LCA summary report for Eastman methanolysis technology (North America)

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EXECUTIVE SUMMARY AND KEY TAKEAWAYS

Eastman's methanolysis technology is a type of material-to-material molecular recycling that enables a diverse variety of difficult-to-recycle waste polyesters to be unzipped (depolymerized) into their constituent monomers. Eastman commissioned Quantis to complete a cradle-to-gate life cycle assessment (LCA) to compare the environmental footprint of dimethyl terephthalate (DMT) monomer made by methanolysis to conventional Eastman DMT made from fossil-based raw materials. The study was critically reviewed by a panel of third-party, independent LCA experts from academia, research, and consultancy. It is confirmed to be in line with the requirements of ISO 14040 and 14044 LCA standards.

The key conclusions are as follows:

- **DMT from Eastman methanolysis technology has a 29% lower global warming potential than fossil-based DMT.**
- **DMT from methanolysis ranks significantly better than fossil-based DMT on 13 out of the 14 environmental impact indicators studied.**
- **By using waste plastic as a raw material instead of conventional fossil-based materials, Eastman's methanolysis technology can deliver benefits for both waste avoidance and the environment.**

BACKGROUND

Eastman, a global specialty materials company, is dedicated to building a circular economy that creates value from plastic waste. We are leading the way by advancing innovative recycling technologies and products, forging collaborations at local and global levels, and identifying solutions to lessen our environmental footprint. Our commitment to material circularity is grounded in the belief that plastic and textile waste can be not only eliminated but reinvented by a prescriptive, closed-loop process supported by companies, consumers, manufacturers, policymakers, and governments—working together to ensure a better world in which waste is reduced and materials are used, reused, recycled, and recreated over and over again.

Advancing material technologies and circular solutions are central to Eastman's commitment to deliver change now. Through Eastman's material-to-material molecular recycling technologies, including polyester renewal technology (PRT), we are creating value from waste. These technologies break down plastic waste into molecular building blocks and rebuild them into new materials—enabling circularity for materials that were previously destined to be discarded as waste. We are creating new products with recycled content that enable companies across industries and applications to meet their sustainability commitments. We are dedicated to reducing our own environmental impact as part of our commitment to create a sustainable future by delivering value from waste and, as a result, lessening our use of fossil-based resources.

INTRODUCTION

Eastman is leading the way by commercializing innovative material-to-material molecular recycling technologies and products to support the transition to a circular economy for plastics on the global scale. As part of our polyester renewal technology (PRT), Eastman is commercializing an advanced recycling process called methanolysis. Methanolysis uses a type of chemistry called depolymerization to break down polyester waste into its basic polymer building blocks. The depolymerization occurs by reacting polyester waste with methanol. Methanolysis is designed to process difficult-to-recycle waste polyester back into the constituent monomers, which Eastman uses downstream to produce a variety of specialty copolyester plastics. Eastman Kodak was a pioneer in the development of methanolysis technology with multiple patents and commercial-scale operation beginning in the mid-1970s with a capacity of more than 40,000 metric tons per year. The Eastman Kodak facility was operated until 2007. Eastman builds on this legacy, leveraging decades of expertise in methanolysis recycling technology.

In February 2021, Eastman announced a $250 million USD investment to a build a methanolysis plant at its Kingsport, Tennessee, location in the U.S. The plant will have an annual capacity of recycling more than 100,000 metric tons of waste polyester. Construction was started in March 2021 and is expected to be finished by the end of 2022. Methanolysis will be an impactful solution, as low-quality polyester waste that is typically diverted to landfills can instead be recycled into high-quality specialty polyesters suitable for use in a variety of end-use applications, many of which have extended time in use compared to single-serve packaging.

Methanolysis creates an opportunity to chemically recycle plastic waste streams that are typically not suitable for mechanical recycling and would be considered difficult-to-recycle items due to factors such as impurities and color. See Figure 1. Using pre- and post-consumer waste as feedstock to create new materials delivers a truly circular solution for these items that do not currently have a viable, large-scale recycling solution.

