CHEMISTRY THAT MATTERS™

CERTIFIED CIRCULAR POLYMERS VIA ADVANCED RECYCLING OF MIXED PLASTIC WASTE

LIFE CYCLE ASSESSMENT (LCA) STUDY SUMMARY

MARCH 2021

SABIC'S TRUCIRCLE™ PROGRAM – COMPLEMENTARY SOLUTIONS

PORTFOLIO

MECHANICALLY RECYCLED PRODUCTS

Compounds with high recycled content and booster resins for recyclate containing compounds that can improve processability and end-use properties

Maximize value for waste

CERTIFIED CIRCULAR PRODUCTS

Virgin resins and chemicals from difficult-to-recycle used plastics produced through advanced recycling

Scope of current LCA study

Reduce use of fossil fuels

CERTIFIED RENEWABLE PRODUCTS

Resins and chemicals from bio-based feedstock that are not in direct competition with the human food chain and that can help mitigate potential effects of climate change

SERVICES

DESIGN FOR RECYCLABILITY

Tailored resins for the development of products that have improved recyclability characteristics

CLOSED LOOP INITIATIVES

Value chain collaborations to recycle plastic back into high quality applications and help prevent valuable used plastics from becoming waste

Advanced recycling based on pyrolysis of plastic waste is one of the key product solutions of SABIC's TRUCIRCLE™ program. The LCA study focuses on this solution.

LIFE CYCLE ASSESSMENT STUDY: 4 KEY ASPECTS

FROM LINEAR TO CIRCULAR

1 This study aims at substantiating the environmental performance of SABIC's polyolefins produced from the advanced recycling of mixed plastic waste via pyrolysis route in comparison to production of the same polymers via fossil route.

2 This study has a comparative context but may be best-described as an assessment of "own product improvement", as the project assesses the sustainability aspects of substitution of fossil feedstocks in SABIC crackers with feedstocks produced via advanced recycling.

3 In the scope of this study, advanced recycling involves thermal pyrolysis of plastic waste streams and their subsequent hydrotreating to produce naphtha-equivalent feedstocks for steam cracking, which in turn can be used to produce chemicals and polyolefins.

4 The advanced recycling route to polyolefins has a smaller overall carbon footprint. SABIC's certified circular polymers have the potential to save approximately 2kg of CO_2 emissions for every kg of advanced recycled polyolefins. This study has undergone ISO Critical review by external LCA and domain experts.

GOAL AND SCOPE CONSIDERATIONS

Mixed plastic waste
as feedstock
for production of
polymers

STUDY GOAL:

- To assess the environmental performance of circular polyolefins produced via advanced (chemical) recycling in Europe via pyrolysis of mixed plastic waste streams, for use in Europe markets. This is compared to the environmental performance of the incumbent polyolefin products produced via fossil route.
- To identify hotspots of the product life cycle
- Providing transparent product sustainability information to customers
- Shape further strategy in product and technology development towards improved circularity and other sustainability attributes.

Fossil derived naphtha
as feedstock
for production of
polymers

If mixed plastic waste was diverted away from energy recovery,
what are the consequences at system level

Functional unit: Since the products are assessed at resin production and product disposal level but from a generic context, specifying functionality of the product for use in a generic application is not relevant. Hence we assume here a generic function of delivering 1 kg of polyolefin to the markets in Europe for use in varied applications. The reference flow for assessment of impacts for all of the above products are 1 kilogram of resin (100% wt. basis without additives or fillers).

GOAL AND SCOPE CONSIDERATIONS

Scope 1: Direct impacts from product life cycle

Advanced recycling route vs. fossil route for production of polymers

- (a) Cradle to Gate impacts of production of polyolefins via advanced recycling route
- (b) Cradle to Gate + End of Life (EOL) impacts of production of polyolefins via advanced recycling route
- Products of interest:
  HDPE (High density polyethylene)
  LDPE (Low density polyethylene)
  LLDPE (Linear Low density polyethylene)
  PP (Polypropylene)

