 * 16,5=21,45 kton) and adding this to the original demand for contact-sensitive bottles in 2050 (63,3 kton), leading to a 34% increase in demand (63,3 + 21,45 = 84,75 kton).

and 20% reuse for other rigids in non-contact sensitive applications. Flexibles have the lowest potential for reuse, especially in contact-sensitive applications. Nevertheless, Ellen Mac Arthur foundation (Ellen MacArthur Foundation 2022) and consulted experts see a potential of up to 10% reuse for non-contact sensitive flexibles.

3.2.2 Downstream measures: Collection, sorting, and Recycling

The consulted experts expect for a circular scenario a strong increase in separate **collection** of packaging waste, which was largely in line with the assumptions of SYSTEMIQ (2022), see the circular scenario assumptions in Table 3.2. We assume that 90% of PET beverage bottles (both big and small) will be collected by a deposit system, while the other beverage bottles remain collected via separated collection or mixed waste. While the collection of packaging with mixed waste is assumed to reduce drastically to allow for better sorting, more of the plastics that are still collected with mixed waste will be sent to **recovery** , increasing from ca 38% in 2017 (M. Brouwer et al. 2019) to 80% by 2050. Moreover, the **rejection** rate of separately collected waste at the transfer station will reduce from 9% to 5% in a circular scenario.

Table 3.2: Collection system shares in a circular scenario by 2050

Packaging category	*Deposit system*	*Separate collection*	*Mixed waste*
Bottles - cont. sens.	80%	15%	5%
Rigid – cont. sens.	0%	85%	15%
Bottles - Other	0%	95%	5%
Rigid - Other	0%	85%	15%
Flexible – cont. sens.	0%	80%	20%
Flexible - Other	0%	80%	20%
Beverage cartons	0%	95%	5%

By switching to more separate collection, the overall **sorting** efficiencies will improve, allowing for more waste offered to recycling. Moreover, we assume further sorting improvements, reducing the sorting of packages to unintended sorting streams by 30%.

The packaging types are sorted into eight different material DKR streams. Those streams are then allocated to different **recycling** technologies, see Table 3.3 While mechanical recycling is assumed to stay an important technology for relatively pure streams (e.g., PET bottles collected via deposit system), we assume in addition chemical recycling to provide high quality recyclate and to treat mixed streams that currently lead to low quality outputs when mechanically recycled. It is not possible to predict which chemical recycling technologies dominate by 2050. Our proposed combination of future recycling technologies provides a preliminary proxy of the potential impact of a more chemically recycling focused waste management system. Next to conventional mechanical recycling we assume that dissolution will play a bigger role, despite its current challenges in becoming cost-effective. We assume that depolymerisation technologies will treat a share of PET to treat the degraded mechanically recycled PET plastics and provide virgin quality feedstock. There is a wide range of depolymerisation technologies in development such as glycolysis, methanolysis or enzymolysis. We chose glycolysis as a proxy for them, as it is the most developed at this moment in time and already applied. We assume that pyrolysis and gasification to monomers will cover the chemical recycling of polyolefins, especially for mixed streams that are not suitable for good quality mechanical recycling (MIX DKR in Table 3.3). In the circular scenario, we assume that next to the paper also the plastic content of beverage cartons will be treated by mechanical recycling, however the outputs will not be good enough for producing new beverage cartons.

Not all recycled plastic packages are suitable for closed loop recycling into new packaging products. All chemical recycled plastics have virgin quality and can be used again for the same application, similarly as for dissolution. Also mechanically recycled PET from the deposit system is pure enough to be used again in contact-sensitive packaging, albeit with material degradation that requires mixing with virgin quality feedstock. All other mechanically recycled plastics cannot be used again for contact-sensitive packaging for hygienic reasons. They can partly be used in other packaging applications or in other sectors (e.g., building & construction).

Table 3.3: Allocation of recycling technologies to the sorted streams in a circular scenario by 2050

Sorted stream	*Mechanical recycling*	*Dissolution*	*Pyrolysis*	*Gasification to monomer*	*Depolymerisation (glycolysis)*
PET bottle - Deposit	80%				20%
PET DKR	80%				20%
PET tray DKR	40%	20%			40%
PP DKR	40%	20%	20%	20%	
PE DKR	40%	20%	20%	20%	
FILM DKR	40%	20%	20%	20%	
MIX DKR			50%	50%	
Beverage cartons	100%				

3.3 Selected scenario runs

Table 3.4 shows the different scenario combinations that were applied in our analysis. Base refers to the baseline background scenario (see section 2.2.2), referring to a world that does not work towards meeting the Paris climate targets (SSP2 Base). All other scenarios are run with the SSP2_RCP19 scenario which meets the 1.5 climate target of the Paris climate agreement. The circular scenario combines all circular strategies. To show the individual contributions of the circular strategies we separately run the model for each individual circular measure: Material substitution, Refuse & Reduce, Reuse, and High-quality processing, which includes all scenario improvements on collection, sorting, and recycling.

Table 3.4: The scenario combinations

Scenario name	*Effect on consumption*	*Improvements on MFA*	*Impact scenario*
BAU (fossil)	None	None	SSP2_Base
BAU (renewables)	None	None	SSP2_RCP19
Refuse & reduce (renewables)	Refuse, reduce	None	SSP2_RCP19
Material substitution (renewables)	Material substitution	None	SSP2_RCP19
Reuse (renewables)	None	Reuse	SSP2_RCP19
High-quality processing (renewables)	None	Collection, recovery & rejection, sorting, recycling	SSP2_RCP19
Circular (fossil)	Refuse, reduce, material substitution	Collection, recovery & rejection, sorting, recycling	SSP2_Base
Circular (renewables)	Refuse, reduce, material substitution	Collection, recovery & rejection, sorting, recycling	SSP2_RCP19

4 Results

In the results chapter, we first provide an overview of demand projections for plastic consumer packaging and beverage cartons in a BAU scenario (4.1). Chapter 4.2 introduces and analyses the material and packaging flows for the different scenarios. Chapter 4.3 and 4.4 quantify the avoided primary material demand and global warming impact of the circular scenario in comparison with the BAU for each packaging type. Lastly, chapter 4.5 and 4.6 describe qualitatively the microplastics impact and the potential impact of bio-based plastics.

4.1 Material demand projection for the Business as usual scenario

The BAU projections result in a moderate increase of 17% until 2050 (compared to 2022), with a Compound Annual Growth Rate (CAGR) of 0.52% (see Figure 4.1). This is lower than the historic CAGR of 1.58% (2006-2022), which is mostly due to the relative low GDP & population growth projections of OECD (2023) and Eurostat (2023b) for the Netherlands (0.92% CAGR for GDP/cap). This projection assumes that the past plastic packaging consumption patterns stay the same in their relationship to economic and population growth (BAU). This growth projection has been confirmed with a group of experts, who deemed the growth rate to be realistic for a baseline scenario. For beverage cartons we assume a constant market size of 55kton until 2050 in this baseline scenario (see chapter 3.1).

