RENEWABLE
CARBON
INITIATIVE
CASE STUDIES

Case Studies Based on Peer-reviewed Life Cycle Assessments

Carbon Footprints of Different Renewable Carbon-based Chemicals and Materials

A Brochure of the Renewable Carbon Initiative

November 2023

The Renewable Carbon Initiative (RCI) is an interest group of more than 60 well-known companies founded in September 2020, see last page.

Imprint

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Introduction to this Brochure

In the urgent context of climate change – the UN calls it “humanity’s ‘code red’ warning” – a critical question emerges: Can materials and products derived from renewable carbon reduce greenhouse gas emissions when compared to the established fossil-based counterparts? Answering such a question demands rigorous assessment, and the method of choice for such evaluations is Life Cycle Assessment (LCA). In this brochure, the RCI presents five peer-reviewed LCA case studies – representing the highest possible scientific standard – that examine the carbon footprint of materials and products made from renewable carbon.

The significance of the question lies in the fact that fossil resources are the main cause of human-made climate change, responsible for more than 70% of global warming. Defossilisation is the right strategy to eliminate additional influx of fossil carbon into our carbon cycles and the atmosphere – but at the same time we need to ensure that the alternatives really reduce greenhouse gas emissions.

To achieve defossilisation, renewable carbon feedstocks, which can be bio-based, CO_2-based or recycled, need to substitute the dominant fossil feedstock in the production of chemicals and materials – sectors that rely on carbon as a feedstock and cannot do without. The principle advantage of renewable carbon feedstock is that it originates from atmo-, bio- and technosphere and therefore does not bring additional fossil carbon from the ground into the carbon cycle above the ground. Instead, these feedstocks help to build and realise a truly circular economy and circular carbon loops.

Life Cycles Assessment (LCA) – The Gold Standard

LCAs are worldwide recognised the gold standard for assessing the environmental impacts of products and services. They analyse every stage of a product’s life, providing a comprehensive understanding of their environmental impacts. Peer-reviewed LCAs are particularly valuable as they undergo rigorous expert scrutiny, ensuring the reliability of their findings and enabling reliable public assertions in terms of environmental preference.

In this brochure, we have decided to focus on the carbon footprint only due to several reasons. One is the urgency of climate change, which requires swift and decisive action. By concentrating on carbon emissions, we offer a clear perspective on the potential climate benefits of renewable carbon-based materials over fossil alternatives in light of the ongoing climate crisis.

A second reason is the complexity of LCAs. They involve collecting and analysing data from multiple sources, along several stages of the life cycle, a wide set of different impact categories that can be assessed, and from different perspectives – all in order gain a picture as holistic as possible. But our aim is to provide policy-makers and other stakeholders, who may not be LCA experts, with valuable insights to facilitate decision-making and defining of priorities. In this sense, the brochure highlights a key aspect for climate change mitigation – addressing the carbon footprint of products. These case studies on several materials and products from renewable carbon bridge an existing gap and offer deeper understanding without requiring specialized knowledge.

With this brochure the RCI aims to visualise that there are not only competitive materials and products made of renewable carbon already on the market, but that they also come with significantly lower climate footprints ranging from 30–90%. A key aspect of replacing fossil carbon with renewable carbon is the gained circularity of carbon. The less additional fossil carbon is added to our above-ground cycle of atmosphere, biosphere and technosphere, the smaller will be the amount of carbon emissions that have to be balanced out with expensive atmospheric removal and underground storage of carbon.

It is essential to recognise that the carbon footprint of renewable carbon-based materials is not automatically close to zero for two primary reasons:

Fossil energy in the value chain: The growth or provision of raw materials, transportation, and product manufacturing stages involve energy consumption, and grid mix energy is usually still to a substantial amount derived from fossil sources. In particular the agricultural sector, as a key provider of biomass, is still strongly reliant on fossil resources e.g. for fertilisers, pesticides or simply the diesel needed to run machinery. This reliance on fossil feedstock within the value chain significantly impacts the overall carbon footprint.

Ongoing innovation and optimisation: Many renewable carbon-based materials and products are still in their nascent stages of development in contrast to the over decades highly optimised fossil sector. As innovative processes, they offer substantial promise for reduced carbon footprints but are subject to ongoing refinement and optimization.

With technology advances, increasingly renewable energy, upscaled electrification of transport and machinery, the carbon footprint of renewable carbon-based materials will strongly decrease even further. Combined, these aspects enable products that truly achieve zero or close-to-zero emissions.

All in all, the here presented materials and products show reduced carbon footprints already today, which lowers the remaining emissions gap so that less CO_2 needs to be removed from the atmosphere in the future. At the same time, these materials and products still have significant potential to further reduce emissions in the future.

As you delve into this brochure, we invite you to consider the implications of renewable carbon-based materials on climate change. We believe the case studies provide essential information to guide policy decisions in our pursuit of our climate and net-zero targets.

In this brochure, experts from nova-Institute have summarised and visualised five different peer-reviewed Life-Cycle Assessments for RCI. The following products have been developed by the following companies, and the Life-Cycle Assessments were peer-reviewed by the following independent LCA experts.

PEF-based bottles
Manufactured by Avantium (NL); LCA conducted by nova-Institute; LCA critically reviewed by TÜV Rheinland Energy GmbH (DE), Ecomatters B.V. (NL), ifeu GmbH (DE).

Pyrolysis as part of the plastic value chain
Manufactured by BASF (DE); LCA conducted by Sphera Solutions GmbH (DE); LCA critically reviewed by Ethos Research (UK), Institute for Applied Ecology (DE), Eunomia Research & Consulting Ltd (UK).

Enzymatic Polysaccharides
Manufactured by IFF (US); LCA conducted by IFF; LCA critically reviewed by nova-Institute (DE), individual sugar expert consultant (DE).

Viscose, Modal and Lyocell Fibres
Manufactured by Lenzing (AT); LCA conducted by Copernicus Institute at Utrecht University (NL); LCA critically reviewed by University of Manchester (UK), ifeu GmbH (DE), Michigan Technological University (US).

NEXBTL Technology
Manufactured by Neste (FI); LCA conducted by Neste (FI); LCA critically reviewed by VTT Technical Research Centre of Finland Ltd (FI), Quantis GmbH (CH), Aequilibria Srl-SB (IT).

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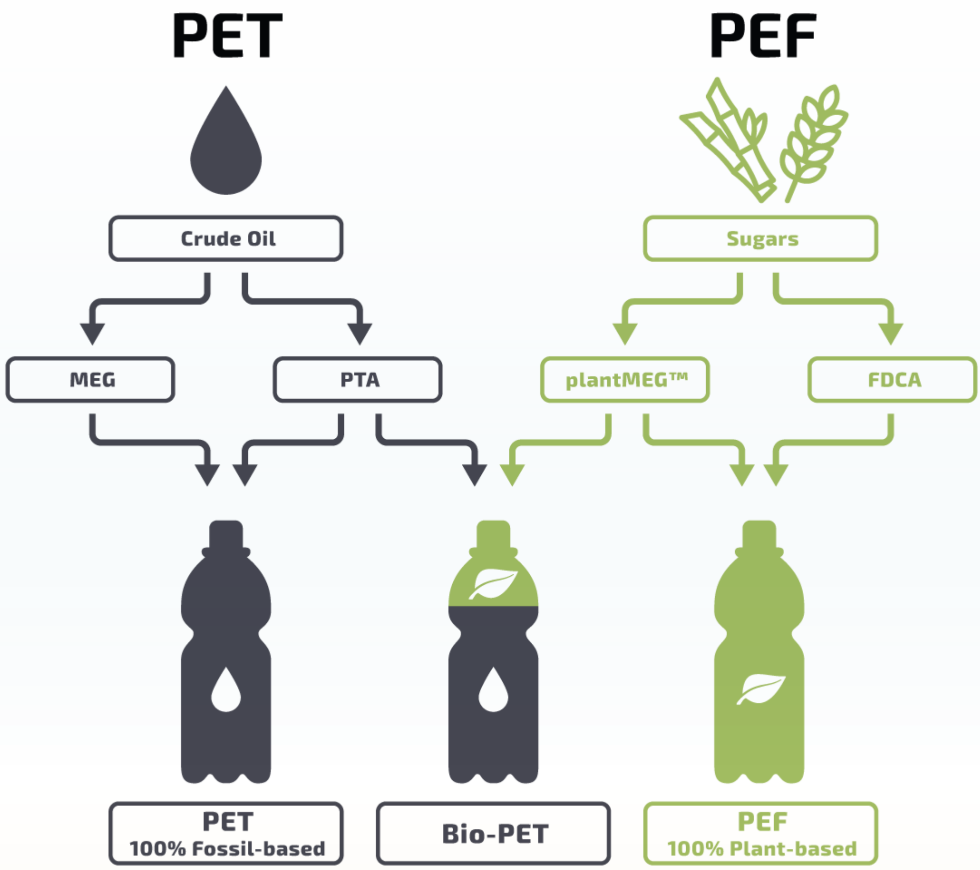
Avantium's YXY® Technology PEF-based Bottles



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Avantium's YXY® Technology PEF-based Bottles

This case study provides you with key LCA insights of Avantium's industrial PEF (polyethylene furanoate) and how PEF can help to mitigate climate change by reducing greenhouse gases.[1]

Avantium is a Dutch company dedicated to developing and commercialising chemistry technologies for the production of chemicals from renewable feedstock instead of fossil resources. The company has developed the YXY® Technology to convert plant-based sugars into FDCA (furandicarboxylic acid), the building block of PEF (polyethylene furanoate): a plant-based and recyclable polymer with increased barrier performance. The barrier properties of PEF in combination with its calculated cost price indicate that PEF can compete with traditional packaging solutions such as small size multilayer PET bottles regarding price, performance and sustainability issues when produced at scale (Figure 1).

When fully technologically developed, PEF can also be produced from cellulose, which is abundant in non-edible biomass, such as agricultural and forestry waste streams. The current process utilises starch from European wheat. To make a 100% plant-based PEF polymer, FDCA is polymerised with plant-based mono-ethylene glycol (MEG). Avantium has successfully demonstrated this YXY® Technology in its pilot plant in Geleen (NL) and has already started the construction of the first commercial 5 kta FDCA Plant in Delfzijl (NL), planned to be operational by 2024.

Plant-based

PEF is a 100% plant-based plastic material, made from sugars derived from plants. The sugars (fructose) required to make FDCA can be produced from agricultural crops, such as wheat, corn and sugar beet. The current process utilises starch from European wheat.

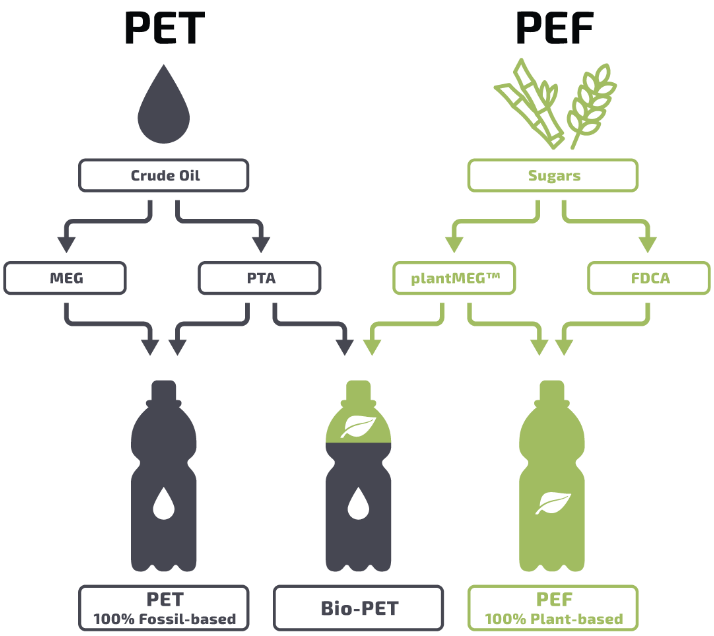


Figure 1:
Plant-based PEF Bottles

1 Based on the main ISO LCA study "Life Cycle Assessment of Avantium's Polyethylene Furanoate (PEF) Bottles" available upon request from Avantium. Summary of LCA also available at https://www.avantium.com/lca/ and https://renewable-carbon.eu/publications/product/pef-a-sustainable-packaging-material-for-bottles-pdf/. The full LCA also assessed a total of 16 impact categories.

