The production of renewable chemicals via thermo-chemical recycling at the plastic conversion plant (PCP)

Report 2

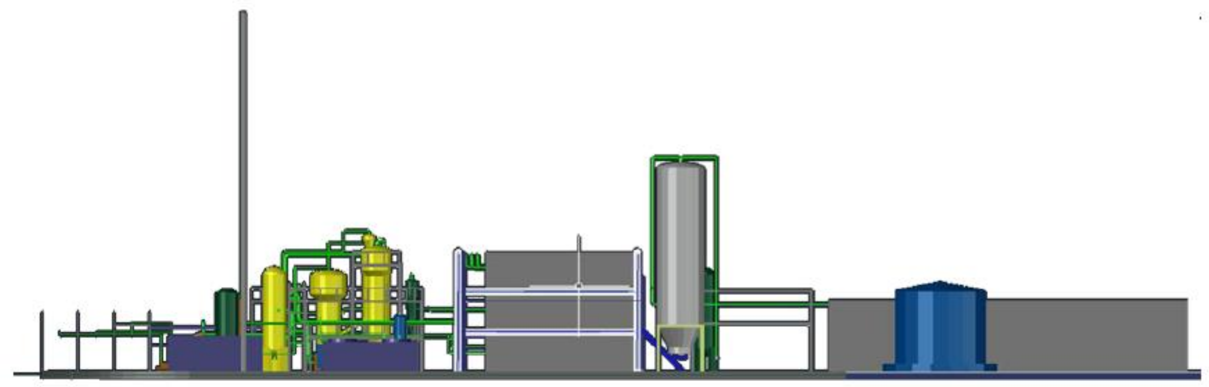

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Figure 1 Preliminary arrangement for the dedicated plant location in Delfzijl. Beris, 2020 out of the report TH, 2020

Preface

PCP B.V. focuses on producing *renewable* chemicals by making a crude mix of benzene, toluene, xylene (BTX), and oil from waste streams via a patented thermochemical recycling process. In the near future, a full-scale Plastic Conversion Plant (PCP) will be built in Delfzijl (The Netherlands).

In the first quarter of 2021, a screening life cycle assessment was commissioned by PCP B.V. to investigate the potential environmental impact of the plastic conversion plant. To compare the change of impact, a reference system (business-as-usual) was defined for both BTX production and mixed plastic waste. At the beginning of 2022, some additional system comparisons were requested including an update of the impact data. Two reports have been written. The first report focuses on additional feedstock scenarios, and the **second report focuses on alternative processing systems.** Both reports present a broader perspective and include an updated life cycle inventory database and the results of the system comparisons.

Disclaimer

This LCA serves as an environmental ***screening assessment*** *in which the intended system (PCP) is analysed and put into perspective next to alternative pathways. The results of this LCA are for PCP B.V. to be used internally including distribution among potentially interested parties (financiers, investors, partners and clients) to give an initial indication. Any further distribution* ***is only allowed*** *with consent of PCP B.V.*

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Abbreviations and Definitions

In the following section abbreviations and definitions in this report are explained:

Abbreviations

DKR-350: Predefined mixed plastic waste sorted by waste processors from mixed plastic waste. Mainly consists of PET, PE, and PP.
F-BTX: Fossil BTX - B, T, and X that is produced via the conventional pathway based on fossil resources
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory – Inventory of all found in- and outputs of the assessed system, including the corresponding emissions
LCIA: Life Cycle Impact Assessment – Assessing and weighing the impacts found in the LCI
MPW: Mixed Plastic Waste, used in this report to refer to DKR-350 as input for the PCP process
PCP: Plastic Conversion Plant
PCP process: Refers to the process of conversing applicable feedstock into BTX and other products at the Plastic Conversion Plant
R-BTX: Renewable BTX - B, T, and X that is produced by the Plastic Conversion Plant based on mixed plastic waste.
WS: Wood scraps, or leftover woods from natural managed forests.

Definitions

Crude BTX: This term is used to refer to a non-purified BTX mixture, which is the final product of the PCP process
Renewable BTX: According to the definition of the Renewable Carbon Initiative, BTX produced via the PCP plant avoids a part of the fossil production route of BTX in a Business-As-Usual case. This means that existing carbon in the biosphere, atmosphere or technosphere is used instead of releasing new carbon from the geosphere (fossil carbon). Therefore the BTX produced at the PCP plant is referred to as Renewable BTX in this report
Renewable carbon: "Renewable Carbon entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere. Renewable carbon can come from the biosphere, atmosphere, or technosphere – but not from the geosphere. Renewable carbon circulates between biosphere, atmosphere or technosphere, creating a carbon circular economy" (The Renewable Carbon Initiative, 2022). Recycling encompasses techniques that help circulate carbon within the technosphere.
Renewable carbon gas: Gas that is produced during the plastic conversion process as a co-product of the conversion from DRK 350 waste into BTX. According to the definition of Renewable carbon, this gas avoids additional natural gas production from fossil sources, and thus this gas will be referred to in this report as renewable carbon gas
Downcycling: to recycle (something) in such a way that the resulting product is of a lower value than the original item

Executive summary

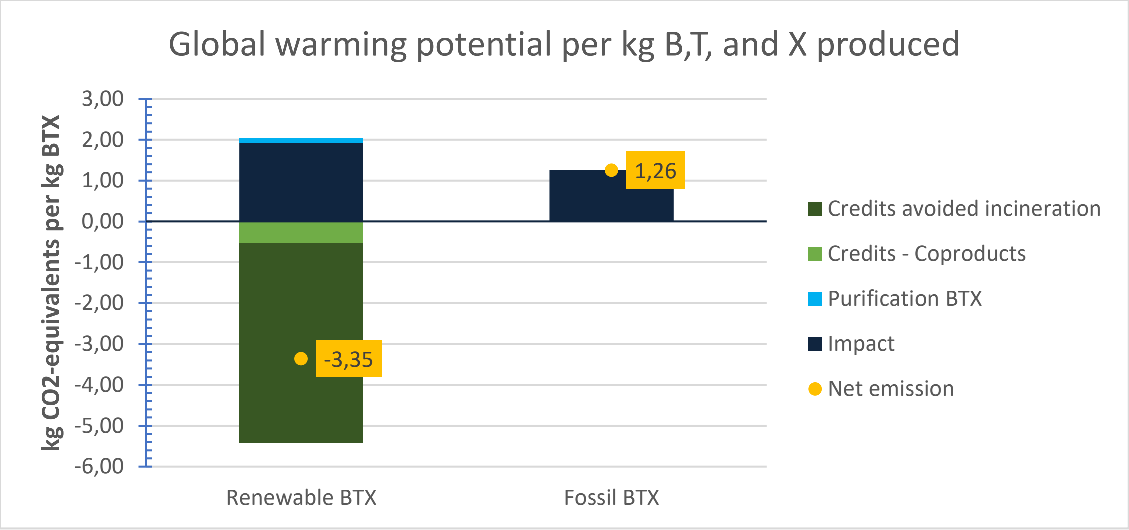
Due to the ever-increasing developments & investments within the plastics recycling market, often the discussion is held on whether chemical- or mechanical recycling is a more ''environmentally friendly'' choice. In reality, these recycling techniques are complementary to each other and both have their strengths and weaknesses. When focussing on the utilization of MPW (DKR350), it could be stated that due to a lower energy demand for mechanically recycling MPW into a product such as a plastics bollard, it will have a better environmental performance in comparison to the more energy-intensive chemical recycling technology.

In this report, a screening LCA has been carried out for PCP B.V. to investigate the potential environmental impact of the soon-to-be-built Plastic Conversion plant. In this plant, mixed plastic waste (MPW) will be converted into a BTX mixture (benzene, toluene, and xylenes). Once separated, the separate B, T and X serve as important building blocks for a large variety of applications, from producing chemicals or substances to building blocks for high-end products like plastics. This produced BTX is referred to as Renewable BTX in this report (R-BTX). In addition to the system in which R-BTX is produced from MPW, two alternative recycling systems are analysed; incineration of MPW and an alternative processing route of MPW to a bollard.

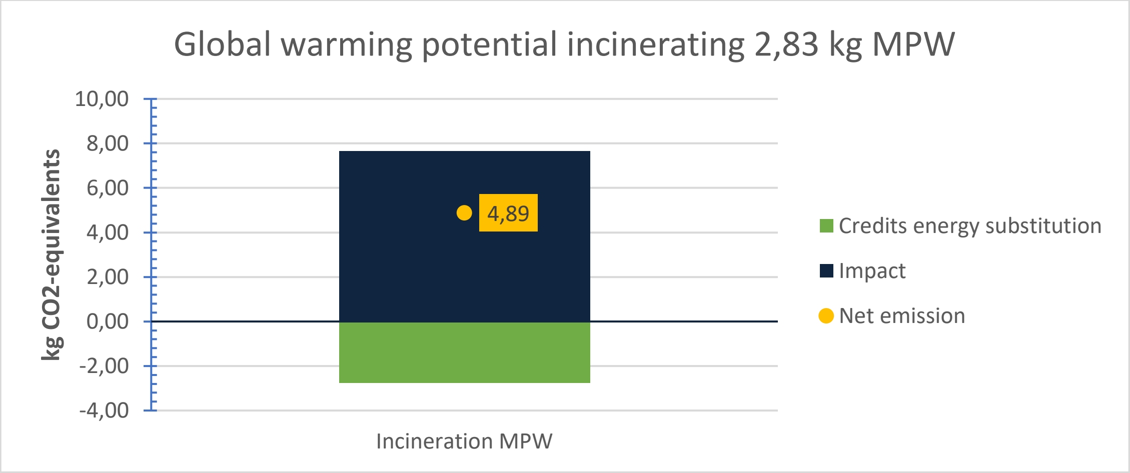
In the main scenario the following functional unit was used: The production of a purified renewable BTX mix by the Plastic Conversion Plant with the equal quality as its fossil-based B, T, and X counterparts, for use in Europe. The reference flow, in which all results will be expressed, has been set on the production of 1 kg purified (virgin fossil grade) B, T, and X.
For the second (incineration) and third scenario (alternative MPW recycling route), the amount of MPW that is required for the production of 1 kg of R-BTX is used: 2,83 kg of MPW. With an input of 2.83 kg of mixed plastic waste, 2.76 kg of bollard product can be made. The resulting impact of the R-BTX production was -3.35 kg, the incineration on 4.89 kg and the alternative processing route to bollard product was -4.29 kg CO_2-equivalents respectively. The credits for avoided incineration and avoided alternative materials for bollards have a large influence on the net emissions.

The credits for the bollard depend on the assumption which alternative materials are avoided, and in the case of wood, the type of wood is of influence as well (European managed wood or tropical managed wood). When putting this into the perspective of this LCA, the production of BTX has to be considered. When the alternative feedstocks are used for other processes, the demand for BTX can only be met by following the fossil business-as-usual route. Therefore, when taking the 'bigger picture' into account, it could be argued that making bollards from MPW prevents the production of renewable BTX.