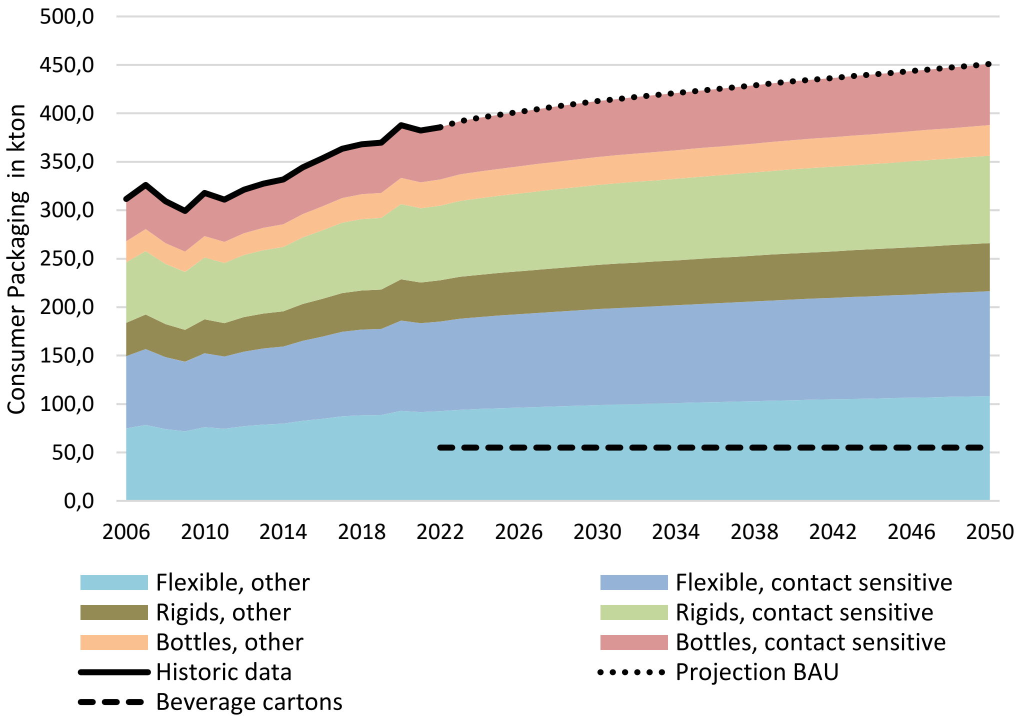

Figure 4.1: Consumer plastic packaging & beverage carton projection for a business as usual scenario.

4.2 Material flow analysis

Based on the collected data (chapter 2.4) and the scenario assumptions (chapter 3) we created dynamic Sankey diagrams that can be used to select scenarios, move and sum up streams and analyse the size and type of specific flows by hovering over them. They can be provided on request. Figures 4.2 and 4.3 provide screenshots of this Sankey tool for the BAU scenario and the circular scenario, summing up all packaging categories, material categories, sorting streams, and losses. Packaging type specific diagrams were also produced and can be provided on request.

The Sankey diagrams clearly show the key differences between the two scenarios. We can see that in the circular scenario the losses to energy recovery are drastically reduced, driven by a switch to separate collection (see chapter 3.2.2) and improved sorting. Moreover, reuse plays a significant role in meeting the market demand, and thus reducing new material input into the sector. By having more chemical and thermal recycling and a more efficient deposit system for beverage bottles, more high-quality recyclate is available. Hence, less lower-quality recyclate is produced, which only can be used in applications with lower quality requirements, which excludes contact-sensitive packaging. By providing a larger share of recyclate as feedstock, the high-quality processing of waste flows in a circular scenario further reduces the need of primary materials, adding to the reductions achieved by substitution, refuse, reduce, and reuse (see chapter 3.2.).

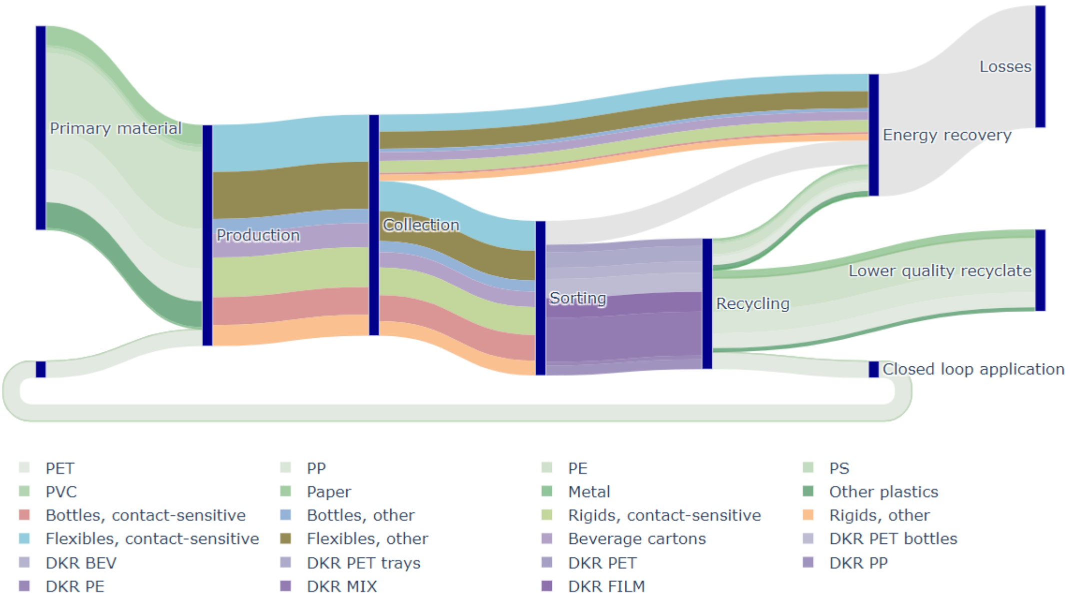

Figure 4.2: Material flow analysis of all analysed packaging types in the current situation and in 2050 (BAU scenario). Notes: both 2022 and 2050 have the same MFA assumptions, at different scales, and therefore this Sankey looks the same in both years.

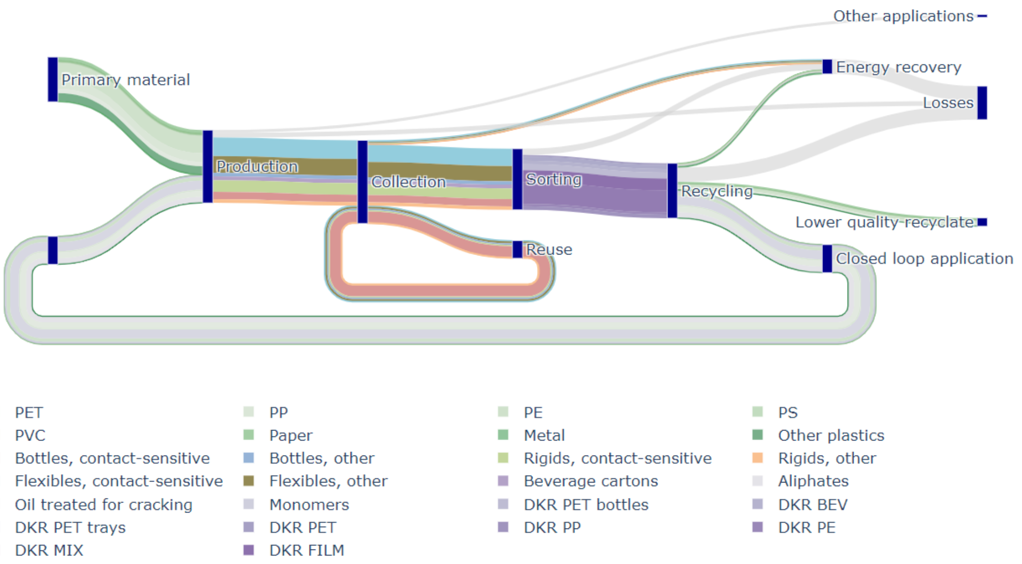

Figure 4.3: Material flow analysis of analysed packaging types in 2050 for a circular scenario. Scale of this Sankey is different from the scale of Figure 4.2.