Scope 2: Indirect impacts and consequences of plastic waste diversion

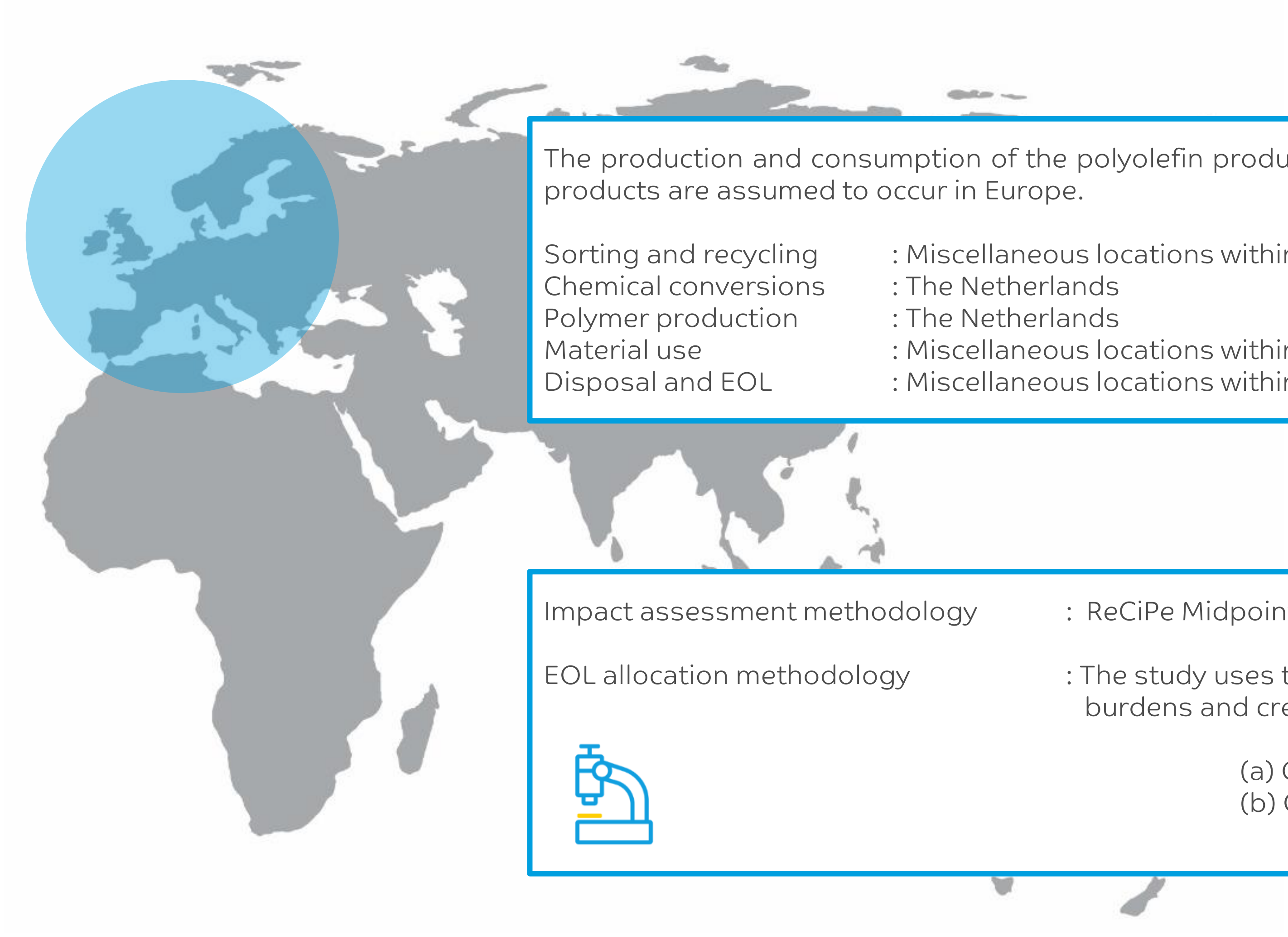
Diversion of mixed plastic waste to advanced recycling in comparison to incineration (with energy recovery)*

- (a) Cradle to Gate impacts of production of polyolefins via advanced recycling route including system expansion to assess the impacts of diverted mixed plastic waste (from energy recovery)
- (b) Cradle to Gate + EOL impacts of production of polyolefins via advanced recycling route including system expansion to assess the impacts of diverted mixed plastic waste (from energy recovery)
- Products of interest:
  HDPE
  LDPE
  LLDPE
  PP

* In this case, the additional emissions and burdens linked to the compensation for lost heat and power from energy recovery are included and are assumed to be sourced from natural gas and average EU electricity grid mix respectively.

Exclusions: The following system components of the various polymer product systems are expected to be comparable across both alternatives and hence are omitted from the assessment to ensure its generic applicability: 1. Processing of polymer resin into finished products such as pipes, films, bottles, etc. 2. Fabrication of polymer parts into final products 3. Use of the polymer product 4. All logistics (transportation and storage) that are incurred during and in between the above phases of the life cycle.

GEOGRAPHICAL AND METHODOLOGICAL CONSIDERATIONS



The production and consumption of the polyolefin products as well as recycling and disposal of End of Life (EOL) plastic products are assumed to occur in Europe.