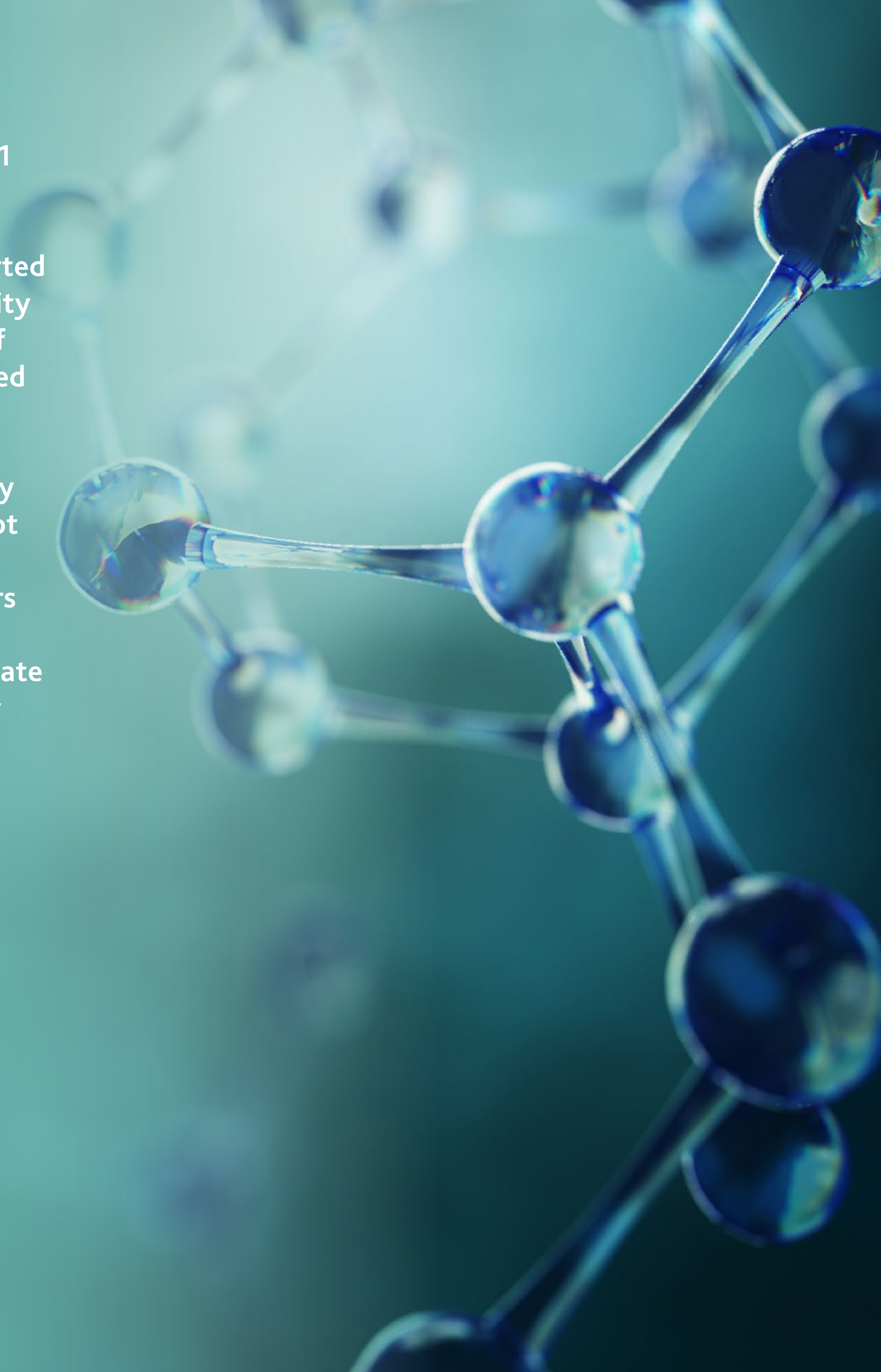
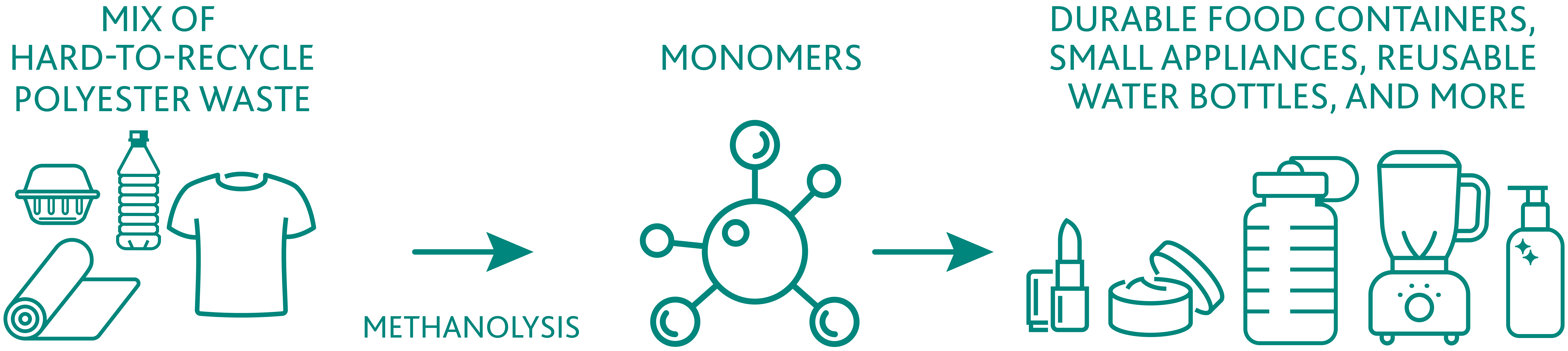


Figure 1. PRT general overview



MIX OF HARD-TO-RECYCLE POLYESTER WASTE

METHANOLYSIS

MONOMERS

DURABLE FOOD CONTAINERS, SMALL APPLIANCES, REUSABLE WATER BOTTLES, AND MORE

This cradle-to-gate study evaluates the global warming potential and other environmental indicators of Eastman's methanolysis technology in the production of virgin-quality dimethyl terephthalate (DMT) and ethylene glycol (EG) monomers from a variety of waste polyethylene terephthalate sources. Since the methanolysis process produces both recycled DMT (rDMT[1]) and rEG as coproducts, it is necessary to address this multifunctionality in the LCA. According to the methodology guidelines in ISO 14044, it is most preferable to avoid allocation if possible. DMT is a specialty material and EG is a commodity. Allocation was avoided in this study by using an LCA approach called "system expansion," which enables the LCA to focus exclusively on the production of rDMT by subtracting out the avoided production of EG coproduct from conventional commodity sources outside of the methanolysis system boundary. The methanolysis results for rDMT are compared against conventional DMT made with paraxylene raw material sourced from fossil fuels.

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[1] The letter "r" is added as a prefix to denote recycled "rDMT" and "rEG" as being DMT and EG produced through methanolysis, while reference to DMT and EG without the "r" prefix implies conventional material produced from virgin raw materials.

Eastman is focused on sourcing waste polyesters that complement mechanical recycling rather than compete against it.

Eastman's methanolysis operations will source waste polyester materials from a variety of pre- and post-consumer origins that would otherwise be landfilled or downcycled.

The planned feedstock mix for methanolysis includes:

- Procurement of existing waste PET streams such as green pallet strapping, fines and dust from recyclers, and colored waste from reclaimer reject streams
- Partnering to provide outlets for difficult-to-recycle PET waste such as carpet, films, rejects, and other proprietary streams
- Scaling up new streams such as mixed and colored PET not fit for mechanical recycling and PET sourced from ocean-bound plastics. This includes items such as thermoforms and colored nonbeverage packaging.

SCOPE

Study goals

- Carry out an ISO 14040/14044 conformant cradle-to-gate LCA of rDMT produced from polyester waste via Eastman's methanolysis facility in Kingsport, Tennessee, U.S.A.