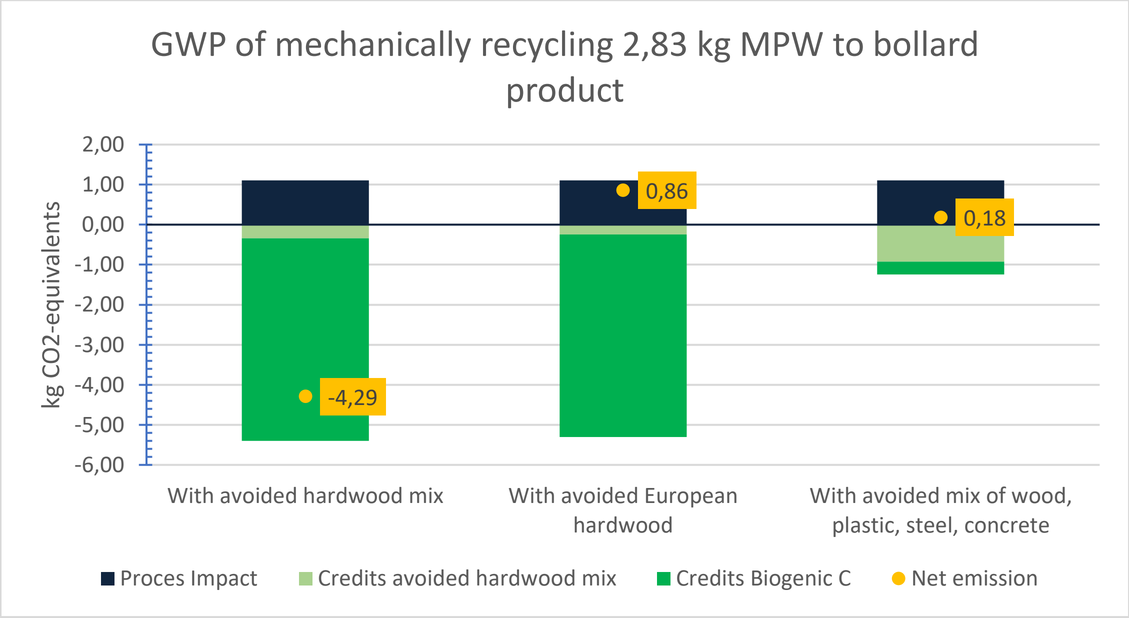
Finally, as further explained in this report, many important circular economy aspects are omitted in this comparison such as material quality/performance, material value, supply & demand. Therefore, in addition to the LCA approach taken above, an exploration of alternative approaches is given in the discussion. In short, it can be concluded that comparing chemical recycling with mechanical recycling proves to be a complex practice in which in addition to the associated emissions also factors such as material value and supply and demand have to be added. To make a fair comparison that is future-oriented, the market dynamics (carbon tax) and changes over time would have to be included in the overall environmental impact.



The environmental impact of producing 1 kg of Renewable B,T, and X via the PCP plant



The environmental impact of incinerating 2.83 kg MPW in a waste-to-energy plant with energy recovery



The environmental impact results of processing 2.83 kg MPW into 2.73 kg bollard material.

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Introduction: Renewable Carbon

In all everyday products, carbon is an important element: it is the backbone of almost all chemicals and materials used by mankind today. This demand for carbon is nowadays met by the use of fossil resources: resources that have been storing carbon in a long cycle for millions of years. After the products made from these fossil resources have served their purpose, this 'fossil' carbon is released and adds to the present carbon dioxide (CO_2) in the atmosphere, which in its turn is one of the contributors to climate change. Between 2015 and 2020, more than half of the total global carbon demand originated from the chemical and derived materials sector (Nova institute, 2021) and this demand is expected to grow between now and 2050 by roughly 100%.

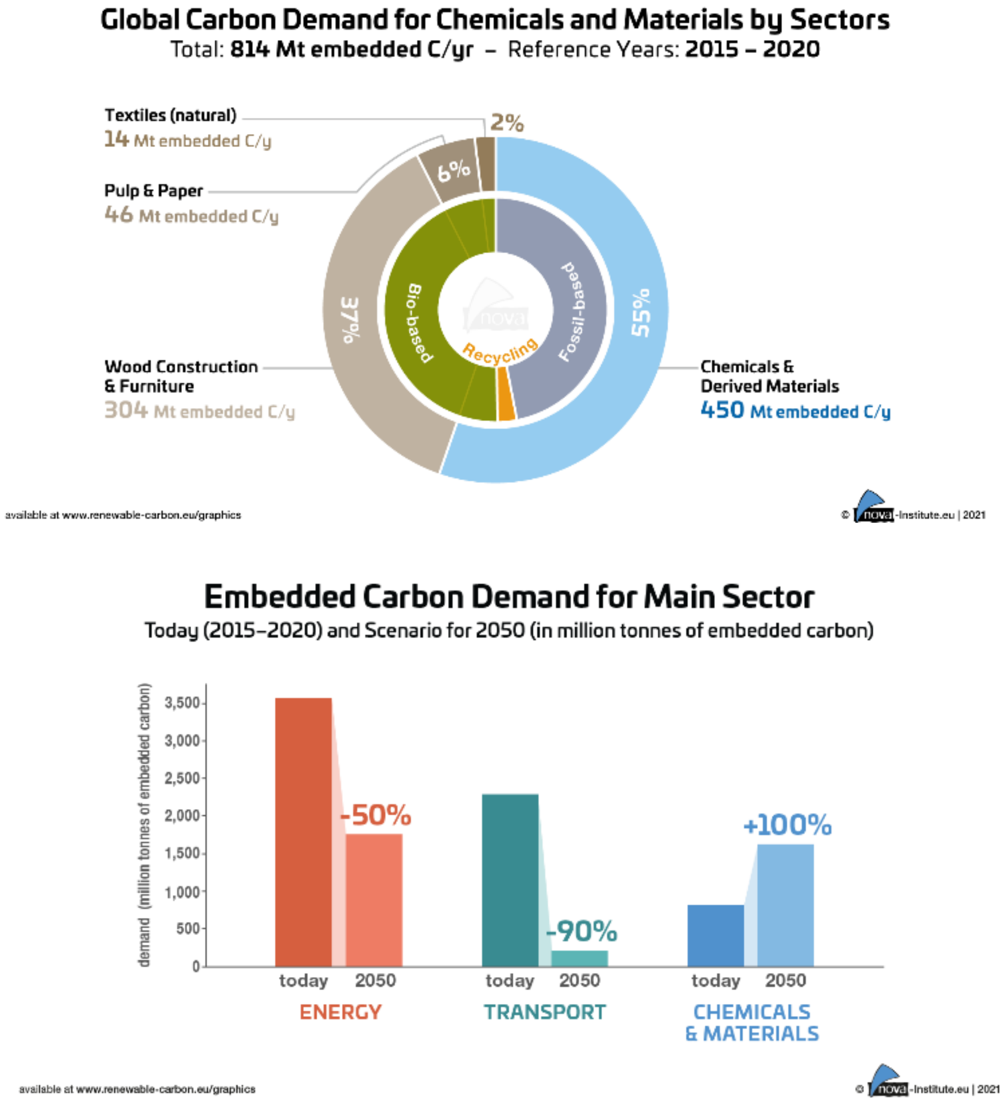

Figure 2 Above: The global carbon demand for chemicals and materials by sectors. More dan half of the carbon demand is placed by the Chemicals and derived materials sector. Below: The embedded carbon demand (what is stored in products) and the projected demand for the energy, transport and chemicals & materials sector. Both figures: Porc. et. al. 2021. Figures are available at www.renewable-carbon.eu/graphics

With the necessity to reduce the amount of emitted carbon, solutions have been proposed over the years. A few examples are emission reduction of carbon dioxide, utilizing biobased resources, and the transition towards a circular economy. The Renewable Carbon Initiative has launched a vision that combines these loose solutions into one overarching vision, creating a sustainable loop of carbon (renewable carbon). This vision consists of three options that can reduce the increase of fossil carbon, on one hand, and utilizes the existing and future demand for carbon on the other hand (The Renewable Carbon Initiative, 2022):

1. Use of biogenic carbon from biomass
2. Capture and use of carbon in processes
3. Recycling to ensure the carbon stays in the cycle

Cascaded recycling

To store carbon as much as possible in its various forms and to keep it that way at its end of life, the principles of the four R's are of relevance:

1. **Reduce** – prevent the use of a material or product in the first place
2. **Reuse** – reuse of a material or product saves the demand for a replacement
3. **Recycle** – save materials by recycling them into similar or other products
4. **Recover** – non-recyclable parts still can be incinerated to recover heat and/or electricity

This principle is included in the waste hierarchy of the current National Waste Management Plan (Ministry of Infrastructure and Water Management. 2021). Translated, it includes the following steps from most to least preferred:

A. Prevention
B. Preparation for re-use
C1. Recycling of the original functional material in a similar or comparable application
C2. Recycling of the original functional material in a non-similar or comparable application
C3. Chemical recycling (however in some sector plans it also can be placed at C1 or C2)
D. Other useful applications, among others energy recovery
E1. Incineration intended to remove material
E2. Dumping or landfill

In 2019, a study by CE Delft was carried out in which the policies on chemical recycling in the Netherlands were discussed. There, the authors suggested splitting C3, chemical recycling and dividing it over C1 (depolymerisation, solvolysis) and C2 (Pyrolysis, Gasification), depending on the specific chemical recycling technique. These techniques are classified as widely applicable (including food grade materials) and can achieve a virgin quality value. (CE Delft, 2019b). Based on a waste perspective of 1 kg of plastic waste, reported emission reductions are between 1 and ~3 kg CO_2-equivalents.

When this hierarchy is combined with a retained material value and the circularity of the resulting output, the following additional distinction between the different steps can be made (see figure 3). Note that there is a difference between upcycling, recycling and downcycling which depends on the destination of the recycled material(s). In the case of upcycling, the recycled material is utilized in a product with a higher material value. Recycling means the recycled material is used for the same or comparable value. With downcycling, the recycled material is used in a product of a lower value than the original item (e.g. recycling paper sheets into toilet paper). Furthermore, incineration with energy recovery and without energy recovery are different as well. Renewable BTX is situated in the D1/D2 scale as the resulting products (R-BTX) can be used in the production of comparable and/or higher value products.

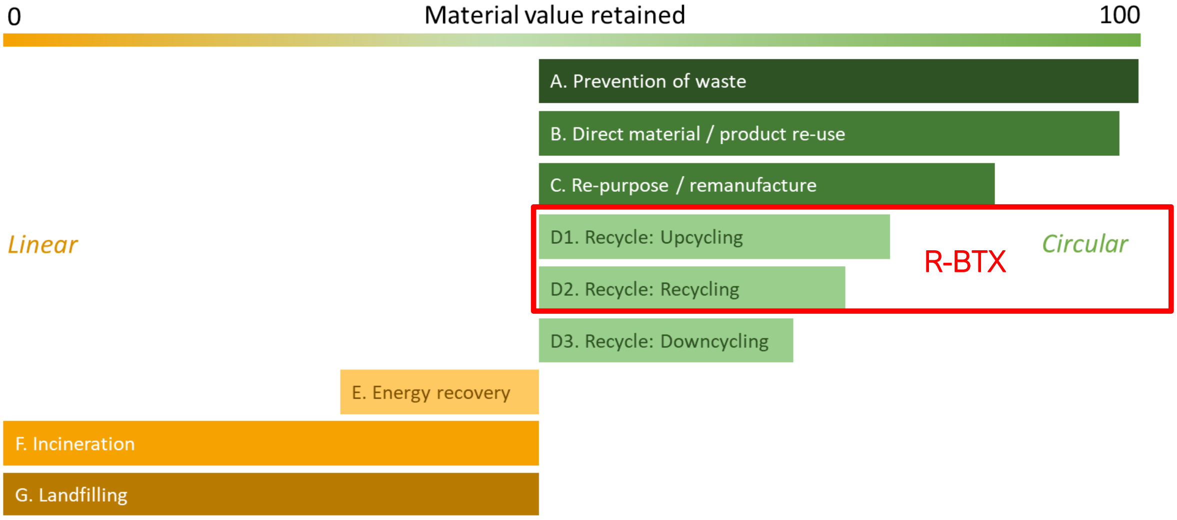

Figure 3 The "Material value hierarchy of Ecoras" is based on the waste hierarchy principles (Own work). The scale illustrates the combination of the previously explained 'ladders' with the inclusion of material value retention. In the scale, D1/2/3 cannot reach 100 as these steps result in recycling process losses (efficiency) and/or losses in mechanical properties.

Mechanical and chemical recycling

There are two distinguishing pathways to recycling plastics: mechanical recycling and chemical recycling. Both mechanical and chemical recycling are classified under the levels C1-C3 of the waste hierarchy and D1-D3 in the material value hierarchy. In general, the following differences are reported:

Mechanical recycling

- Less energy-intensive than chemical recycling
- Suitable for clean plastic thermoplastics
- Reduces the material back to small shredded granulates suitable for reprocessing
- High carbon-to-carbon recycling
- Downcycling of the material(s) in case of mixed (plastic) waste streams
- For specific plastics such as clear bottle-grade PET (separately collected) closed-loop recycling can be done (e.g. bottle-to-bottle recycling).