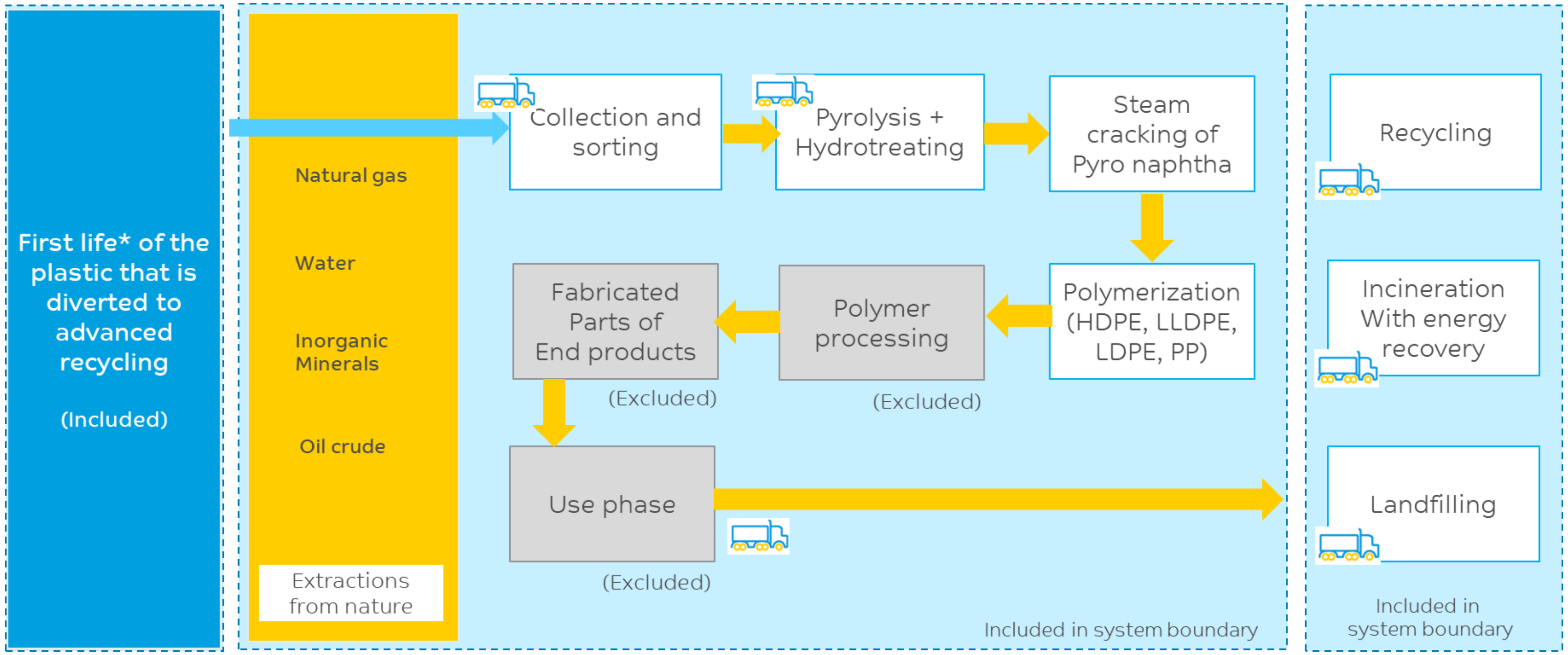
Sorting and recycling	: Miscellaneous locations within Europe
Chemical conversions	: The Netherlands
Polymer production	: The Netherlands
Material use	: Miscellaneous locations within Europe
Disposal and EOL	: Miscellaneous locations within Europe

Impact assessment methodology : ReCiPe Midpoint (H) V1.13 / Europe Recipe H

EOL allocation methodology : The study uses two different EOL allocation approaches to allocate burdens and credits between two lives of the material.

(a) CFF – Circularity Footprint Formula
(b) Cut-off EOL allocation

SYSTEM BOUNDARY – CRADLE TO GATE + EOL FOR ADVANCED RECYCLING ROUTE



What are the various components of the life cycle?

* First life here refers to the burdens of the previous life of the mixed plastic waste