- Compare the environmental impacts of rDMT via methanolysis with conventional DMT produced by Eastman from fossil-based paraxylene in Kingsport, Tennessee, U.S.A.

- Establish a life cycle inventory (LCI) for rDMT made from Eastman methanolysis to use as a basis for developing downstream LCA studies of copolyester products that are produced by Eastman using rDMT material

- Communicate the potential environmental performance and capabilities of methanolysis technology to Eastman's stakeholders

- Explore contributions, scenarios, and uncertainties

The target audience for this study is internal and external stakeholders with interest in molecular recycling of plastics, the circular economy, and the products that Eastman manufactures based on molecular recycling.

Functional unit

The subject of analysis is the Eastman methanolysis process for rDMT production with the environmental footprint of conventional Eastman DMT used as benchmark. Conventional DMT is produced at Eastman from paraxylene.

The functional unit of the study is the production of one metric ton (tonne) of rDMT or DMT meeting Eastman's internal specifications for usage as an intermediate for downstream production of copolyesters and other specialty products at Eastman's site in Kingsport, Tennessee. Coproduced ethylene glycol (rEG) is treated using system expansion via substitution. Both rEG and rDMT are suitable for use as copolyester intermediates. rDMT is chemically identical to and produced to equivalent internal quality specifications as Eastman DMT from fossil-based paraxylene for the purposes of copolyester production. Eastman DMT was chosen as the reference because of the availability of high-fidelity primary data for comparison.

System boundary

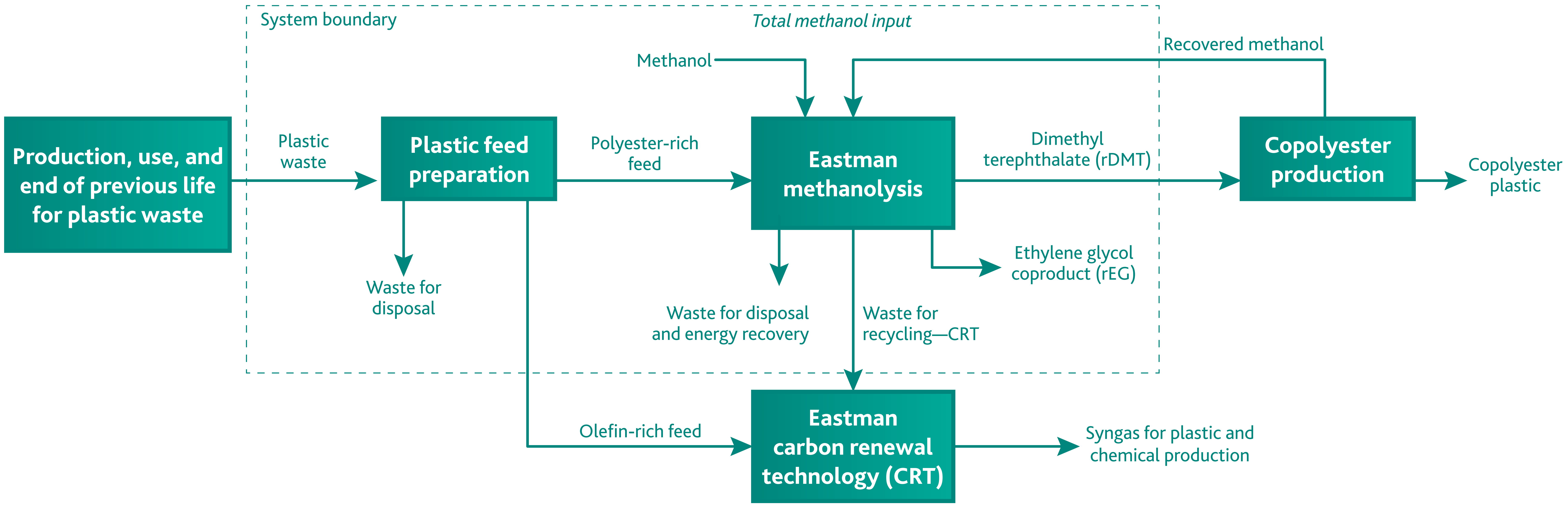
The scope of the study is cradle to gate. The cradle begins at raw material extraction; see Figure 2. In the case of plastic waste feeds, the cradle begins at the end of the previous life of the material when it is deemed to be waste. The "gate" is internal to Eastman at the point where rDMT and rEG (intermediates) are manufactured. This aligns with the scope of comparison of rDMT to conventional DMT.

Eastman's production of conventional DMT is used as a benchmark for comparison. The LCA of Eastman's conventional DMT is based on a 2016 internal study using Eastman's actual manufacturing data. Conventional EG purchased from the U.S. market according to Eastman's use specifications is assumed in coproduct substitution.

The reference year of the methanolysis study is the 2020 engineering design with the expected feedstock mix on start-up in 2023. The reference geography is North America. Eastman's methanolysis plant will be located in Kingsport, Tennessee, U.S.A.

