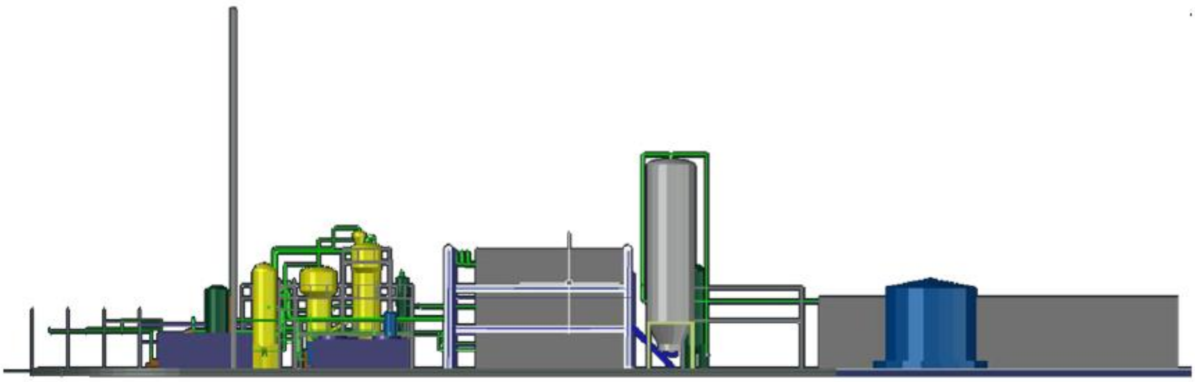
A screening Life Cycle Assessment of producing chemicals via thermo-chemical recycling at the plastic conversion plant (PCP)

PCP B.V.



Duinkerkenstraat 13
9723 BN Groningen
050-317 55 50
info@ecoras.nl

Preface

Commissioned by PCP B.V., a screening Life Cycle Assessment (LCA) has been carried out by Ecoras in the first quarter of 2021. PCP B.V. focusses on the production of *renewable* chemicals by producing a crude mix of benzene, toluene and xylene (BTX) and oil from mixed plastic waste via a patented thermo-chemical recycling process. In the near future a full-scale Plastic Conversion Plant (PCP) will be built in Delfzijl (The Netherlands), which will use this technique to process mixed plastic waste (MPW) into a crude-BTX /oil product.

This study evaluates the potential environmental performance related to the thermo-chemical recycling process of mixed plastic waste into crude BTX/oil and compares it to other relevant scenarios.

The authors would like to thank Adam Fontaine from TransitionHERO for his expert judgement.

Authors: Micha Klaarenbeek, Amarens de Wolff; *Ecoras*

Figure frontpage:

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

Disclaimer

This LCA serves as an environmental screening assessment in which the intended system (PCP) is analysed and compared to alternative pathways. The results of this LCA are for PCP B.V. to be used internally including distribution among potential interested parties (financiers and investors). The impact results presented in this report will give an initial indication of the expected environmental impact of the PCP system.

Authors:	Micha Klaarenbeek, Amarens de Wolff; *Ecoras*		
Quality Check / Supervision	Sven Jurgens, Jon Salt		
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Final Draft v1	14-4-2021	- first final draft	S. Jurgens
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Final Draft v2.1	3-5-2021	- Updated chapter 3.2.1: internal re-use of carbon gas	S. Jurgens
Final report	4-5-2021		S. Jurgens

Abbreviations and Definitions

Below the abbreviations and definitions used in this report are explained

Abbreviations:

DKR-350: Predefined mixed plastic waste sorted by waste processers from mixed plastic waste.

F-BTX: Fossil BTX - B, T and X that is produced via the conventional pathway based on fossil resources

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 DKR-350 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.

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

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 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, 2021)

Renewable BTX: According to the definition of Renewable carbon, the BTX produced via the PCP plant avoids a part of the fossil production route of BTX in a Business-As-Usual case. Therefore the BTX produced at the PCP plant is referred to as Renewable BTX in this report

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 in this report as renewable carbon gas

Executive summary

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.

The LCA starts with defining the system and the boundaries of the investigation. In the following figure (2) a general overview of the system investigated is shown. In the upper green box the future PCP system (New scenario) is given. The MPW enters the PCP plant at the factory gate. The type of MPW mixture is defined as DKR350, a mix of several types of plastics and a maximum percentage of impurities.

After arrival, the MPW is processed through the plastic conversion plant which results in a crude mix of BTX and energy in the form of renewable carbon gas. This energy has the potential of partially avoiding fossil energy production.

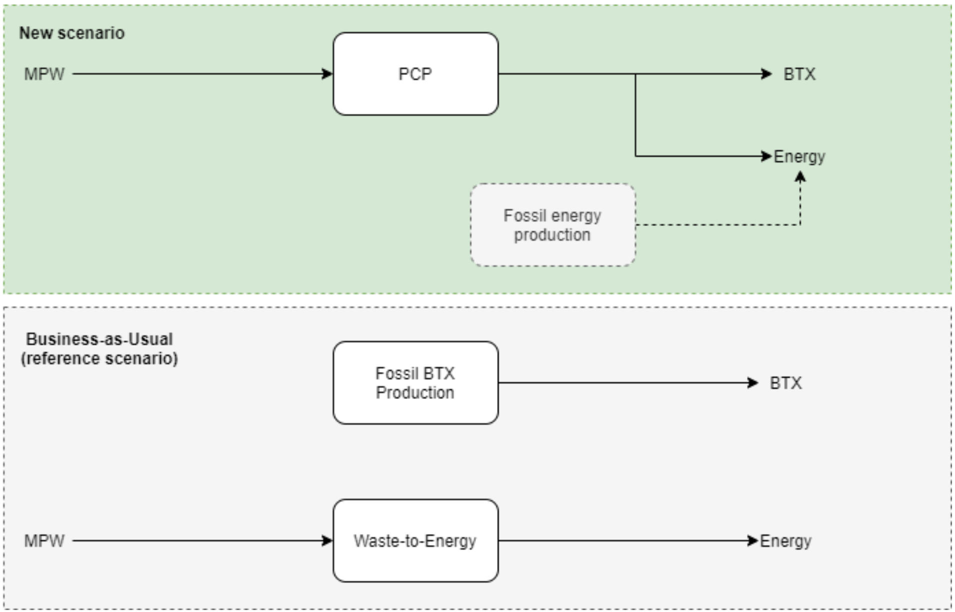

Figure 2 General overview of the investigated system. In the upper box the general steps are shown for the PCP process, which takes place at the Plastic Conversion Plant. The system starts when the plastic arrives at the factory gate. It then follows the conversion in the plant, of which the end products are BTX (mix) and energy in the form of renewable carbon gas as co-product. In the business-as-usual scenario, the BTX is produced via a fossil production route. MPW is transported to a waste to energy plant, where the plastic is incinerated for heat and electricity production.

In the present day the treatment of MPW and the production of BTX and energy are following different paths. In order to compare the change of impact a Business-as-Usual (reference scenario) was defined as well. In general, BTX is produced from Naphtha, a co-product from crude oil processing. Secondly, MPW is mostly transported to Waste-to-Energy plants, where the mix is incinerated for energy production. If the PCP process would take place, some of the BTX and MPW would be diverted from their business-as-usual routes to the route of PCP. The goal of this LCA was to gain insight into the differences in environmental impact between the aforementioned scenarios.

Within the LCA, two perspectives were central in the investigation: waste management of the plastic and the production of a BTX mixture.

Waste perspective

In this perspective, the management (or processing route) of waste was the point of focus. Therefore, 1 kg of sorted mixed plastic waste was followed throughout the PCP process. The functional unit, in which all the emissions and data are expressed is defined as follows: Waste management of 1 kg of sorted mixed plastic waste (DKR 350) in Europe.

At the time of writing, incineration of the DKR350 MPW in a waste-to-energy plant is the most common waste management scenario. Therefore it was used as the business as usual scenario. In the future, it is possible that with the development of new techniques the reference scenario needs to be updated. In figure 3 the outcome of the screening LCA is shown. In the left bar the emissions, credits and net value of the PCP is shown, and in the right bar the same type of impacts is shown for the reference situation. The net emission from incinerating the of 1 kg MPW is 1.73 kg of CO_2-equivalents. In the new scenario, where the MPW is processed at the PCP plant, the net emission is 0.13 kg CO_2-equivalents.

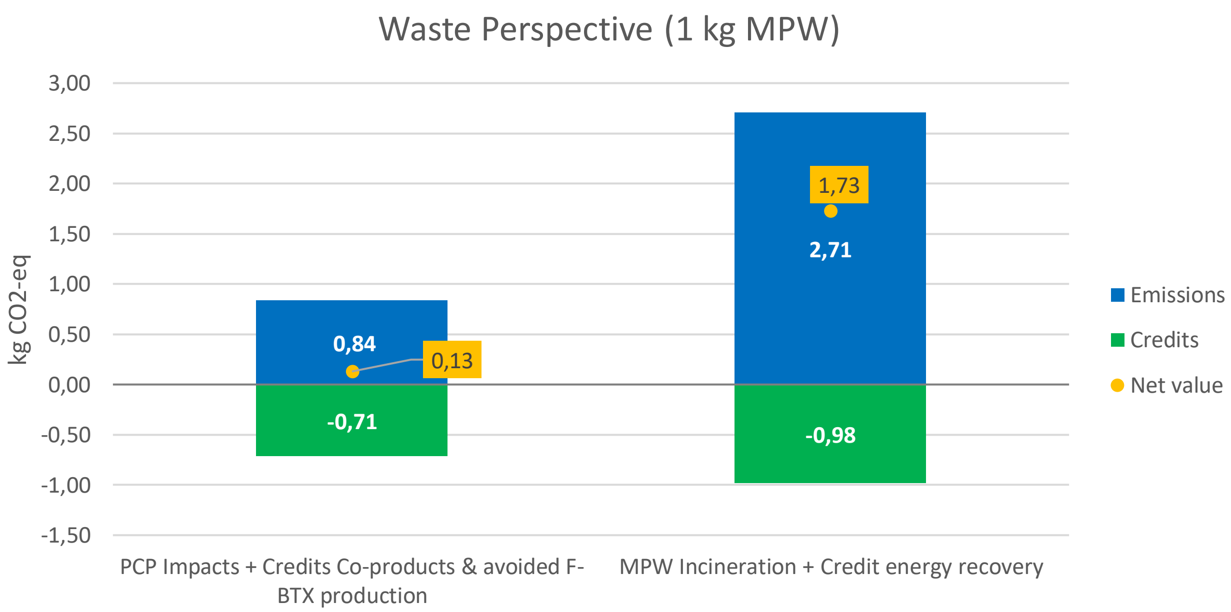

Figure 3 Results from the LCA in which the PCP process on the left is compared with the Business-as-usual on the right. For this perspective the MPW is processed in a waste-to-energy plant and is referred here as incineration of the MPW. In blue the emissions of both processes are given. In green the credits (avoided production of substitute processes) are given. When the emissions and credits are combined the resulting impact is shown as a yellow dot in the bar.