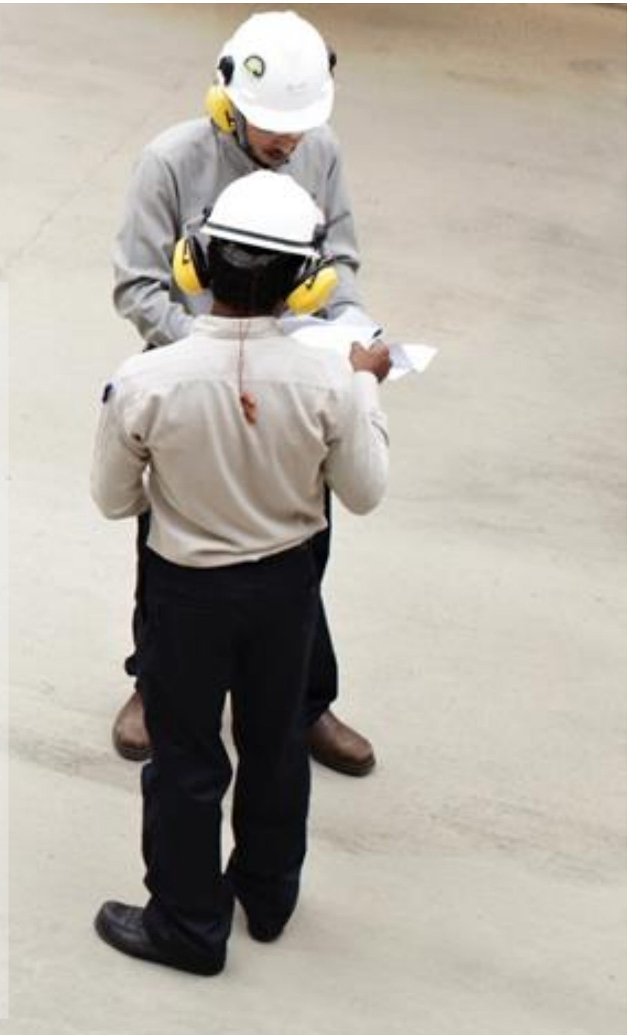
DATA SOURCES, QUALITY, CHOICES AND ASSUMPTIONS

- Data sources: The study uses a combination of internal and confidential data sources for new process route such as pyrolysis and hydrotreating, data mostly based on PlasticsEurope Eco-profiles for other common process steps such as polymerization, cracking along with internal data, publicly available inventory for sorting and recycling from key external works (e.g. Franklin Associates 2018). Background datasets were mostly based on the most updated Ecoinvent datasets (version 3.5 in most cases).

- The study assumes that pyrolysis uses mixed plastic waste of low quality as feedstock to the process. Typically, these mixed plastic waste streams are a liability to the sorting facilities and hence have to be disposed of to an incineration facility or to a landfill. In current scenario and in consideration of future aspirations of various EU member states, landfilling of mixed plastic waste is not considered to be an option in near future.

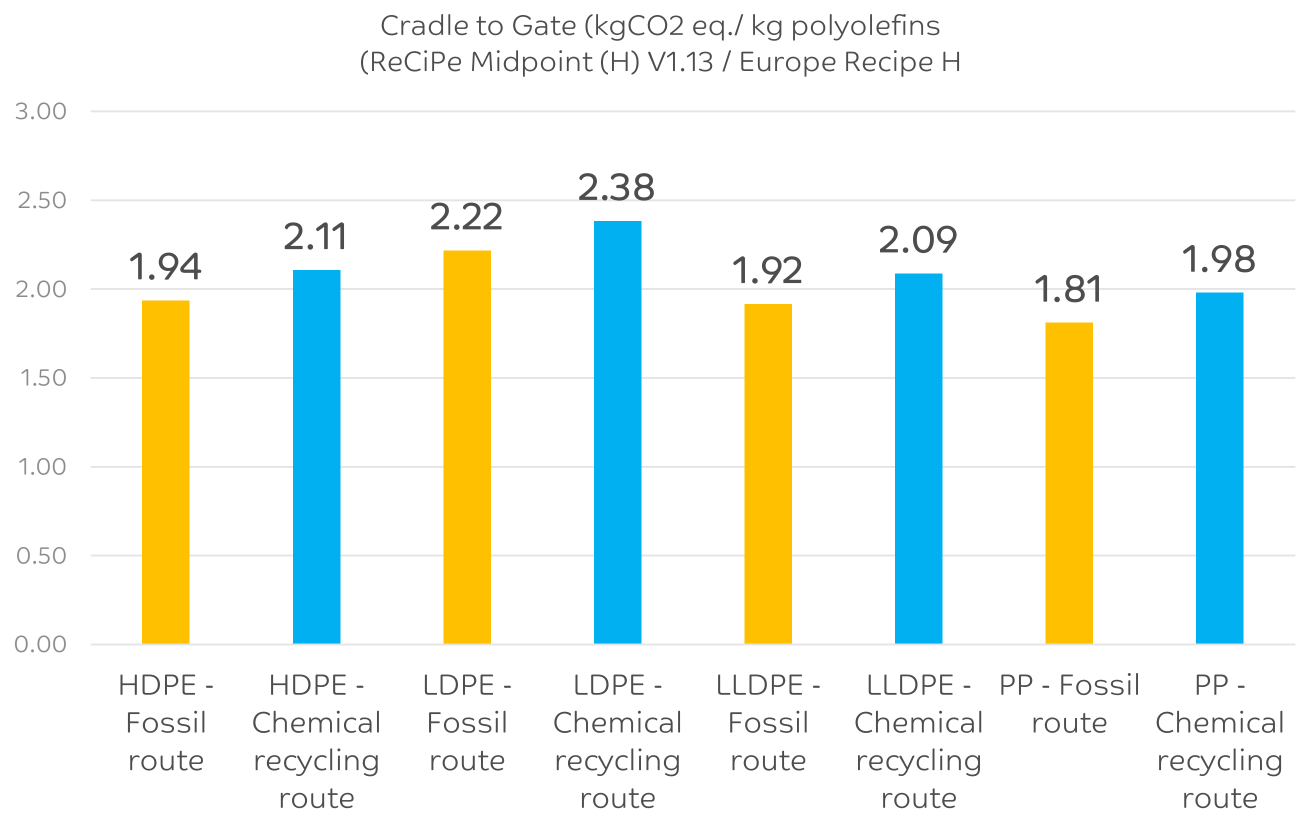
- While data that is currently being used in the models represent the highest quality of data available for pyrolysis process, primary data based on a world-scale facility for both pyrolysis and hydrotreating is not available at this point of time as these assets are still being built at smaller scales. Thus, this presents a future opportunity for validation and improvement once such data becomes available in future.