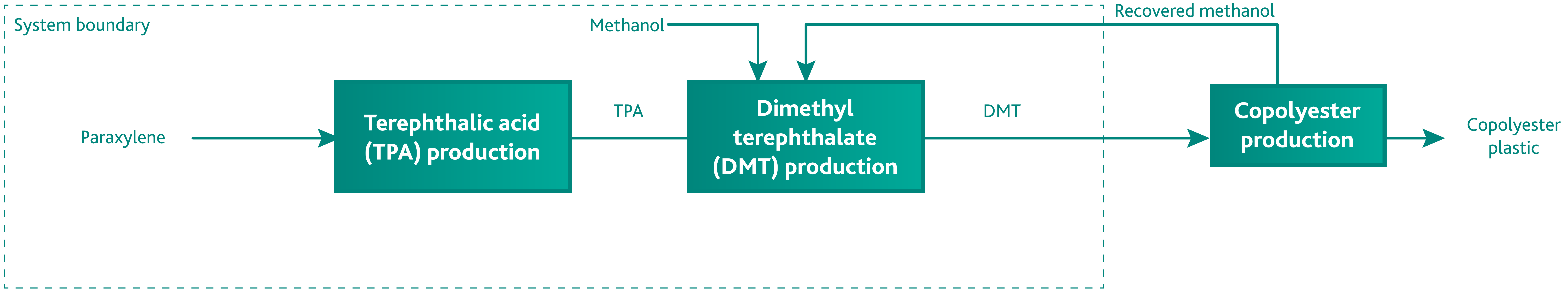
Figure 2. Overview of system boundaries

Eastman methanolysis system



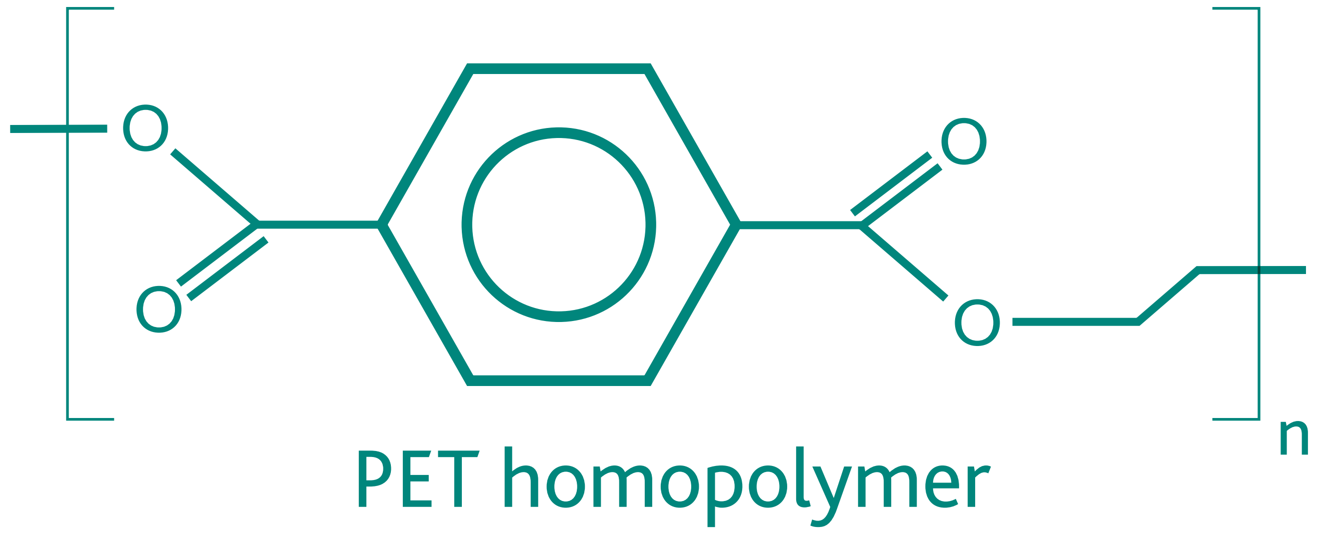
Note: Figure shows a simplification of the methanolysis system and its mass flows to produce rDMT and rEG based on the planned feedstock mix for 2023.

Comparative system: conventional DMT production at Eastman



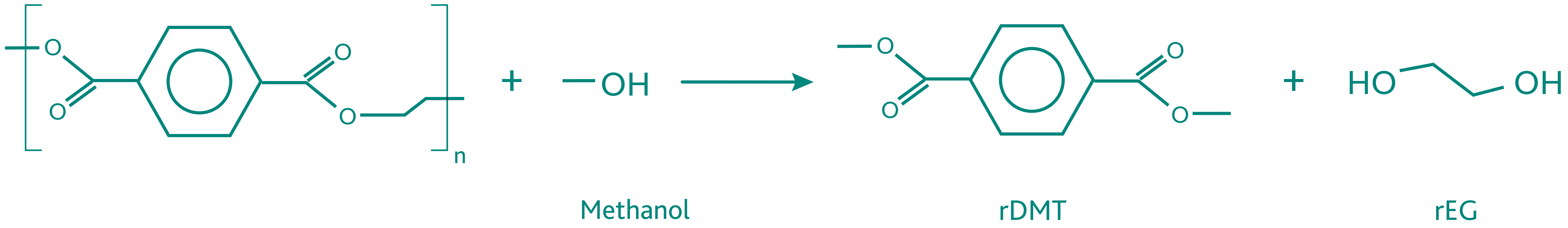
The methanolysis facility produces rDMT and ethylene glycol (rEG) containing recycled content from pre- and post-consumer polyethylene terephthalate (PET) plastic waste. See Figure 3.

Figure 3. Chemical structure of polyethylene terephthalate (PET)



In the presence of methanol and catalyst at elevated temperatures and pressures, PET polymer depolymerizes to form rDMT and rEG as shown in Figure 4. This is the main methanolysis reaction.

Figure 4. Reaction of PET and methanol forming rDMT and rEG



LIFE CYCLE INVENTORY

Data and calculations

GaBi v.9.2.1.68 software was used to develop the life cycle inventory (LCI) and impact assessment modeling. Eastman used a combination of data sets within GaBi and internally developed life cycle analysis (LCA) models to create the GaBi models for methanolysis. External data sources were ecoinvent 3.0, GaBi professional database, and USLCI.

The inventory flows for methanolysis are based on the final engineering design, equipment specifications, and environmental permits for the plant currently under construction and are based on the planned waste polyester feedstock mix and rDMT production quantities for year 2023. The sources of inventory data consist of primary data from Eastman whenever possible (such as for energy, utility systems, and conventional DMT production) and are supplemented by data sets available in GaBi software when needed. Data quality is assessed with a pedigree matrix. U.S. rail and truck transportation data are from USLCI/GaBi. Energy consumption within Eastman's gates is based on Eastman's primary data for internal power generation systems.