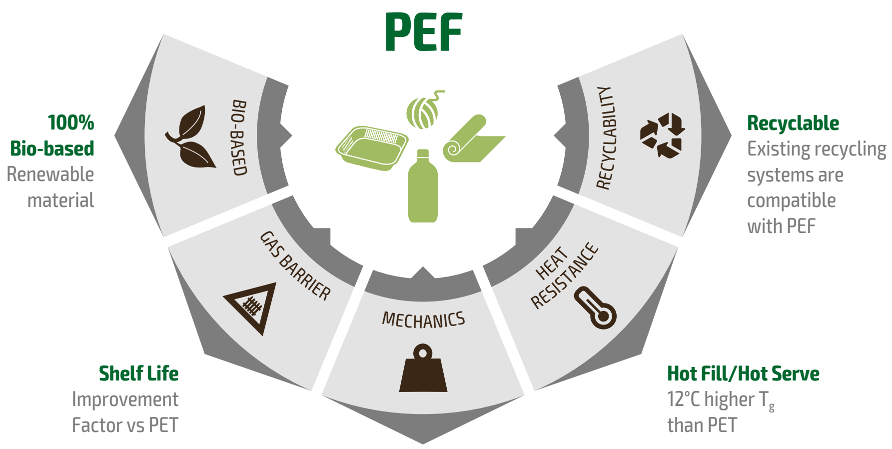


Figure 2: PEF Properties

The other key building block is commercially available bio-based MEG, currently produced from sugarcane. In this respect, Avantium opened a demonstration plant for plantMEG™ in 2019 and plans to operate the first commercial plant for the production of plant-based MEG from sugar beet using Avantium's Ray Technology™.

Improved Performance

Compared to today's widely used petroleum-based polymers (e.g. ~10x better for O_2, ~15x better for CO_2, and ~2.5x better for water than PET) PEF has enhanced barrier, mechanical and thermal properties (Figure 2). The barrier properties of PEF make this polymer very attractive for a use in the packaging sector, leading to a longer shelf life of packaged products and allowing for lightweight designs. PEF also offers enhanced mechanical stiffness and allows for increasing shaping possibilities. In terms of thermal properties, PEF has a superior ability to withstand heat and can be processed at lower temperatures.

Recyclability of PEF

PEF has proven fit-for-purpose with existing sorting and recycling facilities and can be recycled mechanically in a similar way using the same equipment used to recycle PET. In addition, PEF can easily be distinguished from PET and other plastics using near-infrared technology. This will allow PEF to be sorted from any PCR or deposit system waste streams once the market has grown sufficiently to enable an individual PEF material recycling stream.

PEF-based Bottles

PEF can be used as a monolayer in bottles for soft drinks, beer, and juices, replacing glass bottles, aluminium cans, and multilayer bottles. Multilayer bottles are a valid alternative when the required shelf life cannot be guaranteed by monolayer packaging alone. Currently, many multilayer PET bottles include polyamides (PA), such as MXD6 for barrier properties.

However, a common issue for incumbent barrier materials such as PA is their poor compatibility with PET, making it essential to sort out the PA from the PET in the recycling stream. It was demonstrated that PEF has a much lower influence on the quality of the rPET product, making the recycling process with these PEF-based multilayer structures much more robust.[2]

2 PEF as a multilayer barrier technology: a sustainable way to enable long shelf life in PET bottles. Publisher: PETnology/tecPEt GmbH. Available at: https://www.petnology.com/online/news-detail/pef-as-a-multilayer-barrier-technology-a-sustainable-way-to-enable-long-shelf-life-in-pet-bottles

LCA of PEF[1]

Avantium partnered with the nova-Institut GmbH under the framework of the PEFerence project[3], to perform a full cradle-to-grave Life Cycle Assessment (LCA) for the first years of commercialisation of the YXY® Technology (from 2024–2027), assessing the potential environmental impacts of PEF-based bottles in comparison to conventional PET alternatives. The LCA met the requirements as per ISO 14040/44. A critical peer review of the study, including experts of incumbent technologies, was conducted in order to verify that the LCA met the requirements for methodology, data, interpretation, and reporting.

Products and Functional Unit

500 mL monolayer PEF bottle (16–19 g) and a 500 mL PET multilayer bottle with 10% PEF (20 g), ensuring a minimum of 12 weeks CO_2 shelf life and required mechanical strength for transport and use.[4,5]

System Boundaries

The LCA covered all relevant life cycle stages from cradle-to-grave: from the biomass cultivation (wheat for fructose and sugarcane for bio-MEG feedstocks supply) and crude oil extraction (reference system) to the production of PEF and PET bottles including their end-of-life options (recycling and incineration). Transport activities were included (Figure 3).

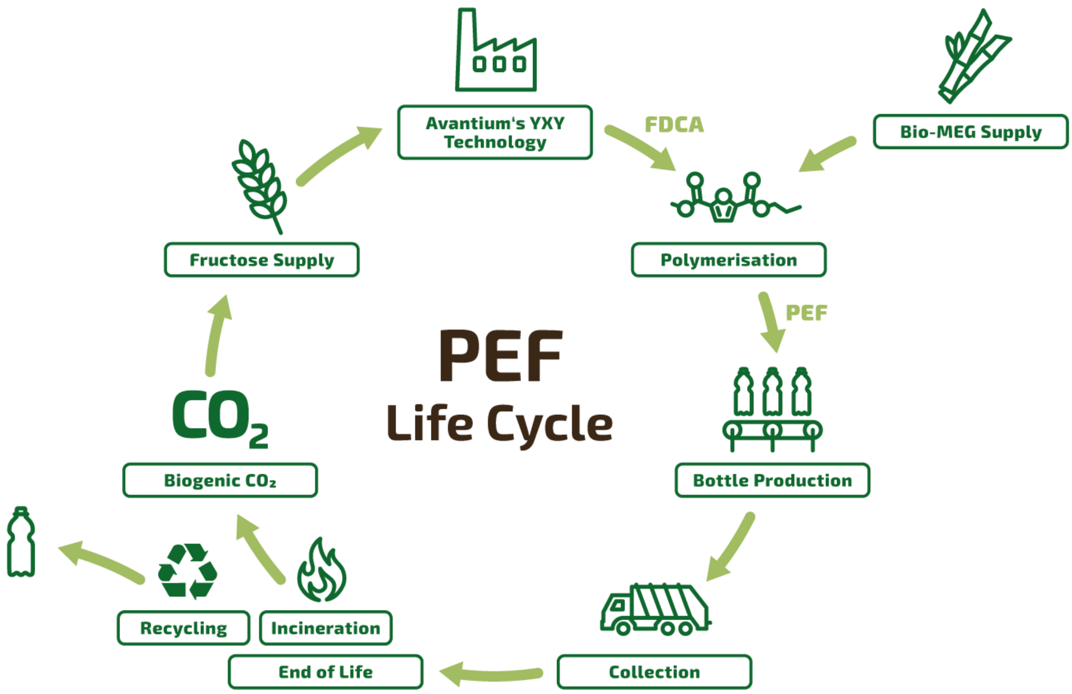


Figure 3: Life Cycle Stages of Monolayer PEF Bottles

3 PEFerence has received funding from the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement no. 744409.

4 As reference PET bottles monolayer and multilayer PET/PA bottles were also evaluated. Bottle weights for PEF and PET bottles were derived from model calculations based on gas permeability values. For the equivalent benchmark bottles this resulted in 20–24 g (PET monolayer) and 20 g (PET/PA multilayer, 7% PA).

5 Sensitivity analyses of the results towards different PET reference bottle weights, other allocation procedures, recycling and incineration rates in other countries and other aspects are included in the main report.

End-of-Life

It is assumed that the commercialisation of PEF-based products will initially take place in the Netherlands, Belgium, and Germany. These countries show relatively high rates for average PET bottle waste collection and recycling and no longer practice landfilling. The fate of PET bottles in these countries was considered as being representative for PEF bottles. For instance, a 65%–35% mechanical recycling – incineration ratio was considered for the Netherlands. In addition it was assumed that for the first years of commercialisation PEF will be recycled in the PET recycling stream.

Allocation

Upstream activities (wheat cultivation and milling) produce several co-products (gluten, dietary fibres, oil). In the YXY® Technology, a number of co-products, mainly humins (a polymeric, heterogeneous species with multiple functionalities) are formed. The environmental burdens between products and co-products were allocated by mass.[5]

Inventory Data

The core data used in the LCA were primarily supplied by Avantium, its engineering partner Worley and its feedstock supplier. Secondary data were mostly based on Ecoinvent v3.9. Reference PET bottles were modelled using Ecoinvent data for bottle grade PET production available from most recent Eco-profiles of the European plastics industry.

Impact Categories

The LCA assessed a total of 16 impact categories included in the Environmental Footprint EF 3.1 method (European Commission).[6]

Climate Change Impact Results[7]

The contribution of the individual life cycle stages of PEF-based bottles shows that the release of GHGs is distributed relatively evenly along the production value chain. The main contributing stages are the feedstock supply (fructose), the core YXY® Technology and the bottle production. Processes like the polymerisation step were found to have a minor contribution.

In addition, the material and energy recovery upon recycling and incineration contribute with a reduction of around 25% GHG emissions with respect to the overall emissions.

6 For this case studies brochure focus is on Climate Change potential only, but results of the other impact categories can be found in the main ISO LCA study and summary brochure (See footnote 2).

7 The EF 3.0 climate change indicator was adapted to see the contribution of the CO_2 uptake during feedstock growth and the biogenic C-related emissions upon incineration (-1/+1 approach).

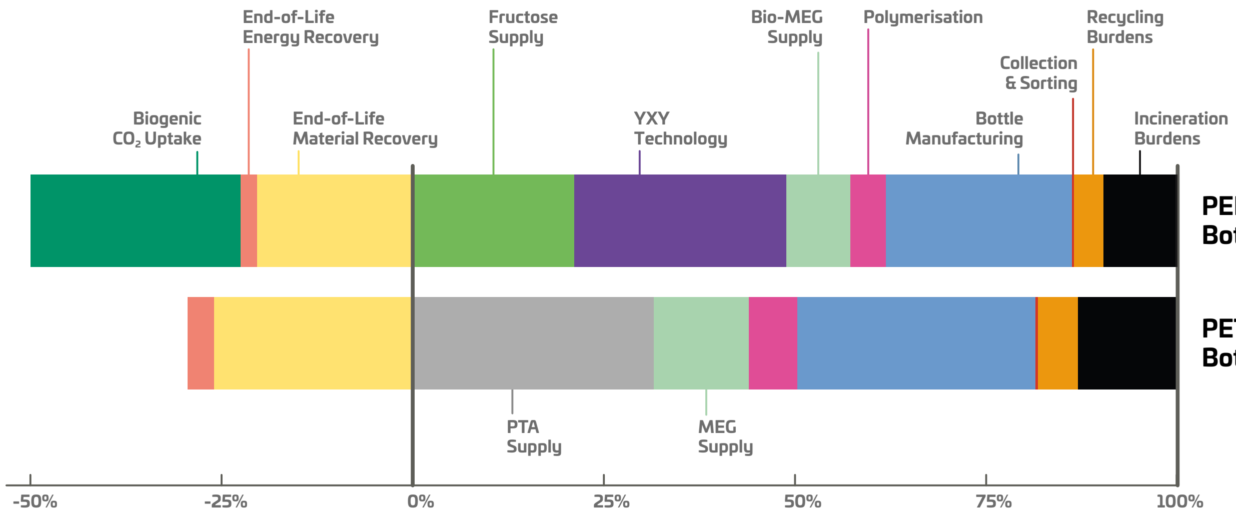


Figure 4: Contribution Analysis to Global Warming of a 500 mL PEF Bottle and PET Bottle

The following conclusions were highlighted from the comparative analysis:

- The use of 100% renewable carbon in PEF instead of fossil carbon in PET for producing 500 mL bottles would result in significant reductions in greenhouse gas emissions (-62%) over the life cycle of the bottles (Figure 5).
- The lower environmental footprint of the bio-based alternative can be attributed, to a great extent, to the use of renewable C and the improved barrier and mechanical properties of PEF, allowing for a substantial reduction of polymer usage in the manufacture of bottles (light-weighting designs).
- Moreover, the emissions from the bio-based bottle upon incineration are compensated by the CO_2 removal during the renewable feedstock growth.
- Additionally, significant reductions of around 39% in GHG emissions could be achieved in multilayer packaging (e.g. PET/PA) by replacing typical fossil-based barrier layers (e.g. polyamide PA) with PEF. PEF also enables the recyclability of these typically non-recyclable systems.