- Study assumes additional burdens of heat and power production in compensation for waste plastics diverted away from energy recovery based on currently dominant source such as natural gas for heat and average grid mix for power. In future, each additional need for power and heat may come from renewable sources, which implies that the current assumptions are quite conservative.



The above list only provides a summary list of the most relevant information on these topics and the detailed study report provides a comprehensive description of these topics.

CRADLE TO GATE: CARBON FOOTPRINT COMPARISON – DIRECT IMPACTS



Based on chart, the comparison of carbon footprint (global warming potential) indicates that direct impacts of advanced recycling route has about 6-8% higher carbon footprint than fossil-based naphtha route for all polyolefins. The two routes can be considered to have comparable carbon footprint as differences are within the error margins of the assessment.

It must be understood that several conservative assumptions are used for the pyrolysis process. Future versions of this technology has potential for improved energetics which might make these two routes very comparable.

CRADLE TO GATE+EOL: CARBON FOOTPRINT COMPARISON – INDIRECT IMPACTS

2kg CO_2 avoided

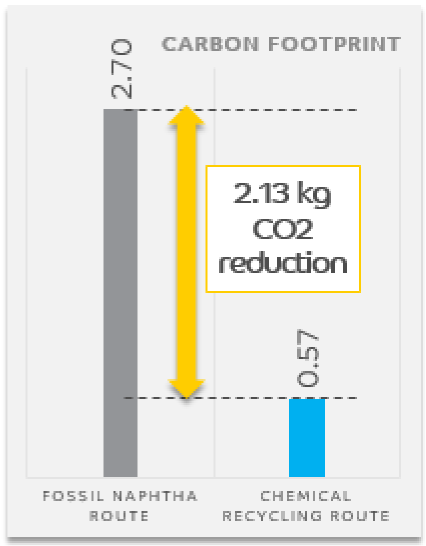
per kg of polyolefins produced via advanced recycling route.
Mainly enabled by avoidance of mixed plastic waste incineration.

Notes:
1. Images are not drawn to scale.
2. The above results are for HDPE via advanced recycling route but the result trends are consistent also for LDPE, LLDPE and PP, all of which were assessed by this study.

* The study assumes that when plastic waste is diverted away from incineration, the shortfall in heat and power production otherwise derived from incineration of waste plastics is compensated with those from traditional sources (avg. electricity grid for power and natural gas for the heat).

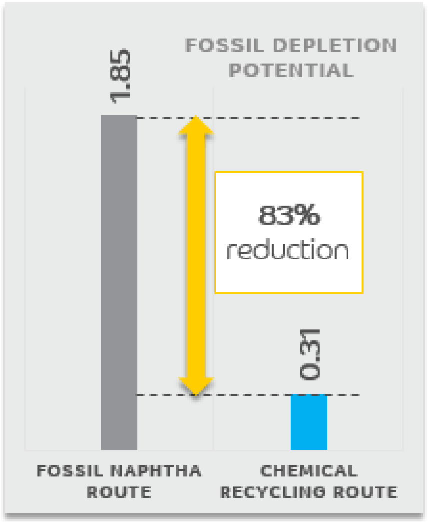
OTHER KEY STUDY RESULTS

- ## Cradle to Gate + EOL:



The results of this "Cradle to Gate + EOL" study indicate that SABIC Circular polymers could potentially avoid about 2 kilograms of CO_2 emissions for every kilogram of advanced recycled polyolefins.