The following processes are excluded from the scope due to expected contributions below the cutoff criteria: construction and installation of equipment, packaging systems, labor, worker commuting, and administrative systems.

Allocation principles

1. Coproducts

rDMT and rEG are coproduced in the same process. The Life Cycle Metrics for Chemical Products[1] guidance decision tree (section 5.2.1.2), indicates that system expansion should be used. Therefore, credit is given to the footprint of rDMT for avoided production of fossil-based EG.

2. Recycled material cutoff approach

No burden or benefit from the first life of the material is included in the scope of this LCA. The cutoff method is applied. The beginning of life for waste polyester is determined from the point that the polyester becomes waste. In the absence of Eastman's polyester renewal (methanolysis) technology, the waste polyester would be discarded and sent to either landfill, incineration, or other disposal. The waste polyester material is not assumed to have any life cycle burden at the point it becomes "waste." The polyester material accrues burden for processing steps and transportation necessary to deliver the material to Kingsport in a form that can be handled by the methanolysis facility.

3. Comparability assumptions

The LCA for the conventional pathway to fossil-based DMT uses both a cutoff rule to exclude negligible flows of 0.5% by mass and a substitution method for coproduct allocation between energy and material flows from the process. This study uses the same assumptions and allocation framework to ensure comparability between systems.

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[1] *Life Cycle Metrics for Chemical Products. WBCSD Chemicals. 2014.* *https://www.wbcsd.org/Projects/Chemicals/Resources/Life-Cycle-Metrics-for-Chemical-Products*

LIFE CYCLE IMPACT ASSESSMENT

The impact assessment phase of an LCA is aimed at evaluating the magnitude and significance of potential environmental impacts across various categories. The impact assessment methodology used in this study is the Environmental Footprint (EF) method that was developed by the European Commission. It is a state-of-the-art method which is relevant to many of Eastman's stakeholders. Quantis used the EF 3.0 method as implemented in GaBi software.

The EF method assesses 16 different potential impact categories, of which 14 were assessed in this study. Land use and ionizing radiation impacts were excluded due to low relevance and lack of data. The methodology and its impact categories are further described in Appendix 1.

Table 1. Environmental footprint indicators for rDMT via methanolysis

Impact category	Unit per metric ton rDMT	rDMT via methanolysis
Climate change	kg CO_2 eq	1490
Acidification	mol H^+ eq	0.7
Eutrophication, freshwater	kg P eq	–4.2E-04
Eutrophication, marine	kg N eq	0.46
Eutrophication, terrestrial	mol N eq	5.0
Human toxicity, cancer	CTUh	5.1E-07
Human toxicity, noncancer	CTUh	3.2E-06
Freshwater ecotoxicity	CTUe	–1650
Ozone depletion	kg CFC-11 eq	6.4E-10
Particulate matter	Disease incidences	2.2E-05
Photochemical ozone formation	kg NMVOC eq	1.6
Resource depletion, minerals, and metals	kg Sb eq	5.0E-04
Resource depletion, fossils	MJ	14400
Water scarcity	m^3 water-deprived eq	–109

The European Joint Research Centre classifies each impact category according to the maturity and robustness of its underlying models:[1]

- **Level I: Recommended and satisfactory**
- **Level II: In need of some improvements**
- **Level III: To be applied with caution**

These levels should be considered when interpreting the results.

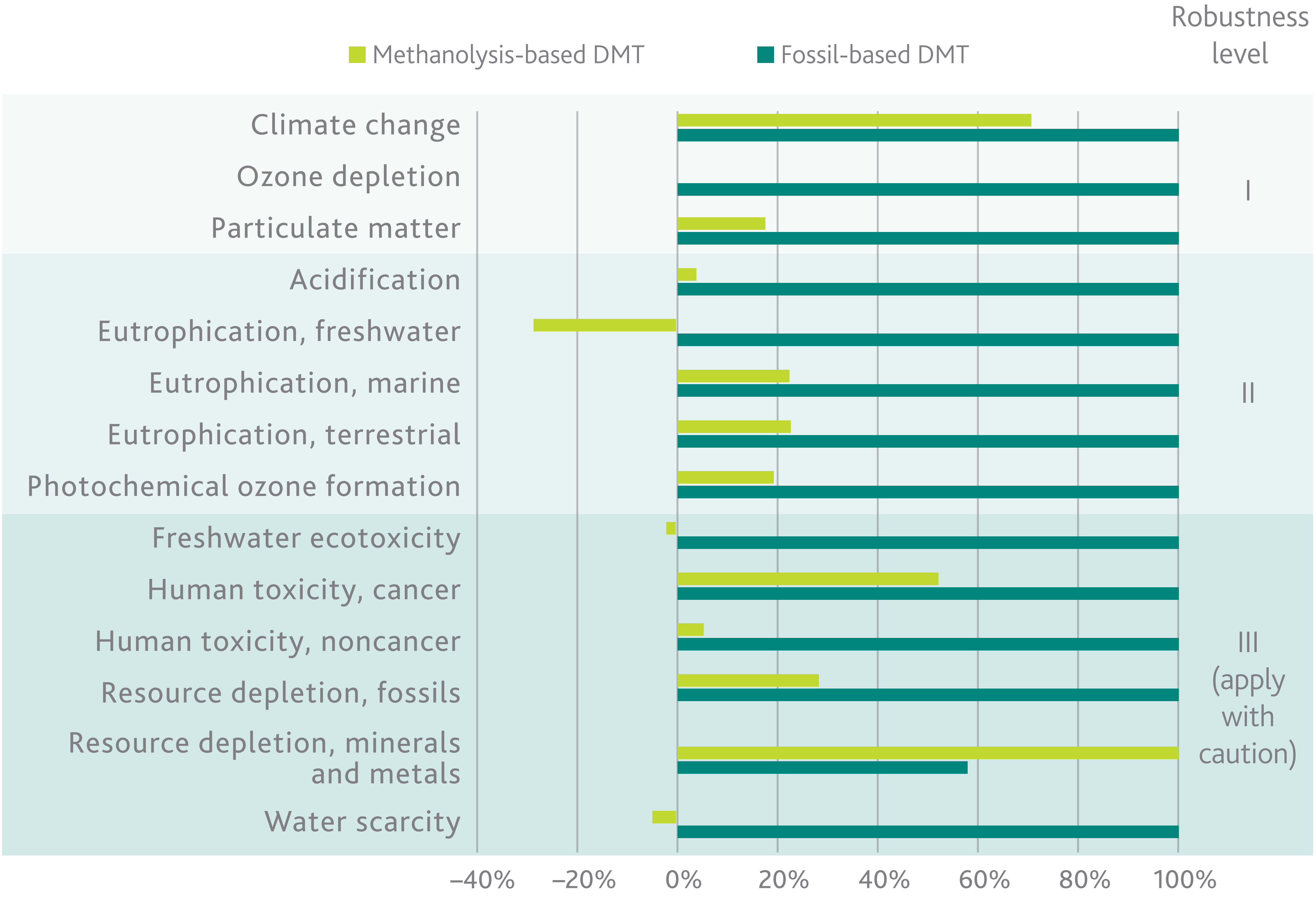
The impact assessment results for rDMT are shown in Table 1 and the relative comparison to conventional Eastman DMT is shown in Figure 5.