Chemical recycling

The term "Chemical recycling" encompasses different techniques (de-polymerisation, pyrolysis, gasification – CE Delft, 2019b)

- More energy-intensive than mechanical recycling
- Can process contaminated mixed plastic waste streams
- Produces high valuable, virgin grade, drop-in chemicals
- Processes the material (in the case of the BioBTX technology) back to the building blocks B, T, X,
- Lower carbon-to-carbon yield than compared to mechanical recycling
- Upcycling of the product, allows for re-entering the value chain in the most valuable applications

Mechanical and chemical recycling are complementary to each other. With the combination of both, new virgin grade materials can be made out of waste streams via chemical recycling, after which they can again be mechanically recycled for lower-end applications. When this is not possible anymore, chemical recycling can be used again to make virgin-grade products again.

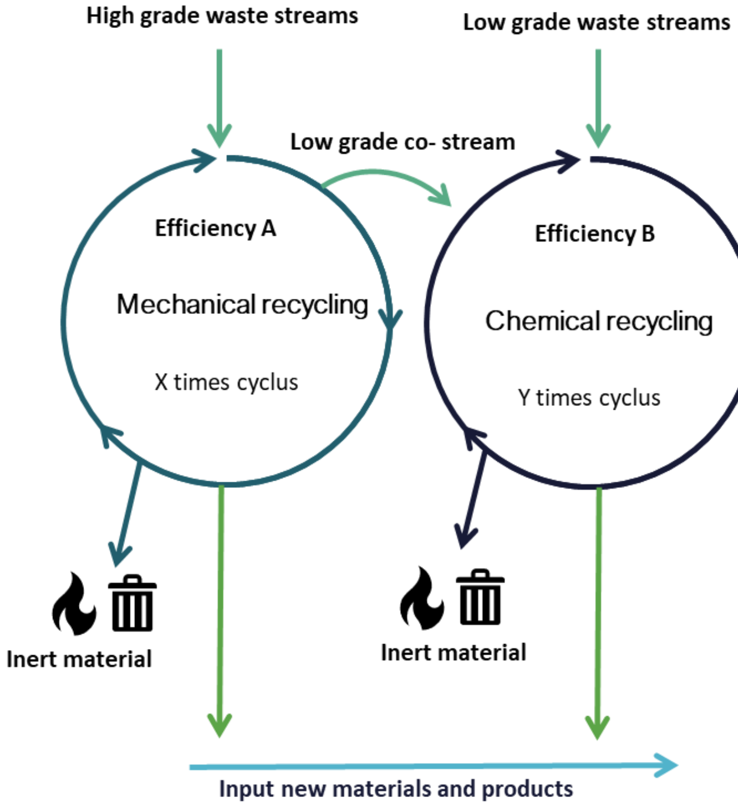

Figure 4 Schematic overview showing how mechanical and chemical recycling are connected. Both methods have their own efficiencies, the maximum amount of cycles a material can be recycled, the grade of waste streams that can be handled and process inputs. (own work)

The Plastic Conversion Plant (PCP)

The Plastic Conversion Plant (PCP) focuses on producing a *renewable* crude mix of benzene, toluene, xylene (BTX), and oil from waste streams via a patented thermochemical recycling process. The purpose of the upcoming demo plant is to demonstrate the feasibility of producing BTX from waste plastics on a commercial scale. The project will be implemented based on a phased approach:

- Phase 1: 16 kt/year will be installed, based on plastics feed (DKR350) after pre-treatment (dry basis). The pre-treatment will be done by a 3rd party at another location.
- Phase 2: the capacity will be tripled to 48 kt/year based on plastics feed after pre-treatment. In this phase, the in-house pre-treatment installation will also be installed. In this phase, the plant will be fully operational.

The demo plant is centred around two processes. The first step includes the thermal cracking of the feedstock. The second is the catalytic conversion of the pyrolysis vapours to BTX to maximise the BTX yield most economically. For this environmental assessment, Phase (2) will be taken as the baseline (48 kt/year).

Perspective

BTX is an important intermediate chemical product and serves as a basis for a multitude of different products. Some examples are food packaging, sports equipment, building & construction, automotive industry, textile and pharmaceuticals (Petrochemicals Europe, n.d.). As the demand for derived chemicals and materials is expected to increase until at least 2050 (figure 2, Porc et. al. 2021), so will the demand for BTX.

The following figure, made by Nova institute (2022), emphasises the relevance of renewable carbon sources for some important intermediate products. The process of the PCP fits well in the yellow (plastic waste) and green pathways (biomass) to the aromatics. It provides a renewable alternative for the production of the aromatics Benzene, Toluene, and Xylene.

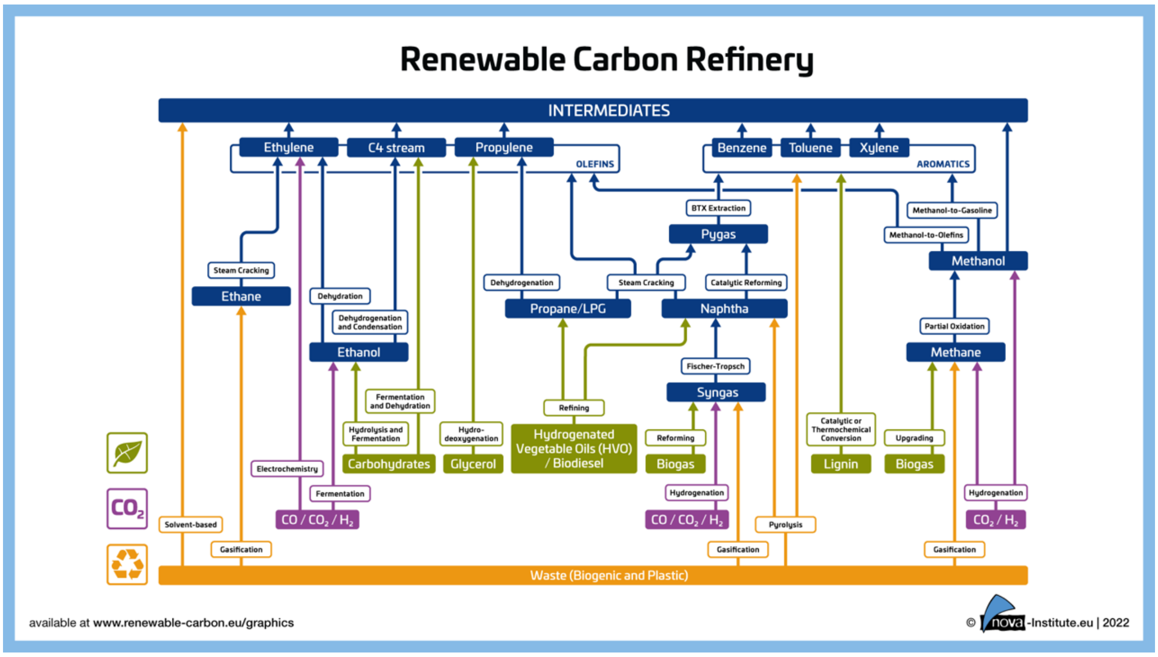

Figure 5 Schematics showing potential future pathways in which important chemical intermediates (including the aromatics B, T and X) can be produced from biogenic waste sources, captured CO_2 and recycled plastics. . Source: Nova Institute, 2022. Figures are available at www.renewable-carbon.eu/graphics

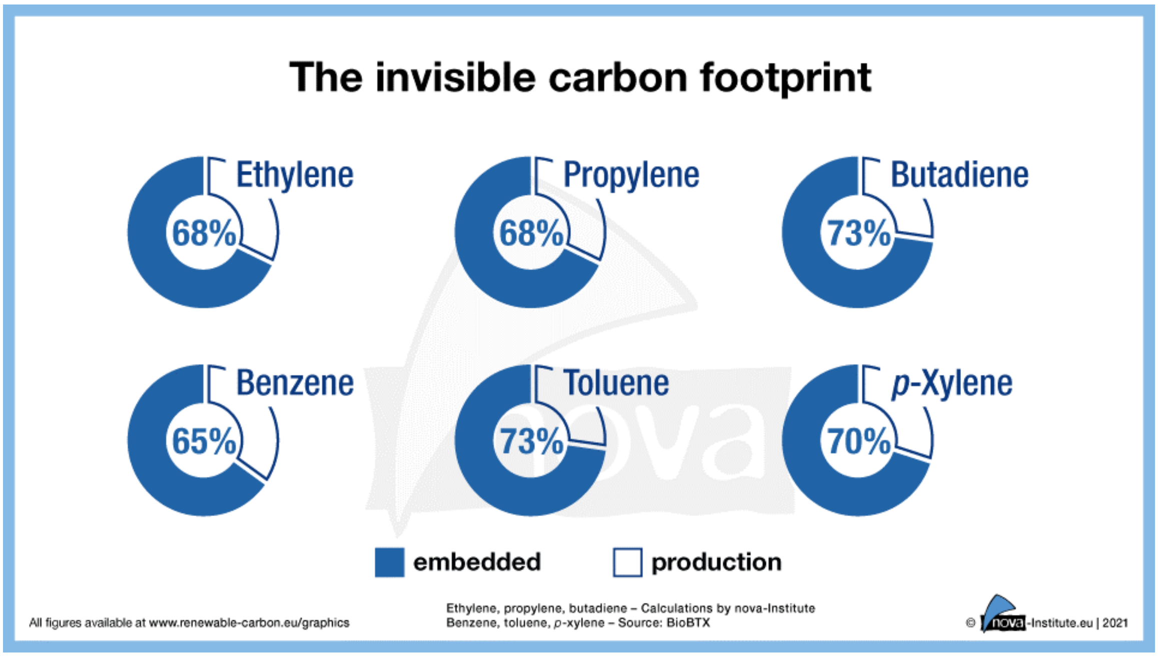

Figure 6 The invisible carbon footprint of some important building blocks for plastics. Shown is that more than half of the carbon footprint originates from embedded carbon that is stored in the product itself when compared to production emissions. Kähler et.al., 2021. Figures are available at www.renewable-carbon.eu/graphics

Besides the fact that BTX is normally produced from fossil resources, this figure from Nova institute (2021) shows the distribution of the carbon footprint when not only the production but also the embedded carbon in the material itself is considered. Therefore, by increasing the production and ensuring that the carbon sources are from renewable sources, carbon can be stored quite well during the lifetime of the products, and stay even longer in the loop when the material is reused and recycled often.

Method

This screening LCA builds on the previous LCA report (Klaarenbeek & De Wolff, 2021) by updating the previous results with the most recent data and calculating new impact results for additional systems (e.g. alternative product route) including their business-as-usual reference system. The methodological steps were inspired by the ISO guidelines (ISO 14040 / 14044) when applicable, but this LCA is not intended to comply with them. The methodological steps are further addressed in the following subsections.

In the description of the life cycle impact assessment, the necessary information for the investigated main scenario is given first (indicated in blue). This is followed by a second and third main scenario, which uses a different perspective on the functional unit (indicated in green). Other systems which are relevant for identifying avoided processes and/or materials, called system references, are included in the final section (indicated in orange). For each system, a general description, the perspective of the system and the relevant LCI data are discussed.

Goal and scope definition

The overall goal of this LCA is to assess the potential environmental advantages and disadvantages of using the PCP process as an alternative to the current-day practice of (fossil-based) chemical production and investigates the effects of a different feedstock. Therefore, the consequence of PCP versus these scenarios in the near future will be investigated. The results of this LCA are for PCP B.V. to be used internally including distribution among potentially interested parties (financiers, investors, partners and clients).

The overall scope of this study has been set on a European level but with several focus points on the Netherlands for feedstock (MPW and WS), the processing (future plant in Delfzijl) and for some of the co-products (gas, avoided energy). When datasets were not available for the required level, the dataset in the following order of scope, from small to large, was used: NL (The Netherlands), RER (Europe without Switzerland), CH (Switzerland), RoW (Rest of World), GLO (Global).

System boundaries

System expansion is used to incorporate the changes in the system beyond the PCP process itself. This was also applied for co-products until the point of product replacement. The *ceteris parabis assumption* was used to narrow down the system boundaries. This means that any processes between two compared products that do not change as a consequence of a considered choice are allowed to be excluded based on the assumption that the *difference in impact between* the two analysed systems is equal (Brandao et. al. 2017, Weidema, 2003 and Odegard et. al. 2017, as mentioned in Schenk. et al. 2020). This was applied to transport, as no changes are expected switching between the systems. In the reference, the mixed plastic waste is incinerated in an energy plant in Delfzijl. No additional transport is needed as the PCP will be located in the same area and any changes should be neglectable. If the PCP was instead used to produce bollards from mixed plastic waste, the same logic will apply.