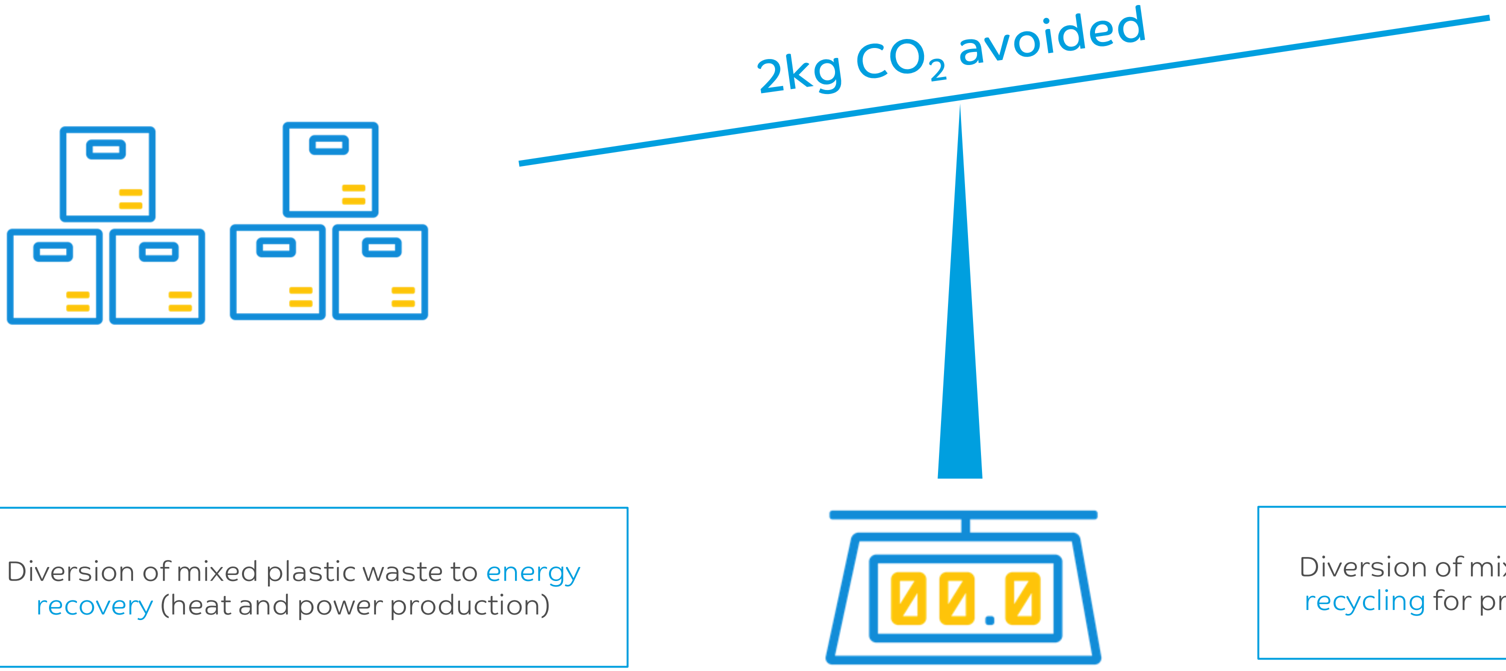
- ## Cradle to Gate:



At cradle to gate, the impacts related to fossil depletion impacts are about **80-84% less for advanced recycling route** in comparison to fossil route by virtue of avoidance of naphtha feedstock.

CARBON FOOTPRINT IMPACTS

SABIC certified circular polymers could save approximately **2kg of CO_2 emissions for every kg of advanced recycled polyolefins** diverted to polymer production vs. energy recovery.