Product perspective

In this perspective the production of 1 kg of BTX is chosen as a functional unit. The functional unit, in which all the emissions and data are expressed was defined as follows: Functional unit for product perspective approach: Producing 1 kg virgin grade B,T and X for use in Europe.

In the Business-as-Usual situation the production of fossil BTX takes place via the refining of Naphtha (co-product of crude oil refining). Expected is that as long as crude-oil is still refined and thus Naphtha is produced as well, the business-as-usual scenario of BTX production will most likely stay the same. The emissions from this process account for 1,26 kg of CO_2 equivalents. In the new scenario in which BTX is produced via the PCP process the net result is -3,03 kg CO_2 equivalents. This negative emission value is primarily due to credits from the generated by-products and avoided MPW incineration.

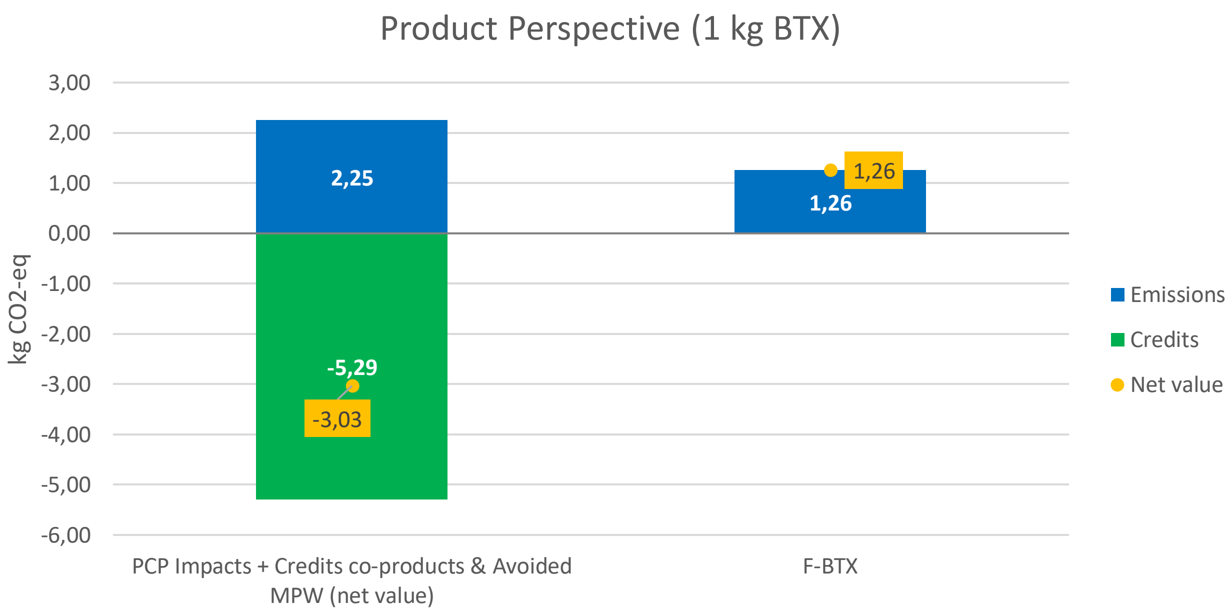

Figure 4 Results from the LCA in which the PCP process on the left is compared with the Business-as-usual on the right. For this perspective the BTX is produced via the refining of Naphtha and is referred here as F-BTX. In blue the emissions of both processes are given. In green the credits (avoided production of substitute processes) are given. When the emissions and credits are combined the resulting impact is shown as a yellow dot in the bar.

Structure of the report

The structure of the report follows the guidelines provided in ISO 14040 and 14044. In chapter 1 more general information about the Plastic Conversion Plant and its process can be found. The method of the LCA is further addressed in chapter 2. Here the data used to calculate the impacts is given as well. The results of the study are presented in chapter 3. The data is presented step by step in order to provide insight in the structure of both emissions as credits before the complete figure is shown. In chapter 4 the main assumptions and data limitations are discussed. In chapter 5 the results and discussion points are concluded.

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1. The Plastic Conversion Plant (PCP)

The purpose of the 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 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 in order to maximise the BTX yield in a most economical manner. For this environmental assessment Phase (2) will be taken as the baseline (48 kt/year).

1.1. General PCP process description

The general process of the PCP is described in the report 'Basis of Design' by TransitionHERO (TH, 2020). Here below a summary is given:

In general the following process steps are 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

In more detail, the process itself works as follows:

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), BioGreen units have been chosen as reactor type. This step is further mentioned as the process in Reactor 1 (referred to as R1). Here, under 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 led through a fluidized bed (containing a catalyst) which converts the inflowing vapours 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 they are ready for storage, transport and further use.

2. Method

The LCA has been carried out according to the ISO guidelines (ISO 14040 / 14044) and consists of five steps: Procedures, Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation of the results. These steps are further addressed in the following subsections.

2.1. Goal and scope definition

The overall goal of this LCA is to assess the potential environmental impact of the Plastic Conversion Plant when it is fully operational and processes 48 kton mixed plastic waste (MPW) per year into crude-BTX-oil mixture. The scope of this study has been set on an European level when looking at the input of MPW and the export of the produced crude-BTX/oil. The processing itself will take place at the (future) PCP in Delfzijl, the Netherlands.

2.1.1. Function and functional unit

In this assessment, the system is analysed from a product- and a waste perspective. Since the two perspectives are different, two functional units and thus two LCA's are defined:

Functional unit for waste perspective approach: Waste management of 1 kg of sorted mixed plastic waste (DKR 350) in Europe.

Functional unit for product perspective approach: Producing 1 kg virgin grade B,T and X for use in Europe.

These two systems were chosen in order to assess the potential environmental advantages and disadvantages of using the PCP process as an alternative to current day practices of waste management and (fossil-based) chemicals production.

2.1.2. System boundaries

The goal of this LCA is to evaluate the consequence of the PCP plant versus a situation where there is no PCP plant. Therefor a consequential approach was used in this study.. This means that this research focusses on changes in the system as a consequence of a change in demand for the functional unit[1]. System expansion is used to incorporate the changes in the system beyond the PCP process itself. In the following two sub-sections the specific boundaries per functional unit are defined. First the system of the waste perspective will be shown, and following that, the system of the product perspective. Also the reference systems are included to illustrate which present day pathway the PCP process is compared with. In the analysed systems the transport activities are excluded because they are out of the scope of this analysis. In figure 5 both perspectives are combined into one (high level) overview.

2.1.3. Waste perspective

In this case, the PCP is planned to process DRK350 by converting it into a mixture of BTX, oil and several by-products such as gasses and waxes. The functional unit is defined as the treatment of 1kg of DRK350 (mixed plastic waste). The scope of the study comprises the point of collection and transportation of MPW from households, sorting and gasification/pyrolysis of DRK350 to produce BTX and other aromatic oils, as the main products and char + RC gasses as a co-products. The main products BTX and other aromatics have to be purified before they can be used as feedstock for further industrial processing. In the current EU waste management system, the main and most commonly used processing route for the MPW stream is incineration, also referred to as waste-to-energy.

2.1.4. Product perspective

In the product perspective, the PCP process is seen as an alternative process to produce a fossil grade BTX mix (F-BTX). In order to make a fair comparison between fossil based BTX and the 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 the fossil based BTX. In order to make the product comparison on an equal basis, a purification step is added to the PCP process. Data for this process step are extracted from a previous study regarding the production of BioBTX (Schenk & Tecante

[1] Consequential-LCA (2020). Why and when? Last updated: 2020-10-01. www.consequential-lca.org

et. Al. 2020). It was assumed that the ratio between B,T and X were equal (see Appendix B). For a more detailed overview of the system used in the LCA comparsion see Appendix D.

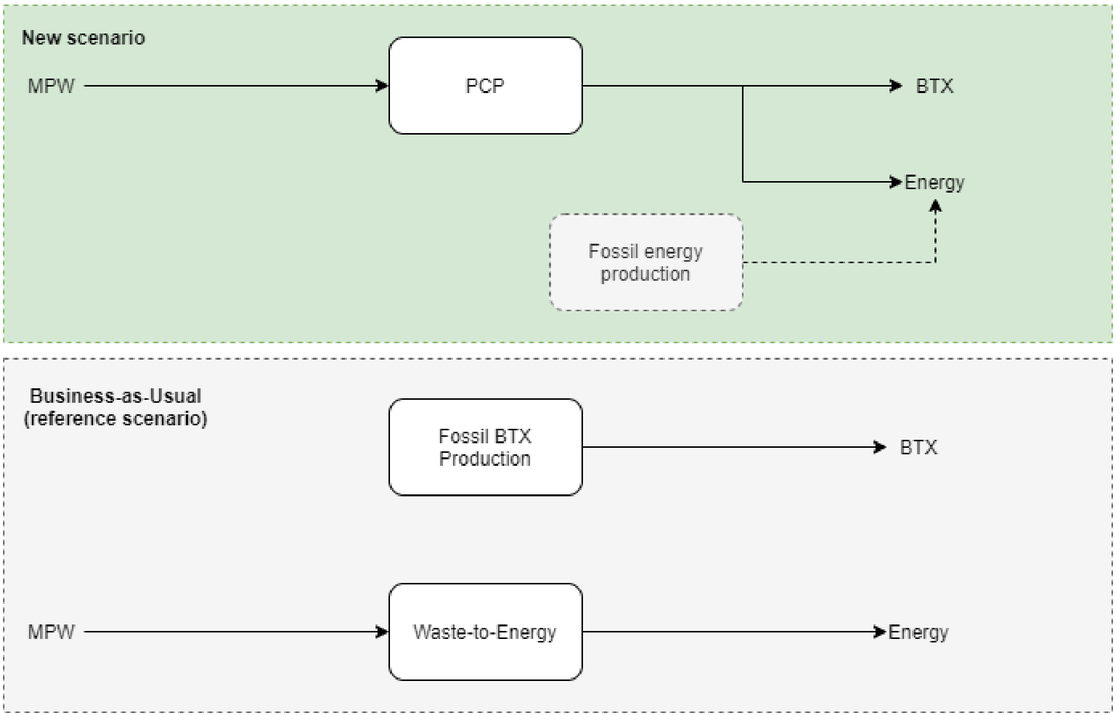


Figure 5 System boundaries for the production of BTX. On the top the PCP process of producing BTX is demonstrated. On the bottom the business-as-usual system for fossil based BTX and the incineration of MPW in a waste-to-energy plant are demonstrated in a high level overview.