rDMT from methanolysis has significantly lower impacts than conventional DMT in 13 out of the 14 impact categories studied. The climate change impact for rDMT is 29% lower.

Resource depletion of minerals and metals is the one category in rDMT scores a higher impact; however, the significance of this result is limited because the methodology has a Level 3 (low) robustness and there are no relevant amounts of mineral or metals used in the production of rDMT or DMT. Three of the impact categories have a net negative comparison due to system expansion for EG coproduct.

For assessing human and eco system toxicity impacts in an LCA, the methodologies recommended by the Environmental Footprint Method are not yet fully developed and produce highly uncertain results, which is why they're classified as robustness level III (vs. Level II or Level I). The human health and eco toxicity indicators are based on the USEtox consensus model, which is a starting point for further scientific development. These models estimate the transport and fate of emissions and their exposure to people or aquatic organisms using a generalized framework which summarizes the results in terms of cumulative toxicity units. But the methodology has significant gaps, including lack of data and characterization factors for substances, data quality issues and lack of regionalization, all resulting in high uncertainty. USEtox is attempting to integrate the impact of toxic emissions into an LCA as a complement to other, better-proven tools, such as risk assessment, environmental impact assessment, and health and safety regulations for product level, workplace, and local environments. USEtox is not intended to predict any specific impacts to human or ecological health, such as cases of cancer. For more information about the USEtox model and reported limitations, please see peer reviewed articles and studies here and here.

Figure 5. Relative life cycle impact assessment of DMT made by methanolysis compared to conventional



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[1] *European Commission (2017). PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.*

CONCLUSION AND INTERPRETATION

The most important conclusion of this study is that rDMT from Eastman methanolysis technology has a substantially lower environmental footprint than fossil-based DMT. Using the system expansion method and substituting for avoided EG production, rDMT has a carbon footprint that is 29% lower than conventional fossil-based DMT. rDMT from methanolysis ranks better than fossil-based DMT on 13 out of 14 EF impact indicators considered. The relevance of outlying 14th impact category result is questionable due to low robustness of the impact assessment methodology.

By using waste plastic as a raw material instead of conventional fossil-based materials, Eastman's methanolysis technology can deliver benefits for both waste avoidance and environmental impacts. The methanolysis footprint advantage does not include any additional credit for avoided waste treatment of the waste plastic feedstocks.

CRITICAL REVIEW

A critical review of the full confidential report was performed by an independent panel of experts and a final review statement was issued on January 5, 2022. The review panel confirmed that the study followed the guidelines and is consistent with the international standards for LCA (ISO 14040:2006 and 14044:2006). The critical review statement is provided in Appendix 2.

SCENARIO AND SENSITIVITY ANALYSES

Various scenarios were analyzed to evaluate the potential effects on the results and conclusions of the study.

These included the following:

1. Influence of coproduct allocation, including mass allocation, economic allocation, and alternate data sets for EG system expansion
2. Feedstock mix changes, including future use of a higher percentage of materials such as thermoforms and nonfood packaging
3. Decarbonized electricity
4. Avoided disposal. The system boundary and functional unit were expanded to include the avoided disposal of the methanolysis waste plastic feedstock via landfill and incineration (with and without energy recovery).
5. Alternate disposition of residual methanolysis waste

None of the assessed scenarios change the conclusion of the study that rDMT produced with methanolysis has lower overall environmental impacts as compared to conventional DMT.

Avoided disposal of the waste plastic feedstock was the most sensitive scenario. The base case of the study did not include any credit for avoided disposal. The scenarios for including such credits reveal that avoided landfill results in 6% further improvement for rDMT in climate change and larger improvements in other categories. Avoidance of incineration without energy recovery results in a net negative climate change impact for rDMT of –1130 kg CO_2 eq per tonne. Avoidance of incineration with energy recovery results in a near-zero net climate change impact for rDMT. A nonintuitive result for the incineration with energy recovery scenario is that the other 13 impact categories (beyond climate change) show an increased impact compared to the rDMT base case. However, the incineration with energy recovery scenario does remain advantaged compared to conventional DMT in every impact category except for resource depletion of minerals and metals.

APPENDIX 1: OVERVIEW OF LIFE CYCLE IMPACT ASSESSMENT USING EF METHODOLOGY

Life cycle assessment (LCA) is a systematic approach to assess the environmental aspects and potential impacts of product systems. ISO 14040:2006 defines four key stages of an LCA:

1. Goal and scope definition
2. Life cycle inventory (LCI) analysis
3. Life cycle impact assessment (LCIA)
4. Interpretation

LCI involves a compilation of the flows of energy, emissions, and materials between the product system and the environment throughout the life cycle scope. The LCIA accounts for how LCI flows contribute to various environmental impact categories according to standard impact assessment methodologies. The LCIA is intended to provide a multi-criteria perspective of environmental and resources issues.