Figure 4.4 compares the fate of the plastic packaging groups at the end of their life for the Business as usual (BAU) scenario and the circular scenario. In the BAU scenario only PET bottles collected with a deposit system have sufficient quality to be recycled back into bottles or trays in contact-sensitive applications. All other product groups end up in mixed streams and are mechanically recycled, thus providing lower quality recyclate which allows for mostly open loop applications. Overall, 55% of the packaging material ends up incinerated in the BAU scenario, namely 278 kton in 2050.

The share of incinerated material reduces to 18% in the circular scenario, leaving 62 kton energy recovery. In the circular scenario reuse plays a dominant role in beverage bottles but also to a certain extent in other packaging categories. Moreover, dissolution, depolymerisation, pyrolysis and gasification are applied, providing high-quality recyclates that are suitable for closed-loop recycling. Through separate collection and improved sorting higher purity in sorted streams is achieved which also allows for higher quality recycling. Nevertheless, in Figure 4.4 mechanically recycled packaging which was not collected via a deposit system is still classified as lower quality recyclate, since it is still not suitable for contact-sensitive applications. Their share though reduces substantially compared to the BAU scenario.

Despite the lower losses to energy recovery (18%) in the circular scenario, still 40% of the material is lost in total, namely 141 kton. This is because 22% of the packaging material is lost in the chemical recycling processes. Pyrolysis and gasification have substantial losses when also considering the transformation of pyrolysis oil or aliphates (from gasification) into new plastics (via steam cracking and polymerisation). While these technologies lead to high quality recyclates, they perform worse in terms of material output than for example mechanical recycling. The flexibles show the highest material losses even in the circular scenario, due to their little reuse potential and a high share of pyrolysis and gasification.

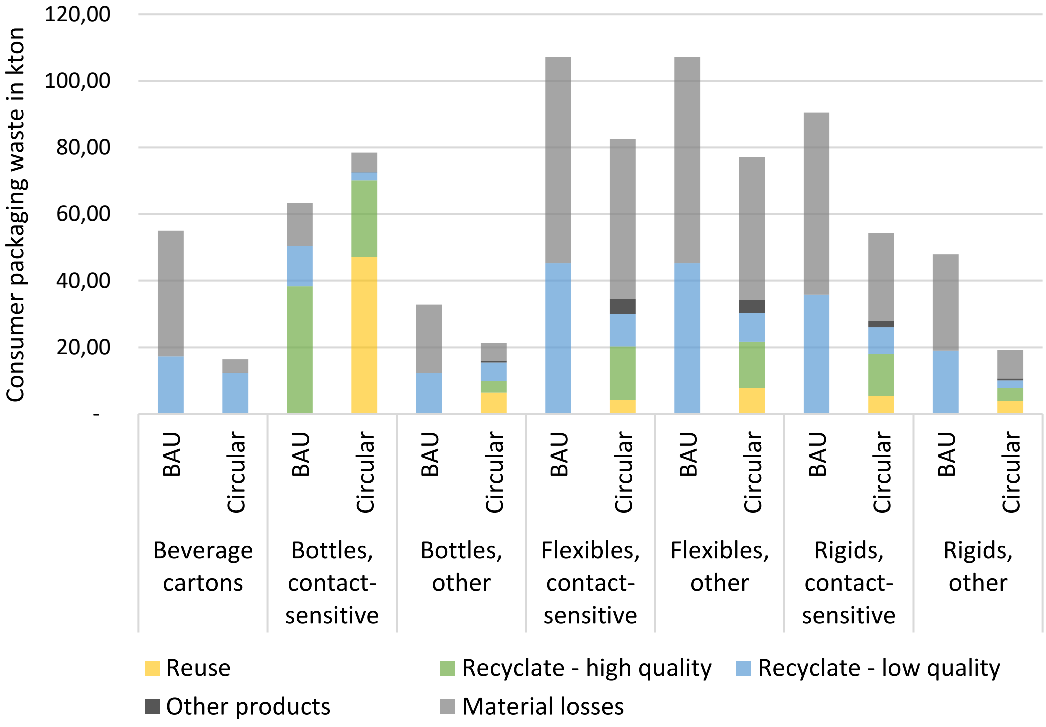

Figure 4.4: Fate of packaging products at the end of their use.

4.3 Avoided primary material demand of the scenarios and packaging types

Figure 4.5 compares the avoided primary material demand of the scenarios in 2050 in terms of avoided primary material in relation to total material demand of the BAU scenario. The BAU scenario only achieves an overall avoided primary material demand of 8%, which is fully caused by the high-quality recyclate coming from the deposit system for contact-sensitive bottles. In the model we allocated this high-quality recyclate to producing new bottles, leading to an avoided primary material demand of 61% for contact-sensitive bottles in the BAU scenario. This is a simplification in absence of quantitative data. In reality those recyclates are also partly used for producing e.g., PET trays. Moreover, there are today already plastic foils being recycled into plastic bags, or HDPE and PP bottles into bottles and other rigids in non-contact-sensitive applications. Nevertheless, these results for the BAU are in line with the reported recyclate use in plastic packaging of ca. 7% in the EU (PlasticsEurope 2022).

In the circular scenario, the overall avoided primary material demand increases to 67%. We can clearly see that the avoided primary material demand varies substantially between packaging types, ranging from 42% for contact-sensitive flexibles to 98% for non-contact-sensitive rigids. Moreover, we see that the potential of the scenario buttons Material substitution, Refuse & reduce, Reuse, and High-quality processing varies significantly between the packaging types but also in total impact.

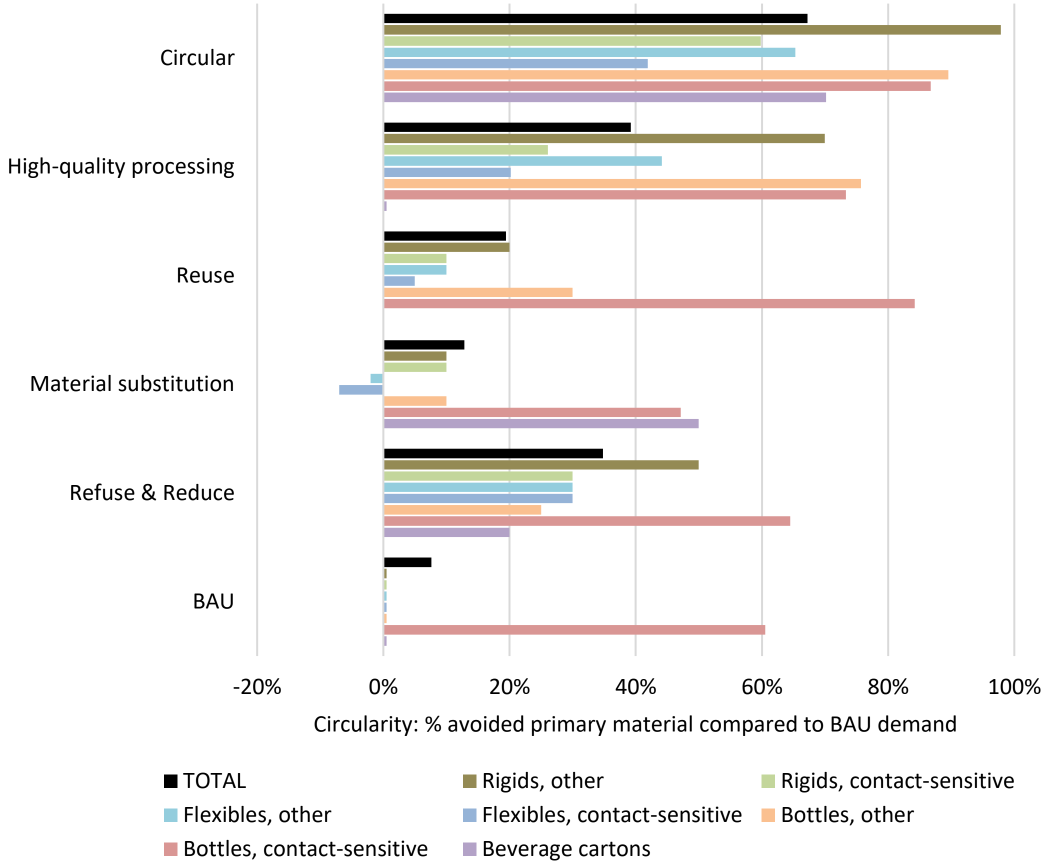

Figure 4.5: Circularity rating of the scenarios in terms of % avoided primary material by packaging type in 2050, compared to the total material demand in the BAU scenario.