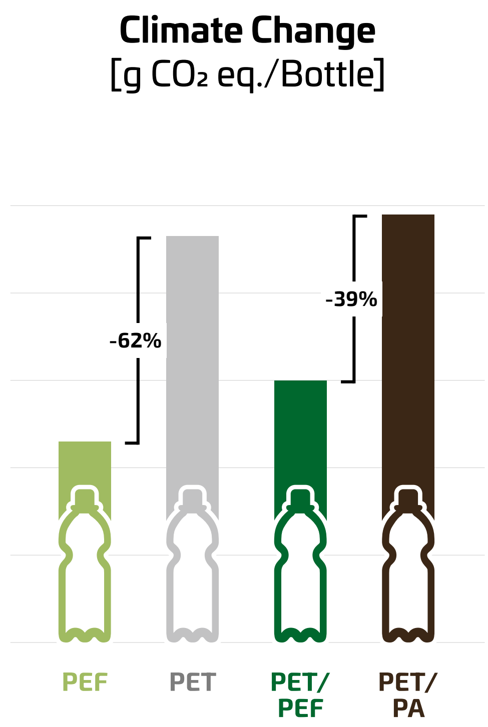


Figure 5: Comparative analysis

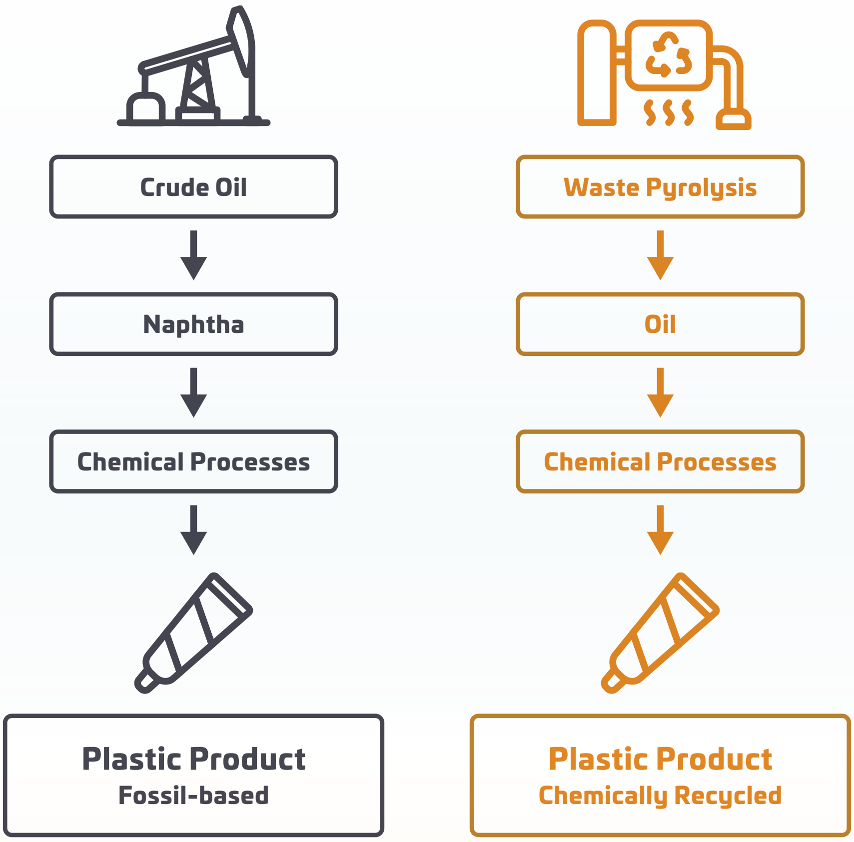
Conclusion

The results showed a significant potential reduction in GHG emissions for renewable PEF-bottles when compared to reference fossil-based bottles. These results represent the first years of commercialisation of PEF-based products in which PEF will be recycled in the PET recycling stream.

Additional GHG reductions are expected once the PEF market has grown sufficiently to ensure a closed-loop PEF-to-PEF recycling.

Moreover, as the PEF technology continues to mature, substantial GHG are expected through increased economy of scale and improved energy efficiency.

Carbon Footprint of Pyrolysis as Part of the Plastic Value Chain



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Carbon Footprint of Pyrolysis as Part of the Plastic Value Chain

This case study describes Global Warming Potential (GWP) impacts of a chemical recycling technology for mixed plastic waste (MPW). The initiating company BASF commissioned a peer-reviewed Life Cycle Assessment (LCA) study, according to ISO 14040 and 14044 standards. BASF operates six Verbund sites and 233 production sites around the world with headquarters in Ludwigshafen, Germany.

Although chemical recycling has been introduced to the industry decades ago, interest in the technologies and its possibilities has been renewed in the past couple of years. Chemical recycling encompasses many different technologies which can for example break down long-chain polymer molecules of plastic waste back into monomers and then subsequently be converted back into plastics. Pyrolysis describes a technology which can convert mixed plastics waste (MPW) into pyrolysis oil through thermal decomposition in an inert atmosphere. The process requires additional sorting and purification steps to fit the specifications of the cracker. The purified pyrolysis oil is then cracked down and further refined for new plastics production.

One advantage of this pyrolysis and subsequent chemical processes is that plastic additives and contaminations are entirely removed and therefore virgin quality is achieved.

In July 2020, BASF SE published the results of a peer-reviewed LCA, conducted by Sphera Solutions GmbH on the evaluation of pyrolysis in three case studies. This summary provides an overview of case study number 2 (product perspective). In this case study, mixed plastic waste (MPW) is converted into low-density polyethylene (LDPE) of virgin polymer quality[8] and compared with virgin, fossil-based production of LDPE. LDPE is a widely used plastic and is best known for its usage in plastic bags and films. Its characteristics include low temperature flexibility, toughness and corrosion resistance. The mixed plastic waste feedstock, obtained from waste collection and sorting, can be (chemically) recycled, thereby displacing the alternative waste treatments like incineration. The other two case studies cover the evaluation of pyrolysis from a waste perspective as well as a product perspective covering plastic products with a lower quality level than virgin-grade.

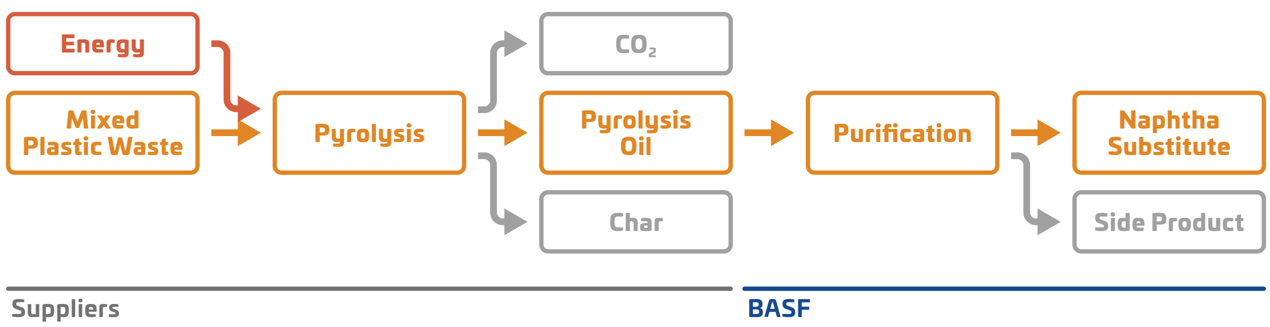

Figure 6: Overview of the pyrolysis process (BASF 2020b)

8 In a mass balance approach, BASF feeds recycled raw materials into its Verbund in the very first steps of chemical production. A corresponding share of these raw materials is then attributed to specific sales products by means of a third-party certified mass balance method. The method is applied to the chemically recycled LDPE in this LCA.

Goal and Scope

The aim of the peer-reviewed LCA study was to evaluate the environmental impacts of pyrolysis as part of the value chain to produce an exemplary chemical product with virgin-grade quality and compare it against the production of an equivalent product via a conventional virgin polymer route. The exemplary chemical product studies are LDPE granulates. The study examines all processes from cradle to gate, i.e. from feedstock provision up to the factory gate. The environmental impacts are reported per 1 t of LDPE in virgin-grade quality produced in 2030 in Germany. In LCA terms, this is referred to as functional unit (FU).

MPW is used as a feedstock for pyrolysis, which would otherwise be burned in waste incineration facilities generating energy whilst emitting CO_2. In order to account for the multi-functionality of this process, an approach called "Upstream System Expansion (USE)" is used. (Together for Sustainability, 2022) In this approach, the energy generated from the MPW incineration has to be substituted by another energy source and the emissions of this energy source are attributed to the pyrolysis processes (this is the upstream system expansion burden). On the other hand, CO_2 emissions from the MPW incineration are displaced and credited to the pyrolysis as well (this is the upstream system expansion credit). To calculate the displaced impacts, 30% of the MPW is assumed to be incinerated in a Municipal Solid Waste Incineration plant (MSWI) whereas the remaining 70% is assumed to be incinerated in a Refuse Derived Fuel plant (RDF), after waste collection and sorting.

As the study is based on forecasting, it uses the anticipated future energy and electricity mixes for Germany in 2030. Furthermore, data on the pyrolysis technology has been obtained from a commercial manufacturer based on 2018 data, whereas data for the steam cracker has been used from BASF from 2018. Steam cracking is a technique in which a gaseous or liquid hydrocarbon like naphtha is diluted with steam and heated in the absence of oxygen in order to obtain smaller hydrocarbons. These data have been obtained from commercial plants and have been used as is, which represents a conservative approach as the technologies can be further optimised. The virgin LDPE production is based on crude oil transformation to ethylene, and the data for the production is based on GaBi database (Sphera, 2019).

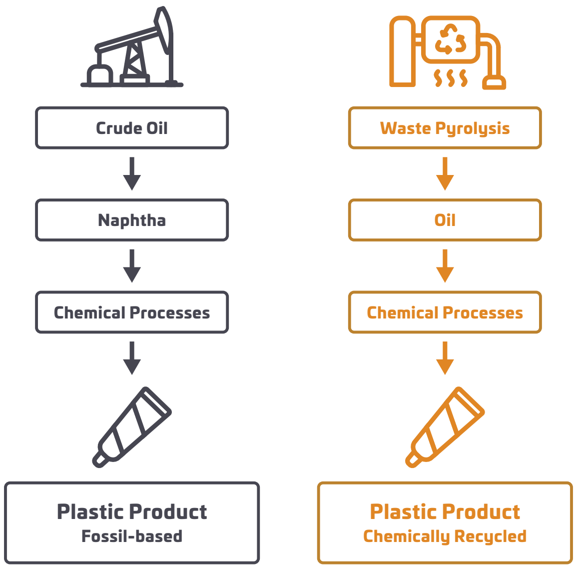

Figure 7: Simplified production of chemically recycled plastics compared with conventional plastic, case study 2 (BASF 2020b)

The sensitivity of the results towards the use of the USE approach has been investigated by considering two additional scenarios for the energy and electricity emissions. First, it considers that the energy from MPW incineration is substituted by fossil energy carriers, which represents a scenario in which the energy and electricity mix are still based on fossil energy carriers. Whereas in the second scenario, the energy is substituted by electricity from hydropower and the thermal energy is substituted by thermal energy from renewable sources; this represents a scenario with high shares of renewables in the energy mix, e.g. in Scandinavian countries in the mid-term future (defossilisation).

Assumptions for this Summary

For simplification purposes, this short summary only considers the impact category of GWP and only case study 2 on the production of LDPE in virgin-grade quality.

Impact Results

The shortened LCA results are visualised in Figure 8. The figure shows the GWP per t LDPE in kg CO_2 eq as well as the contribution of the process emissions, the differential credits and burden from the applied USE approach, and the total result when deducting credit from process emissions and burden.

The results demonstrate that the total greenhouse gas emissions of LDPE derived from the pyrolysis process are significantly lower compared to the virgin polyethylene (PE) production from fossil resources, as indicated by the orange points for the total in the graph. The process emissions are indicated by the grey bar in the figure, which are roughly 40% higher compared to the virgin PE production, as can be seen in the grey bar on the right. The pyrolysis process avoids the incineration of the mixed plastic waste feedstock, resulting in a large differential credit, displayed by the purple bar.

Finally, the green bar represents the green-house gas emissions related to the energy and electricity which have to be additionally generated when the MPW is not incinerated. The additional emissions from the energy which has to be substituted by the German energy and electricity mix in 2030 (green bar) are substantial.