2.2. Life Cycle Inventory (LCI)

To document which data have been used for the life cycle inventory (LCI), the following table has been made. In the table (1) an overview of the used data is given per process step, the source of the used data and if applicable, the assumptions that were made.

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

0. General data PCP			
Process	**Value**	**Unit**	**Notes**
Processed MPW per year	48000	ton	Data from TransitionHERO, Basis of Design (TH. 2020)
Production hours per year	8000	hours	Data provided by TransitionHERO
Hours per production day (average)	21,9	hours	Calculated based on production hours per year
Kg processed MPW per hour	6000	Kg	Data provided by TransitionHERO

In the first table general information about the conversion process of the PCP is given, when it is fully operational (phase 2). Based on this production data the rest of the inventory data could be recalculated into 1 kg processed MPW per hour. Based on these values and the mass balance the data for the second FU, producing 1 kg F-BTX could be calculated as well.

In table 2 the composition of the MPW, also referred as DKR 350, is given. The mix consists of several plastics, some moisture and impurities. All values are expressed in 1 kg MPW.

Table 2 Life Cycle Inventory for the Mixed Plastic Waste (MPW), also referred to as the DKR 350 fraction

0. 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				Percentage -> Data from TransitionHERO, Basis of Design (TH. 2020)
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 contains the inventory for pre-treatment of the raw plastic feed. Processes are 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.

Table 3 Life Cycle Inventory for the pre-treatment of the MPW.

1. Pre-treatment				
Process	**Fraction %**	**Value**	**Unit**	**Notes**
Pre-treatment MPW		**1**	**Kg**	**MPW input**
Input				
Additional sorting MPW		0.058	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)		0.074	MJ	Own calculations** Electricity, medium voltage (NL), market for, **attr. Cut off**. Is in range of numbers:
Output				
Dried MPW (Moisture output)	7,5% to <3%	0,045	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		0,009	Kg	Amount is calculated from 427 metric ton / year over 48.000 ton processed MPW. Data provided by TransitionHERO MSW deposition, landfill incl. landfill gas utilisation and leachate treatment, AT,DE,IT, LU, NL, SE, CH, mix EU-27
Treated MPW		0,95	kg	(1 kg MPW minus Moist output and Impurities removed)
* Electricity impact was assumed to be a general electricity mix for the Netherlands ** Value lies in range of reported values by company CS Plastics (2021)				

In table 4, data for the plastic conversion process is shown. This consists of 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

2. PCP conversion process				
Process	**Fraction %**	**Value**	**Unit**	**Notes**
PCP process - Input		**1**	**Kg**	**Treated Mixed Plastic Waste**
Input				
Treated MPW		1	Kg	
Electricity total installation		0,001	MWh	Data provided by TransitionHERO **Impact data:** Electricity, medium voltage (NL) market for, **attr. Cut off***
HCl removal ($CaCO_3$)		0,01	Kg	Data provided by TransitionHERO **Impact data:** Calcium Carbonate, Precipitated, RER, consequential
Catalyst		0,001	Kg	Data provided by TransitionHERO Based on reference process FCC (Fluid Catalytic Cracking). Active ingredient used there is Zeolite** **Impact data:** Zeolite, Powder (RER) production, consequential
PCP process - Output				
Output				
Waste streams(total)		***0,228***	***Kg***	*<u>Including impurities removed at pre-treatment (0.009 kg)</u>*
Separation wastewater		0,097	Kg	Data provided by TransitionHERO **Impact data:**

				Wastewater, average (EU without Switzerland), market for wastewater, average, consequential
Separation & dechlor unit (HCl)		0,003	Kg	Data provided by TransitionHERO MSW deposition, landfill incl. landfill gas utilisation and leachate treatment, AT,DE,IT, LU, NL, SE, CH, mix EU-27
R1- Bottoms		0,04	Kg	Data provided TransitionHERO MSW deposition, landfill incl. landfill gas utilisation and leachate treatment, AT,DE,IT, LU, NL, SE, CH, mix EU-27
R1 – Total – Cyclone and filter		0,08	Kg	Data provided by TransitionHERO MSW deposition, landfill incl. landfill gas utilisation and leachate treatment, AT,DE,IT, LU, NL, SE, CH, mix EU-27
R2 – Total – Cyclone and filter		0,001	Kg	Data from TransitionHERO MSW deposition, landfill incl. landfill gas utilisation and leachate treatment, AT,DE,IT, LU, NL, SE, CH, mix EU-27
PCP Products				
Crude - BTX	37%	0,37	Kg	Data provided by TransitionHERO
PCP Co-products				
Bio-oil	16,4%	0,17	Kg	Data provided by TransitionHERO Replaces Light fuel oil (EU without Switzerland) market for, consequential
Wax		0,03	Kg	Data provided by TransitionHERO Replaces NL Natural gas mix, technology mix, at consumer, onshore and offshore production incl. pipeline and LNG transport EU-27
Gasses		0,28	Kg	Data provided by TransitionHERO Replaces NL Natural gas mix, technology mix, at consumer, onshore and offshore production incl. pipeline and LNG transport EU-27
* Electricity impact was assumed to be a general electricity mix for the Netherlands ** FCC – Process / active ingredient Zeolite: (Wikipedia, 2021)				

2.2.1. Data for the Reference scenarios

Environmental impact data for the reference cases (incineration MPW and F-BTX production) were based on literature data (Appendix A & B). In order to be able to compare R-BTX with the purified virgin F-BTX, 0.13 kg CO_2-equivalents per 1 kg BTX was added to the PCP process to include the purification step (Schenk & Tecante et. Al. 2020). It was assumed that the composition of the B, T, and X fraction was equal for the two systems, which is given in table 5 (see Appendix B for more information).

Table 5 The ratio of B, T and X used in this LCA. Data are from Plastics Europe, 2013.

Content ratio B, T and X (Plastics Europe, 2013)			
	Benzene	**Toluene**	**Mixed Xylenes**
Content ratio (in BTX)	24%	48,5%	27,5%

2.3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment has been carried out in Microsoft Excel and Simapro version 9.1. In Excel the mass balance of the process was modelled while the impact of the system was modelled in Simapro. For the assessment of the environmental impacts the IPCC 2013 method was chosen to summarize emissions according to their respective global warming potential (in kg CO_2-equivalents), as this was the main objective. This unit includes other gasses that contribute to global warming. The conversion factors can be found in the report from IPCC 2013.

3. Impact results

The results from the LCI and the impact assessment LCIA are presented here. The collected data from the Life Cycle Inventory has been assessed per functional unit. Alongside the basic LCA, several scenarios were assessed to evaluate the consequences of different options.

3.1. LCA results base case

In this section the results for the base scenario are presented for both the waste perspective and product perspective. It should be noted that for the production of 1 kg BTX around 2.68 kg MPW is needed. Therefore the product scenario is 2.68 times higher in impact than the waste perspective for the same process steps.

First, emissions that contribute to the global warming potential are broken down and discussed per process step. The description starts with the smallest impacts and builds on the previous figure. Figure 12 will encapsulate all the PCP emissions. Secondly, the same structure is applied for processes that avoid emissions that contribute to the global warming potential. In the last section both emissions and credits are combined and the overall results are discussed. This includes the consequence of using different perspectives and their effect on the overall result.

3.1.1. Processes contributing to the emissions

3.1.1.1. *Pre-treatment*

The first process contributing to the emissions of the PCP process is the pre-treatment step, where the MPW is treated before being fed into the PCP process. This process contains the required energy for both additionally sorting the MPW and reducing the moisture content from 7,5% to 3%. Also, the treatment of the removed impurities is included. When the system is assessed via the waste perspective, the impact of the pre-treatment of 1 kg of MPW is 0.03 kg CO_2-equivalents. From the product perspective, in which more plastic is needed to produce the 1 kg of R-BTX, 0.08 kg of CO_2-equivalents is emitted during the pre-treatment step (see figure 6).

3.1.1.2. *PCP - Calcium carbonate for HCl removal*

The production of calcium carbonate, required for the removal of acids produced during the PCP process, results in 0.02 kg of CO_2-equivalents and 0.05 kg of CO_2-equivalents for the waste- and product perspective. In figure 7 the impact is added to the emissions of the pre-treatment. It shows that both impacts are in the same order of magnitude.

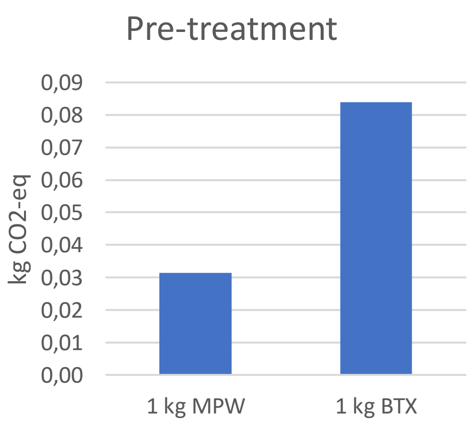


Figure 7 Global warming impact for the pre-treatment step of the process in kg CO_2-equivalents. The left figure represents the waste perspective (1 kg MPW) and the right figure represents the product perspective (1 kg R-BTX). For 1 kg BTX, ~2.68 kg MPW is needed.

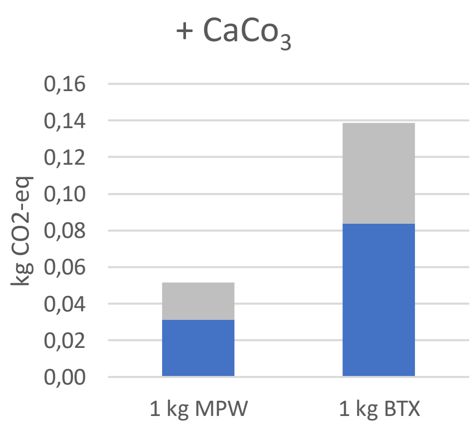


Figure 6 Total impact of the pre-treatment and added production of $CaCO_3$ in kg CO_2-eq. The left figure represents the waste perspective (1 kg MPW) and the right figure represents the product perspective (1 kg BTX). For 1 kg R-BTX, ~2.68 kg MPW is needed.