To make a fair comparison between fossil-based BTX (F-BTX) and renewable BTX (R-BTX) from the PCP, the product quality and composition should be equal. The end product of the currently designed PCP is a mixture of crude BTX. This mixture is not of the same quality- and purification grade as F-BTX. To make the product comparison on an equal basis, the system was extended beyond the factory gate with the addition of an initial distillation step (here: purification) to the PCP process. Sources and references regarding impact data for this process are scarce, however, in earlier research performed by Schenk et al. 2020 an estimated CO_2 emission for the initial distillation process was given (0.13 kg CO_2-equivalents per kg crude BTX). This impact data has been used for this report and is given in the LCI. The specific system descriptions and schematics are presented in their corresponding sections.

Function and functional unit

This assessment focuses on the BTX production by the PCP. For this, the following functional unit has been defined:

The production of a purified renewable BTX mix by the Plastic Conversion Plant with equal quality as its fossil-based B, T, and X counterparts, for use in Europe.

Herewith, the reference flow, in which all results will be expressed, has been set on the production of 1 kg purified (virgin fossil grade) B, T, and X. For the second and third scenarios, the reference flow has been set on the amount of untreated plastic, 2.83 kg, which is needed for the production of 1 kg BTX.

Scenario 1: R-BTX production

The main focus of the study revolves around the Plastic Conversion Plant where alternative feedstocks and a mechanical recycling route are investigated. The current PCP plans focus on the production of renewable BTX from mixed plastic waste. The general process of the PCP is described in the report 'Basis of Design' by TransitionHERO (2020). Here below a summary is given in which the following process steps are (in general) used in the conversion process:

1. Pre-treatment
2. Pyrolysis (R1)
3. Catalytic Vapour Upgrading (R2)
4. Separation system (condensation of BTX and other oils)
5. Off gas system (among other processes renewable carbon gas is collected)
6. Storage and offloading
7. Utilities

When the plant is fully operational the mixed plastic waste (MPW) arrives at the PCP. Here the mix will be pre-treated; meaning impurities are removed, the feedstock is shredded into uniform particles and the moisture content of the mix is lowered from ~ 7,5% to less than 3% (in the base case). After pre-treatment, the MPW is fed into the process, which starts with the pyrolysis of the material in the first reactor. In the Basis of Design (BoD) (TH, 2020), this step is further mentioned as the process in Reactor 1 (referred to as R1). Here, under an inert atmosphere and high temperatures, the feedstock is converted into vapours and char. Before the produced vapours are fed into the next step, the mix is cooled down and filtered through a hot gas filter to remove any solid particles. Next, the vapours are led into the Catalytic Vapour Upgrading system, further mentioned as the process in Reactor 2 (referred to as R2). Here the vapours are converted into a crude BTX mix of (Benzene, Toluene, Xylenes) vapours and coke. After a second cyclone and filter step, the BTX and oil are condensed in several stages after which it is stored, transported and ready for further use.

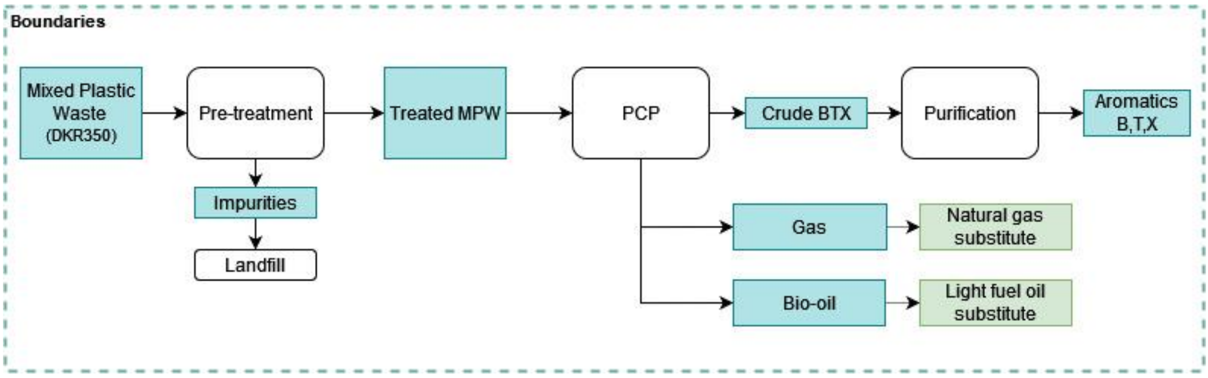

Figure 7 System overview of the Plastic Conversion Plant. Only the main relevant process steps are shown in this figure.

Perspective

The purpose of the PCP plant is to produce renewable BTX (R-BTX) from mixed plastic waste. If the demand for BTX stays the same, a part of the fossil BTX on the market will be replaced with renewable BTX. The plant uses mixed plastic waste as its feedstock for the conversion process. As a consequence, the used plastic is no longer available for its business-as-usual route, for which was chosen incineration in a waste-to-energy conversion plant for heat and electricity production.

Life Cycle Inventory

For this main system, the PCP operates at full capacity and processes 48 kilotons of mixed plastic waste per year. The first table (table 1) gives general information about the PCP. Based on this production data the rest of the inventory data could be recalculated.

Table 1 Life Cycle inventory for all the processes including sources and assumptions made.

General data PCP			
Process	Value	Unit	Notes
Processed MPW per year	48 000	ton	Data from TransitionHERO, Basis of Design (TH. 2020)
Production hours per year	8 000	hours	Data provided by TransitionHERO
Kg processed MPW per hour	6 000	Kg	Data provided by TransitionHERO

In table 2 the general composition of the mixed plastic waste also referred to as DKR 350, is given. The mix consists of several plastics (up to 90%), some moisture, and impurities (max 10%). All values are expressed for 1 kg of treated mixed plastic waste.

Table 3 contains the inventory for pre-treatment of the raw plastic feed. Within this process falls the additional sorting of the plastic, and heating to reduce the moisture content of the mix from 7,5% to 3,5% (base case). Furthermore, treatment is included to remove some of the impurities. As energy mix, the attributional dataset was chosen instead of the consequential dataset (see discussion chapter). From this point on, all the LCI data is expressed for the functional unit: the production of 1 kg BTX.

In the results, the purification from crude BTX to a purified B, T, and X will be added to make the quality between R-BTX and F-BTX equal.

Table 2 Life Cycle Inventory for the Mixed Plastic Waste (MPW), also referred to as the DKR 350 fraction, is achieved after sorting municipal solid waste. Numbers are given per kg MPW.

General data Mixed Plastic Waste (MPW)				
Process	Fraction %	Value	Unit	Notes
Mixed plastic waste		1	Kg	*Not completely 1 (comment authors in report Base of design TH, 2020)*
PET	33.2%	0.33	Kg	Percentage -> Data provided by TransitionHERO
PE	28.1%	0.28	Kg	Percentage -> Data provided by TransitionHERO
PP	28.1%	0.28	Kg	Percentage -> Data provided by TransitionHERO
PVC	0.5%	0.005	Kg	Percentage -> Data provided by TransitionHERO
Impurities	10%	0.10	Kg	Percentage -> Data provided by TransitionHERO
Impurities				
Sands and stone	11.8%	0.01	Kg	Percentage -> Data from TransitionHERO, Basis of Design (TH. 2020)
Biomass	11.8%	0.01	Kg	Percentage -> Data from TransitionHERO, Basis of Design (TH. 2020)
Paper	29.4%	0.03	Kg	Percentage -> Data from TransitionHERO, Basis of Design (TH. 2020)
Other plastics	17.6%	0.02	Kg	Percentage -> Data from TransitionHERO, Basis of Design (TH. 2020)
PS content	23.5%	0.02	Kg	Percentage -> Data from TransitionHERO, Basis of Design (TH. 2020)
Aluminium & other metals	5.9%	0.006	Kg	Percentage -> Data from TransitionHERO, Basis of Design (TH. 2020)
Moisture content				
Moisture	7.5%	0.075	Kg	Percentage -> Data provided by TransitionHERO

Table 3 Life Cycle Inventory for the pre-treatment of the MPW. Here all values are given for the functional unit of producing 1 kg BTX.

Pre-treatment				
Process	Fraction %	Value	Unit	Notes
Input				
Pre-treatment MPW		2.83	Kg	
Additional sorting MPW		0.16	MJ	Jeswani et al. (2021) - estimated from Kaitinnis (2019) *Also, see Appendix C.* Electricity, medium voltage (NL), market for, **attr. Cut off***
Drying MPW after sorting (energy input)		0.20	MJ	Own calculations** Electricity, medium voltage (NL), market for, **attr. Cut off*** Is in the range of numbers:
Output				
Treated MPW		2.68	Kg	
Dried MPW (Moisture output)	to <3%	0.12	Kg	7,5% is given by TransitionHERO as the moisture content in the base case and <3% after pre-treatment. For LCI 3% after drying is assumed
Removed Impurities		0.03	Kg	The amount is calculated from 427 metric tons/year over 48.000 tons processed MPW. Data provided by TransitionHERO Municipal solid waste (ROW), treatment of, sanitary landfill, consequential
Treated MPW		2.68	kg	(2.83 kg MPW minus moist output and impurities removed)
** Electricity impact was assumed to be a general electricity mix for the Netherlands* *** Value lies in the range of reported values by company CS Plastics (2021)*				

In table 4, data for the plastic conversion process is shown. This table contains the input data of the process, output data, products, and co-products. The catalyst was based on a reference technique (Fluid Catalytic Cracking - FCC) where Zeolite acts as the active catalyst.

Table 4 Life Cycle Inventory for the conversion process of the MPW into BTX at PCP. Data are given for the FU of producing 1 kg BTX.

PCP conversion process for the production of 1 kg BTX				
Process	Fraction %	Value	Unit	Notes
Input				
PCP process - Input				
Treated MPW		2.68	Kg	Input in the process
Electricity total installation		9.95	MJ	Data provided by TransitionHERO Electricity, medium voltage (NL) market for, **attr. Cut off***
HCl removal ($CaCO_3$)		0.03	Kg	Data provided by TransitionHERO Calcium Carbonate, Precipitated, (RER), consequential
Catalyst		0.003	Kg	Data provided by TransitionHERO Based on the reference process FCC (Fluid Catalytic Cracking). The active ingredient used there is Zeolite** Zeolite, Powder (RER) production, consequential
Output				
PCP process - Output				
Separation wastewater		0.0003	m^3	Data provided by TransitionHERO Wastewater, average (EU without Switzerland), market for wastewater, average, consequential
Separation & dechlor unit (HCl)		0.009	Kg	Data provided by TransitionHERO Municipal solid waste (ROW), treatment of, sanitary landfill, consequential
R1- Bottoms	12%	0.11	Kg	Data provided TransitionHERO Municipal solid waste (ROW), treatment of, sanitary landfill, consequential
R1 – Total – Cyclone and filter		0.21	Kg	Data provided by TransitionHERO Municipal solid waste (ROW), treatment of, sanitary landfill, consequential
R2 – Total – Cyclone and filter	0.1%	0.003	Kg	Data from TransitionHERO Municipal solid waste (ROW), treatment of, sanitary landfill, consequential
PCP Products				
Crude - BTX	37%	1	Kg	Data provided by TransitionHERO An additional impact of 0.13 kg CO_2-equivalents per kg is needed to create a purified B, T, and X product.
PCP Co-products				
Bio-oil	20.3%	0.44	Kg	Data provided by TransitionHERO Replaces light fuel oil (EU without Switzerland) market for, consequential
Wax	28%	0.08	Kg	Data provided by TransitionHERO Replaces Natural gas, high pressure (NL), market for, consequential
Gasses		0.75	Kg	Data provided by TransitionHERO Replaces Natural gas, high pressure (NL), market for, consequential
* Electricity impact was assumed to be a general electricity mix for the Netherlands ** FCC – Process / active ingredient Zeolite: (Wikipedia, 2021)				

Scenario 2: Incineration of MPW

Mixed plastic waste stands for the plastic fraction that is present in municipal solid waste (MSW). This excludes the plastics that are collected separately. For example, PET bottles are collected via a separate collection system in supermarkets and result in a clean waste stream. Besides plastics, municipal solid waste contains a range of different substances that are difficult to separate. Examples include food (packaging) waste, paper, metals and products that are difficult to separate such as multi-layer packaging material.