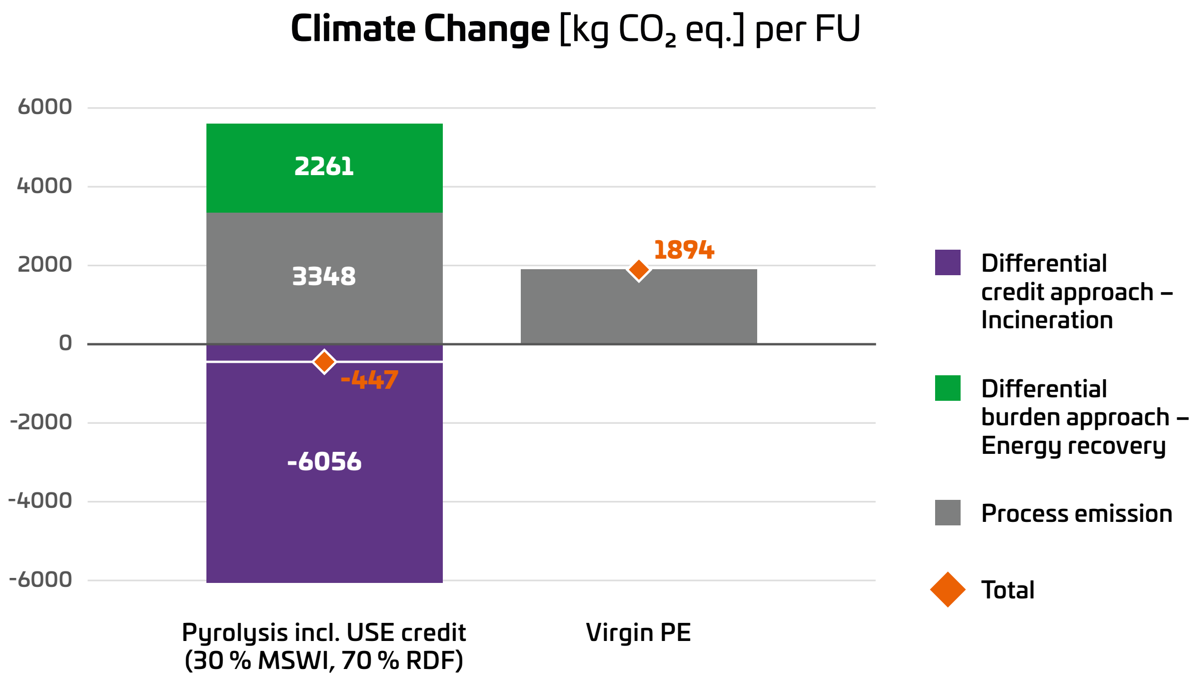

Figure 8: Global Warming Potential (GWP) of LDPE produced from the pyrolysis process and virgin PE in the baseline scenario (Germany 2030), FU = functional unit (BASF 2020)

49% of the process emissions in the production of chemically recycled LDPE originate from the pyrolysis step in which the main contributor is direct CO_2 emissions. The cracking process is responsible for 21% of the impact, whereas 13% originate from waste collection, the sorting process and transportation, 10% from polymerisation and 6% from purification.

The sensitivity of the LCA results concerning the emissions of the energy which have to be substituted is high, as is displayed in Figure 9. Using the baseline scenario (Germany 2030) the total emissions are -447 kg CO_2 eq. When the substituted energy is provided by fossil sources, the total emissions increase to 3115 kg CO_2 eq, higher than the 1894 kg CO_2 eq total emissions from virgin PE.

When the substituted energy is provided by defossilised energy sources the total pyrolysis emissions decrease to -2407 kg CO_2 eq, which might represent the situation e.g. in Scandinavian countries in the mid-term future. These results show that the climate change results of the pyrolysis system suffer from the use of fossil energy sources, whereas future defossilisation of the energy and electricity sources would benefit the pyrolysis system. The defossilisation of the energy industry is a mid-term goal for Germany and other European countries.

For the results of the other impact categories and two further case studies regarding the use of recycled feedstock derived from pyrolysis of mixed plastic waste, the original report can be consulted.

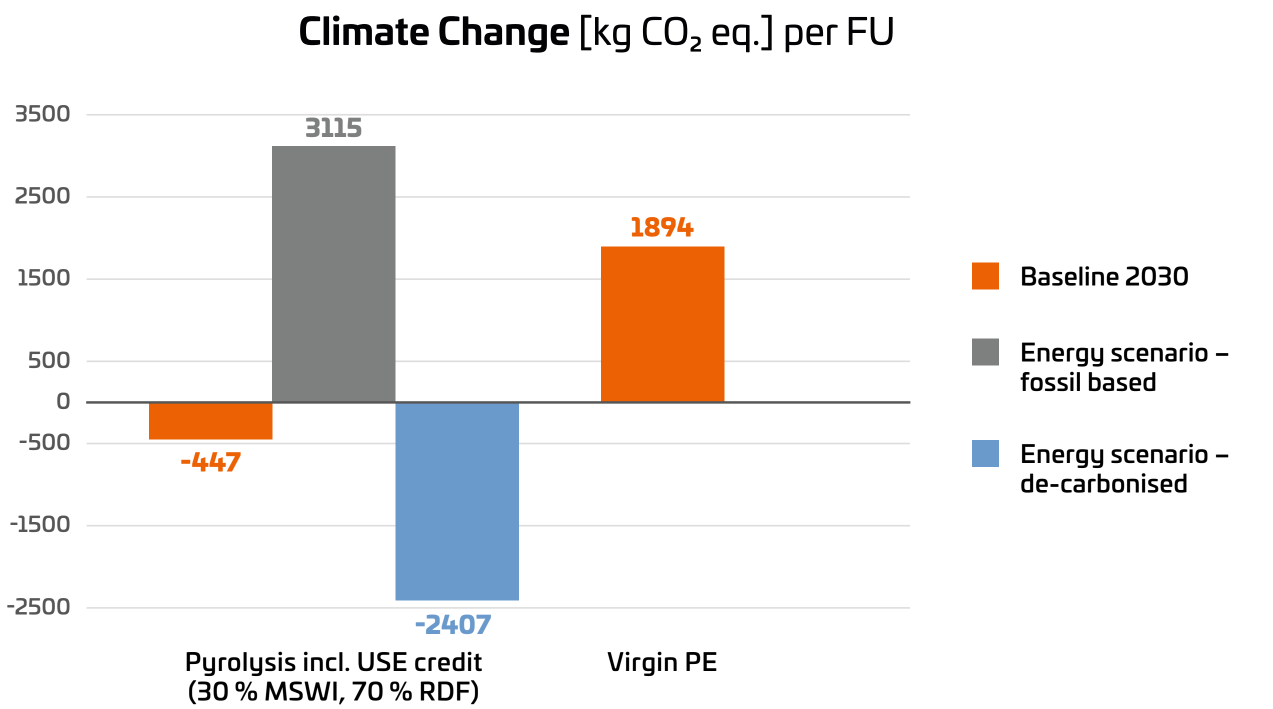

Figure 9: Sensitivity analysis of the Global Warming Potential (GWP) of LDPE using different energy to substitute the energy recovered from MPW incineration (BASF 2020)

Conclusion

The LCA shows that the recycled LDPE produced through pyrolysis is a more favourable choice in terms of climate change compared to virgin LDPE production in Germany in 2030, when using mixed plastic waste which would otherwise have been incinerated. Due to the use of the upstream system expansion approach, the results show a high sensitivity towards the energy sources which are used to replace the energy obtained from the incineration of MPW. If these energy sources are fossil-based, the production of virgin PE is more favourable in terms of climate change. If the energy sources are defossilised, the LDPE produced in the pyrolysis system is more favourable compared to virgin production. This shows that as the world moves away from fossil energy sources, the pyrolysis process for the recycling of mixed plastic waste becomes increasingly attractive from a climate change perspective.

In general, the production processes for bio-based, CO_2-based and recycling chemicals and materials currently do not match the maturity of the production processes for fossil-based chemicals and materials. However, even at this state of technology, the renewable material processes show various advantages concerning the environmental footprint in the near future. This insight highlights the need for a transition from fossil-based to renewable materials and chemicals to achieve net-zero targets.

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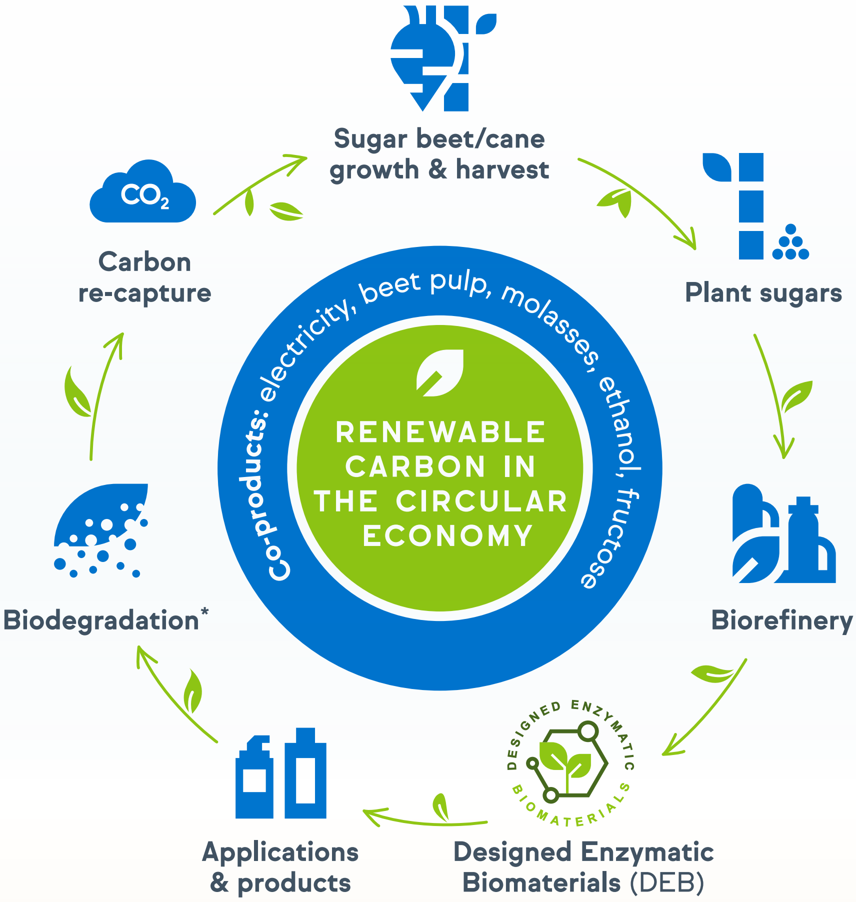
Sphera, 2019. Product sustainability data, more information at: **https://sphera.com/product-sustainability-data/**

Designed Enzymatic Polysaccharides: **Diversification Opportunity for the Beet Sugar Biorefinery and Sustainable Agriculture**



* Depending on the industry and application-specific DEB based product formulation and certification requirements.

November 2023

Designed Enzymatic Polysaccharides: **Diversification Opportunity for the Beet Sugar Biorefinery and Sustainable Agriculture**

Designed Enzymatic Biomaterials (DEB): This case study describes the Climate Change Potential (CCP) impacts of biomaterials derived from enzymatic polymerisation, an emerging platform technology for the biorefinery integrated conversion of beet sugar to biomaterials.
The platform technology has been developed by IFF (International Flavors and Fragrances), a leader in food, beverage, health, biosciences, home and personal care and sensorial experiences.

The Technology

Enzymatic Polymerisation: In nature, enzymes within plants connect together simple sugars, products of photosynthesis, into the material substance constituting all biomass. For example, cellulose or starch are polysaccharides – both part of the family of poly-sugars – and are built from simple sugars. This enzymatic polymerisation process will enable access to polysaccharides which are found in nature but are now accessible at industrial scale. These designed polysaccharides have the consistency required for typical industrial and consumer applications (Figure 10).

Specifically, the process integrates directly into existing sugar beet or sugar cane biorefineries and converts sugars into polysaccharides, which find applications across a series of end use markets typically replacing fossil-based incumbent materials (examples are shown in the figure below). Polysaccharides derived from this bioprocess are not only renewably sourced but also readily biodegradable, which is often a desired end-of-life characteristic.

Either sugarcane or sugar beet can be the feedstock for this process technology, both of which are globally available and fully fungible feedstocks produced within biorefineries operating and accessible at scale. Compared to agricultural crops farmed globally, both sugar beet and sugar cane already provide leading land-use efficiency with regard to biomass yield per hectare land. Sugar beet for example, as annual, multi-use rotational crop, has proven sustainable and continuous productivity and yield improvement through decades.

This emerging biomaterial platform technology connects directly sustainable agriculture within rural communities with the biorefinery infrastructure of existing beet or cane sugar processing to further expand the biocircular economy.