3.1.1.3. *PCP -FCC Catalyst*

The impact of producing the catalyst for the PCP process is 0.005 kg of CO_2-equivalents and 0.01 kg of CO_2-equivalents respectively. Added to the previous processes in figure 8, this process only has a minor influence compared to the other two steps.

3.1.1.4. *PCP - BTX purification*

The BTX purification step has been added to the process to compare the production of F-BTX with the R-BTX from the PCP process. In the literature most impact data in relation to F-BTX production included the purification step, but did not specify which part of the impact was used. In the current Basis of Design (TH, 2020) the purification step has not been added. Therefore, impact data for purification has been derived from a previous study (Schenk & Tecante et. Al, 2020) to make both processes equal, an impact of 0.05 kg of CO_2-equivalents was added for the waste perspective and 0.13 kg of CO_2-equivalents for the product perspective. In the graph in figure 9 these impacts were added.

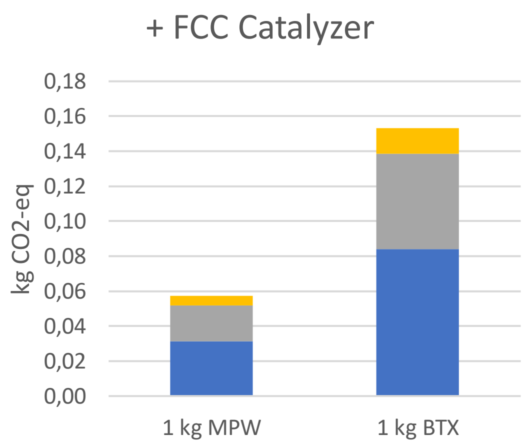


Figure 9 Total impact of the previous processes with added prodution proces of the catalyzer. The left figure represents the waste perspective (1 kg MPW) and the right figure represents the product perspective (1 kg BTX). For 1 kg R-BTX, ~2.68 kg MPW is needed.

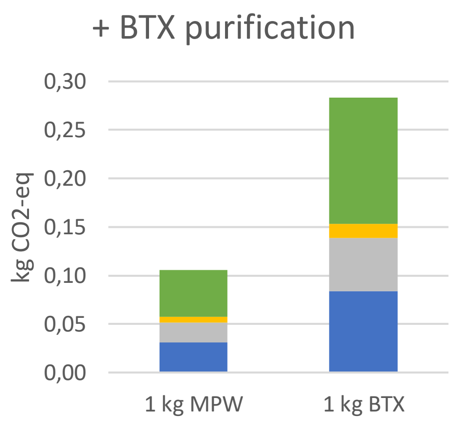


Figure 8 Total global warming impact for the previously mentioned processes and added purification step in kg of CO_2-equivalents. The left bar represents the waste perspective (1 kg MPW) and the right bar represents the product perspective (1 kg R-BTX). For 1 kg BTX, ~2.68 kg MPW is needed.

3.1.1.5. *PCP - Treatment waste*

This process consists of two subprocesses: incineration of the inert substances produced in the PCP process and the treatment of the wastewater. The impact is 0.10 kg of CO_2-equivalents (WP) and 0.26 kg of CO_2-equivalents (PP). In figure 10 this impact was added. This process has a larger contribution to the overall impact than the previous processes.

3.1.1.6. *PCP - Total Electricity demand*

The electricity demand required by the PCP installation has the largest contribution to the total emissions: The impact is 0.65 and 1.75 kg of CO_2-equivalents respectively for the scenario's (WP & PP). The main reason is that the entire PCP will run on electricity. It is now assumed that no gas(LNG) will be used in the entire process. Due to the big impact of the electricity, the relative influence of the other process decrease significantly. The numbers are not clearly visible anymore in figure 11. Therefore in figure 12 the graph has been magnified to give a better overview of all the contributing processes.

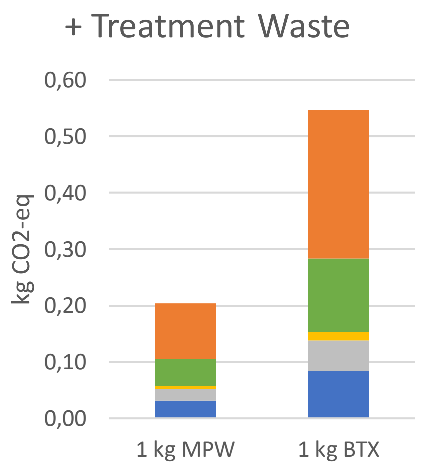


Figure 10 Total imapct of the previous processes and added treatment of waste fractions in kg of CO_2-equivalents. The left bar represents the waste perspective (1 kg MPW) and the right bar represents the product perspective (1 kg BTX). For 1 kg R-BTX, ~2.68 kg MPW is needed.

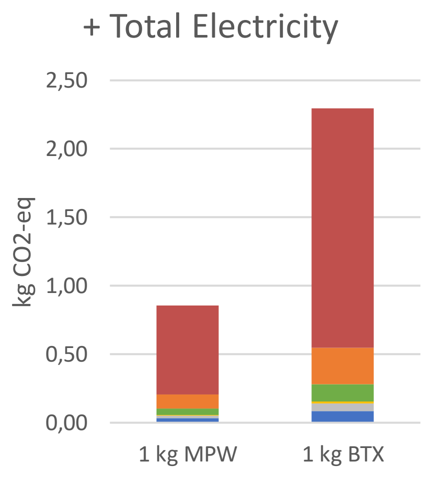


Figure 11 Total impacts of the previous mentioned processes in kg of CO_2-equivalents. and added the last emission (Total Electricity demand) to the graph. The left bar represents the waste perspective (1 kg MPW) and the right bar represents the product perspective (1 kg BTX). For 1 kg R-BTX, ~2.68 kg MPW is needed.

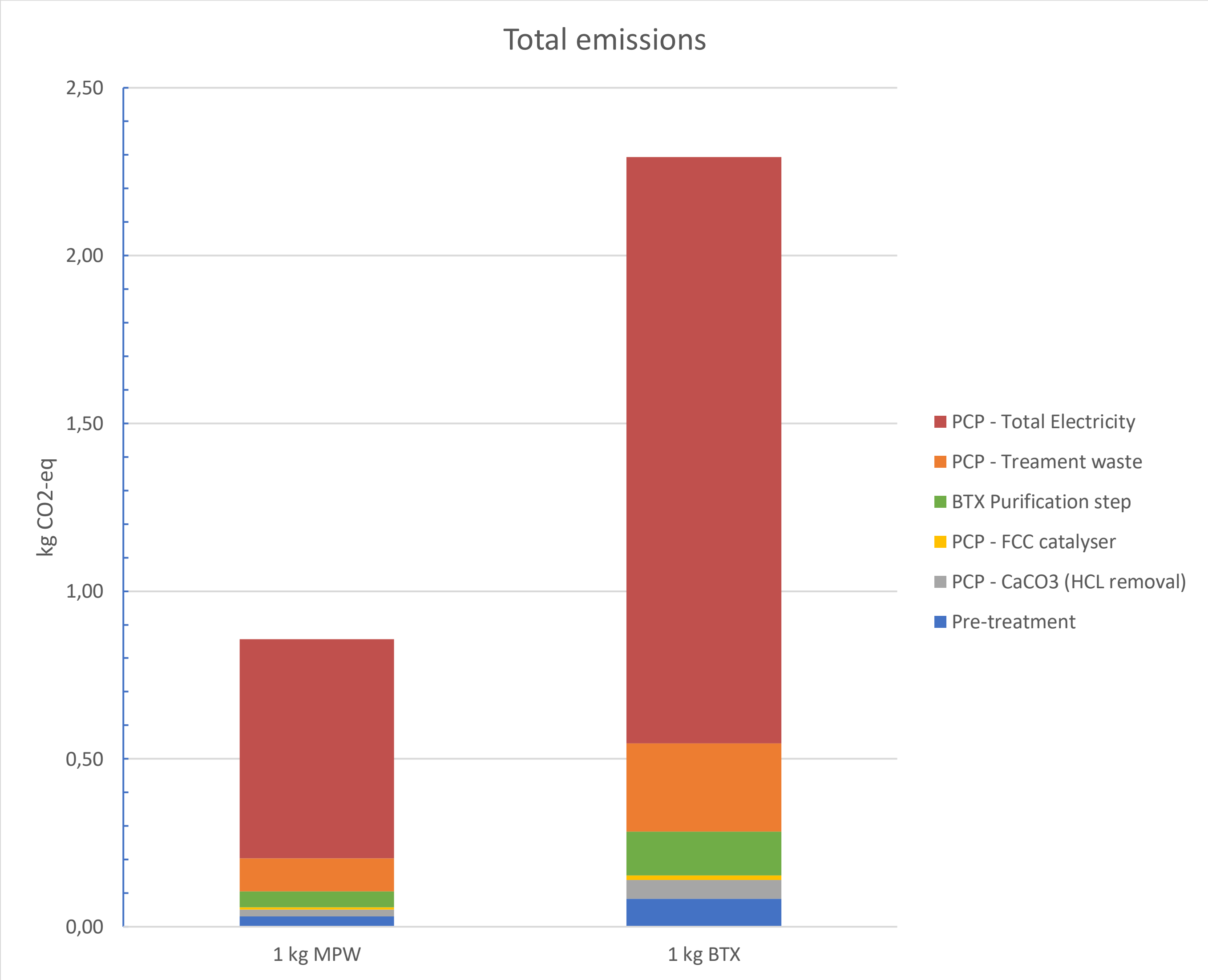


Figure 12 Total impacts of both perspecives in kg of CO_2-equivalents. The left bar represents the waste perspective (1 kg MPW) and the right bar represents the product perspective (1 kg BTX). For 1 kg R-BTX, ~2.68 kg MPW is needed.