With the help of a diverse set of sorting techniques at the waste handling facility, several fractions can be collected from this waste stream. These are defined as DKR fractions. For this LCA focus is laid upon DKR350, which is a mixed plastic waste (MPW) stream. It is described as: *"Used, completely emptied, system-compatible articles made of plastics that are typical for packaging (PE, PP, PS, PET) incl. packaging parts such as bottle caps, lids, labels, etc."* (DKR, 2009). Furthermore, a maximum of 10% impurities is accepted in this stream. In this reference system, assumed was that the mixed plastic waste fraction is incinerated in a waste-to-energy powerplant for heat and/or electricity production.

Reference flow: previously the reference flow of 1kg of renewable BTX mix was used. For this route, the amount of untreated MPW that is required for the production of 1 kg of R-BTX is used: 2,83 kg. Therefore, this scenario is evaluated from a waste management perspective.

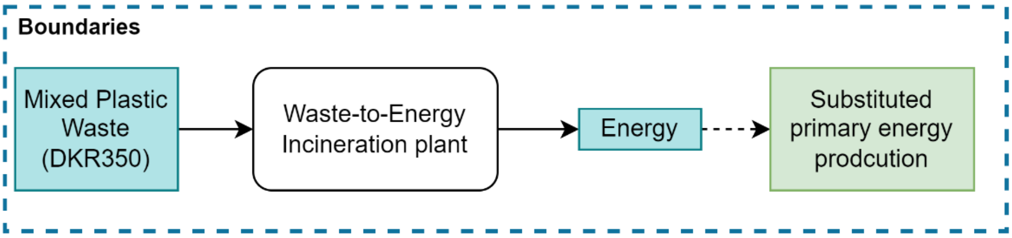

Figure 8 Schematic overview of the incineration of Mixed Plastic Waste into a Waste-to-Energy plant to produce heat and electricity.

Life Cycle Inventory

The impact of the feedstock reference was based on the report of CE Delft 2021. The impact data is shown in table 5 below. In the first row, the impact data for 1 kg of untreated MPW (DKR350 waste plastic mix) is given and in the second row the amount has been recalculated to 2.83 kg untreated MPW to match the FU.

Table 5 Data inventory for the incineration of MPW. MPW stands here for a DKR350 waste plastic mix.

Incineration: Inventory for the incineration of mixed plastic waste				
Amount	*Impact*	*Energy substitution*	*Net emissions*	*Additional information*
	Kg CO_2-equivalents	Kg CO_2-equivalents	Kg CO_2-equivalents	
1 kg MPW	2.71	-0.98	1.73	Mixed plastics from households in AVI
2.83 kg untreated MPW	7.66	-2.77	4.89	Mixed plastics from households in AVI
* Source: CE Delft, 2021				

Scenario 3: Downcycling of MPW

In reality, chemical- and mechanical recycling are complementary to each other and both have their strengths and weaknesses. When focussing on the utilization of MPW (DKR350), it could be stated that due to a lower energy demand for mechanically recycling MPW into a product such as a plastic pellet, it will have a better environmental performance in comparison to the more energy-intensive chemical recycling technology. However, when this is stated, many important circular economy aspects are omitted such as material quality/performance, material value, supply & demand. Therefore, in addition to the LCA approach taken below, an exploration of alternative approaches is given in the discussion.

Reference flow: previously the reference flow of 1kg of renewable BTX mix was used. For this alternative MPW recycling route, the amount of untreated MPW that is required for the production of 1 kg of R-BTX is used: 2,83 kg. Therefore, this scenario is evaluated from a waste management perspective.

As a resulting product, a bollard made from mixed plastic waste was chosen as an example of recycled material application. These posts are a common sight in many public spaces and some variants are made from lower-value mixed plastics such as DKR 350.

Figure 9 Shape and type of the chosen bollard

Perspective

In this alternative recycling system, the MPW is mechanically recycled and is used for the production of plastic bollards. As a consequence, this amount of plastic no longer follows its business-as-usual scenario (incineration). Also, the required BTX still has to be produced. Since the main focus is the BTX production, not the whole bollard was modelled, but only the transformed amount of material which was otherwise incinerated or used for the functional unit.

Life Cycle Inventory

In practice, the MPW used for bollards consists of a mix of DKR310 (foils) and DKR350 (MPW). It is technically possible to produce bollards from only DKR 350 but is aesthetically less attractive for customers (communication production company). However, to make an equal comparison with the PCP and incineration process, a feedstock of 100% DKR350 was chosen. The pre-treatment process needed to get the DKR350 fraction was therefore assumed to be the same as at the PCP, see table 6.

To produce a black bollard, which is the most commonly sold version, small amounts of low-density polyethylene (virgin quality) and carbon black (colour) are added (information retrieved from EPD of production company). As avoided material, a hardwood mix was chosen. For the data, see table 7.

Table 6 Data inventory for the mechanical route. The values show only the transformed amount of material which was otherwise incinerated or used for the functional unit (= 2.83 kg untreated MPW).

Mechanical recycling: Pre-treatment				
Process	Fraction %	Value	Unit	Notes
Input				
Pre-treatment MPW		2.83	Kg	
Additional sorting MPW		0.16	MJ	Jeswani et al. (2021) - estimated from Kaitinnis (2019) *Also, see Appendix C.* Electricity, medium voltage (NL), market for, **attr. Cut off***
Drying MPW after sorting (energy input)		0.20	MJ	Own calculations** Electricity, medium voltage (NL), market for, **attr. Cut off*** Is in the range of numbers:
Output				
Treated MPW		2.68	Kg	
Dried MPW (Moisture output)	to <3%	0.12	Kg	7,5% is given by TransitionHERO as the moisture content in the base case and <3% after pre-treatment. For LCI 3% after drying is assumed
Removed Impurities		0.025	Kg	The amount is calculated from 427 metric tons/year over 48.000 tons processed MPW. Data provided by TransitionHERO Municipal solid waste (ROW), treatment of, sanitary landfill, consequential
Treated MPW		2.68	kg	(2.83 kg MPW minus moist output and impurities removed)
** Electricity impact was assumed to be a general electricity mix for the Netherlands* *** Value lies in the range of reported values by company CS Plastics (2021)*				

Table 7 Data inventory for the PCP conversion process. The values show only the transformed amount of material which was otherwise incinerated or used for the functional unit (= 2.83 kg untreated MPW).

Mechanical recycling: Production of bollard material, scaled to equal MPW input				
Process	Fraction %	Value	Unit	Notes
Production Bollard				
Input				
Treated Mixed Plastic Waste		2.68	Kg	
LDPE*		0.07	Kg	Polyethylene, low density, granulate (GLO), market for, consequential
Carbon black*		0.01	Kg	Carbon black (GLO), market for, consequential
Electricity*		5.09	MJ	Electricity, medium voltage (NL), market for, **attr. Cut off**. Changed to medium voltage NL mix due to the size of the PCP and thus production quantities and the assumption all the production takes place in NL
Heat*		1.07	MJ	Heat, district or industrial, natural gas, (Europe without Switzerland), heat production, natural gas, at industrial furnace >100 KW, consequential
Output				
Bollard		2.76	kg	
** Information on amounts retrieved from EPD of a production company using only waste plastics. Recalculated to amounts needed per plastic input*				

System references: Business-as-usual pathways

In the following paragraphs, two additional relevant reference systems are described and discussed. These systems are necessary for calculating avoided materials and/or processes.

Reference: Fossil B, T, and X

In the present situation, most aromatics are made from crude oil, which is a fossil resource. This oil is refined into naphtha and other products. After steam cracking, among others, pygas are produced. From this gas the aromatics B, T and X (F-BTX) can be extracted and used for further processing.

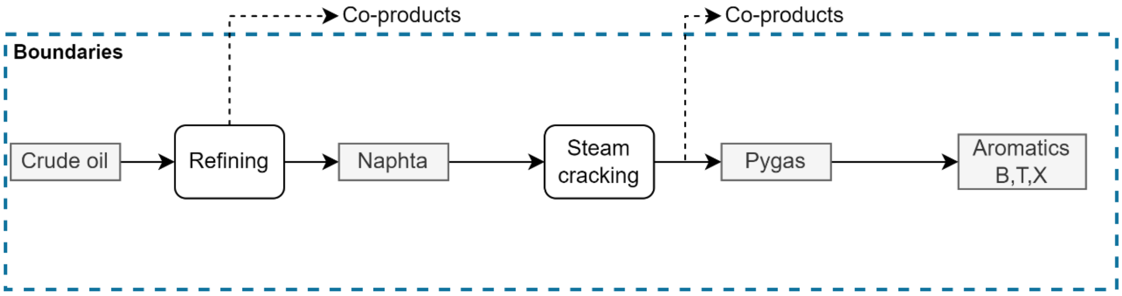

Figure 10 A schematic system overview with the relevant steps in which crude oil is transformed into aromatics B, T and X.

Life Cycle Inventory

Environmental impact data of F-BTX was based on literature. To compare both systems, assumed was that the composition of the B, T, and X fractions was equal. This composition is shown in table 8.

Table 8 Manual calculations of environmental impact data B, T, and X

Reference BTX: GWP concerning the content ratio of 1 kg BTX in the compared systems (PCP vs Business-as-Usual) - *Manual calculation*			
	Benzene	*Toluene*	*Mixed Xylenes*
Content ratio (in BTX from PCP)	24%	48,5%	27,5%
GWP per kg (Plastics Europe, 2013)	1,86	1,22	0,79
GWP contribution	0,45	0,59	0,22
GWP from 1kg fossil BTX	0,45 + 0,59 + 0.22 = ~**1,26 kg CO$_2$ per kg BTX**		

Reference: Product materials for bollards

Bollards can be made from different kinds of materials: wood, concrete, steel and virgin plastic. Of the chosen bollard type, the most common reference product is hardwood. Therefore the standard product reference for scenario 3 uses a hardwood mix consisting of tropical sourced and European sourced hardwood (see table 17).

However, when considering the function of bollards, there are more shapes and thus materials possible. In a similar study of SGS search (Van Ewijk et. al. 2018), the researchers assumed the following mix and distribution of materials were avoided by making bollards from mixed plastic waste. The composition was taken from the report from TNO (Ansems & Ligthart, 2017).

- 1/4 virgin plastics
- 1/4 hardwood (mix tropical Azobe hardwood and European managed hardwood)
- 1/4 steel
- 1/4 concrete (general concrete mix)

For virgin plastics, a 50/50 mix of polyethylene and polypropylene (CE Delft 2011) was taken (Van Ewijk et. al. 2018) and included the injection moulding to compensate for the preservation step in the case of hardwood. This second reference was analysed too to investigate the effects on the environmental impact.

Life Cycle Inventory

In the reference, the distribution of replaced materials does take place. Therefore, these amounts of material are considered here. Table 9 shows the hardwood mix, which was the standard reference scenario. Table 10 shows the LCI for the extended material mix, which was used to check the sensibility of the credits and overall score of Scenario 3.

Table 9 Data inventory for the hardwood mix reference.

Reference materials bollard: Hardwood mix				
Materials replacing 2.76 kg Bollard product				Based on LCI of Van Ewijk et. al. 2018
Hardwood, Azobe		0.001	m^3	Sawlog and veneer log, azobe, debarked, measured as solid wood {RER} market conseq. S
Preserved Hardwood, Europe		0.002	m^3	Sawnwood, hardwood, raw, dried (u=20%) {RER}, market
Preservation process European hardwood		*0.015*	*kg*	*Wood preservation, vacuum pressure method, organic salts, CR-free, outdoor use, ground contact {GLO}, market, conseq. S*
Source: Van Ewijk et. al. 2018				

Table 10 Data inventory showing the composition for the extended material mix.