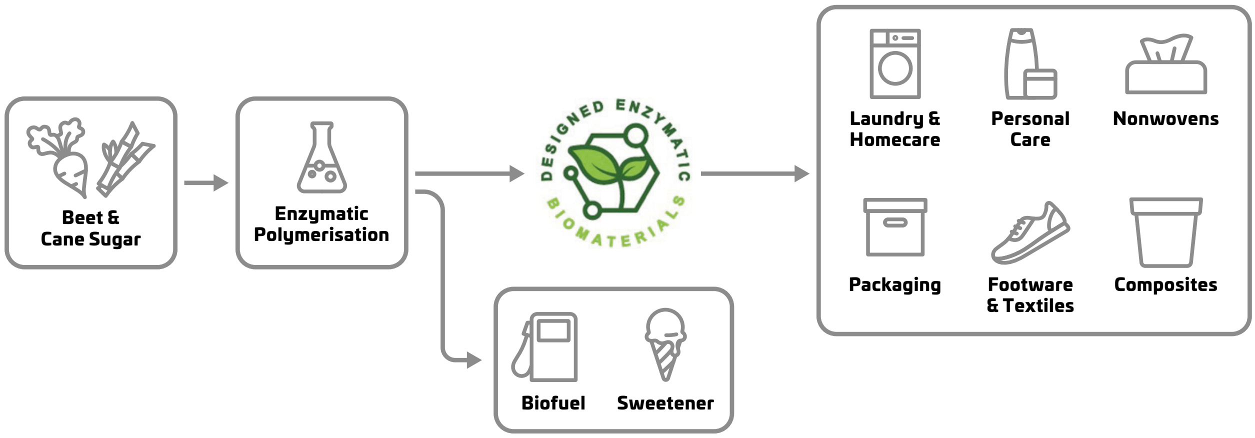


Figure 10: Designed Enzymatic Biomaterials

For example, attractive for the integration of the enzymatic polymerisation process within a beet sugar biorefinery is the fact that sucrose process streams are directly converted into the polysaccharide and a co-product fructose stream.

This process is 100% carbon efficient, no sugar is wasted through process losses or waste streams, and the entire material balance is converted to products within the biorefinery. The process parameters of the enzymatic polymerisation are tailored to achieve specific material properties to fit the application requirements.

LCA of Designed Enzymatic Polysaccharide Production

Life Cycle Analysis: IFF has carried out an extensive comparative Life Cycle Assessment (LCA), according to ISO 14040 and 14044 standards. To ensure compliance and validity of the LCA results, the study has been peer reviewed by a panel composed of experts from nova-Institute GmbH (DE) and leading subject matter experts within the EU beet sugar industry. The goals of this LCA assessment were

- To focus process design towards optimum sustainability impact;
- To quantify the critical environmental impacts of designed enzymatic polysaccharide production and subsequent applications.

For the sake of simplicity, this case study focuses on the baseline scenario with sugar beet production in Western Europe, use of co-product as food sweeteners and the substitution approach to account for co-product use. Results for other co-product uses, production from Brazilian sugar cane and for other allocation methods are included in the underlying LCA study.

Integrated Biorefineries

The peer-reviewed assessment included the options to integrate manufacture with existing European (EU) sugar beet mills or sugar biorefineries. Within biorefinery integration, specific end uses for the co-product fructose are included in the assessment, as well as appropriate fuel sources for sugar processing and the biomaterial enzymatic polymerisation processes.

The co-product fructose stream is used as a sweetener for soft drinks or confectionary products. Here, beet pulp co-product is used as animal feed, while energy is provided by natural gas boilers and grid electricity or natural gas cogeneration. The integration of co-products illustrates the benefits of process integration, feedstock utilization and optimization within a biorefinery.

Key Impact Areas of the LCA

Within this assessment it is critical to consider multiple key impact areas such as Global Warming Potential (GWP), non-renewable energy use (NREU), land use, water consumption, and water scarcity – together these parameters characterize the environmental impacts or benefits of the integrated biomaterial manufacturing process. For this case study, only GWP results are included.

The details provided in this case study are focusing on the EU manufacture:

- Functional unit: 1 kg of dry designed enzymatic polysaccharide (12.4% moisture);
- System boundaries: Cradle-to-gate;
- Energy sources are assumed to be natural gas and grid electricity supply.

The designed enzymatic biomaterial is produced from sugar beet derived from the beet refining process. The typical biorefinery streams include sugar beet farming, beet sugar refining with multiple co-products (biofuel ethanol, renewable electricity, beet pulps & molasses for animal feed, refined sugar for food applications), and which are now supplemented with the enzymatic biomaterial product from enzymatic polymerisation, along with the co-production of fructose (further converted to biofuel ethanol production or refined fructose syrup used as a sweetener) (Figure 11).

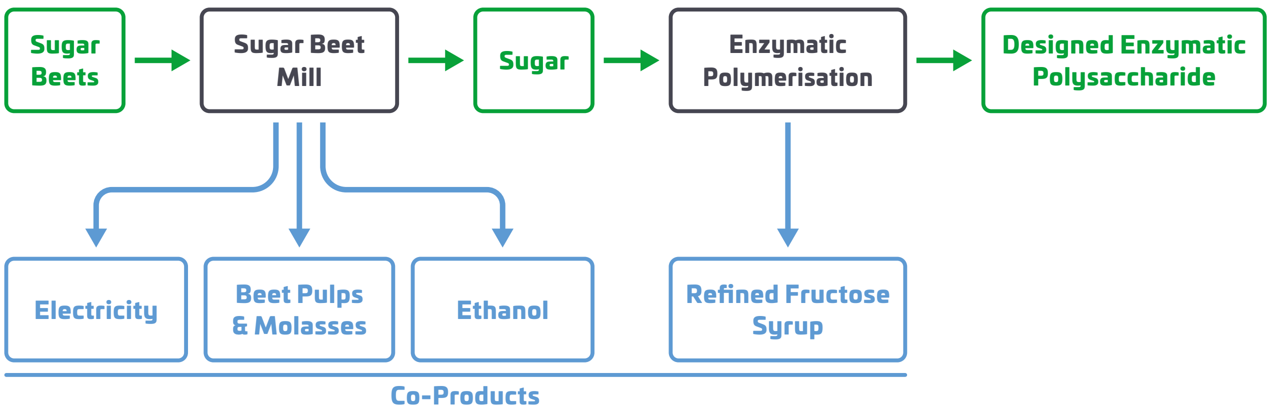


Figure 11: System boundaries for Designed Enzymatic Polysaccharide from sugar beets

A substitution approach was used to allocate the environmental burdens to the different co-products. Initially all burdens are assigned to the determining products: sugar (at the sugar mill) and enzymatic biomaterial (at the polymerisation facility). The burdens associated with displaced products in the market are subtracted from the overall impacts at each facility in succession:

- The produced electricity replaces electricity from the regional grid.
- The beet pulp & molasses are used for livestock and displace animal feed on an equivalent feed energy and feed protein basis.
- Ethanol co-produced in the sugar mill displaces equivalent amount of fermentable sugars required for production.
- Refined fructose syrup replaces fructose syrup produced from EU wheat starch.

Global Warming Potential Results

Excluding carbon sequestration, the GWP is 0.57 kg CO_2 eq. per kg designed enzymatic polysaccharide on a cradle-to-gate basis when the fructose co-product is used as a sweetener. Additionally, 1 kg of the designed enzymatic polysaccharide contains 0.39 kg biogenic carbon. Hence, during the sugar beet plant growth, 1.43 kg CO_2 was removed from the atmosphere. In contrast to fossil carbon, emissions of biogenic carbon do not contribute to global warming because all emissions at end-of-life of the product (through incineration or biodegradation) were removed from the atmosphere during plant growth.

So, when an LCA is carried out only from cradle-to-gate (where end-of-life is not included in the scope), the important difference between fossil and biogenic carbon embedded in the product must be reflected. To do so, the embedded carbon can be considered as negative GWP and positively influence the overall sum of emissions in a cradle-to-gate perspective. The credits for biogenic carbon uptake exceed the sum of impacts and co-product credits, providing a net benefit of 0.86 kg CO_2 eq. per kg DEB on a cradle-to-gate basis when using substitution. This is indicated by the black bar in the figure below (Figure 12).

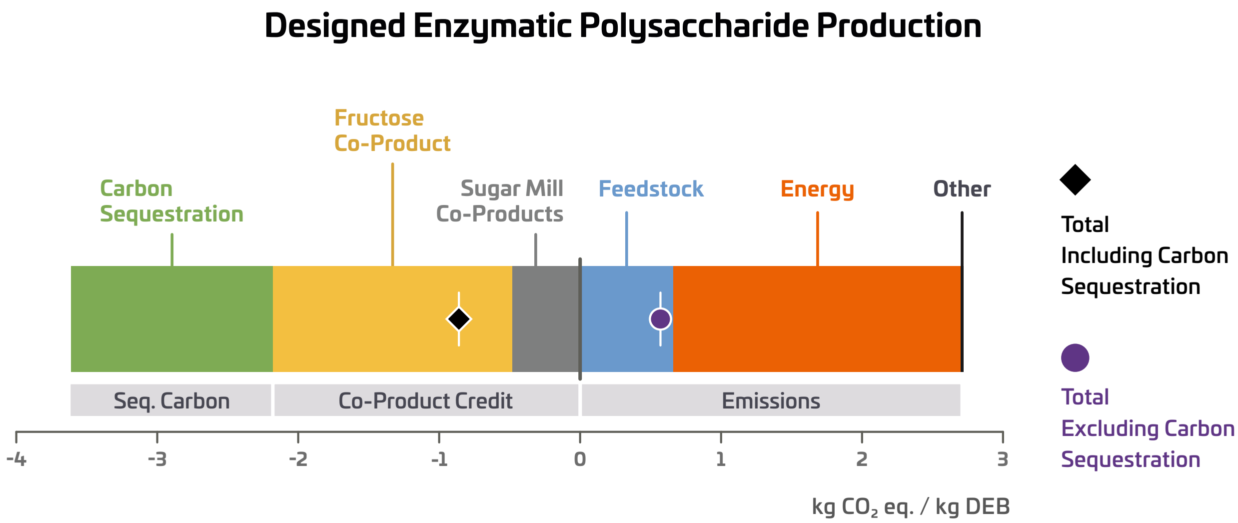


Figure 12: Global Warming Potential of DEP production

The largest impacts are caused by the fossil energy required to power sugar beet mills (assuming natural gas use). A switch to 100% renewable energy will reduce the impact from energy and further improve the GWP results significantly. Even co-generation provides substantial GWP savings.

Comparison of the designed enzymatic biomaterial (DEB) impact to synthetic materials from fossil carbon sources on a cradle-to-gate basis is difficult due to the difference between biogenic and fossil-based carbon. Ideally, end-of-life is included for both products to make a more accurate assessment. Biogenic carbon is removed from the atmosphere when making DEB, but in many applications, returns to the atmosphere at the end of life through incineration or biodegradation. On a cradle-to-gate basis, however, the biogenic carbon is physically sequestered in the designed biomaterial. At the end of life, a fossil-based material has the potential to further add contribution to GWP due to either incineration or degradation, while a biogenic carbon material has the potential to lose the benefit of the sequestered carbon.

In addition, the enzymatic biomaterials will fully biodegrade while the appropriate fossil derived incumbent material will typically not biodegrade but potentially generate microplastic contamination.

Conclusion

Designed Enzymatic Biomaterial manufacture integrated within a beet sugar biorefinery offers attractive opportunities to deliver direct low environmental impacts across key critical assessment categories essential for a successful transition towards a circular bioeconomy. The low greenhouse gas balance is especially significant, as greenhouse gas emissions related to the agricultural inputs and the enzymatic polymerisation manufacturing process are lower than the biogenic carbon uptake of the product itself.

These LCA results reveal that a consequent utilisation of all products and co-products from this integrated biorefinery can improve GWP impacts. In this application sugar beet is a particularly suitable renewable feedstock that yields several valuable co-products in a high biomass utilisation efficiency manner, supporting the transition towards the EU bioeconomy integration in existing rural communities (Figure 13).