3.1.2. Processes contributing to emission credits – Co products

3.1.2.1. *PCP - Avoided light fuel oil*

During the PCP process co-products are produced, besides the R-BTX. It is assumed that these co-products will replace a substitute product on the market. The co-product Bio-oil can be seen as a substitute of light fuel oil. The amount of this product replaced by the bio-oil, resulted in an avoided impact (credit) of -0.07 kg of CO_2-equivalents for the waste perspective and -0.20 kg of CO_2-equivalents for the product perspective (see figure 13). Again, the difference in these two perspectives is due to the fact that for the product perspective more MPW has to be processed in order to produce 1 kg of R-BTX, and thus more co-products are produced as well.

3.1.2.2. *PCP - Avoided natural gas mix*

There are two co-products that were assumed to replace a natural gas mix: wax and product gas. The amount of replaced gas results in a credit of -0.17 kg of CO_2-equivalents for the waste perspective and -0.45 kg of CO_2-equivalents for the product perspective. Added to the graph (figure 14) the credits for natural gas are larger than for the replaced Light fuel oil.

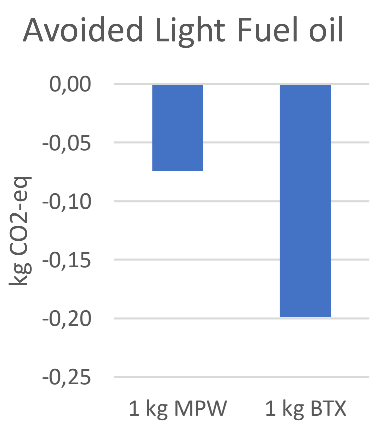


Figure 14 Global warming potential credits for avoided light fuel production in kg of CO_2-equivalents. On the left are the credits shown for the waste perspective (1 kg MPW) and on the right for the product perspective (1 kg BTX).

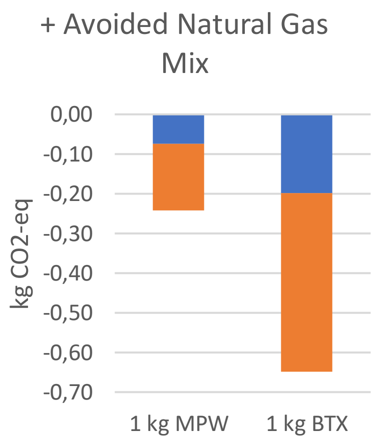


Figure 13 Global warming potential credits for avoided natural gas mix, added to the previous process in kg of CO_2-equivalents. On the left are the credits shown for the waste perspective (1 kg MPW) and on the right for the product perspective (1 kg BTX).

3.1.3. Processes contributing to emission credits – Avoided reference systems

Depending on the perspective of the PCP process and to which reference process it is compared, some additional avoided processes could be appointed to PCP. The values are presented here, but will be further discussed in 3.1.4. Overall Results.

3.1.3.1. *PCP -Avoided incineration of mixed plastic waste*

Depending on the system boundaries, there can be argued that the incineration of the plastic waste, which was assumed to in the reference scenario, is now avoided as consequence of the fact that the PCP process is using the MPW to process it into renewable BTX. In that case, for the waste perspective, an avoided emission, thus credit, of -1.73 kg of CO_2-equivalents is acquired. For the product perspective the credit is -4.64 kg of CO_2-equivalents due to the larger required amount of MPW (see figure 15).

3.1.3.2. *PCP - Avoided production of fossil BTX*

Similar to the discussion of the avoided incineration of MPW, it can be argued that the produced virgin grade Benzene, Toluene and Xylene, will replace the same amount of fossil-based B, T, X. Therefore, an avoided emission of -0.47 kg of CO_2-equivalents (WP) and -1.26 kg of CO_2-equivalents (PP) can be accounted for (see figure 16).

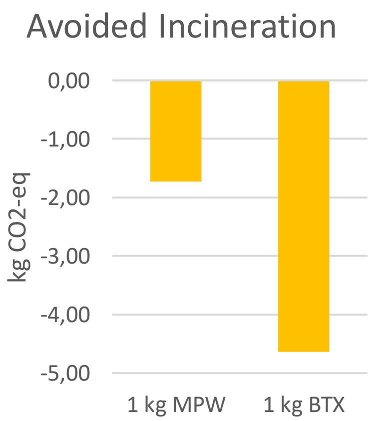


Figure 15 Environmental credits for avoided incineration for the global warming potential in kg of CO_2-equivalents. On the left are the credits shown for the waste perspective (1 kg MPW) and on the right for the product perspective (1 kg BTX).

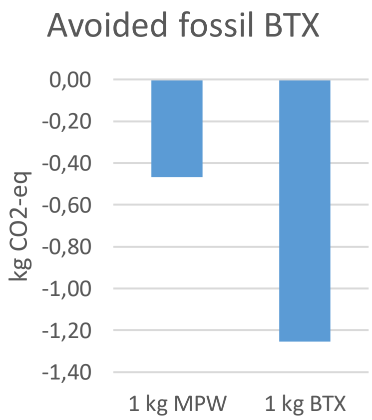


Figure 16 Environmental credits for avoided fossil BTX production for the global warming potential in kg of CO_2-equivalents. On the left are the credits shown for the waste perspective (1 kg MPW) and on the right for the product perspective (1 kg BTX).

3.1.4. Overall results

To calculate the overall environmental impact, both the emissions and credits must be accounted for. As it depends on which process is compared to which alternative, and therefore which system boundaries are chosen, the following paragraphs address the differences per perspective.

3.1.4.1. *Description of the waste perspective*

In figure 17 the total emission impact is shown together with the environmental credits for the waste perspective. The left bar gives an indication of the emissions that are generated by the PCP Process. The middle bar adds the credits generated by the process. The right bar demonstrates the Business-as-Usual situation in which the MPW is incinerated.

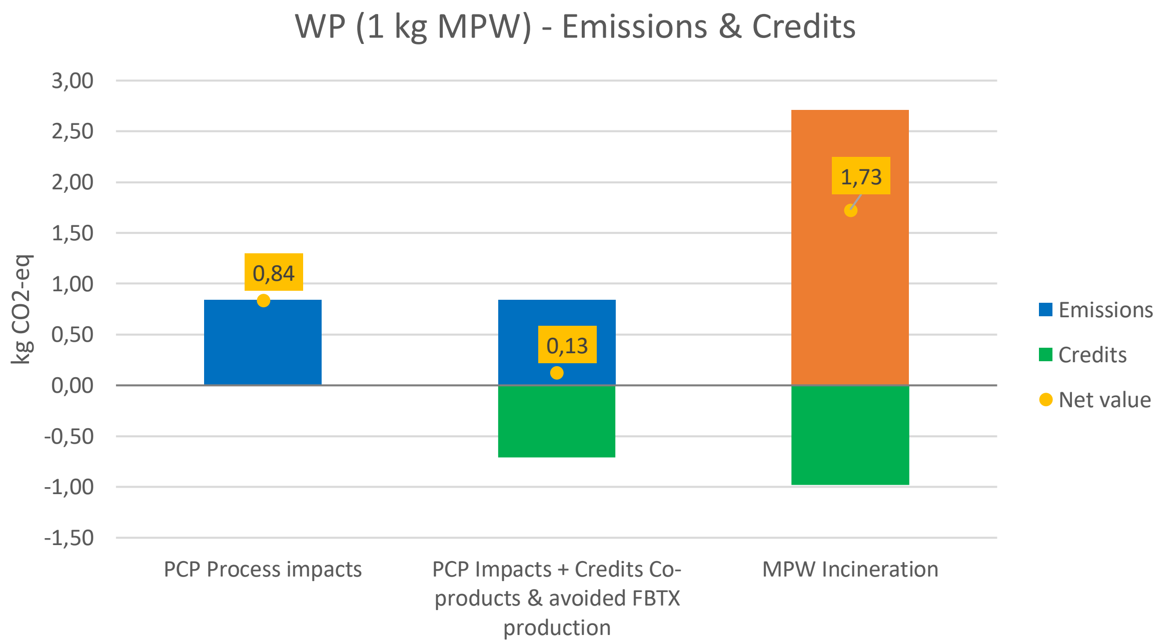


Figure 17 Emissions and credits for the analysed & compared systems in the Waste Perspective

Overall results Waste perspective in short:

- Emissions: 1 kg MPW which is processed in the Plastic Conversion Plant leads to a gross emission of 0.84 kg of CO_2-equivalents
- Credits: Via the PCP route products are produced which are replacing the following processes as a consequence:
  - Production of a natural gas mix and light fuel oil; resulting in a total environmental credit of -0.24 kg of CO_2-equivalents
  - Production of fossil BTX with a net environmental credit of -0.47 kg of CO_2-equivalents
- 1 kg MPW which is processed in a municipal incineration facility leads to a net emission of 1.73 kg of CO_2-equivalents. This net emission includes the credits gained due to energy production.

This means that processing 1 kg MPW through the route of PCP leads to a net CO_2 emission of 0.84 - 0.24 - 0.47 = 0.13 kg of CO_2-equivalents. Comparing the PCP route with the reference route (incineration) a total CO_2 reduction of ~1.60 kg CO_2-equivalents per kg MPW is achieved (difference between the two net emissions).

3.1.4.2. *Description of the product perspective*

In figure 18 the total emission impact is shown together with the environmental credits for the product perspective. The far-left bar is added to give an indication of the PCP process emissions only. The inner-left bar adds the credits generated by co-products. The inner-right bar adds the credits caused by the avoided MPW incineration (energy recovery is included). The far-right bar demonstrates the emissions from BTX production from a Business-as-Usual (fossil) situation.

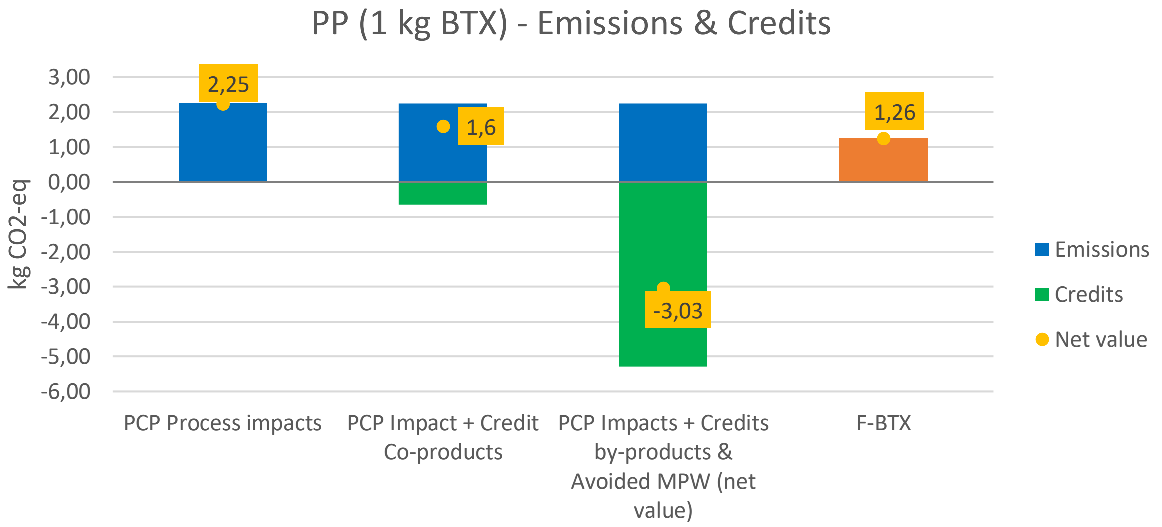


Figure 18 Emissions and credits for the analysed systems in the PP.