Reference materials bollard: Extended avoided mix		
Process	Fraction %	Notes
Hardwood, Azobe	25%	Sawlog and veneer log, azobe, debarked, measured as solid wood (RER), market, consequential
Hardwood, European-managed forest	25%	Sawn wood, hardwood, raw, dried (u=20%), (RER), market, consequential And Wood preservation, vacuum pressure method, organic salts, CR-free, outdoor use, ground contact {GLO}, market, consequential
Polypropylene, virgin grade	12.5%	Polypropylene, granulate, (RER), production, consequential
Polyethylene, virgin grade, low density	12.5%	Polyethylene, low density, granulate (GLO), market for, consequential
Steel	25%	Steel, low-alloyed, (GLO), market for, consequential
Concrete	25%	Concrete, normal, (RoW), market for concrete, normal, consequential
Source: Van Ewijk et. al. 2018		

Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment has been carried out in Microsoft Excel and SimaPro version 9.3.0.3. In Excel, the mass balance of the process was modelled while the impact of the system was modelled in SimaPro. Chosen was to focus the assessment on the Global warming potential and therefore the impact method IPCC 2021 GWP 100 V1.00 was used. This unit includes other gasses that contribute to global warming. The conversion factors can be found in the report from IPCC 2021.

Impact results and interpretation

Based on the LCI and the impact assessment (LCIA), the resulting global warming impact of the scenarios is presented in this chapter. The impacts shown are based on a cradle to factory gate scope and include direct in and outputs. Processes that do not change regardless of the scenario, were excluded based on the assumption that the *difference in impact between* the two analysed systems is equal. Therefore, no transport is included in the presented data. All results are based on the following functional unit:

The production of a purified renewable BTX mix by the Plastic Conversion Plant with equal quality as its fossil-based B, T, and X counterparts, for use in Europe.

The reference flow was set on the production of 1 kg purified (virgin fossil grade) B, T, and X for the first scenario. For the second and third scenarios, the reference flow was changed to the amount of untreated plastic, 2.83 kg, which is needed for the production of 1 kg BTX. The impacts from scenario 1 (R-BTX production) will be presented first, followed by scenario 2 (incineration of MPW as a business-as-usual scenario), and ends with scenario 3 (alternative processing route of MPW).

Scenario 1: R-BTX production

In this section, the effects and consequences of producing R-BTX via the PCP were investigated. Identified avoided processes were the replacement of natural gas and light fuel oil by the co-products of the system. Furthermore, the MPW used for this process cannot be incinerated and therefore also credits for avoiding this process were included.

The resulting impact, including the resulting credits from the replaced processes, is shown in the following graph. The net impact of this system is -3.35 kg CO_2-equivalents. This number consists of the total emission of 2.05 and a total credit of -5.41 kg CO_2-equivalents respectively. The main contributor factor to the total credit is the avoided incineration of 2.83 kg of untreated MPW. When compared to F-BTX, a difference of -4.61 kg CO_2-equivalents can be observed.

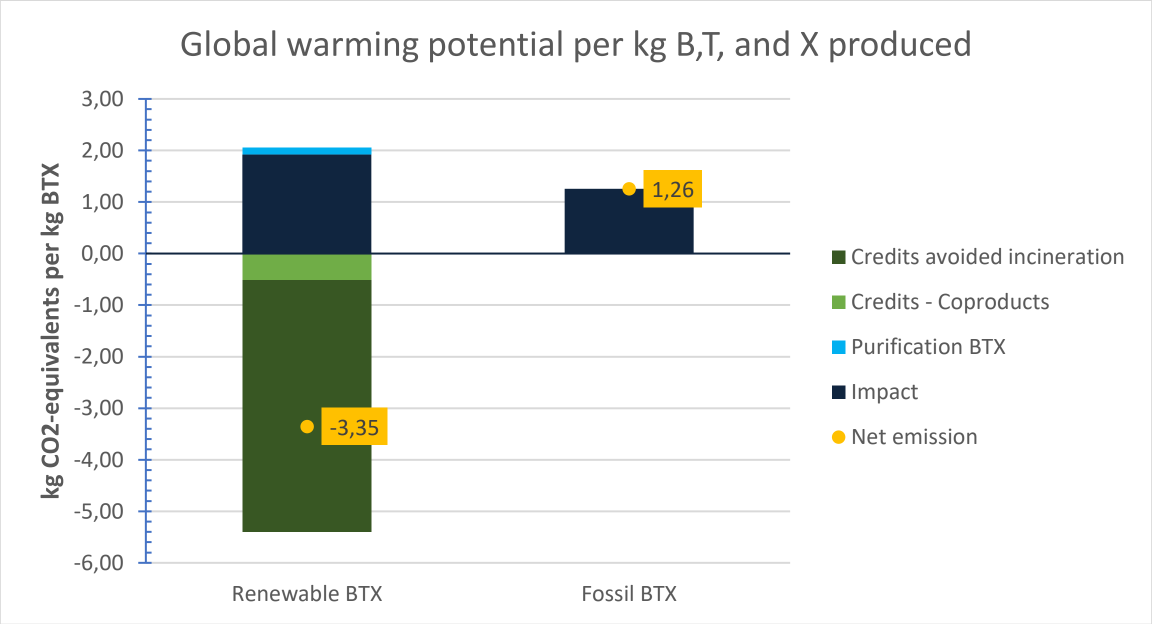

Figure 11 Resulting global warming impact of the PCP main system. The impact is related to the production of 1 kg of B,T and X.

When the amount of F-BTX is avoided by the production of R-BTX due to a steady state in demand on the market, the overall impact lowers from 1.26 kg CO_2-equivalents to -4.61 kg CO_2-equivalents.

Scenario 2: Incineration of MPW

The effects and consequences of the business-as-usual of processing mixed plastic waste were investigated. Identified avoided processes were the replacement of a Dutch energy mix, consisting of a mix of fossil and renewable energy.

The resulting impact, including the resulting credits from the replaced processes, is shown in the following graph. The net impact of this system is 4.89 kg CO_2-equivalents. This number consists of a total emission of 7.66 kg and a total credit of -2.77 kg CO_2-equivalents respectively for incinerating 2.83 kg untreated MPW.

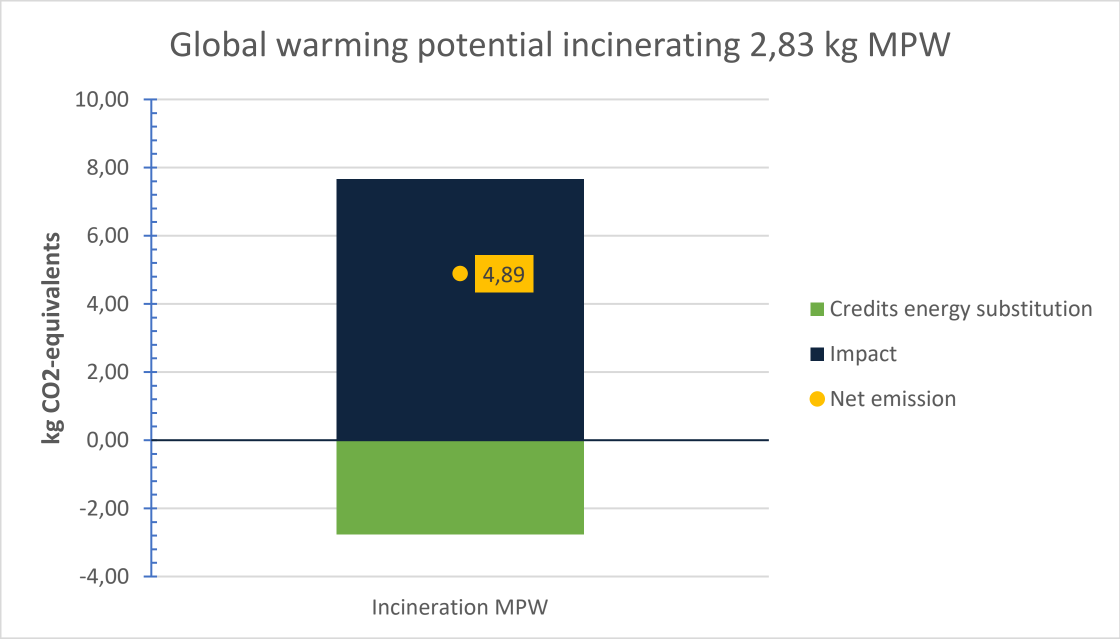

Figure 12 The global warming impact of the incineration of MPW. The impact is related to the use of 2.83 kg of untreated MPW.

When this scenario is put into perspective of the FU, this feedstock is not available for the production of R-BTX. Therefore, the demand still has to be met by producing F-BTX via the business-as-usual route.

Scenario 3: Downcycling of MPW

In this section, an alternative processing route of MPW was investigated. With the production of bollards from MPW, it was found that several different production processes are avoided. One identified avoided process was the replacement of a hardwood mix (Tropical and European managed wood) for the bollard production.

With an input of 2.83 kg of untreated mixed plastic waste, 2.76 kg of bollard product can be made. The resulting impact of this alternative processing route is 1.11 kg CO_2-equivalents. An avoided hardwood mix gives an environmental credit of -5.4 kg CO_2-equivalents. This brings the net impact to -4.29 kg CO_2-equivalents.

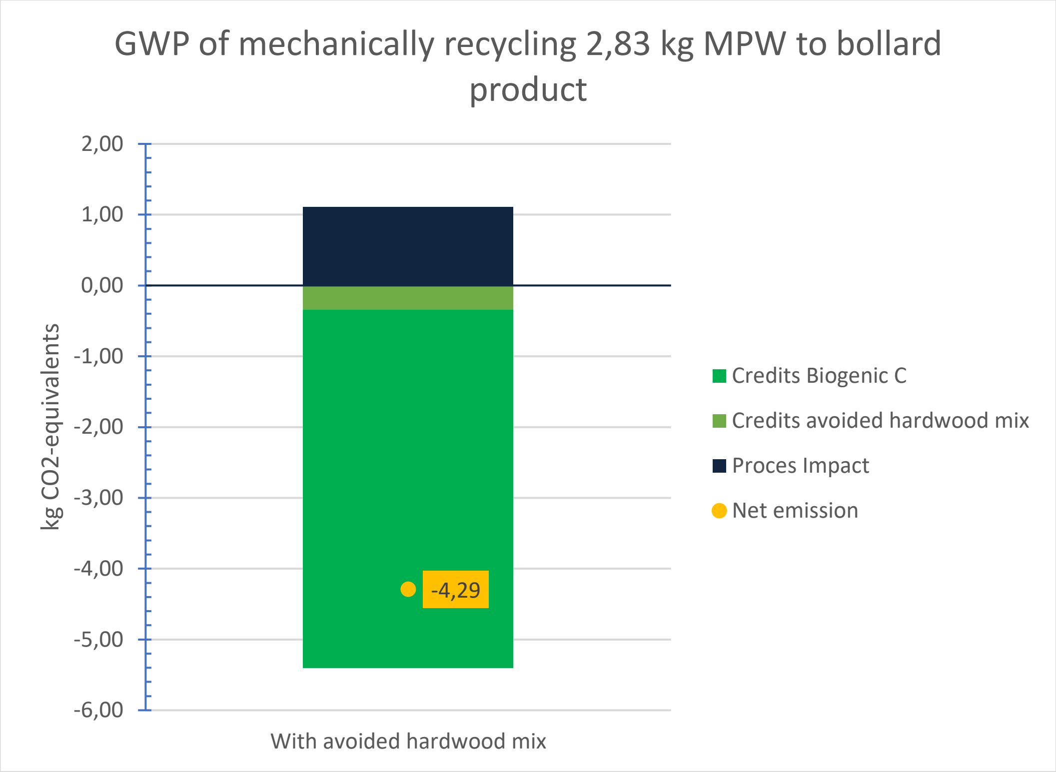

Figure 13 Results of mechanically recycling MPW to bollard product. As avoided materials, here an average hard wood mix was chosen.

When putting this into the perspective of this LCA, the production of BTX has to be considered. When the mixed plastic waste is used for other processes, the demand for BTX can only be met by following the fossil business-as-usual route.

The amount of credits for the bollard does depend on the assumption which alternative materials are avoided, and in the case of wood, the type of wood is of influence as well (European managed wood or tropical managed wood).

Therefore, in the next figure, the following material options are shown:

- Avoided material reference 1: 50% Hardwood, Azobe and 50% Hardwood, European managed forest
- Avoided material reference 2: 100% Hardwood, European managed forest
- Avoided material reference 3: 25% hardwood mix, 25% virgin mix of PP and PE (50/50), 25% steel and 25% concrete)

Based on these variants, the net results fall between -0.13 and -4.29 kg CO_2-equivalents with these assumptions.