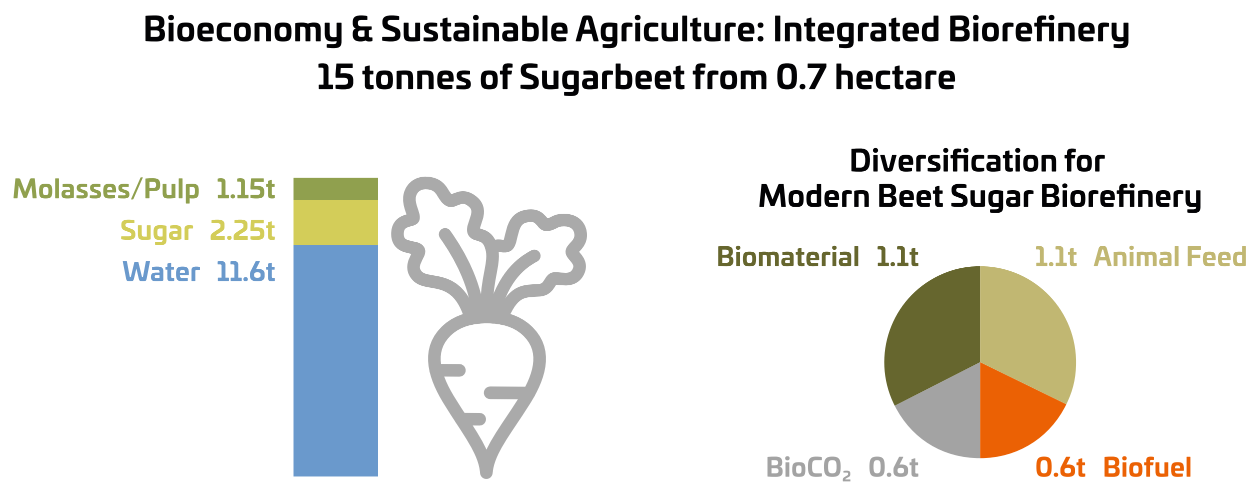
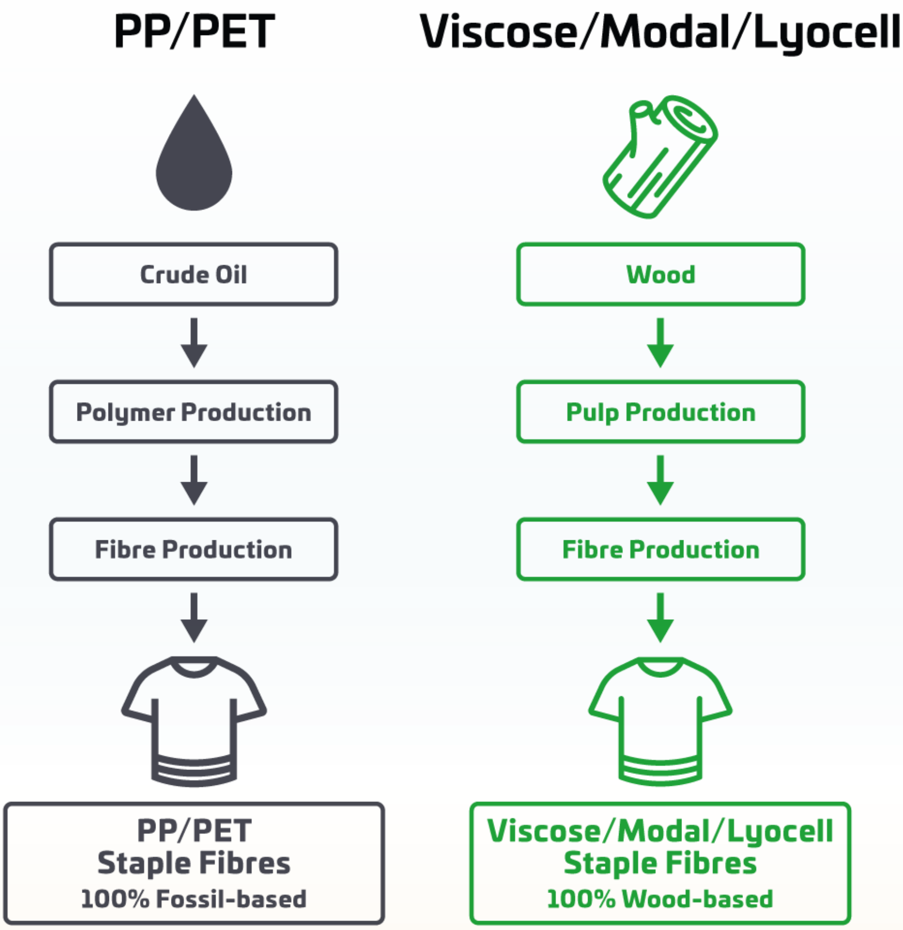


Figure 13: Sugar Beet: Efficient Land & Biomass Use

Lenzing's Viscose, Modal and Lyocell Fibres



Lenzing's Viscose, Modal and Lyocell Fibres

Cellulose is a key structural component of cell walls of plants and trees, and therefore a wood-based and in a wider sense bio-based material. Cellulose fibres are used for a wide range within textile, nonwoven and other industrial applications, ranging from home textiles over apparel textiles to technical textiles with very high property demands like tyre chord.

The LCA study[9] examined the three types of wood-based cellulose staple fibres that the company Lenzing can produce – viscose, modal and lyocell fibres. Lenzing is a world leading and globally active company with headquarters in Austria. A sample of one examined cellulose staple fibre type is shown in Figure 14.

Lenzing produces the three fibre types viscose, modal and lyocell fibers, which are sold under the brand names of TENCEL™ (lyocell and modal) and LENZING™ ECOVERO™ (viscose) in textiles, respectively VEOCEL™ (lyocell, viscose) in nonwovens business. The fibres differ in terms of their technical as well as haptical and optical properties due to their different production processes. The viscose fibre is produced in a conventional viscose process. Generally, viscose production is energy-intensive and requires large quantities of chemicals such as caustic soda and sulphuric acid. The modal fibre is produced in a modified viscose process, resulting in higher wet modulus fibres. The lyocell fibre is produced with the lyocell process, which uses less solvents and was commercialised in the early 1990s. Nowadays, all three types of fibres are produced simultaneously in large quantities.

Figure 14: Cellulose staple fibres.
Copyright by Lenzing, Photographer: Markus Renner

9 Shen, L. and Patel, M. K. 2010: LIFE CYCLE ASSESSMENT OF MAN-MADE CELLULOSE FIBRES. Group Science, Technology and Society (STS), Copernicus Institute, Utrecht University (Ed.), Lenzinger Berichte 88 (2010) 1-59, 2010. Download at https://www.lenzing.com/de/?type=88245&tx_filedownloads_file%5bfileName%5d=fileadmin/content/PDF/03_Forschung_u_Entwicklung/EN/Lenzinger_Berichte_88_2010.pdf

LCA of Cellulose Fibres

Already in 2010 Li Shen and Martin K. Patel from the Copernicus Institute of Utrecht University conducted a Life Cycle Assessment of man-made cellulose fibres viscose, modal and lyocell from Lenzing. In the study the fibres were named as follows: Viscose fibre as "Lenzing Viscose", modal fibre as "Lenzing Modal" and lyocell fibre as "Tencel". Nowadays, Tencel is the trademark for lyocell and modal fibres and the nomenclature used in the study is not anymore in line with current branding. However, here the naming from the peer-reviewed LCA study is used for the results of the study so the reader is able to compare the results of this summary with the original LCA study.

The LCA study was reviewed by three external and independent experts[10]. The reviewers verified that the LCA was conducted accordingly to the standards of LCA (ISO 14040 / 14044).[9]

The goals of the peer-reviewed LCA study were:

1. Identify the environmental impacts of Lenzing's man-made cellulose staple fibres viscose, modal and lyocell, produced in Europe and Asia.
2. Identify the environmental advantages and disadvantages of man-made cellulose fibres compared to cotton, bio-based polylactic acid (PLA) fibres and fossil-based polyethylene terephthalate (PET) and polypropylene (PP) fibres. For fibre comparison, fibres with similar properties to the cellulose fibres were chosen.

In the goal and scope phase the following aspects were defined:

- Functional unit: 1 t staple fibre
- System boundaries: cradle-to-factory gate
- Impact categories: Global Warming Potential 100 (GWP100a), Cumulative Energy Demand, Non-Renewable Energy Use (among others)
- Impact assessment method: CML 2000 baseline method

The system boundaries start at the extraction of raw materials from the environment (cradle). At that time, Lenzing used wood only from FSC certified wood suppliers. Nowadays, Lenzing operates also other pulp mills and uses PEFC certified wood, too. Additionally, Lenzing only uses wood with a quality which is unable to be used in furniture so the wood for the fibres does not compete with the need of wood for other high valued products.

In the next process step at Lenzing's production site in Europe the wood is processed to cellulose pulp. Finally, the cellulose pulp is transformed into cellulosic fibres in Lenzing's viscose, modal and lyocell processes (factory gate). For more details see the original LCA.[9]

10 Professor Adisa Azapagic, from The University of Manchester, UK;
Jürgen Giegrich, from the Institute for Energy and Environmental Research (IFEU) in Heidelberg, Germany;
Professor David Shonnard, from the Michigan Technological University in Houghton, MI, USA

Lenzing provided the production data from 2010 for the fibres viscose, modal and lyocell ("Tencel") for the European production site as well as some data from an Asian production site. For the comparison of Lenzing's cellulose fibres with reference fibres like cotton, PLA, PET and PP fibres, also for those fibres cradle-to-factory gate data was collected.

The fossil-based PET and PP fibres were modelled using datasets from PlasticsEurope representing average Western European production in the year 2000. The production data for PLA and cotton fibres were obtained from literature sources.

For this summary, the following data is selected:

- Comparative analysis between fossil-based PET/PP and Lenzing's man-made cellulose fibres. (A simplified process scheme of the fossil- and wood-based production pathways is shown in Figure 15.)
- Data only from European production sites
- Data from the year 2010
- GWP comparison of the fibres

Nowadays, Lenzing operates three additional lyocell production sites. Therefore, the here shown results are not representative anymore but shall show that already in 2010, companies like Lenzing provided a material with environmental benefits. For more in-depth information, see the original LCA.[9]

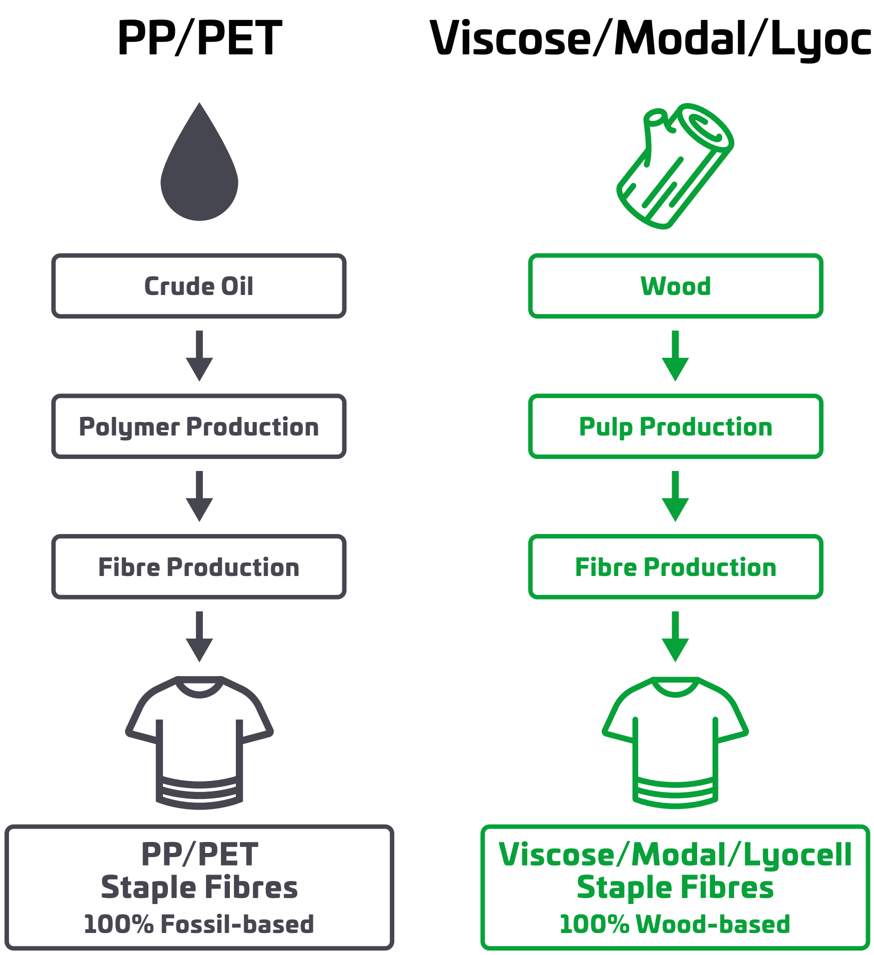


Figure 15: Schematic overview of fibre production for PP / PET and Viscose / Tencel / Modal fibres

Climate Change Impact Results – Cradle-to-factory Gate Boundary

The cradle-to-factory GWP results in t CO_2 equivalent (eq.) per t staple fibre for PET, PP, "Lenzing Tencel Austria", "Lenzing Modal" and "Lenzing Viscose Austria" fibres are visualised in Figure 16.