Overall results product perspective in short:

- Emissions: 1 kg (virgin grade) BTX which is produced in the Plastic Conversion Plant leads to a gross emission of 2.25 kg of CO_2-equivalents
- Credits: Via the PCP route products are produced which are replacing the following processes as a consequence:
  - Production of a natural gas mix and light fuel oil; together the environmental credit is -0.65 kg of CO_2-equivalents
  - Incineration of 2.68 kg mixed plastic waste which would lead to a net environmental credit of -4.64 kg of CO_2-equivalents
- 1 kg (virgin grade) BTX which is processed via a fossil production route leads to a net emission of 1.25 kg of CO_2-equivalents

This means that producing 1 kg (virgin grade) BTX through the route of PCP leads to a net CO_2 emission of 2.25 – 4.64 – 0.65 = -3.03 kg of CO_2-equivalents. Comparing the PCP route with the reference route (FBTX) a total CO_2 reduction of ~4.28 kg of CO_2-equivalents per kg (virgin) BTX is achieved (difference between the two net emissions).

3.2. LCA Scenarios

Besides the investigated base scenario, some other scenarios were investigated to explore their potential impact on the overall environmental emissions. First is the choice to use the renewable carbon gas produced during the PCP process directly onsite, which would result in less electricity use. The second scenario investigated the investment to use 100% certified green electricity for the PCP process, which contributes to reduce the environmental impact and the global warming potential.

3.2.1. Scenario: Local re-use of renewable carbon gas at the PCP plant

One of the co-products produced during the conversion is renewable carbon gas. In the base scenario this gas is assumed to be used outside of the system, replacing the production of a natural gas mix. Furthermore the required energy in the form of electricity is imported in this scenario. In the *local re-use gas for internal use* scenario the internal use of the gas for electricity production is further investigated. This would have an impact on the total electricity demand of the plant and the credit for replacing natural gas.

In table 6 calculations provided by TransitionHERO (TH, 2020) show the expected gas production per year and how much of the total electricity demand (49406 MWh/year) could be covered by using the produced gas for electricity production. In the high scenario the electricity production can cover 100% of the demand. In the low scenario only 69% can be covered and thus 31% still needs to be imported.

Table 6 Calculations by TransitionHERO to investigate how much of the total electricity demand can be replaced by electricity from product gas

Scenario	**Product gas produced by PCP** (m^3)	**Onsite electricity production** (% re-use)	**Efficiency (gas -> electricity)** (% efficiency)	**Theoretical produced electricity** (MWh per year)	**Total yearly electricity demand covered*** (%)
low	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
high	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Data provided by TransitionHERO – personal communication / expert judgement * Based on the Total electricity demand of 49 406 MWh per year					

3.2.1.1. *Calculation the effects on the global warming potential*

Re-using the gas internally for electricity production will bring changes into how the emissions and credits are considered. In the base case the renewable carbon gas is sold on the market and it will result in a avoided natural gas production. The electricity demand is covered by buying externally produced electricity. When the gas is used for internal electricity production and use, the gas does not replace any natural gas on the market anymore and therefore the credit is not applicable. In the case that only a part of the electricity demand can be covered, a part of the emissions still comes from the imported electricity, but also from burning the gas to electricity and the efficiency of the process. In the last case only the electricity and efficiency from gas to electricity is applicable as no additional electricity has to be imported.

Table 7 The used cases explained: In the low case there is not enough gas to meet the total electricity demand of the PCP plant. In the high case there is enough for the PCP plant and there is even enough to still sell some on the market

Impact changed	**Base case**	**Local re-use gas case** *Low case*	**Local re-use gas case** *High case*
External electricity	[redacted]	[redacted]	[redacted]

Renewable Carbon Gas electricity	[redacted]	[redacted]	[redacted] *m^3*
Remaining gas for market	[redacted]	[redacted]	[redacted] m^3

Table 8 The resulting global warming impact in kg CO_2-equivalents for the base, low and high cases expressed for the waste perspective (processing 1 kg MPW). The product perspective (production of 1 kg R-BTX) is shown in brackets

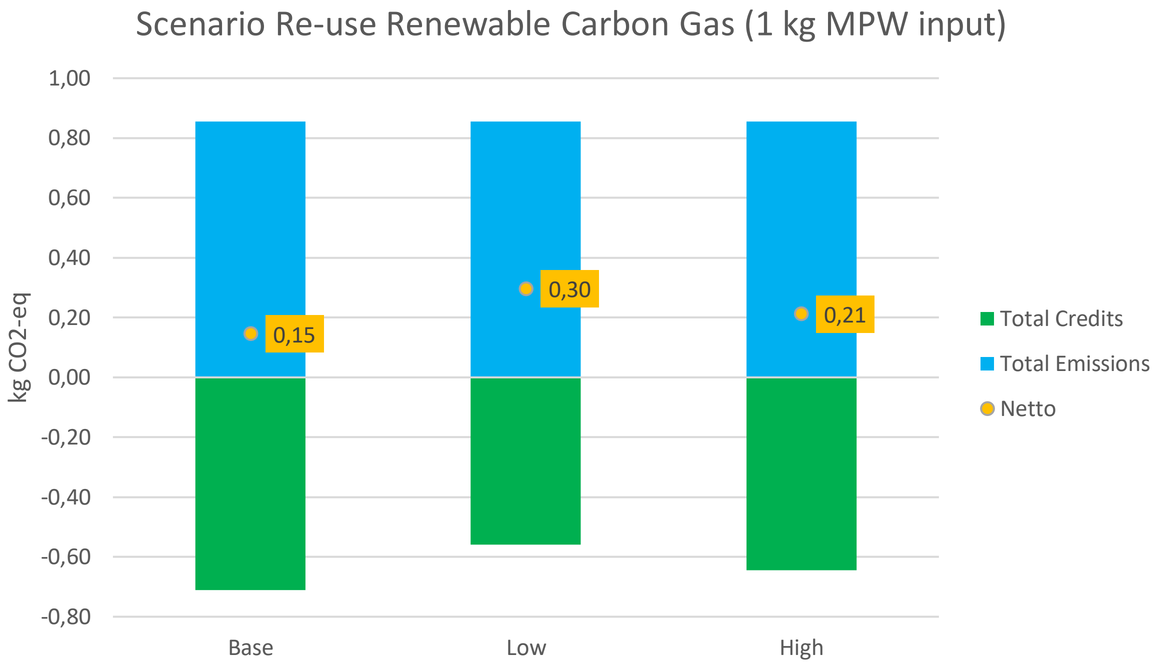
Impact changed	**Base case**	**Local re-use gas case** *Low case*	**Local re-use gas case** *High case*
External electricity	[redacted]	[redacted]	[redacted]
Renewable Carbon Gas electricity	[redacted]	[redacted]	[redacted]
Remaining gas for market	[redacted]	[redacted]	[redacted]

The change in impact between the cases are shown in figure 19. The emissions of the process does not change at all: 0.86 kg CO_2-equivalents for the WP and 2.29 kg CO_2-equivalents for the PP. However there are changes in the credits of which the low case changes with 0.15 kg CO_2-equivalents and the high scenario with 0.07 kg CO_2-equivalents. This results in a changed net value for both low and high case.

In conclusion, using the 'renewable carbon gas' as energy source for internal energy demand decreases the use of external grid power. However, with the current assumptions, the emissions of not having to use grid power almost exactly compensate for the increased emissions by incinerating the 'renewable carbon gas'. The incineration of which, although termed renewable, still results in carbon emissions.

A possible advantage of using renewable carbon gas for internal energy demand could be to use the waste heat from electricity production for the pre-drying step. If used in that manner the purchase of grid electricity could be reduced further. This should be investigated in future research.

Also , it should be noted that this scenario is analysed within the current system boundaries used for the LCA. Therefore, emissions from incineration of the natural gas mix are not accounted for in the base case PCP process. If the renewable carbon gas is used within the boundaries (in the low and high scenarios), the emissions do get accounted for. Therefore it would be interesting to investigate a scenario where the system is expanded to include the emissions of using the by-products further downstream.