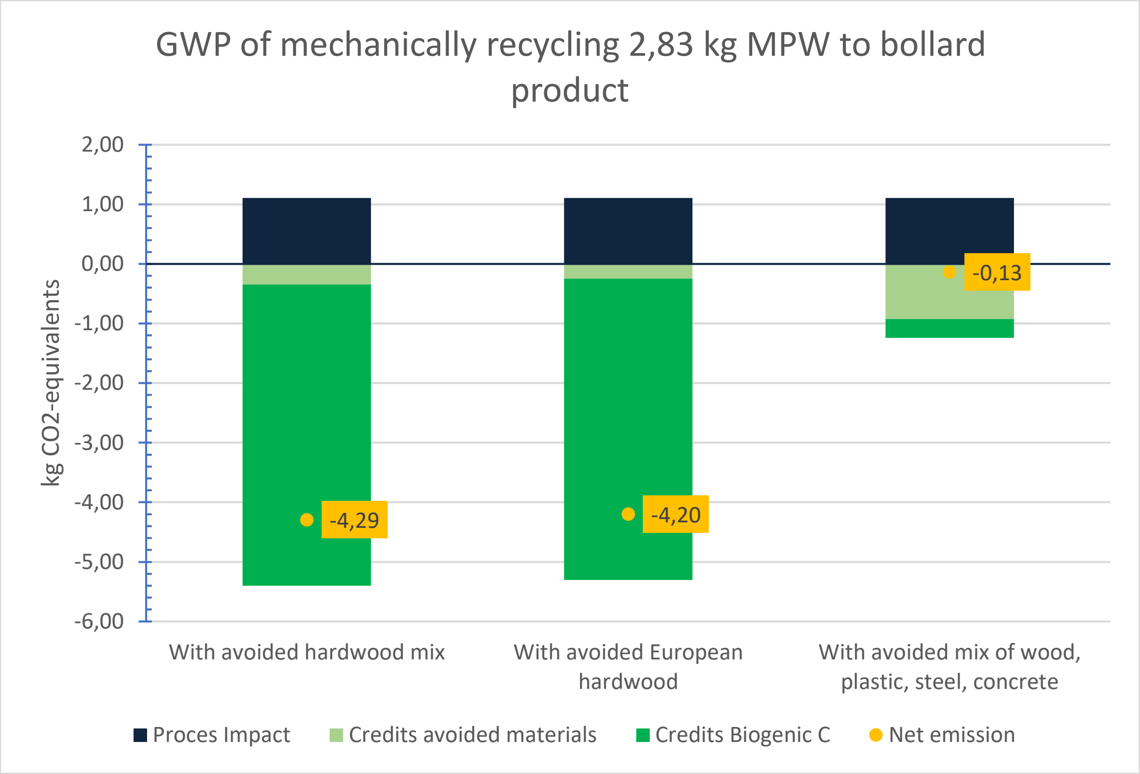

Figure 14 Comparison of results with three different avoided material mixes and the impact of the production of BTX. The amount of material needed to produce 1 kg BTX has been diverted to mechanical recycling. The resulting impacts of this recycling route are shown.

Discussion

Environmental impact of electricity production

In the Life Cycle Inventory (Method chapter) it was noted that all the impact data for electricity production was attributional, instead of consequential. Normally when deciding if an LCA is followed via the attributional or consequential approach, the input data should be handled in the same approach. However consequential data only encompasses the change in the market due to a change in demand and supply by the new system.

In the case of this LCA, this can be de debated. Would it be more likely that the general production mix of the Netherlands would just increase its total yearly production as the demand rises? And would this not only be accountable to our process but also other future processes or the expansion of other current industries?

In SimaPro it appeared that there was a factor of 10 in the difference between the two approaches. The attributional and consequential approach contained in SimaPro at least the following processes:

Consequential: Electricity production mix of hard coal, and natural gas, and importing a portion from German electricity mix and heat and co-generation (Natural gas, hard coal), lignite were contributing to the impact.

Attributional: Additional electricity production by wood, natural gas and wind (higher and lower power capacities) were the largest contributors to the impact.
It was chosen in this LCA to use the attributional data as it is more likely that one process does not indirectly lead to quick sudden changes in peak energy demand but it would be more likely that the total production would rise slightly.

Data limitations separation and purification of BTX components

During the LCI a limited amount of reference data was found regarding the energy use for BTX separation and purification is available.

To minimize the number of assumptions in this area, a simplified approach has been taken in which the average emissions for Benzene, Toluene and Xylene (mixed) are converted into a BTX content ratio that is in line with BTX from the PCP. This mix is then used as an emission for calculating the impact results. As the B, T and X products from this data source are in a more purified state than the BTX products gained from the PCP, an additional step was added to the currently proposed PCP system: purification (initial distillation). Sources and references regarding impact data for this process are scarce, however, as mentioned in the methods, an estimated CO_2 emission for the initial distillation process was used of 0.13 kg CO_2-equivalents/ kg BTX. In a later stadium, a check on this number would be advised, although it is not the largest contributor to the total impact of global warming.

Impact variances for incineration of MPW

The environmental credits due to the prevented incineration of the MPW have a considerable share in the total emissions. The emission data that has been found in the literature varies between 2.5 and 3.0 kg CO_2 per kg MPW. To further specify the exact emissions from incinerating this MPW stream, a theoretical approach has been used to calculate the CO_2 emissions. However, due to the limitations of this approach, the total emissions are lower than the emissions found in the literature. This is likely because emission factors such as methane and other lifecycle activities are not included in the simplified approach. A summarizing table of this theoretical approach and literature findings regarding the emissions from MPW incineration can be found in *Appendix B.*

Developments in environmental impact analysis

As methodologies in environmental impact assessment are evolving, it is important to touch upon the latest developments. Many of these new methodological developments are aiming towards including the circularity of new production systems in the LCA methodology. Below, a quick description of these methods is given and their implications for BioBTX are described.

Plastic-to-Plastic yield

This 'plastic-to-plastic yield' approach, published by CE Delft in 2022, is a method in which the efficiency of the recycling process can be compared. This approach is the first exploration of ways in which the progress/developments of chemical recycling can be monitored on a national level.

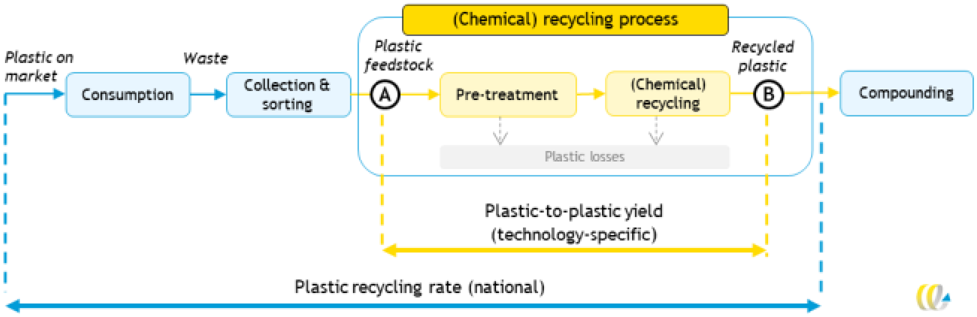

Figure 15 Scope of a plastics-to-plastic yield approach within a (chemical) recycling process. From: CE Delft, 2022

Unfortunately, there are still limitations to this approach as it does not take into account the different types of end-products that these recycling systems produce. For example, the PCP recycling process converts 1kg MPW to crude BTX with an efficiency of 40%. With this 0.4kg of crude BTX, approximately 1.5-2.0 kgs of plastics can be made. As of this moment, there is no way for taking this conversion factor into account.

Although this approach could lead to a more fair comparison between the performance of recycling processes, aspects such as material (plastic) quality and final market value are still excluded. These aspects are however incorporated in the Circular Footprint Formula.

Circular Footprint Formula

As stated before, several issues arise when assessing the environmental impacts or benefits of MPW recycling routes. How can the burdens or benefits be shared between the product being recycled and the next product that will use the recycled material for its manufacturing? What is the quality of the recycled material versus the virgin one? Is there downcycling? In this regard, the European Commission developed the so-called Circular Footprint Formula (CCF). This formula defines the rules to allocate the environmental burdens or benefits of recycling, reusing or recovering energy between, for example, the supplier and the user of recycled materials.

In a study from Jeswani et al. (2021), this formula was used to compare the impacts of chemical recycling (via pyrolysis) of MPW with mechanical recycling and energy recovery. Parameters within this formula are of interest to this study, as they include material quality aspects and market demand.

Table 11 Overview of CFF parameters, adapted from Jeswani et al. 2021

Parameters in the circular footprint formula (CFF)			
	Pyrolysis*	Mechanical recycling	Incineration (30%) and incineration with energy recovery (70%)
A Factor	0.5	0.5	0.5
B Factor	0	0	0
QScout	1	0,5	n/a
*In the pyrolysis system, the plastics are pyrolysed to produce oil, which is then purified and used as feedstock to produce virgin-grade LDPE granulate			

The CFF parameters (A, B and QScout) were used in the study from Jeswani to account for different quality of recyclate and various allocation factors.

A Factor

As detailed in the Product Environmental Footprint (PEF) guidelines (EC, 2018c), factor A captures both aspects of recycling (recyclability and recycling content) by allocating environmental burdens and credits between the 'virgin' and 'recycled' life cycles as per market realities. A low A factor (<0.5) reflects a low supply and a high demand for recyclable materials, while a high A factor (>0.5) reflects a high supply and a low demand for recyclable materials. The default value for the A factor for plastic materials in the PEF guidelines is 0.5, which reflects an equilibrium between supply and demand.

B Factor

This factor represents an allocation factor for energy recovery technologies and is used to share burdens and credits for energy recovery between the end-of-life energy recovery process and recovered energy. The default value for B in the PEF guidelines is zero (EC, 2018c), which means that all burdens and credits associated with incineration are allocated to the energy recovery process. In contrast, if B = 1, all burdens and credits are allocated to the recovered energy, and the end-of-life process carries no burdens.

QScout

This factor takes into account the quality of the outgoing secondary (recycled) materials. The ratios are based on the market values of virgin and recycled materials. For the pyrolysis option, the QScout is assumed to be equal to 1 as it produces virgin-grade plastic. Since the economic value of the granulate produced by mechanical recycling of MPW is about 50% of the economic value of virgin-grade plastics (Lindner, 2020), the QScout for the mechanical recycling system is assumed at 0.5.

When taking the above CFF parameters into account, the comparison of R-BTX production and mechanical recycling of MPW changes accordingly as both A factor and Qscout values are different for the two systems. These values have an impact on the impact results of the LCA when the CFF is utilized. As it is unlikely that the demand for plastic bollards is going to increase as much as the demand for Renewable BTX, the difference in the A factor will likely become greater over time.

Table 12 Overview of CFF parameters, with estimated PCP data.

Parameters in the circular footprint formula (CFF)		
	PCP – R-BTX production	Mechanical recycling into bollards
A Factor*	<0.5	>0.5
B Factor	0	0
Qscout**	≥1	0.5
*Based on industry expert knowledge **Based on market value demonstrated in the table below		

As stated earlier, comparing chemical recycling with mechanical recycling is a complex practice in which in addition to the associated emissions also factors such as material value and supply and demand have to be added. Finally, even after including these factors, the market dynamics (carbon tax) and changes over time would have to be included in the overall environmental impact to make a fair comparison that is future-oriented.

Table 13 Overview of the monetary value changes throughout the recycling process. This table is for indicative purposes only.

	Value per kg						
System	Waste phase-MPW	Pre-treated MPW	Conversion phase	Purification phase	Compounding phase	Conversion to the final product	Material value after the one cycle
Mechanical recycling into a bollard	<€0,00	€0,10	+/- €1,00 (Final product)				50%**
Chemical recycling - PCP	<€0,00	€0,10	€0,90 - €1,00	>€1,00	No data	€3,0 - €5,0*	100%
* value depends on the type of plastics that are made from R-BTX ** primarily due to material degradation							

Conclusion

In this report, a screening LCA was carried out for PCP B.V. The first report was focussing on the impact of different feedstocks, while this report looked into the production of BTX via mixed plastic waste versus the incineration and alternative recycling route of its feedstock.