The most impact has the high-quality processing measure with 39% total avoided primary material demand. Rigids in other applications have the strongest material reduction potential (40%), due to eliminating empty space and having more concentrated products (see section 3.2.1), leading to a total avoided primary material demand of 50% through refuse & reduce. Reuse only avoids 19% primary material in total but is the most effective strategy for contact-sensitive bottles (84%). Material substitution has the lowest total avoided primary material demand (13%) but has a very high potential for beverage cartons (50%), at the cost of the reduction being compensated by bottles and flexibles (see section 3.2.1).

High-quality processing through improved collection, sorting, and recycling achieves a total circularity of 39%. It is the highest for non-contact-sensitive bottles (76%), closely followed by contact-sensitive bottles and non-contact-sensitive rigids with 73% and 70% respectively. For contact-sensitive bottles this is due to the deposit system and the following high-quality mechanical recycling and depolymerisation. Nevertheless, the improvements compared to the BAU are not so substantial, as this was the only packaging category already performing reasonably well in the BAU (61%). Bottles, rigids, and flexibles for non-contact-sensitive applications perform better than their contact-sensitive counterparts. This is because we assume that they can make use of lower-quality recyclates coming from contact-sensitive applications, for which the mechanically recycled packaging is not hygienic enough if it does not come from close-loop deposit systems. The reduction potential for flexibles in the high-quality processing scenario is limited since many of them end up in mixed sorted streams, which are to a larger extent being treated by pyrolysis and gasification to monomers. Both of which provide virgin quality recyclate but at the cost of lower total efficiency when considering polymer to polymer recycling.

After applying all the strategies of the circular scenario, still 165 kton demand for primary material remains, of which 149 kton for plastic consumer packaging. When aiming for phasing out fossil feedstocks, this remaining virgin material demand would have to be provided by other waste sources, from biomass or carbon capture and utilization technologies.

4.4 GHG impact of the scenarios and packaging types

Figure 4.6 shows the Greenhouse-gas (GHG) emissions of all packaging types combined by process steps, covering the production, collection, sorting and the different waste treatment technologies. Below the x-axis the impact of the avoided energy and products are shown. Thermal recycling sums up pyrolysis and gasification to monomers. “Recyclate to polymer” is an aggregate for the downstream processing steps to create new polymers from the outputs of pyrolysis, gasification, and depolymerisation, namely hydrotreatment, steam cracking and repolymerisation. Next to the two main scenarios (BAU, circular) we also see the results of the individual circular scenario buttons: Material substitution, Refuse & reduce, Reuse, and “high-quality recycling” which combines the effect of improved collection, sorting, and recycling. All scenarios are run with a green electricity mix that is in line with the 1.5-degree climate target of the Paris agreement (renewables). Only BAU (fossil) and Circular (fossil) are run with a more emission intensive electricity mix for comparison, representing a world that does not adhere to the climate targets.

In the BAU scenario, the GHG emissions increase by 12% from 1696 kton to 1901 – 1906 kton CO2-eq. by 2050, depending on the applied electricity mix in the background scenario. The BAU scenario with a renewable electricity mix has slightly higher net GHG emissions than the BAU scenario without climate policy because incineration with energy recovery receives less benefits as it does not substitute electricity from fossil fuels anymore. We see that the virgin material production and energy recovery are the biggest emission drivers, followed by the manufacturing of the packaging products (forming). Collection, sorting and recycling have comparably low impacts, which do increase in a circular scenario with more recycling and the adoption of more energy-intensive recycling technologies.

The circular scenario including a fossil electricity mix can reduce the GHG emissions to 983 kton. The circular scenario with a greener electricity mix can reduce emissions even further to 722 kton. The circular scenario has less avoided product outside its system boundaries as most material is used again for packaging, while in the BAU scenario most recyclate is used by other sectors. Moreover, we can see that energy recovery becomes less beneficial with a greener electricity mix, as less fossil energy is avoided. The emissions of mechanical recycling are substantially lower than the emissions from dissolution, chemical and thermal recycling which all have a larger energy consumption, and – in the case of thermal recycling – high losses of plastics in the process. With a greener electricity mix, all processes with high electricity consumption drastically reduce in impact, in particular dissolution and sorting.

Figure 4.6: Greenhouse gas emissions of the consumer packaging system per scenario, showing the contributions of each processing step. Notes: Thermal recycling sums up pyrolysis and gasification to monomers. “Recyclate to polymer” is an aggregate for the downstream processing steps to create new polymers from the outputs of pyrolysis, gasification, and depolymerisation, namely hydrotreatment, steam cracking and repolymerisation.

Figure 4.7 shows the contributions of the different packaging types to the overall packaging emissions. Finally, Figure 4.8 shows the GHG emission reduction potential of each packaging type and each scenario in comparison to the BAU scenario with the baseline electricity mix. In total, the circular scenario with a fossil electricity mix achieves around 48% GHG emissions reductions compared to the BAU scenario with the fossil energy mix. With a renewable electricity mix, this reduction could be further increased to 62%. Including a renewable electricity mix, high-quality processing and refuse & reduce are the most impactful scenario buttons, reducing the emissions by 31% and 25%, respectively, compared to BAU (Base). Reuse achieves 14% GHG emission reductions and material substitution 13%.

Beverage cartons achieve the highest GHG emission reductions (85%), followed by other rigids and bottles with both 79%. Also contact-sensitive bottles and rigids achieves substantial improvements, with 68% and 66% respectively. The flexibles have the lowest emission reductions with 41% in contact-sensitive applications and 47% in other applications. Do note that the high reductions in beverage cartons are due to partial substitution with other packaging types.

When we look at the varying impact of the scenario buttons on the different packaging types, we see similar patterns as in Figure 4.5 on the avoided primary material demand, with high-quality processing and Refuse & Reduce showing the highest improvements, followed by Reuse and Material substitution. Again, contact-sensitive bottles and flexibles perform worse in the Material substitution scenario, as their amount increased as they substitute beverage cartons and other packaging types. Flexibles and beverage cartons perform worse in the Reuse scenario, as the benefit of substituted energy through incineration drastically decreases with a cleaner energy mix. In Figure 4.8, the impact benefit of the low-quality recycled material is allocated to where it came from, while in Figure 4.5 contact-sensitive low-quality recyclate was attributed to other applications. This explains why the difference between contact-sensitive and other applications is lower than in the circularity assessment (see e.g. for flexibles). Lastly, we see that the BAU scenario with a renewable energy mix performs worse than the BAU baseline scenario for most packaging types. This is because of the lower impact benefit of energy recovery, as it does not substitute fossil fuel based electricity anymore.