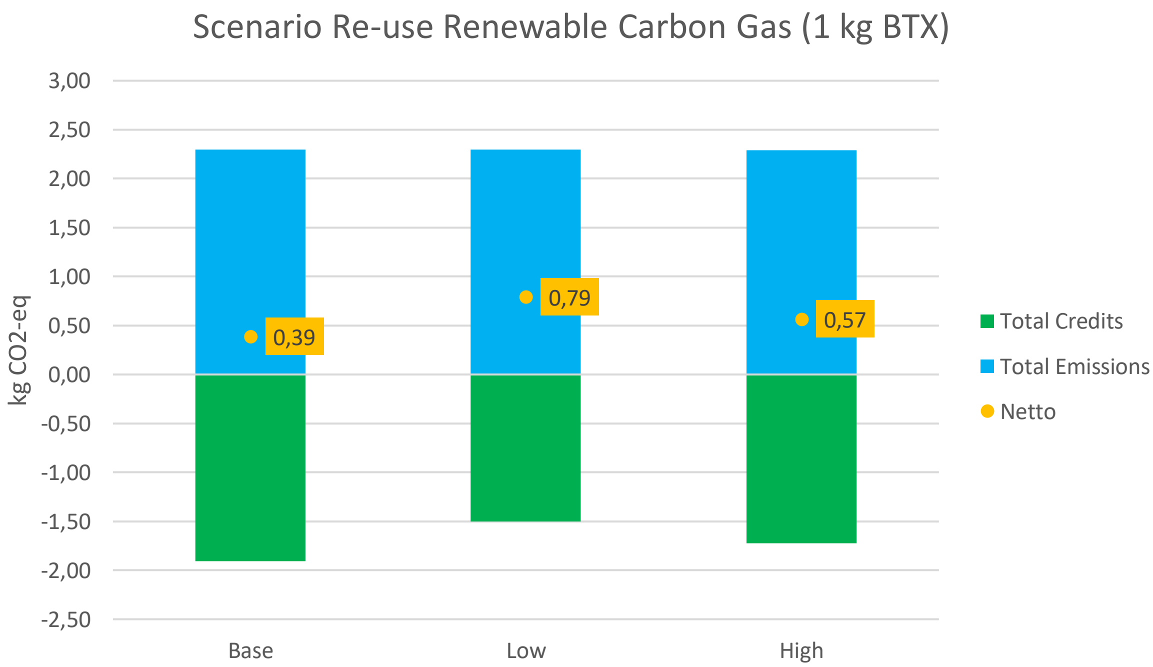


Figure 19 These two graphs illustrate the outcome of using the renewable carbon gas (RCG) for internal electricity production instead of selling the RCG on the market. In the upper figure the cases (base, low and high case) are shown for the waste perspective (1 kg MPW processed). In the lower graph the results are shown for the product perspective (1 kg R-BTX produced)

3.2.2. Purchasing 100% green electricity

In the study from CE Delft (2020), an alternative method was investigated regarding the possibility for determining the CO_2 reduction with green purchased electricity. At the moment the most commonly used method is to allocate the CO_2 reduction on the basis of ownership of green certificates. A so called *Guarantee of Ownership* (GvO or GO). This is allowed in a number of protocols for monitoring CO_2 emissions, such as the Greenhouse Gas Protocol, the *CO_2 prestatieladder* and PIANOo. Organisations that buy and redeem the GO may claim the CO_2 reduction in full. However, there are some requirements regarding the type of certificates, for example, for the CO_2 prestatieladder and PIANOo, the certificates must come from the Netherlands and have to be reported in a specific manner.

An alternative method is to opt for economic allocation: in this case it comes down to the person who pays for the CO_2. The party that pays for the CO_2 reduction may also attribute it to their own balance (or proportionally if there are multiple sources). In this way the contribution is determined based on the various financers who in turn work on the realization of the purchased renewable energy. An important question in this regard is: to what extent does the purchase of GOs now contribute to the development of additional capacity in the supply of renewable electricity?

CO_2 reduction of 1 kwh of electricity purchased with Dutch GvOs based on economic allocation

The data below (table 10) can be used to calculate the contribution of the GOs to the realization of onshore wind. This varies from 24% in the case of static revenues to 32% in the case of dynamic revenues. Based on the elaboration of economic allocation in the case study of onshore wind, the contracting authority can thus calculate +/- 24-32% of the CO_2 reduction (CO_2 emissions per kWh were 405 grams in 2018*) instead of 100% in case of allocation based on ownership of the ownership of the GO. This leads to the following figures of allocation of GOs for the production of renewable electricity.

* This is based on the integral method published by PBL, in conformity with methodology KEV (PBL, 2020). It does not include lifecycle emissions.

Table 9 Allocation percentages per type of 'green' energy and the amount of CO_2 that is allowed to be used as credit

	Allocation-percentage static	Allocation-percentage dynamic	CO_2-reduction static gram/kWh	CO_2-reduction dynamic gram/kWh
Average Wind on land	24%	32%	97	130
Average solar-PV	11%	12%	45	49
Average Biomass	5%	5%	20	20

The advice from CE Delft here is: *use the dynamic figures as tender, as we suspect that they better reflect the contribution of GvOs to the realization of renewable energy.*

In this report the potential CO_2 impact reductions from purchasing green electricity are not visualized in graphs as those values are more suited for a company-wide CO2 impact study (e.g. emission scopes stated by The Greenhouse Gas Protocol used in accounting and reporting methods).

3.3. Sensitivity analysis

3.3.1. Reference waste scenario - Incineration

One of the key contributors to the net environmental (GWP) impact is the avoided MPW incineration. Therefore, a short literature study was performed to analyse the different scenarios and data sources in regard to MPW incineration (see table 11). The net emissions for MPW incineration have a range between 1,5 and 2,0 kg CO_2 per kg MPW. In this report, the average has been taken from all the data sources which is about 8% higher than the SimaPro calculations. This difference is primarily due to the differences in the contents (other than plastics) of the MPW stream in the SimaPro calculation methodology. The average from literature has been taken as a baseline because it represents the most up-to-date available data from a similar scope (EU). This also allows for a better comparison with other MPW routes (such as other Chemical recycling methods).

Table 10 Data used for the sensitivity analysis and the resulting environmental impact

Scenario	Net emissions Incineration of 1 kg MPW	Net impact	
		PP (kg CO_2 eq. per kg BTX)	WP (kg CO_2 eq. per kg MPW)
High emission scenario (BASF, 2020)	1,92	-4.80	-1,79
This report	1,73	-4,29	-1,6
Low emission scenario (ME, 2018 & 2019)	1,5	-3,67	-1,37
Ecoinvent – Simapro calculation *SimaPro Waste scenario – 3 plastic mix waste streams. Waste-to-energy plants. Area: Europe*	1,66	-4,10	-1,53

More background information on the methods used in the scenario's above can be found in Appendix A

For an objective comparison, information should be provided regarding the chosen waste scenario scope (world region), (Waste-to-energy) Plant data, MPW content composition, water content. These data however, are not always covered in the analysed reports. Therefore, the results from these sensitivity analyses should not be highly relied upon, but instead should be regarded to as impact ranges. In short, we analysed the differences in impact between three different data scenario's:

High Emission scenario:

- +/- 12% higher impact for PP and WP when compared to this report.

Low Emission scenario:

- +/- 14,5% lower impact for PP and WP " "

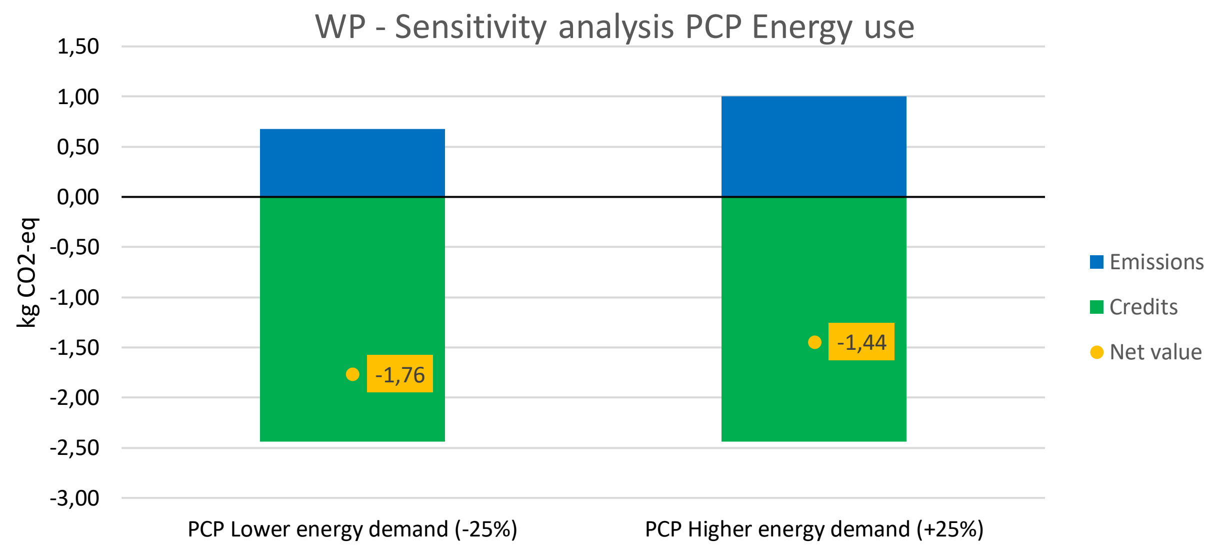
Emission data from Ecoinvent:

- +/- 4,5% lower impact for PP and WP " "

The data above indicate a data range of +/- 15% meaning that the chosen reference MPW emission scenario will have significant impact on the net impact. In case of future publication of these LCA results, this parameter should be further explored.

3.3.2. PCP energy use

As the PCP is still in the engineering phase, the final energy requirements are still to be determined. In order to determine the contributing effect of energy use on the final impact result (net value), two scenarios were analysed. In the first scenario the PCP has a 25% lower energy demand, in the second a 25% higher energy demand. A simplified approach has been performed in this analysis in which the credits remain the same for the two scenarios. It is possible that in the real-life scenario the credits will be positively or negatively affected by a change in energy demand. The results can be found in the graphs (figure 20) below, giving an indication for both perspectives. These graphs contain the net emissions (Chapter 3.1.3) when comparing the waste management routes for MPW (WP) and production routes for BTX (PP). Although the difference is significant, the PCP process will still result in a net negative CO_2 emission compared to fossil production of BTX/incineration of plastic waste.



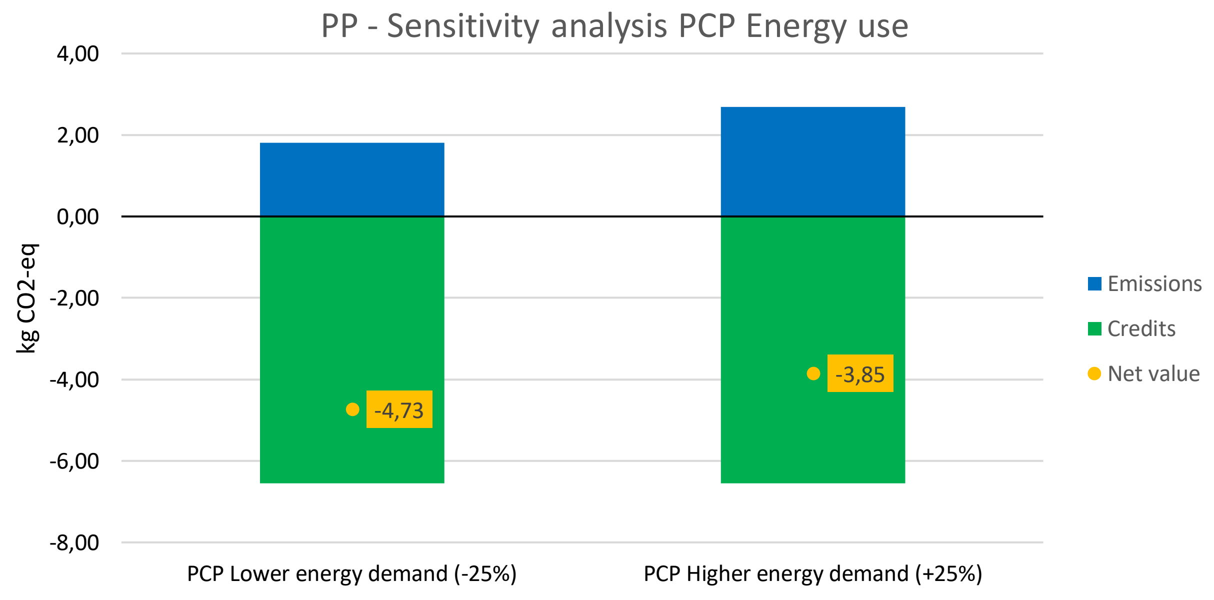


Figure 20 Results from the sensitivity analysis for the waste perspective (upper graph) and product perspective (lower graph)

4. Discussion

4.1. Environmental impact of electricity production

In the Life Cycle Inventory (Chapter 2) it was noted that all the impact data for electricity production was attributional, instead of consequential. Normally when decided 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 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 own total yearly production as the demand rises? And would this not only be accountable to our own process, but also to 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, 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.