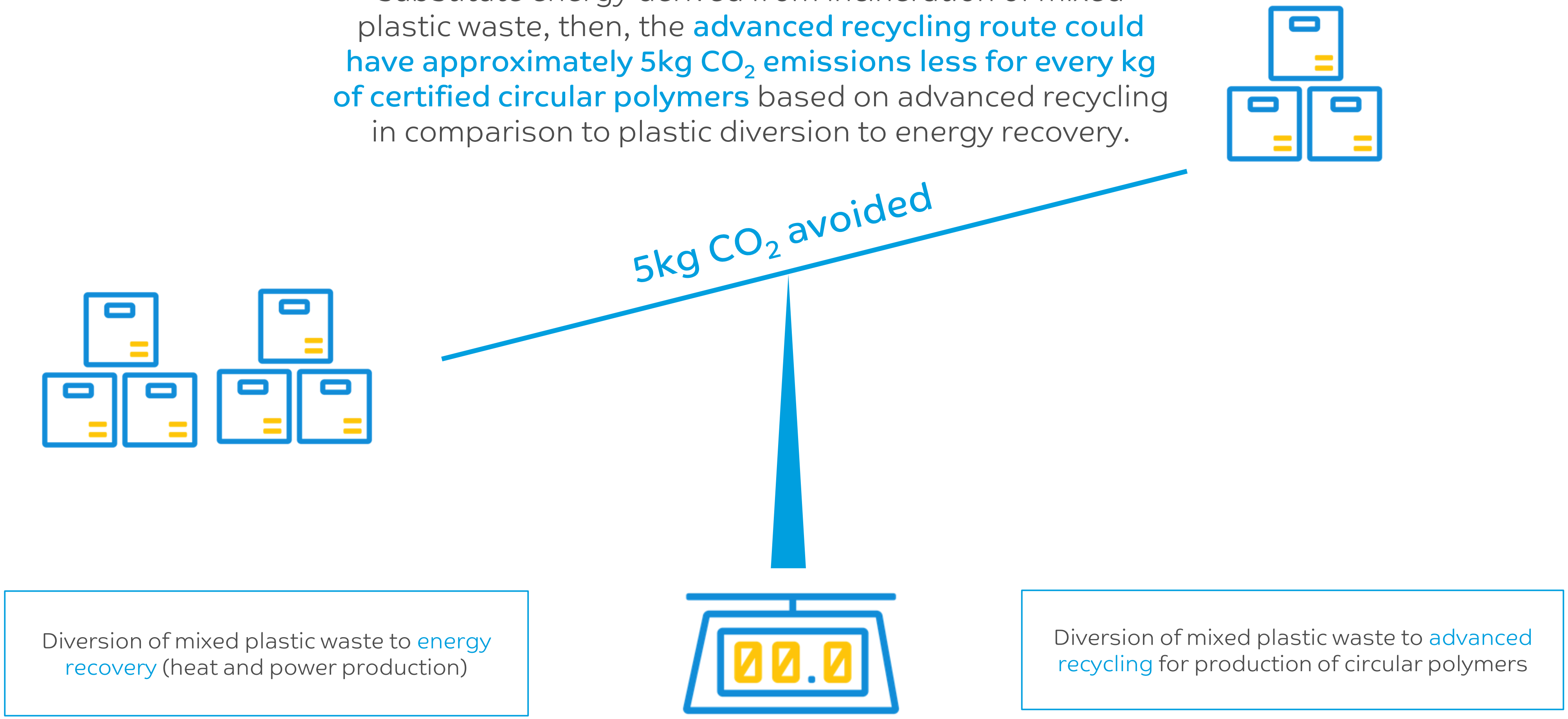


Diversion of mixed plastic waste to energy recovery (heat and power production)

Diversion of mixed plastic waste to advanced recycling for production of circular polymers

FUTURE POTENTIAL ON CO_2 BENEFITS

When using renewable sources of heat and power substitute energy derived from incineration of mixed plastic waste, then, the **advanced recycling route could have approximately 5kg CO_2 emissions less for every kg of certified circular polymers** based on advanced recycling in comparison to plastic diversion to energy recovery.



LCA OUTCOME AND KEY FINDINGS

Carbon footprint	Favorable	Fossil and advanced recycling routes have comparable carbon footprint. But advanced recycling leads to avoidance of ~2 kg of CO_2 emissions for every kg of certified circular polyolefins (when the indirect benefits of avoiding mixed waste plastics being sent to energy recovery are included).
Fossil depletion	Favorable	Primarily enabled due to the avoidance of fossil based naphtha as feedstock for cracking and subsequent polymerization to polyolefins.
Terrestrial acidification	Favorable	Primarily enabled due to the avoidance of oil extraction and refining processes that are linked to sour natural gas, use of heavy fuel oil in refinery and crude oil transport.
Marine Eutrophication	Trade-off	Due to additional landfilling burdens associated with sending reject metal and other contaminants from waste plastics during pyrolysis process to landfill.
Photochemical Oxidant Formation	Favorable	Primarily enabled due to the avoidance of oil extraction and refining processes that are linked to sour natural gas, use of heavy fuel oil in refinery.
Particulate Matter	Favorable	Primarily enabled due to the avoidance of naphtha production and related O&G processes.
Water depletion	Trade-off	Mostly linked to hydropower generation linked to electricity consumption and partly linked to the cleaning requirements for plastic sorting and other related processes.
Terrestrial, Marine and Freshwater Eco-toxicity & Human toxicity	Not - interpreted	These impacts are not interpreted as the modelling uncertainties of these impact categories are report to be orders of magnitude higher than the scale of differences observed for the two routes.
Ozone layer depletion, land occupation, metal depletion	Not - interpreted	These impacts are considered to be non-relevant to the context of the study and hence not interpreted.