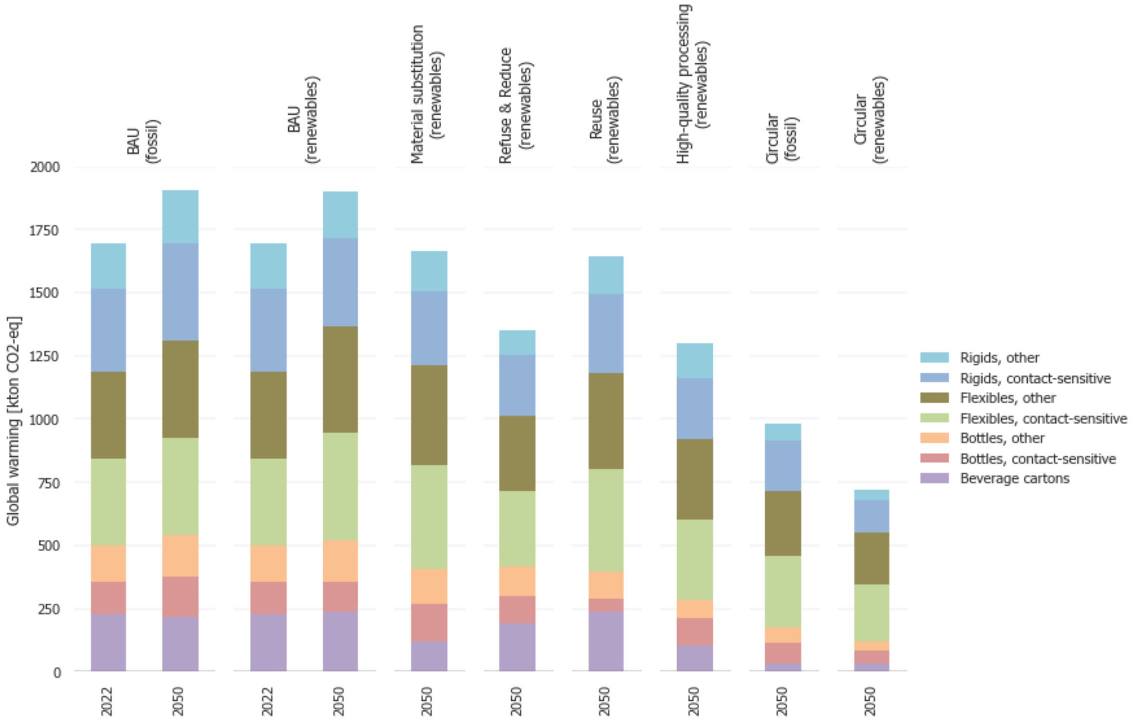

Figure 4.7: Greenhouse gas emissions of the packaging system in 2050 per scenario, showing the contributions of each packaging type.

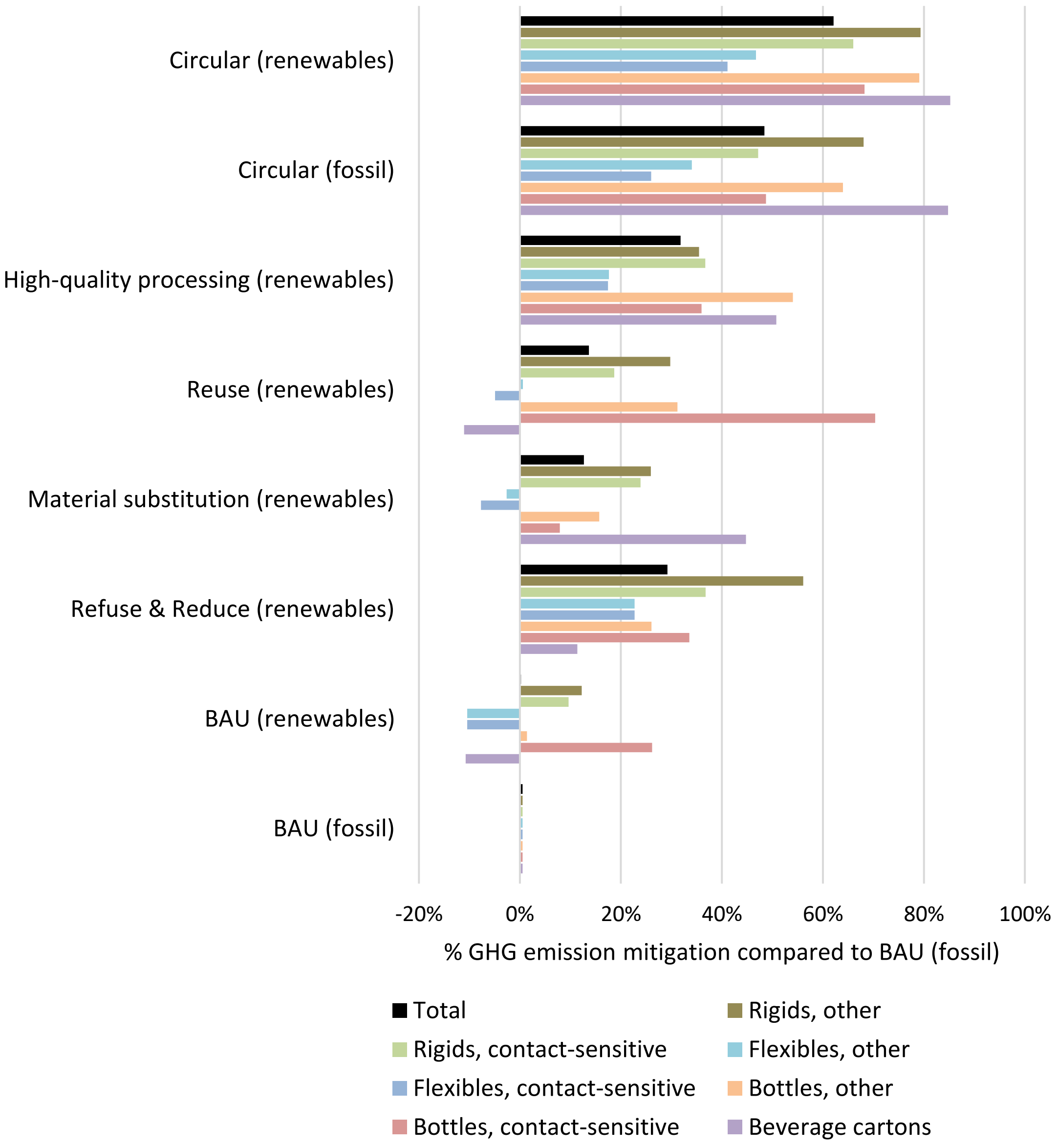

Figure 4.8: GHG emission mitigation compared to the BAU (Base) scenario by packaging type and scenario.

4.5 Microplastics

Microplastics are formed due to weathering and degradation of plastic products. Additionally, microplastics can also be added intentionally to product, such as in cosmetics and agricultural products (A. E. Schwarz et al. 2023). Most microplastics are formed due to inadequate waste management and littering of plastic products. Once littered, due to environmental variables including UV exposure, water exposure, chemical exposure and mechanical abrasion, the plastic product that was initially littered breaks down into microplastics. The breakdown to microplastics can also occur to plastic products that are still in use, such as tearing of packaging plastics, or the peeling of paint. The size of the degraded microplastics depends strongly on the polymer type, as assessed by Boersma et al. (2023). where the polyolefins HDPE and LDPE degrade in relatively large particles (240-270 micron), PS and PMMA form the smallest particles ((3.2-3.8 micron).

Size matters as smaller particles have highest surface area to weight ratio, hence exposing species and humans to leaching additives and potential ability to pass the blood barrier (Leslie et al., 2022). This can have adverse effects on health. this is explored in various studies showing that micro and nanoplastic exposure can have health and lethal effects (Corella-Puertas et al. 2023).