Life cycle impact assessment results present potential and not actual environmental impacts. They are relative expressions which are not intended to predict the final impact or risk on the natural media or whether standards or safety margins are exceeded. Additionally, these categories do not cover all the environmental impacts associated with human activities.

EF methodology

Different LCIA methods are available. The method used in the methanolysis study is the Environmental Footprint (EF) method version 3.0 (European Commission 2017).[1] It is the result of a European Commission program that analyzed several life cycle impact assessment (LCIA) methodologies to reach consensus on the best state-of-the-art impact assessment science. It is the official method to be used in the Product Environmental Footprint (PEF) context of the Single Market for Green Products (SMGP) initiative (European Commission 2013) and is relevant to many of Eastman's stakeholders.

The EF method specifies standard methodologies for modeling potential impacts across a defined set of environmental impact assessment categories. The results of the EF LCIA are midpoint scores for each impact category. The score in each impact category is set to a common basis. For example, the climate change impact potential is calculated by using global warming potential (GWP) characterization factors for all greenhouse gas emissions and expressing the results on the basis of kilograms of carbon dioxide equivalents emitted to the atmosphere.

The EF method assesses 16 impact categories; however, only 14 of them were evaluated in this study. Land-use change and ionizing radiation were excluded due to low relevance for methanolysis and lack of data.

Climate change

Indicator of potential global warming impacts due to emissions of greenhouse gases (GHGs) to the atmosphere. GWP accounts for radiative forcing caused by GHG emissions such as carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O). The capacity of a GHG to influence radiative forcing is expressed in kilograms of carbon dioxide equivalents and considers a time horizon of 100 years following the guidelines from the Intergovernmental Panel on Climate Change (IPCC 2013).

Model: Bern—global warming potentials (GWP) over a 100-year time horizon (IPCC 2013)

Unit: kg CO_2*-eq*

Acidification

Indicator of the potential acidification of soils and water (i.e., acid rain) due to emissions of gases such as sulfur oxides and nitrogen oxides. Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems, and the built environment. The impact metric is expressed in mole H+-eq (hydrogen ions to soil and water equivalents).

Model: Accumulated Exceedance model (Seppälä et al. 2006; Posch et al. 2008)

Unit: mol H+ -eq

Freshwater eutrophication

Indicator of potential degradation of freshwater aquatic ecosystems due to excessive enrichment of nutrients such as phosphorus materials. The impact metric is expressed in kilograms of phosphorous equivalents.

Model: EUTREND (Struijs et al. 2009)

Unit: kg P-eq

Marine eutrophication

Impact category that addresses impacts from nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilized farmland which accelerate the growth of algae and other vegetation in marine water. The degradation of organic material consumes oxygen, resulting in oxygen deficiency. The impact metric is expressed in kilograms of nitrogen equivalents.

Model: EUTREND (Struijs et al. 2009)

Unit: kg N-eq

Terrestrial eutrophication

Impact category that addresses impacts from nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilized farmland which accelerate the growth of vegetation in soil. The degradation of organic material consumes oxygen, resulting in oxygen deficiency. The impact metric is expressed in moles of nitrogen equivalents.

Model: Accumulated exceedance model (Seppälä et al.2006; Posch et al. 2008)

Unit: mol N-eq

Human toxicity, noncancer effects

Impact category that accounts for the potential adverse health effects on humans caused by the intake of toxic substances through inhalation of air, food/water ingestion, and penetration through the skin insofar as they are related to noncancer effects that are not caused by particulate matter or ionizing radiation. The impact metric is expressed in CTUh (comparative toxic units for humans in terms of cases).

Model: USEtox® (Rosenbaum et al. 2008)

Unit: CTUh

Human toxicity, cancer effects

Impact category that accounts for the potential adverse health effects on humans caused by the intake of toxic substances through inhalation of air, food/water ingestion, and penetration through the skin insofar as they are related to cancer. The impact metric is expressed in CTUh (comparative toxic units for humans in terms of cases).

Model: USEtox® (Rosenbaum et al. 2008)

Unit: CTUh

Freshwater ecotoxicity

Impact category that addresses the potential toxic impacts on freshwater ecosystems. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem. The impact metric is expressed in CTUe (comparative toxic unit for ecosystems in terms of the estimated potentially affected fraction (PAF) of species integrated over volume and time, i.e., PAF*m^3*y).

Model: USEtox® (Rosenbaum et al. 2008)

Unit: CTUe

Ozone depletion

Impact category that accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substances; for example, long-lived chlorine and bromine-containing gases (e.g., CFCs, HCFCs, and halons). The emission factors are calculated using ozone depletion potentials (ODP) reported by the World Meteorological Organization (WMO). The ODP is a relative measure for the potency of a substance to destroy the ozone layer. Stratospheric ozone filters out most of the sun's potentially harmful shortwave ultraviolet (UV) radiation. When this ozone becomes depleted, more UV rays reach the earth. Exposure to higher amounts of UV radiation can cause damage to human health.

Model: EDIP based on the ODPs of the WMO with infinite time horizon (WMO 1999)

Unit: kg CFC-11 eq

Particulate matter

Impact category that accounts for the potential impact on human health caused by emissions of particulate matter (PM) smaller than 2.5 micrometers and its precursors (NO_x, SO_x, NH_3) into the air.

Model: PM method recommended by UNEP (UNEP 2016)

Unit: disease incidence

Photochemical ozone formation

Impact category that accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) and sunlight. High concentrations of ground-level tropospheric ozone can damage vegetation, human respiratory tracts, and man-made materials. The impact metric is expressed in kilograms of nonmethane volatile organic carbon equivalents (NMVOC).

Model: LOTOS-EUROS (van Zelm et al., 2008)

Unit: kg NMVOC-eq

Resource use, minerals and metals

Indicator of the depletion of natural, nonrenewable resources such as rare minerals and metals. A characterization factor is determined for each type of material based on total reserves and extraction rate, and it is normalized to common basis relative to scarcity of antimony metal. The unit is kilograms of antimony equivalents.