The grey columns show the fossil carbon emissions related to the production processes for each fibre type. The results show a GWP of 4.1 and 2.8 t CO_2 eq./t fibre for PET and PP fibres respectively. The results for the wood-based process emissions are lower than for the PET and PP fibres with 2.5 t CO_2 eq. per t fibre for "Lenzing Tencel Austria", 1.2 t CO_2 eq. per t fibre for "Lenzing Viscose Austria" and 1.5 t CO_2 eq. per t fibre for "Lenzing Modal". This shows that the GWP process emissions for the production of wood-based fibres is lower than the process emissions for the production of fossil-based fibres when both fibre types (wood and fossil-based) are produced in Europe.

The green columns represent the biogenic carbon embedded in the wood-based products, which can be considered as negative GWP. This is plausible, as during the feedstock growth (wood) carbon was removed from the atmosphere and embedded in wood, then called "embedded biogenic carbon".

During the End-of-Life, which is not considered here, the embedded biogenic carbon in the wood-based product but also the embedded fossil carbon in the fossil-based product is released into the atmosphere and both contribute to the GWP in a cradle-to-grave scenario.

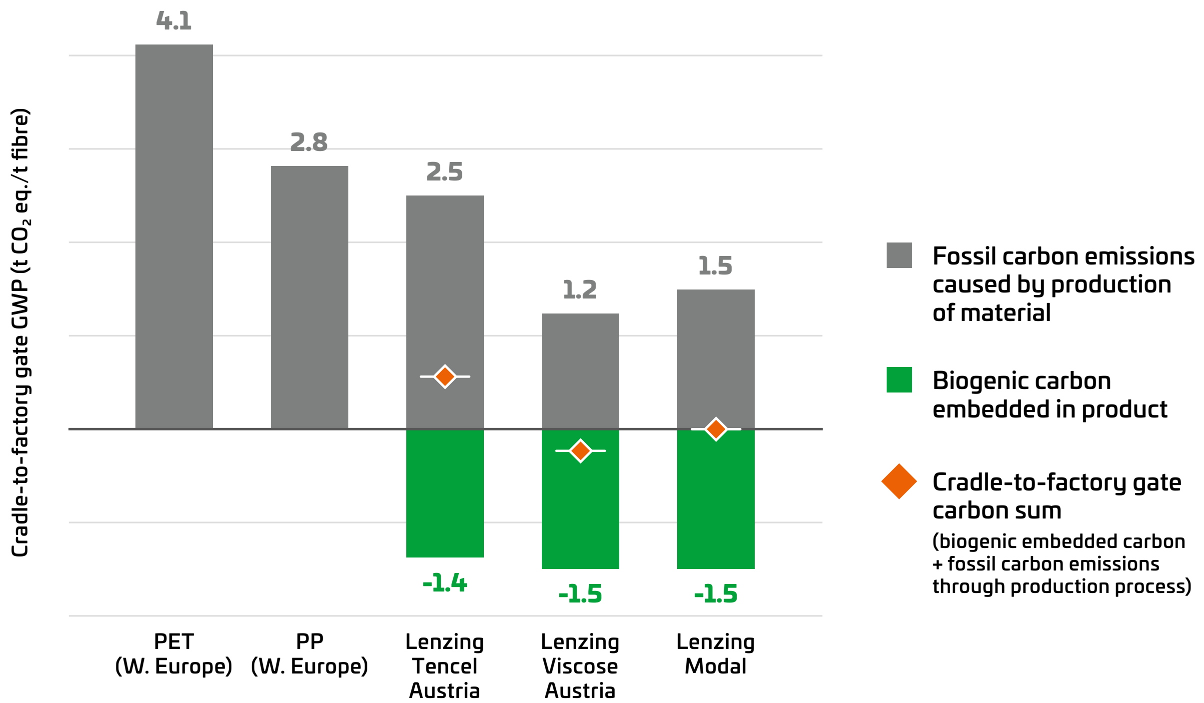


Figure 16: Global Warming Potential (GWP) of PET, PP, Lenzing Tencel Austria, Lenzing Viscose Austria and Lenzing Modal fibres for a cradle-to-factory gate system boundary

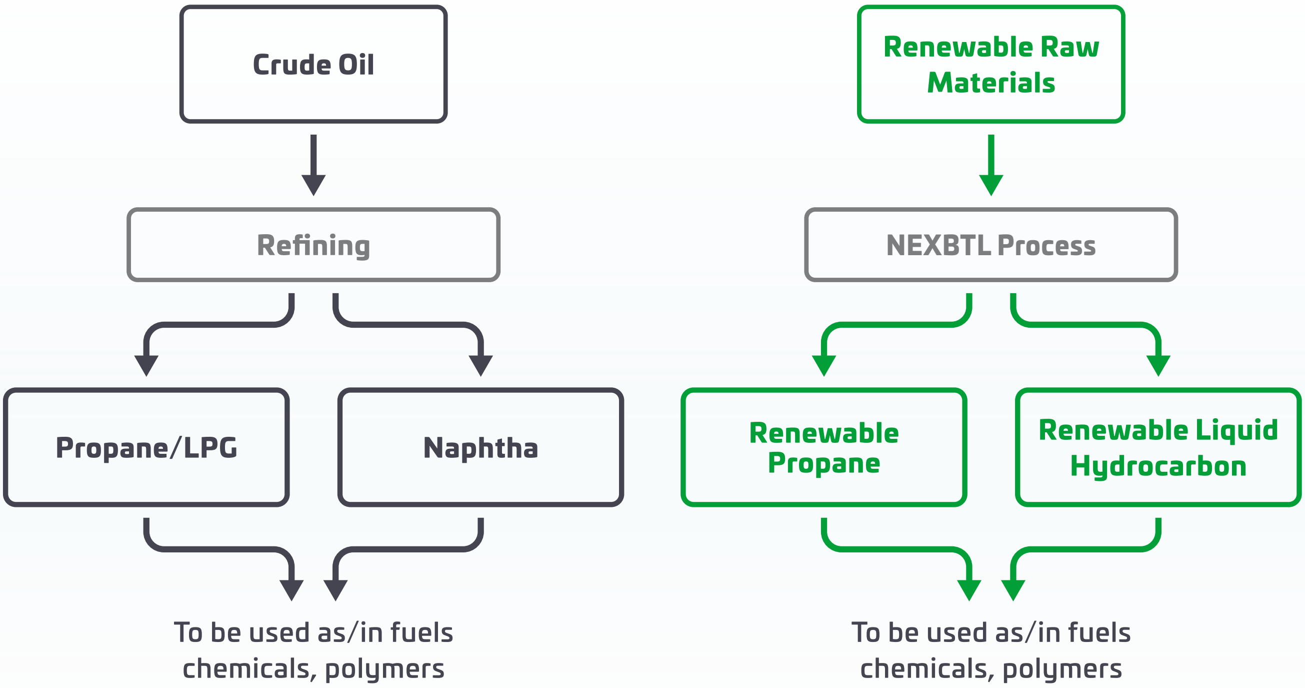
The cellulose fibres contain around 1.4 to 1.5 t CO_2 eq. embedded biogenic carbon per t fibre. If embedded biogenic carbon is considered as negative GWP in a cradle-to-gate scenario, it positively influences the overall sum (net) of emissions, which is visualised with the depicted orange dots, see Figure 16. Then the net GWP emissions are even lower for the wood-based products, for European data.

Conclusion

The LCA results show that the wood-based man-made cellulose fibres “Lenzing Tencel Austria”, “Lenzing Viscose Austria” and “Lenzing Modal” produced in Europe offered already in 2010 the potential for reducing greenhouse gas emissions compared to petrochemical PET and PP synthetic fibres produced in Europe.

This shows, that these naturally bio-based cellulose fibres are a more favourable choice from a climate change point of view than their reference fossil PP and fossil PET fibres. As the study was conducted in 2010 it is probable that the processes for producing viscose, lyocell and modal fibres at Lenzing have undergone some changes and optimisations. Therefore, the here shown results are not representative anymore but shall show that already in 2010, companies like Lenzing provided a material with environmental benefits. For more information, please see the original LCA study.[10]

Neste NEXBTL Technology
Renewable Products



Neste NEXBTL Technology Renewable Products

Neste is the world's leading producer of sustainable aviation fuel and renewable diesel, and renewable feedstock solutions for various polymers and chemicals industry uses. The company developed a proprietary technology called NEXBTL™ to produce renewable products from a wide variety of renewable fats and oils, even low-quality waste and residues. These renewable products can typically replace conventional kerosene or diesel as fuel for aviation or automotive, or replace for example naphtha as a key feedstock used in steam cracking.[11]

Neste uses a wide variety of sustainable, globally-sourced raw materials each year to produce its renewable products. Currently, over 90% of these are wastes and residues. Used cooking oil, animal fat waste, and various wastes and residues from vegetable oils processing represent the top three waste and residue raw material categories Neste uses.

NEXBTL technology is currently used at Neste's renewable products refineries in Porvoo (Finland), Rotterdam (The Netherlands) and Singapore with a current (2022) total capacity of 3.3 Mt of renewable products. Neste's total renewable capacity is set to increase to 6.8 Mt by the end of 2026.

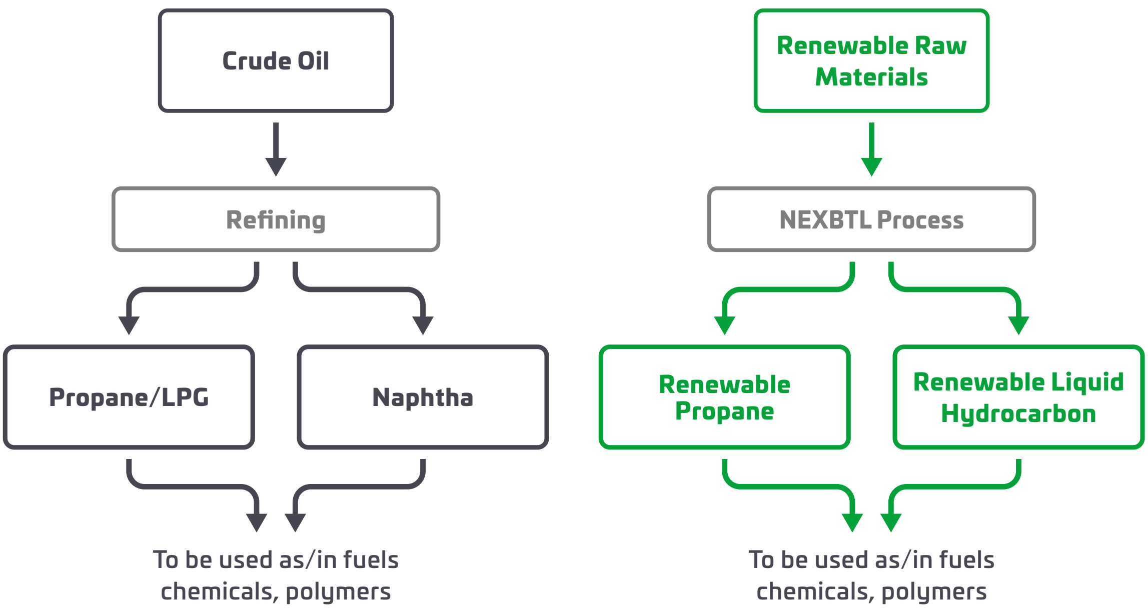


Figure 17: Schematic overview of Neste's value chain vs. a conventional fossil-based value chain

11 Steam cracking is a process in which naphtha is thermally cracked by using steam to produce lighter hydrocarbons; those hydrocarbons can in turn be used for the synthesis of conventional chemicals and polymers.

LCA of Neste's Renewable Feedstock for the Polymers and Chemicals Industry

Neste performed a cradle-to-gate Life Cycle Assessment (LCA) for the production of renewable hydrocarbons for use as cracker feed via the NEXBTL process, including potential greenhouse gas (GHG) emissions released by the products at the End-Of-Life, in order to assess its environmental impacts. The LCA met the requirements as per ISO 14040/44 and ISO 14067. A critical review of the study by peers, including experts of incumbent technologies, was conducted in order to verify that the LCA met the requirements for methodology, data, interpretation, and reporting.

Products and Functional Unit

Renewable liquid hydrocarbons, renewable propane and polypropylene (based on steam cracking of the liquid hydrocarbon), served as intermediates and end products of the LCA study. One kilogram (1 kg) of a given intermediate or end product was chosen as the functional unit.

This short summary focuses mainly on the Global Warming Potential (GWP) impact category related to the production of **renewable liquid hydrocarbons.** In the full LCA study a wider set of impacts were evaluated.

Fossil naphtha was used as a fossil reference to the renewable liquid hydrocarbons. Naphtha is the most representative fossil reference product in this context since the renewable hydrocarbons can be used to substitute fossil naphtha in a steam cracker.