With around 25%, Packaging is one of the main contributors for direct microplastics in the environment on a yearly basis, about 1.2 kt in 2017. This only included direct losses (production, use and recycling) and still excludes degradation occurring in the environment. This will be higher as about 14 kt of packaging plastic are approximately lost to the environment in the Netherlands in 2017 alone. The remaining direct microplastics emissions come mostly from car tyres (ca. 50%), textiles and agriculture (A. E. Schwarz et al. 2023).

In countries without adequate waste management, the dumping of non-collected waste is the highest contributing factor. The types of polymers that occur in the environment align with the consumption of the polymers and include LDPE, PP and HDPE (A. E. Schwarz et al. 2023). Other sectors and polymers that contribute to Microplastics in the Netherlands are agriculture and car tyres. It was found that most plastic is not in aquatic environments (like rivers, shorelines and oceans) but on land (terrestrial soils). this includes natural soils, residential soils and along roadsides (A. E. Schwarz et al. 2023).

4.6 Potential role and impact of bio-based plastics

Introduction

Bio-based plastics are defined as plastics that are derived from biobased sources. They can be differentiated as drop-in bio-based plastics, which have the same chemical structure as their fossil counterparts, such as bio-PP or bio-LDPE, and novel bio-based plastics such as PLA, PEF and PHA. Some bio-based plastics are biodegradable when they meet the definition of being able to decompose rapidly by microorganisms under natural conditions, while other bio-based plastics can be as persistent in natural environments as conventional fossil-based plastics.

Bio-based plastics cover less than 1% of the global plastic market, with PLA, starch blends, and drop-ins such as bio-PE, bio-PP, and bio-PET making up a major part of it (European Bioplastics 2023b). The European Bioplastics (2023b) expects a tripling of the market of bio-based plastics by 2027, from 2217 kton in 2022 to 6291 kton. With 48%, packaging is the biggest market for bio-based plastics, e.g., for wrapping organic food or packaging for premium products (European Bioplastics 2023a).

Our analysis in section 4.3 showed that even in the circular scenario, 147 kton of demand for primary plastic consumer packaging remains, if not reduced by recyclates from other sectors. If we want to phase out fossil fuels this would need to be provided by either biomass or carbon capture and utilization.

Impacts of bio-based plastics

Research showed that using biomass as feedstock could play a role in reducing the GHG emissions of the plastic sector (Meys et al. 2021; Paul Stegmann et al. 2022; Zheng and Suh 2019). Life Cycle Assessments (LCA) usually conclude that bio-based plastics perform better than fossil-based plastics in terms of Global Warming Potential (GWP) (Bishop, Styles, and Lens 2021; Gironi and Piemonte 2011; Moretti et al. 2021; Spierling et al. 2018). These LCAs usually consider the biogenic carbon uptake from the atmosphere during crop growth (CO_2 sequestration). End of life incineration of these bio-based plastics will then result in biogenic CO_2 emissions which have previously been sequestered in the growth phase of the biomass feedstock. These biogenic emissions are not counted according to IPCC emission guidelines (Eggleston H.S. et al. 2006).

If this carbon uptake is not included in the LCA, bio-based plastics usually perform similarly to fossil plastic when only production is considered (Morão and de Bie 2019).Recycling bio-based plastics is possible, and recycling options are similar to fossil-based plastics. These include mechanical recycling (Farah, Anderson, and Langer 2016)depolymerization (A. Schwarz, Ferjan, and Kunst 2023), and incineration.

For some environmental impact categories, bio-based plastics score worse compared to fossil-based plastics. This is especially the case for land-use change, marine eutrophication, and ecotoxicity indicators, which can be 100-1,000 times higher (A. Schwarz, Ferjan, and Kunst 2023). The increase of impacts in these categories highlight the trade-off of using bio-based plastics, as well as the importance of their recyclability. Making bio-based plastics circular could substantially improve the impact for GWP and other impact categories as less raw material is required. However, the same is the case for circular fossil-based plastic.

Biomass feedstocks

Novel bioplastics are currently mostly made from sugar rich crops, including maize, cassava, sugarcane or beets. For PLA, Totalenergies Corbion produces PLA from Thai Sugarcane (Corbion 2022), while Natureworks and Futerro/ Galactic produces PLA from Maize grown in the USA (NatureWorks 2022) and Futerro/ Galactic (Galactic 2022). When using sugar-based crops, potential competition with space for food crops arises.

Recent technologies have found algae to be a future source of sugars for PLA (Bulota and Budtova 2015). Lignocellulosic biomass is also increasingly considered as a feedstock for biorefineries and bio-based plastics (Abe et al. 2021; Mujtaba et al. 2023; P. Stegmann, Londo, and Junginger 2020). Bioplastic production from biogenic waste streams is still in its infancy, and additionally, the supply of secondary biomass (waste streams) is limited. The advantage of these secondary biomass streams is the lower impact on land use and biodiversity, as only residues are used. The residues again include multiple levels; primary residues (food crops, e.g. on marginal lands and agriculture/ forestry residues), secondary residues (processing waste) and tertiary residues (MSW, used oils) (Hoefnagels and Germer 2018).

Hoefnagels and Germer (2018) estimate a total domestic biomass supply within the European Union of 115 – 525 Mt in 2020, which could increase to 195 – 595 Mt by 2050. However, the share of wastes and residues are substantially lower. Van Harmelen, Schouten, and Stegmann (2023) estimated that a total of 8236 kton biomass waste and residues were available in the ARRRA region (Belgium, Netherlands, North Rhine Westphalia) in 2020. This would be equivalent to around 141 PJ, while the Dutch chemical sector alone consumed 805 PJ of energy carriers (Oliveira and van Dril 2021), of which ca. 402.5 PJ for feedstocks (van Harmelen, Schouten, and Stegmann 2023). This highlights the scarcity of biomass residues and wastes in comparison to feedstock and energy demand. Even more so, when considering the competition between countries and other industry sectors (e.g., for heating). Nevertheless, these residues and wastes would be sufficient to meet the demand of the remaining 149 kton primary plastic packaging demand in the circular scenario.

5 Discussion & conclusions

5.1 Results

The consumer plastic packaging demand grows to 451 kton by 2050 in a business-as-usual scenario, beverage cartons stay constant at 55 kton.
Following current consumption patterns, the Business as usual (BAU) scenario projects a 17% increase in consumer plastic packaging demand, from 386 kton in 2022 to 451 kton in 2050. The demand for beverage cartons is assumed to stay constant at 55 kton.

We created a circular scenario for consumer packaging based on refuse, reduce, and high-quality processing.
Next to a BAU scenario, assumptions for a circular future were defined via a literature review, a workshop, and feedback from experts. This scenario considers upstream circular strategies to narrow the loop, thus reducing the material demand (refuse, reduce, material substitution), to slow the loop, thus keeping products in use (reuse, lifetime extension), as well as downstream strategies regarding better waste collection, sorting and recycling (high-quality processing). These strategies are calculated by the model separately and combined in the circular scenario. Demand is reduced by eliminating unnecessary packaging applications, substituting packaging with other materials, and reducing the material amount per packaging by smarter design and reducing empty space. Material substitution within the system boundaries (e.g., beverage cartons being replaced by plastic bottles) has been considered, but substitution with, e.g., bio-based plastics, glass, or metal packaging has not been considered in the circular scenario. Furthermore, reuse plays a dominant role in beverage bottles but also to a certain extent in other packaging categories. Moreover, application of dissolution, depolymerisation, pyrolysis and gasification-to-monomer recycling technologies are analysed, which provide high-quality recyclates that are suitable for closed-loop recycling, even for contact-sensitive applications (see Figure 5). Through more separate collection and improved sorting, higher purity in sorted streams is achieved which also allows for higher quality recycling. This means that also mechanically recycled plastics can be used in packaging again, albeit not in contact-sensitive applications unless they are collected via a deposit system.