The above results are based on an LCA study that has undergone ISO Critical review

ISO CRITICAL REVIEW

CRITICAL REVIEW PANEL

- Dr. Ing. Martin Baitz, Director Content thinkstep GmbH / Sphera , Leinfelden-Echterdingen, Germany *
- Dr. Guy Castelan, acting as independent expert (Project Manager in charge of LCA activities of PlasticsEurope) *
- Dr. Rajesh Kumar Singh, Managing Director thinkstep Sustainability Solutions Pvt. Ltd./Sphera, India *
- Dr Peter Shonfield, Technical Director UK, thinkstep Ltd. *

EXCERPTS FROM CONCLUDING REMARKS OF REVIEW PANEL

- The system under study was very carefully defined and modeled.
- The assumptions are transparently described and are found to be suitable and acceptable concerning the conclusions.
- SABIC managed to generate comprehensive, transparent and consistent results. Due to the complex nature of the product systems, assumptions had to be made based on the "precautionary principle" approach.
- The study has been carried out in conformity with ISO 14040 and ISO 14044.
- The study is reported in a very comprehensive manner, including a transparent documentation of its scope, within the limits of data confidentiality.
- The critical review panel found the overall quality of its methods scientifically and technically valid and the used data appropriate and reasonable.

* Titles and profile description of the Critical Review panel members were based on information at the time of the study review during 2019-20

OTHER SUPPORTING CLARIFICATIONS & FAQ (1/2)

What are the various polyolefin products that are assessed by this study?
HDPE (High Density Polyethylene)
LDPE (Low Density Polyethylene)
LLDPE (Linear Low Density Polyethylene)
PP (Polypropylene)

What are the various scopes of this study?
This LCA study considers the following scopes for all of the above polyolefin products:
Cradle-to-Gate
Cradle-to-Gate + End-of-Life
Cradle-to-Gate + End-of-Life, including impacts of waste diversion from incineration

Can advanced recycling be considered as an alternative to other waste plastics recycling options such as mechanical recycling, landfilling and energy recovery (incineration)?
Typically, good-to-high quality waste plastics are best suited for mechanical recycling and will continue to be utilized in mechanical recycling processes. However, the lower quality mixed plastic waste streams are sometimes even a liability for a sorting unit and has to be diverted to energy recovery or to landfill. Landfilling is also being banned in several EU member states and thus energy recovery represents the only plausible alternate option to advanced recycling. However, it is key for the reader to understand that mechanical and advanced recycling as well as energy recovery compliment each other towards enabling an effective waste management and waste valorization strategy and will have to co-exist together in driving effective sustainable solutions to the society.

Is this study ISO Critical Reviewed?
This study has undergone a rigorous ISO Critical Review process, reviewed by a panel comprising four renowned experts in the field of the study, including three experts from Sphera (formerly Thinkstep) and one from PlasticsEurope. The study aims at conformance with ISO 14040:2006 and ISO 14044:2006, and the third-party full panel critical review aims for conformance with ISO 14071.

Can this study be extended or adapted at cracker products level?
Yes, this study can be adapted to assess the environmental performance of cracker products based on advanced recycled feedstock.

OTHER SUPPORTING CLARIFICATIONS & FAQ (2/2)

Why is this study carried out only at Cradle-to-Gate and Cradle-to-Gate + End-of-Life? Is *Use* phase not modelled?
The study mainly focuses of polyolefin products that are produced from advanced recycling route. Also, the intention was to keep the study scope generic for polyolefin to be used in any application. Hence specific components such as *Use* phase was not modelled. This does not create any bias towards fossil or advanced recycling route and thus paves way for a fair comparison that has broader applicability.

Is this study relevant for other geographical regions such as Asia-Pacific (APAC) or Americas?
The study is quite representative of polyolefin production and consumption in Europe. As many practices (such as waste management and recycling rates) as well as life cycle components (such as electricity grid composition) vary by geography, this study can be carefully extended to relevant regions with a comparable scenario and options for plastics End of Life (EOL).

How does the study treat the burdens of incoming waste plastic streams? In other words, what methodological framework is used to allocate EOL plastic burdens?
This study uses two different EOL Recycling allocation methodologies
(a) Cut-off EOL allocation (this assumes that the waste plastic carries zero burdens from its previous life into the current life of the advanced recycled polyolefin)
(b) CFF EOL framework: The Circularity Footprint Formula (CFF) that has been proposed by PEF Guidelines has also been applied. This considers a default share of allocation between current and past life

Why does the study take into account the indirect benefits of avoiding energy recovery?
In current practices, the lower quality of mixed plastic waste that is not suitable for mechanical recycling can only be diverted to a landfill or to energy recovery. Since landfilling is being banned in many countries, it can no longer be considered a plausible fate for mixed plastic waste. But when the mixed plastic waste is diverted for energy recovery, it can help generate useful heat and power. It also helps from waste volume reduction perspective. But it releases more CO_2 emissions than other alternative sources of heat and power.

Henceforth, for the study to be complete, the overall effects of waste plastics diversion to advanced recycling has to be taken into account. Thus, it is being considered through the indirect benefits.

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