Model: CML 2002 (Guinée et al., 2002 and van Oers et al. 2002)

Unit: kg Sb eq

Resource use, fossils

Indicator of the depletion of natural, nonrenewable fossil fuel resources such as crude oil, coal, and natural gas. This impact indicator accounts for extraction of fossil materials for use as both fuels and feedstocks. Characterization factors are determined for each type of fossil resource based on its extraction rate and the ultimate reserves in the earth. The unit is megajoules (MJ) of energy.

Model: CML 2002 (Guinée et al., 2002 and van Oers et al. 2002)

Unit: MJ

Water scarcity footprint

This impact indicator assesses the potential of water deprivation. It builds on the assumption that the less water remaining available per area, the more likely another user will be deprived. It is based on the AWARE 100 model, the recommended method from WULCA for water consumption impact assessment in LCA.

Model: AWARE 100 (Boulay et al., 2016)

Unit: m^3 *world eq*

Interpretation of human toxicity and ecotoxicity indicators

Eastman is serious about risk assessment and the safe manufacturing and use of its products through key initiatives such as Responsible Care and REACH, in addition to complying with all existing regulations on human toxicity and ecotoxicity. Assessing toxicity impact through LCA methodologies is a less developed science. Special caution is needed when interpreting LCIA results for human and ecotoxicity. Compared with impact categories such as GWP and AP, the assessment of toxicity in LCA is more challenging and can be highly uncertain due to data gaps and methodological limitations. Literature demonstrates significant discrepancies between methodologies (Rashid and Liu, 2021).[2] Some LCIA toxicity factors have been shown to vary over eight orders of magnitude.[3] Toxicity indicators are included in this study for the sake of completeness and relevance. Life cycle impact assessment of human and ecotoxicity is based on modeling and does not involve any actual testing on people or animals.

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[1] *Sala, et al. Suggestions for the update of the Environmental Footprint Life Cycle Impact Assessment. Impacts due to resource use, water use, land use, and particulate matter, EUR 28636 EN, Publications Office of the European Union, Luxembourg, 2019, JRC106939.*

[2] *Siti Safirah Rashid, Yong-Qiang Liu. Comparison of life cycle toxicity assessment methods for municipal wastewater treatment with the inclusion of direct emissions of metals, PPCPs and EDCs. The Science of the total environment, 756, 143849.*

[3] *Henderson, A.D., Hauschild, M.Z., van de Meent, D., Huijbregts, M.A., Larsen, H.F., Margni, M., McKone, T.E., Payet, J., Rosenbaum, R.K. and Jolliet, O., 2011. USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. The International Journal of Life Cycle Assessment, 16(8), pp.701-709.*

APPENDIX 2: CRITICAL REVIEW STATEMENT FOR THE STUDY "LIFE CYCLE ASSESSMENT OF METHANOLYSIS"

Background

The life cycle assessment (LCA) study “Life Cycle Assessment of Methanolysis” was commissioned by Eastman and carried out by Quantis. The study was critically reviewed by a critical review panel (CRP) comprised of:

- Adisa Azapagic (Chair), ETHOS Research, U.K.
- Simon Hann, Eunomia Research & Consulting Ltd., U.K.
- Matthias Stratmann, nova-Institute GmbH, Germany

All members of the CRP were independent of any party with a commercial interest in the study.

The aim of the review was to ensure that:

- The methods used to carry out the LCA study are consistent with the ISO 14040:2006 and 14044:2006 standards
- The methods used are scientifically and technically valid given the goal of the study, and the data used are appropriate and reasonable in relation to the goal of the study
- The interpretation of the results and the conclusions of the study reflect the goal and the findings of the study
- The study report is transparent and consistent

Critical review process

The critical review process involved the following:

- A review of the goal and scope definition at the outset of the project
- A review of three versions of draft reports according to the established criteria and recommendations for improvements to the study and the report
- A review of the fourth and final version of the report, in which the authors of the study fully addressed the comments of the CRP

The CRP did not review the LCA models developed by Quantis, and hence all the findings of the critical review are based solely on the LCA report provided to the CRP during the course of the critical review. Furthermore, due to confidentiality, the CRP did not have access to the LCA study on conventional dimethyl terephthalate (DMT) carried out by Eastman and used as a benchmark for comparison with rDMT in the present LCA study. Instead, a high-level summary related to the equivalency of the two systems was provided in the current LCA report. It should also be noted that the conventional DMT study was not subject to an external critical review process but was instead critically reviewed by Eastman.

Conclusion of the critical review

The CRP confirms that this LCA study followed the guidance of and is consistent with the international standards for life cycle assessment (ISO 14040:2006 and 14044:2006), as follows:

- The methods used are scientifically and technically valid given the goal of the study
- The data used are appropriate and reasonable in relation to the goal of the study
- The interpretation of the results and the conclusions of the study reflect the goal and the findings of the study
- The study report is transparent and consistent

This critical review statement is only valid for the final LCA report as presented to the CRP.

Communication of the study results

The following aspects should be mentioned when communicating the results of the study to external stakeholders:

- Any communication of the outcomes of the study must mention that the results are specific to the methanolysis system and related activities at Eastman and cannot be generalized beyond that.
- It is also important to communicate clearly that the study is based on process design data rather than an existing plant.
- Some of the assumptions affect the results, interpretation, and conclusions of the study. Therefore, it is important that these and their influence on the results and conclusions are described transparently whenever the study or its parts are disclosed to any stakeholders to avoid any potential misinterpretation of the study.
- Whenever a reference is made to the review of the study and its outcome, it should be mentioned that the critical review statement is available in the full report and the statement will be provided on request.

Recommendation

To reduce the uncertainty and increase the robustness of the study, once the rDMT plant is in operation, it is recommended that the current LCA study, based on process design data, be updated and critically reviewed again.

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