The GHG emissions of the Dutch packaging system increase from 1696 kton CO_2-eq. in 2022 to 1901-1906 kton by 2050 in the BAU scenario.
The GHG emissions of the Dutch packaging system were estimated at 1696 kton CO_2-eq. in 2022, which could increase by 12% up to 1901 -1906 kton CO_2-eq. by 2050, depending on the electricity mix. This includes resource extraction, material & packaging production, as well as collection, sorting, and waste treatment, while also covering transportation. Moreover, we consider a benefit for avoided energy from incineration and avoided virgin production through recycling.

Primary material production and waste incineration with energy recovery are the biggest GHG emission drivers, followed by the manufacturing of the packaging products. Collection, sorting and recycling have comparably low impacts. The BAU scenario with a renewable energy mix has slightly higher net GHG emissions than the BAU scenario without climate policy, because incineration with energy recovery receives less benefits as it does not substitute electricity from fossil fuels anymore.

Packaging is currently one of the main contributors to direct microplastic emissions to the environment, representing 25% of the total microplastic emissions in the Netherlands, namely 1.2 kton in 2017. Other main sources include car tyres (circa 50%), textiles and agriculture.

Currently, only a small part of packaging is circular and 55% of materials are lost.
Without changes in our consumption and waste management such a system would lead to material losses of 279 kton in 2050, or 55% of all packaging put on market that year. Moreover, only a small part of the recycled material is used for new packaging material (ca. 7% in EU according to PlasticsEurope). This is because the quality of recyclate out of mechanical recycling is limited by the packaging design and the collection and sorting system. Moreover, EFSA guidelines advice against the use of mechanical recyclate in contact-sensitive applications. We assume recyclate from mechanical recycling is not used in contact sensitive applications unless the used waste source is from a deposit collection system.

The circular scenario increases the avoided primary material demand to 67% and reduces the GHG emissions by 62% compared to the BAU scenarios by 2050.
Overall, the circular scenario avoids 67% of primary material demand by 2050. At the same time, it reduces the GHG emissions by 62% compared to the BAU scenarios, to 722 kton (48% with a fossil electricity mix). The avoided primary material demand varies substantially between packaging types, ranging from 42% for contact-sensitive flexibles to 98% for non-contact-sensitive rigids. The ranges in GHG emission reduction compared to the BAU Baseline scenario range from 41% for contact-sensitive flexibles to 85% for beverage cartons.

The impact of the circular scenario buttons varies substantially between the packaging types.
Moreover, we see that the potential of the three scenario buttons “Refuse & reduce”, Material substitution, Reuse, and “High-quality processing” varies significantly between the packaging types but also in total impact. The most impact on avoided primary material demand have high-quality processing and the refuse & reduce measures with respectively 39% and 35% total avoided primary material demand each. Reuse has the lowest total avoided primary material demand (19%) but has a very high potential for contact-sensitive bottles (84%). Material substitution avoids in total 13% of primary material, mostly by switching to more light-weight flexible packaging.

Refuse & reduce potential is highest for Rigids in non-contact-sensitive applications and for beverage cartons. High-quality processing through improved collection, sorting, and recycling has the highest impact for non-contact-sensitive bottles (76%), closely followed by contact-sensitive bottles and non-contact-sensitive rigids with 73% and 70% respectively. Non-contact-sensitive applications perform better than their contact-sensitive counterparts because we assume that they can make use of lower-quality recyclates coming from contact-sensitive applications, for which the mechanically recycled packaging is not hygienic enough if it does not come from close-loop deposit systems. The reduction potential for flexibles in the high-quality processing scenario is limited since many of them end up in mixed sorted streams, which are to a larger extent being treated by pyrolysis and gasification to monomers. Both of which provide virgin quality recyclate but at the cost of lower total efficiency when considering polymer to polymer recycling.

Including a renewable electricity mix, high-quality processing and refuse & reduce are the most impactful scenario buttons, reducing the emissions by 31% and 29%, respectively, compared to BAU (Base). Reuse achieves 14% GHG emission reductions and material substitution 13%.

There are trade-offs between recyclate quality, recyclate amounts, and GHG impact.
While thermal recycling technologies such as pyrolysis and gasification lead to higher quality recyclates, they perform worse in terms of material output and GHG emissions than for example mechanical recycling. Also, dissolution requires substantial electricity, however, this impact strongly diminishes with a greener energy mix. In the end, an optimized combination of mechanical and chemical recycling pathways needs to be found, that provides the adequate material quality for each application, and which upcycles degraded plastics from mechanical recycling after multiple use cycles.

Even in the circular scenario, primary material is still required and needs to be provided by alternative sources.
After applying all the strategies of the circular scenario, still 165 kton demand for primary material remains, of which 149 kton for plastic consumer packaging. 72% of these 149 kton is needed for contact-sensitive packaging. With 64%, flexible plastic packaging (both in contact-sensitive & other applications) is the biggest consumer of the remaining primary material demand. When aiming for phasing out fossil feedstocks, this remaining virgin material demand would have to be provided by other waste sources, from biomass or carbon capture and utilization technologies.

Bio-based plastics could reduce GHG emissions but increase other impacts and face competition over limited biomass resources.
Biomass as feedstock could play an important role in reducing the GHG emissions of the plastic sector. Life cycle assessments show that bio-based plastics usually have lower GHG emissions than fossil plastics, but substantially higher impacts in other environmental categories such as land-use change or eutrophication. By making bio-based plastics circular and using (agricultural) waste streams as feedstocks these impacts could be reduced. However, biomass supply in the European Union is limited, particularly for wastes and residues. Moreover, plastics would have to compete over these biomass streams with other sectors, e.g., energy.

5.2 Methods & limitations

The efforts by RWS and our literature review revealed that there is still a major gap in publicly available information on the Dutch packaging system. While the interviewed stakeholders agreed that a packaging type specific assessment would be beneficial, only assumptions could be provided on their flows through the waste management system. These gaps were partly filled by using 2017 modelling data from Brouwer et al (2018, 2019). However, combining different data sources and assumptions does not allow for sound conclusions on policy advice, in particular when discussing some packaging types. Key improvements in data collection, transparency, and open-source availability are needed for better assessments in the future. This data collection should follow a consistent methodology that allows for assessing trends over time, life cycle stages, and product categories.

Long-term assessments such as this one cannot project future developments but only provide information on the potential impacts of different future pathways. Our report showed the effectiveness of different circular strategies (refuse, reduce, reuse, high-quality processing), but a more comprehensive scenario assessment would allow to better capture the different potential futures. In particular, we only assessed one recycling scenario by normatively deciding which technologies will be applied by 2050. While these assumptions have been discussed with experts in the field, showing alternative pathways would help to better understand the trade-offs between different strategies. In particular, a comparison of a waste management system with a focus on mechanical recycling with a more chemically recycling focused scenario would be valuable. As both pathways are expected to have major trade-offs in climate impact and amounts and quality of recycled material. Depending on policy priorities (e.g., climate focus, circularity focus) different strategies should be selected.

Our model only captures conventional plastics at this moment. In the future, different types of (bio) plastics will be on the market. Including such novel plastics in the assessment would be a major improvement. And, as our results have shown, improvements in plastic production and alternative feedstocks for virgin plastics are required to phase out fossil fuels and further reduce GHG emissions.