The leading functional unit in this LCA was ***the production of a purified renewable BTX mix by the Plastic Conversion Plant with equal quality as its fossil-based B, T, and X counterparts, for use in Europe.***

Producing renewable BTX out of MPW via the PCP results in a negative net impact of -3.35 kg CO_2-equivalents. Of the credits, the avoided incineration of MPW was the main contributor to causing a negative impact. When the required amount of MPW is instead used for the production of energy via incineration, a net impact of 4.89 kg CO_2-equivalents is found. In the final scenario, the MPW is used to produce bollards. This pathway gives an environmental net impact of -4.29 kg CO_2-equivalents but can vary up to -0.13 kg CO_2-equivalents depending on the choice of avoided materials (hardwood or a combination with steel, concrete and virgin plastic). The investigated scenarios are not 1-on-1 comparable with each other but do give insight on an individual level.

Between 2015 and 2020, more than half of the total global carbon demand originated from the chemical and derived materials sector and this demand is expected to grow between now and 2050 by roughly 100%. BTX is an important intermediate chemical product and serves as a basis for a multitude of different products. The plastic conversion plant contributes to this carbon demand by ensuring that embedded carbon, via renewable BTX, can stay longer in product cycles before being released into the atmosphere. At the same time, by creating renewable BTX, less fossil-based BTX should be needed. However, this does depend on market developments. Comparing chemical recycling with mechanical recycling proves to be a complex practice in which in addition to the associated emissions also factors such as material value and supply and demand have to be added. Finally, even after including these factors, the market dynamics (carbon tax) and changes over time would have to be included in the overall environmental impact to make a fair comparison that is future-oriented.

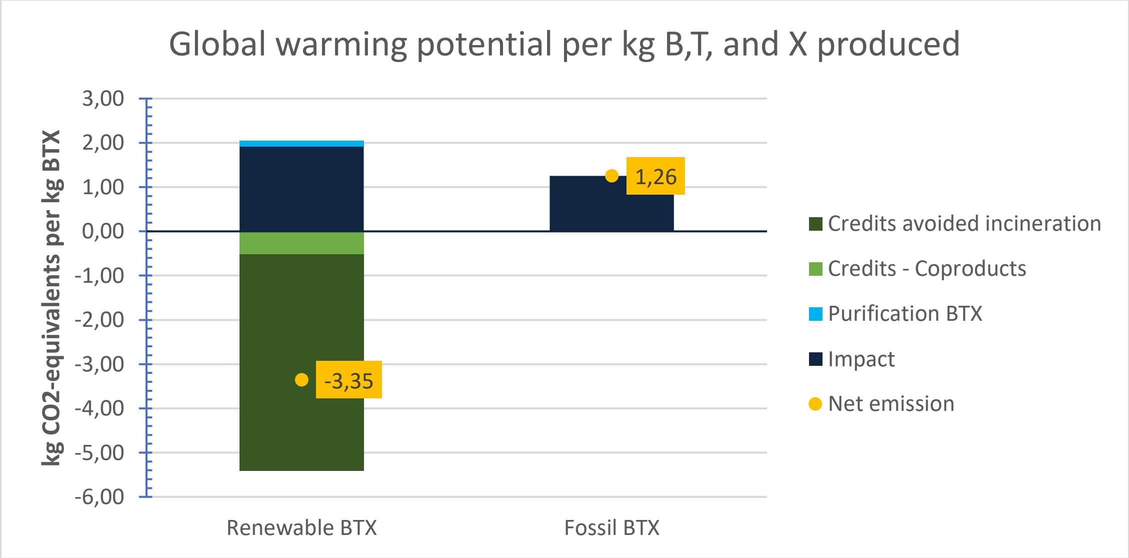

Figure 16 The production of renewable B, T, and X via the Plastic Conversion Plant.

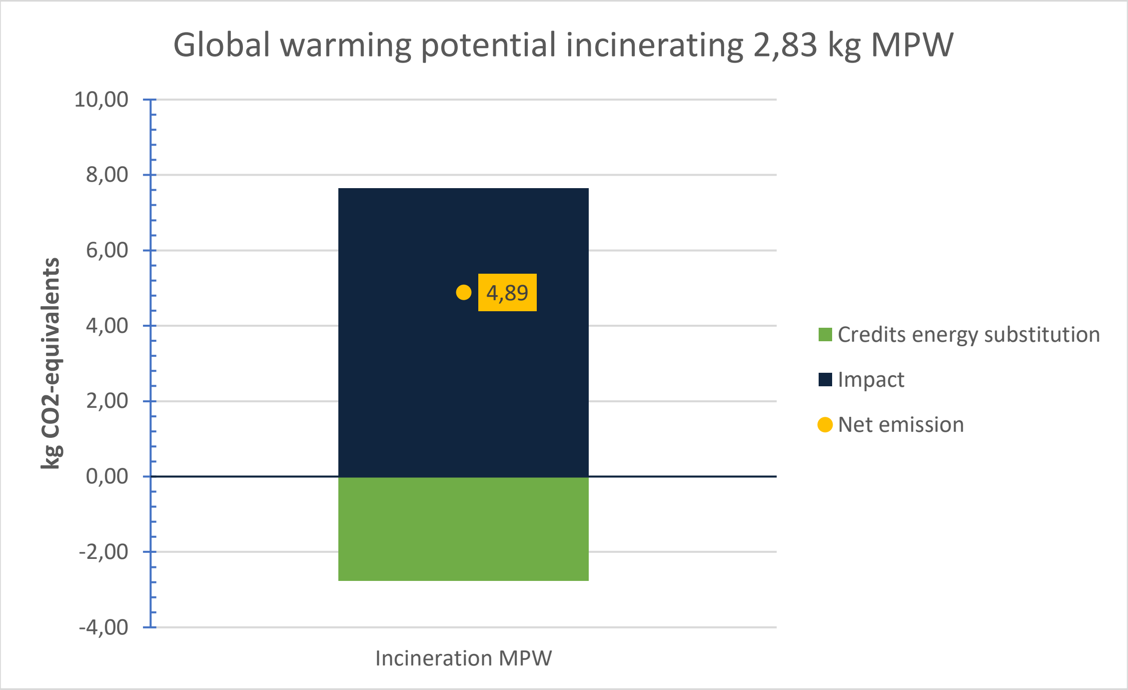

Figure 17 The environmental impact of incinerating 2.83 kg MPW in a waste-to-energy plant with energy recovery

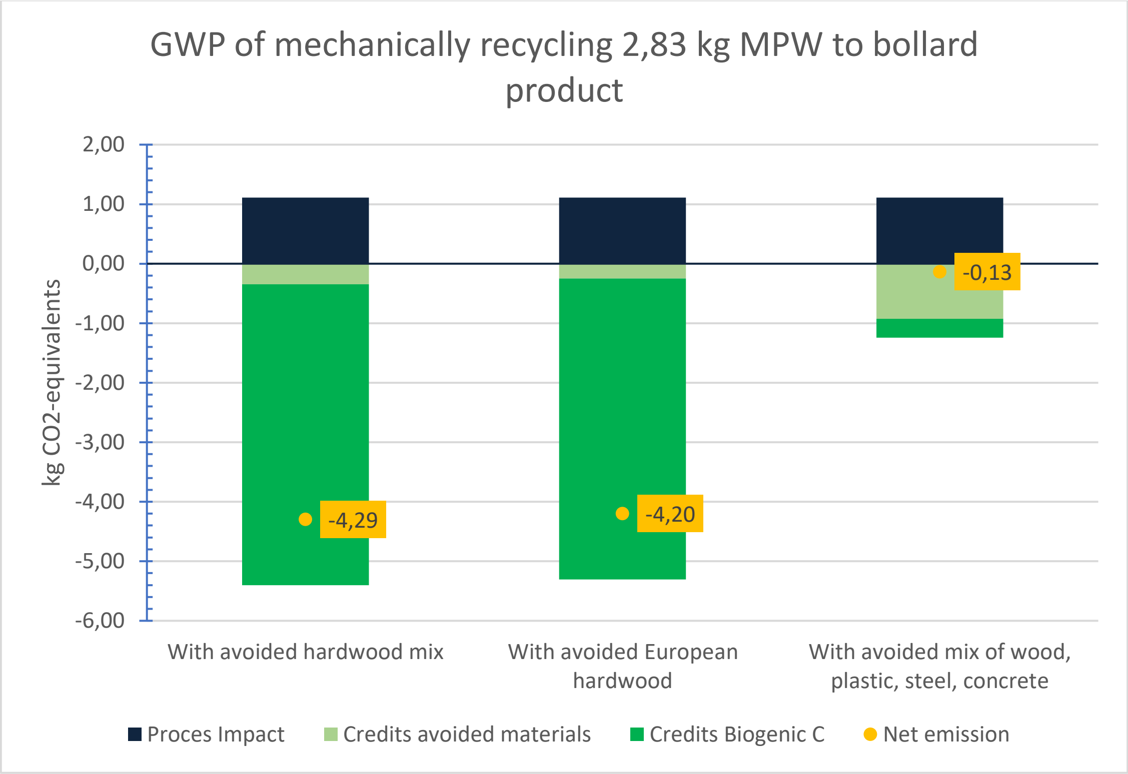

Figure 18 The environmental impact results of processing 2.83 kg MPW into 2.73 kg bollard material.

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Appendix

Appendix A: Update of impact data

The main system analysis has been updated with new datasets and impact methods. The following table contains the old and updated values and shows where changes in the impact have occurred. The highlights in green indicate a lower impact or higher credit in comparison to the previous data, while orange indicates an increase in impact and decrease in credit. Overall, the emissions decreased by ~0.15 kg and the credits by ~0.13 kg CO_2-equivalents respectively. The resulting net impact is lower with 0.11 kg CO_2-equivalents.

Appendix A: Update of the results from the current and previous study

	Report 2021	Report 2022
Perspective	*Per kg BTX*	*Per kg BTX*
Pre-treatment	0.08	0.07
PCP - Total Electricity	1.75	1.61
PCP - CaCO3 (HCL removal)	0.05	0.02
PCP - FCC catalyser	0.02	0.02
PCP - Treatment waste	0.26	0.19
BTX Purification step	0.13	0.13
Total emissions	2.30	2.05
Credit avoided incineration MPW	-4.89	-4.89
Light fuel oil	-0.20	-0.21
Natural gas	-0.45	-0.31
Total credits	-5.54	-5.41
Net impact*	-3.24	-3.36
* Includes the following avoided processes: Incineration of MPW, F-BTX production, Natural gas and light fuel oil		

Appendix B. Literature overview of MPW incineration

Appendix B Literature overview of environmental data of mixed plastic waste incineration

	Kg of CO_2 equivalents per kg MPW	Energy substitution	Net emissions	Additional information
ME 2018 & 2019*	2,7	NA	NA	Theoretical approach*
CE Delft 2019	2,9	-1,4	1,5	Recycling failure/ DKR 350
CE Delft 2021	2,71	-0,98	1,73	Mixed plastics from households in AVI
BASF 2020	2,987	-1,068	1,919	100% MSWI. Area: Germany
BASF 2020 RDF	2,992	-1,276	1,716	100% RDF = MPW with a higher caloric value. Area: Germany
Plastic Energy 2020	2,9	-1,3	1,6	Only the net emissions were given as an exact number. Impact for 1kg of MPW treated
Jeswani et al. 2021	2,5	-0,7	1,8	”*MPW is composed mainly of lightweight plastic packaging materials, such as polyethylene, polypropylene, and polystyrene.* ”German electricity mix
Gear et al. 2018.	NA	NA	1,87	Dry MPW input stream. Incineration to produce electricity displacing energy from the UK grid.

[*] *The value has been calculated based on IPCC (2006), using the following formula: kg CO_2 = kg waste for incineration * oxidation factor of carbon in incinerator (0.98) * conversion factor of C to CO_2 (3.67) * Σ(waste fraction (%) * dry matter content (%) * carbon content (g/g dry weight)). The dry matter content of plastic waste is equal to 1. The carbon content of plastic waste is 0.75 (g C/g dry weight waste). Moreover, the end-of-life emissions vary between different plastics types. The emissions are higher for incineration of e.g. PS and PE (around 3 kg CO_2/kg plastics) and lower e.g. PP and PUR (around 2.5 kg CO_2eq/kg plastics). In summary, ME (2019) and ME (2018) have used 2.7 kg CO_2eq/kg plastics for all incinerated end-of-life plastics.*

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