Neste has an extensive raw materials portfolio, which provides flexibility to meet varying market and customer demands and requirements.

Animal fat waste, used cooking oil and various wastes and residues from vegetable oils processing represent the top three largest waste and residue raw material categories in the order of their current and estimated shares of Neste's total annual renewable raw material inputs.

Neste sources wastes and residues globally for renewables refineries located in Finland, the Netherlands and Singapore.

Neste's supply chain management is based on the company's sustainability policies and principles. Therefore, Neste accepts only sustainably-produced renewable raw materials from carefully selected partners.

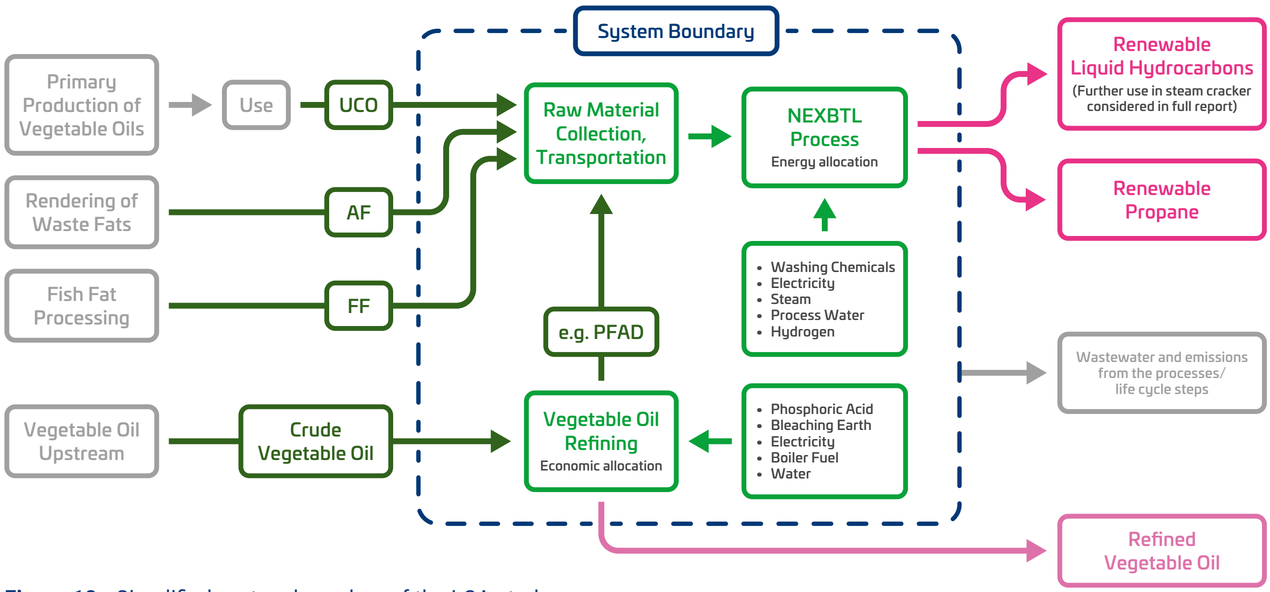


Figure 18: Simplified system boundary of the LCA study

System Boundaries

The LCA covered all relevant life cycle stages from cradle-to-gate, i.e., from resource extraction (cradle) to the factory gate, including all relevant transportation activities. A representative Neste average raw material mix was selected consisting of used cooking oil (UCO), animal fat (AF), and residues from vegetable oil processing. The waste and residues from vegetable oil processing were modelled in the LCA using palm oil fatty acid distillate (PFAD) to represent such raw materials. A small amount of fish fat (FF) was added to the LCA study to widen the raw material pool. UCO, AF and FF are considered waste streams that enter the process with no environmental burden associated, apart from their collection and transportation.

In addition to the collection step, the refining step in which PFAD is separated during crude palm oil processing is included in the system boundary. The collection step of the raw material is followed by the production of liquid hydrocarbons with the NEXBTL process.

End-of-Life

End-of-life emissions have been considered assuming 100% release of the carbon contained in the product to the atmosphere as CO_2. The amount of CO_2 released is calculated from the carbon content of the product based on stoichiometry, but no burdens, nor benefits, from the end-of-life process are considered.

Allocation

The environmental burdens are allocated differently along the life cycle. UCO, AF and FF are considered as waste, as they are no longer fit for human consumption.[12] Thus, the upstream emissions (farming, rendering, production) are allocated to meat/ fish/ fried food, and UCO, AF and FF enter the system boundary without burdens. For the exemplary PFAD raw material, the upstream emissions of palm cultivation are allocated to the food-grade refined palm oil, as PFAD is a processing residue of the vegetable oil refining process. However, the vegetable oil refining burdens are economically allocated between PFAD and the refined palm oil.[13]

12 Waste cooking oil (used cooking oil) is defined as waste in accordance with the definition of waste in the Waste Framework Directive 2008/98/EC and, therefore, is attributed zero GHG emissions at its point of collection in accordance with RED.

13 The scope of the waste and residue raw materials follows the Renewable Energy Directive (RED) requirements for the GHG emission calculations, except for the addition of the crude palm oil refining process allocated to PFAD.

For the NEXBTL process, the environmental burdens were allocated between liquid hydrocarbon and propane based on their energy content.

Inventory Data

Transportation steps from raw material sourcing locations to Neste production sites are included and based on Neste's actual supply chain. The inventory data for the exemplary vegetable oil refining is based on Yung et al (2020).[14] Primary data relating to the hydrotreatment of raw materials is based on Neste's NEXBTL technology and refining process data from the operational units in Porvoo (Finland), Rotterdam (the Netherlands) and Singapore. All relevant material and energy flows are included in the study. Some minor flows are excluded due to their negligible amounts according to the cut-off criteria. GaBi 2021.1, Ecoinvent 3.7.1 and PlasticsEurope databases and peer-reviewed literature have been used as secondary data sources and for the fossil benchmarks. The End-of-Life scenario considers the release of the carbon in the product to the atmosphere as CO_2, assuming a 100% oxidation of the product at the End-of-Life. Incineration processes have not been modelled.

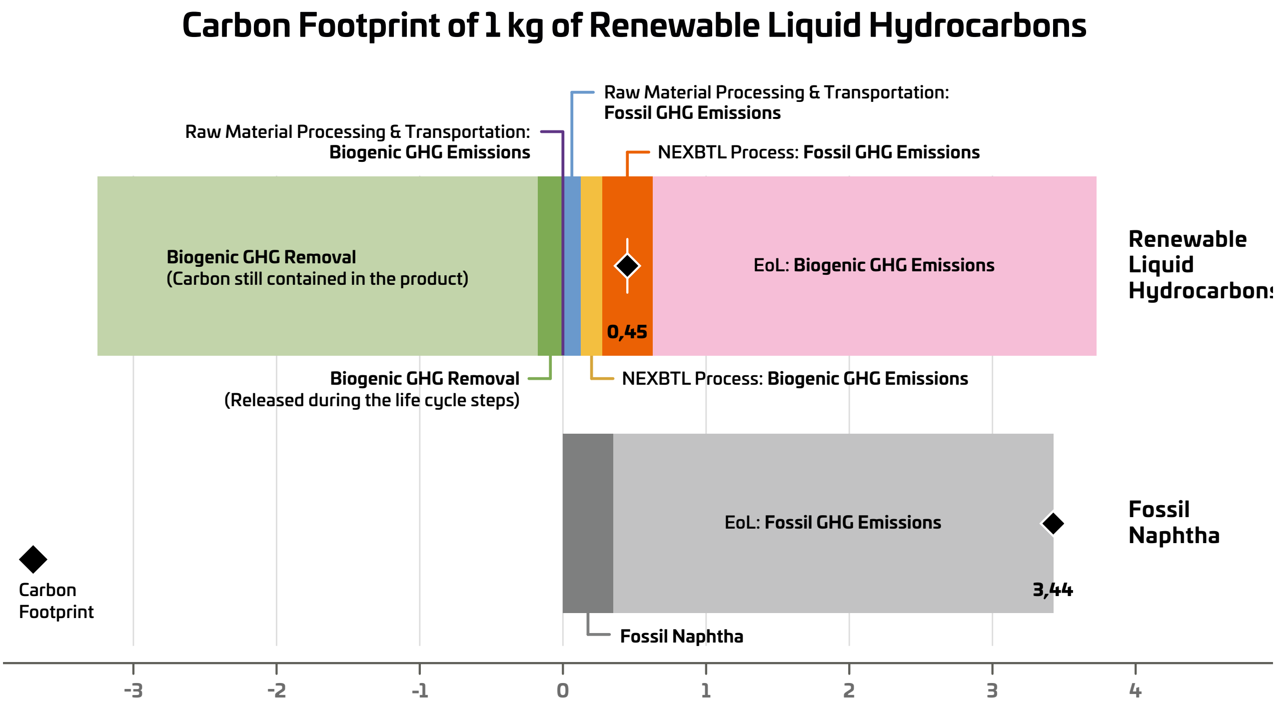


Figure 19: GWP of 1 kg of Neste Renewable liquid hydrocarbons per life cycle step. GWP results include the End-of-Life scenario. The biogenic GHG emissions include biotic carbon dioxide and methane emissions. The GHG emissions during the life cycle are mainly CO_2 emissions. The amount of methane emissions (generated in the background processes) is negligible.

14 Yung, C., Subramaniam, V., Yusoff, S. 2020. Life cycle assessment for palm oil refining and fractionation. Journal of Oil Palm Research Vol. 32 (2) June 2020 p. 341-354. DOI: https://doi.org/10.21894/jopr.2020.0029

Climate Change Impact Results[15]

For the Neste renewable liquid hydrocarbons, the net GWP (including the emission of the biogenic carbon contained in the product at the End-of-Life as CO_2) results in 0.45 kg CO_2 eq./kg of product. Compared to fossil naphtha, the Neste renewable liquid hydrocarbons have at least 85% lower GWP. To a great extent, the lower GWP of the renewable liquid hydrocarbons can be attributed to the biogenic removals from CO_2 uptake during biomass growth and the subsequent biogenic emissions during the life cycle steps and end-of-life (when the biogenic carbon contained in the product is released as CO_2 emission into the atmosphere).

The main contributing stage is the NEXBTL process, more specifically the hydrogen and energy (thermal energy from natural gas, electricity) production.

Conclusion

The results showed a significant potential reduction (> 85%) in GHG emissions for renewable liquid hydrocarbons when compared to reference fossil-based naphtha. A sensitivity analysis, as part of the LCA full report, investigated the impact of certain assumptions made in the study. In all scenarios of comparing the renewable products to the fossil references, the renewable products were found to have lower GWP.[16]

Other products assessed in Neste's LCA included renewable propane and renewable polypropylene from steam cracking of liquid hydrocarbon. Both showed significant potential reduction in GHG emissions (> 80%) when compared to fossil-based products.

Further GHG reduction potential can be expected in the future, through progress in raw material availability, background processes and evolution of the NEXBTL technology. This insight should highlight the need for transitioning from fossil-based to renewable materials and chemicals.

15 Impact assessment method: CML2001 - Aug. 2016

16 Sensitivity analysis of the results towards different allocation procedures for raw materials are included in the main report.

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RCI Position Papers

- **RCI's Position on Comprehensive Carbon Management**
  October 2023
- **RCI's Position on the Commission Proposal for a Green Claims Directive (GCD)**
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- **RCI's Manifesto for the next European Commission (2024-2029)**
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- **RCI's Position on the Commission Proposal for a Packaging and Packaging Waste Regulation**
  May 2023
- **RCI's Position on the Communication on Sustainable Carbon Cycles**
  April 2023
- **Letter to the Commission on the Definition of Natural Polymers in the Reach Microplastics Restriction**
  February 2023
- **RCI's Position on Mass Balance and Free Attribution**
  October 2022
- **RCI's Position on the Draft EU Policy Framework on Bio-Based, Biodegradable and Compostable Plastics**
  October 2022

RCI Scientific Background Reports

- **Case Studies Based on Peer-reviewed Life-Cycle Assessments – Carbon Footprints of different Renewable Carbon-based Chemicals and Materials**
  November 2023
- **Renewable Carbon as a Guiding Principle for Sustainable Carbon Cycles**
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- **Making a Case for Carbon Capture and Utilisation (CCU)**
  July 2023
- **The Use of Food and Feed Crops for Bio-Based Materials and the Related Effects on Food Security**
  June 2023
- **RCI Carbon Flows Report: Compilation of Supply and Demand of Fossil and Renewable Carbon on a Global and European Level**
  March 2023
- **CO_2 Reduction Potential of the Chemical Industry Through CCU**
  May 2022

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