This analysis has focussed on the effect of policy measures on the avoided primary material demand and GHG emission impacts of the packaging recycling system. This however paints an incomplete picture of the full ecological impacts, which also includes dimensions like eutrophication and (eco)toxicity. A focus on minimizing GHG emissions may cause unforeseen trade-offs. The model that has been built, does allow for the comparison between these impact categories using the LCA framework, but this was not in the scope of this report.

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Signature

TNO ⟩ Energy & Materials Transition ⟩ Utrecht, 21 August 2024

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on 2024-08-22 12:04:56

Clare Harvey
Deputy Research manager

Toon van Harmelen
Reviewer

Appendix A

Allocation of product categories

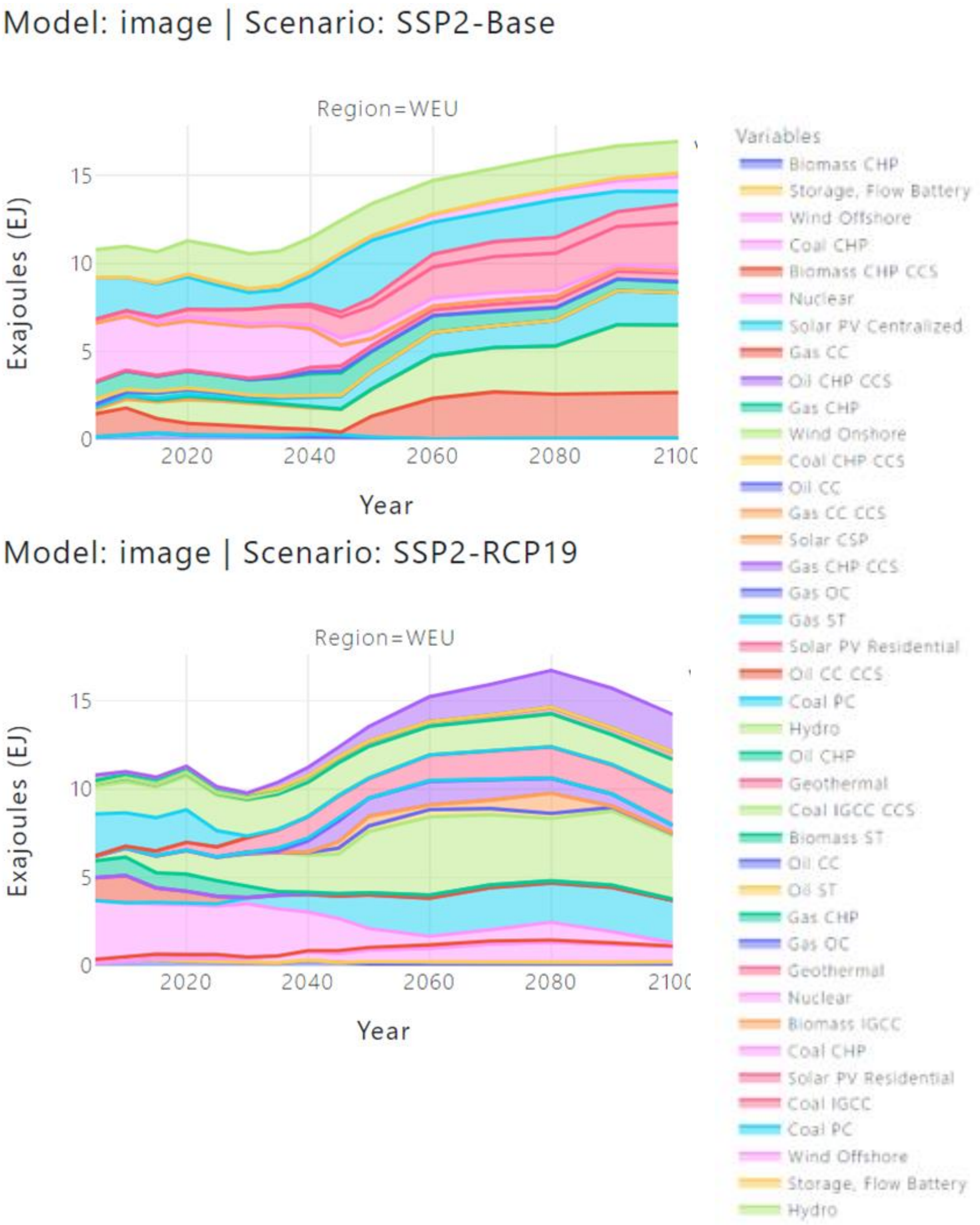
Packaging categories Brouwer et al (2019)	Allocation to our categories
PET bottle clear ≤ 0.5 litre	bottles_contact-sensitive
PET bottle coloured ≤ 0.5 litre	bottles_contact-sensitive
PET bottle clear > 0.5 litre	bottles_contact-sensitive
PET bottle coloured > 0.5 litre	bottles_contact-sensitive
PE beverage bottles	bottles_contact-sensitive
PP beverage bottles	bottles_contact-sensitive
PS beverage bottles	bottles_contact-sensitive
Misc. beverage bottles	bottles_contact-sensitive
PET non-beverage bottles	bottles_other
PE non-beverage bottles	bottles_other
PP non-beverage bottles	bottles_other
Misc. non-beverage bottles	bottles_other
PET thermoforms & rigids	rigids
PE thermoforms & rigids	rigids
PP thermoforms & rigids	rigids
PVC thermoforms & rigids	rigids
PS thermoforms & rigids	rigids
Carriage bags (PE) > A4	flexibles
Carriage bags (PE) < A4	flexibles
PET flexible packages > A4	flexibles
PET flexible packages < A4	flexibles
PE flexible packages > A4	flexibles
PE flexible packages < A4	flexibles

Packaging categories Brouwer et al (2019)	Allocation to our categories
PP flexible packages > A4	flexibles
PP flexible packages < A4	flexibles
PVC flexible packages > A4	flexibles
PVC flexible packages < A4	flexibles
PS flexible packages > A4	flexibles
PS flexible packages < A4	flexibles
Rigid packages made from non-NIR identifiable plastics	rigids
Flexible packages made from non-NIR identifiable plastics > A4	flexibles
Flexible packages made from non-NIR identifiable plastics < A4	flexibles
Misc. plastics (PC, PLA, etc.)	flexibles
Laminated flexible packages and blisters	flexibles
EPS trays	rigids
EPS blocks	rigids

Appendix B

Electricity mix in background scenarios

The CITS model uses the electricity mixes provided by integrated assessment models, in this case IMAGE, via the PREMISE framework (see chapter 2.2.2). In this report, the SSP2-Base mix shown below equals the “fossil” electricity mix, while the RCP19 mix equals “renewable”. Source: https://premisedash-6f5a0259c487.herokuapp.com/


Model: image | Scenario: SSP2-Base
Region=WEU
Exajoules (EJ)
0
5
10
15
2020
2040
2060
2080
210(
Year
Model: image | Scenario: SSP2-RCP19
Region=WEU
Exajoules (EJ)
0
5
10
15
2020
2040
2060
2080
210(
Year
Variables
Biomass CHP
Storage, Flow Battery
Wind Offshore
Coal CHP
Biomass CHP CCS
Nuclear
Solar PV Centralized
Gas CC
Oil CHP CCS
Gas CHP
Wind Onshore
Coal CHP CCS
Oil CC
Gas CC CCS
Solar CSP
Gas CHP CCS
Gas OC
Gas ST
Solar PV Residential
Oil CC CCS
Coal PC
Hydro
Oil CHP
Geothermal
Coal IGCC CCS
Biomass ST
Oil CC
Oil ST
Gas CHP
Gas OC
Geothermal
Nuclear
Biomass IGCC
Coal CHP
Solar PV Residential
Coal IGCC
Coal PC
Wind Offshore
Storage, Flow Battery
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