4.2. Data limitations separation and purification BTX components

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

In order to minimize the amount 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 and these emissions can be found in Appendix B. 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 is added to the currently proposed PCP system: initial distillation (from here: purification). Sources and references regarding impact data for this process is scarce, however in an earlier research performed by Schenk et al. 2020, an estimated CO_2 emission for the initial distillation process was given of 0.13 kg CO_2/ kg BTX. This impact data has been used for this report.

4.3. Scenario gas re-use on site

One of the scenario's in this report demonstrates the potential energy re-use from the product gas that is produced in the PCP. The calculations and assumptions made are based on theoretical data received from TH, 2020. There it is assumed that the product gas has the same caloric value as natural gas. A more detailed and exact result can be specified once the BoD has been updated with the latest PCP process data.

4.4. Impact variances for incineration of MPW

As we see in chapter 3.1 the environmental credits due to the prevented incineration of the MPW has a considerable share in the total emissions. The emission data that has been found in literature varies between 2.5 and 3.0 kg CO_2 per kg MPW. In order 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 literature. This is likely due to the fact that emission factors such as methane and other lifecycle activities are not included in the simplified approach. A summarizing table of literature findings in regard to the emissions from MPW incineration can be found in *Appendix A.*

5. Conclusion

In this report a screening LCA was carried out for PCP B.V. in order to get an initial indication of the environmental impact of the Plastic Conversion Plant. In this assessment, the system was analysed from a product- and waste perspective. Therefore, two functional units were defined:

Functional unit for waste perspective approach: *Waste management of 1 kg of sorted mixed plastic waste (DKR 350) in Europe.*

Functional unit for product perspective approach: *Producing 1 kg virgin grade B,T and X for use in Europe.*

In the previous chapter the environmental impacts of the PCP system were analysed and presented. The results have been summarized further into one chart (see figure 17).

As can be seen in the graph below (figure 21), processing MPW via PCP results in a net emission of 0,13 kg CO_2 per kg MPW (see left bar).Currently the MPW is incinerated, which results in a net emission of 1,74 kg CO_2 per kg MPW incinerated (see right bar). Therefore, the transition from incineration towards a PCP waste management system would reduce the emissions by 1,6 kg CO_2 per kg MPW processed. As stated in the discussion, the chosen reference MPW Incineration scenario and the PCP energy use significantly impact the total emissions. For this assessment an average was taken for MPW incineration and specific (industry) data was used for PCP energy use.

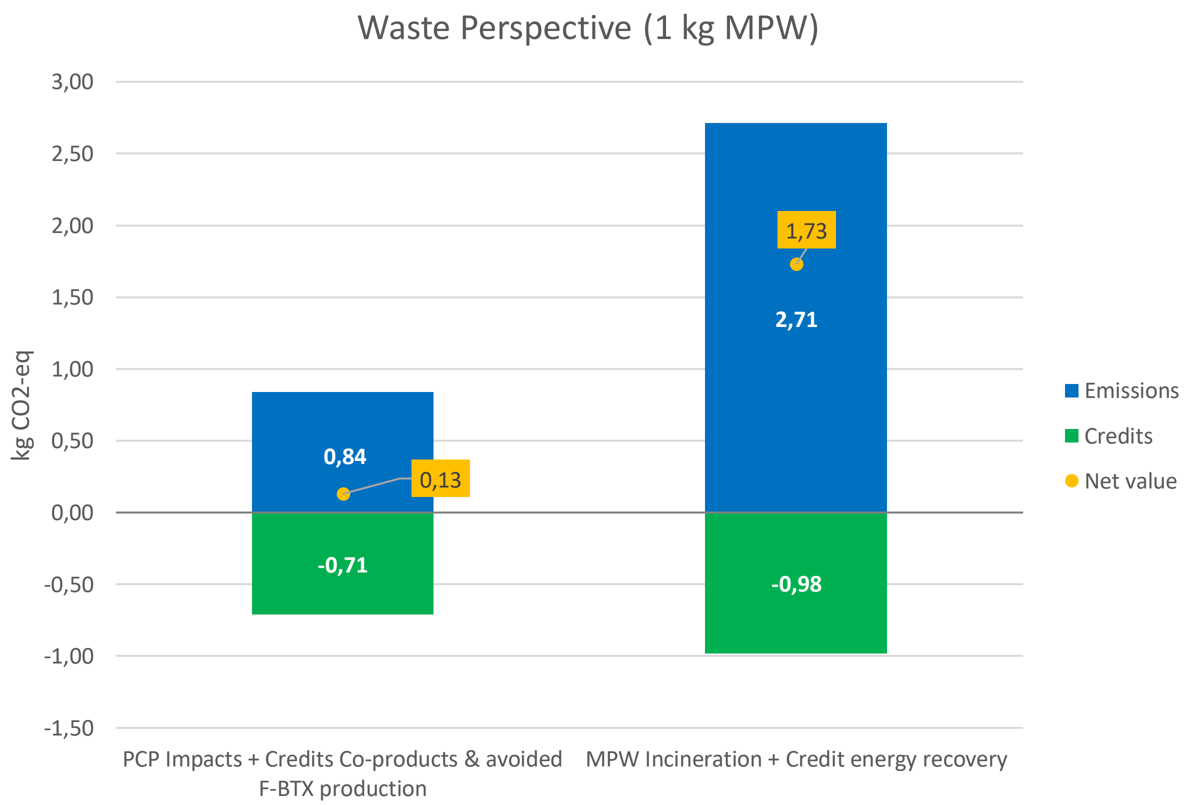


Figure 21 In this graph the results from the PCP management system are compared to the reference MPW incineration as seen from the waste perspective.

In the graph below (figure 22), the impact results for the product perspective are presented. Here it can be seen that the production of BTX via the PCP process emits ~1 kg of CO_2 equivalents more than the business-as-usual (fossil) way of producing BTX (see left bar). This can be explained through the high efficiency in the conventional petrochemical industry. However, when the credits (avoided emissions) for the PCP system are taken into account, the net emission of BTX production via the PCP system becomes -3,03kg of CO_2 equivalents per kg BTX (see right bar). Therefore, the transition from a fossil produced BTX mix to a renewable BTX mix results in a net emission reduction of -4,28 kg CO_2 per kg BTX. With a full PCP plant operational this can results in an annual reduction of 85.600 ton CO_2.

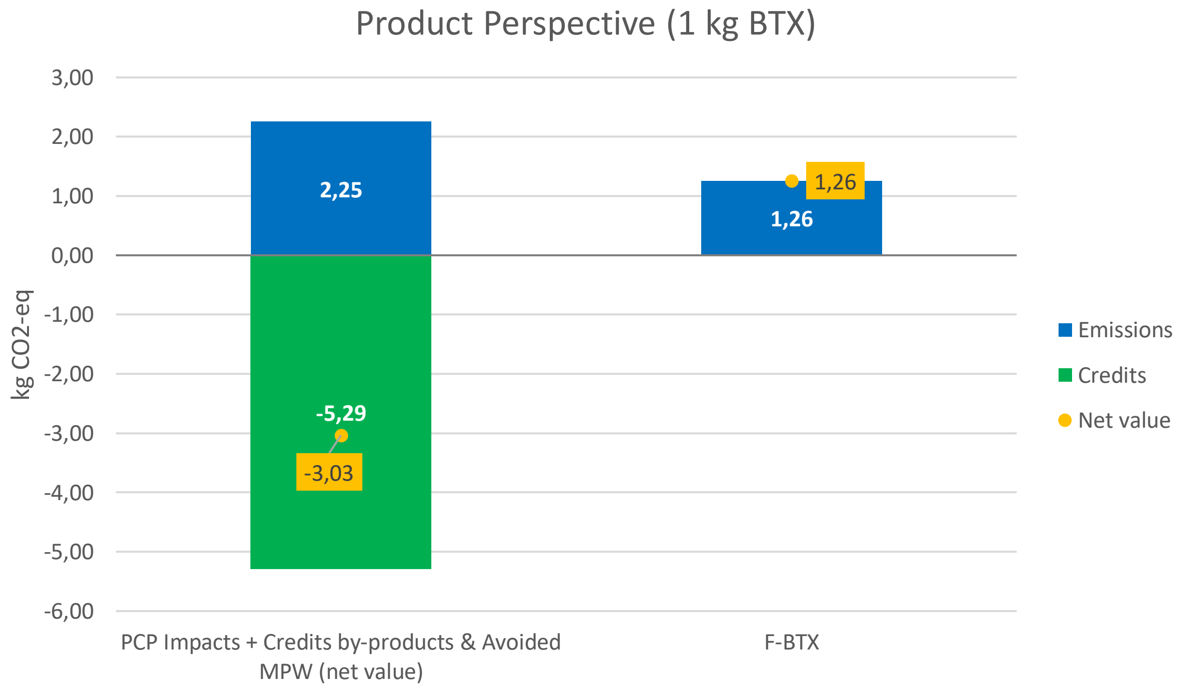


Figure 22 In this graph the results from the PCP product system are compared to the reference fossil based B, T, and X production as seen from the product perspective

6. Literature

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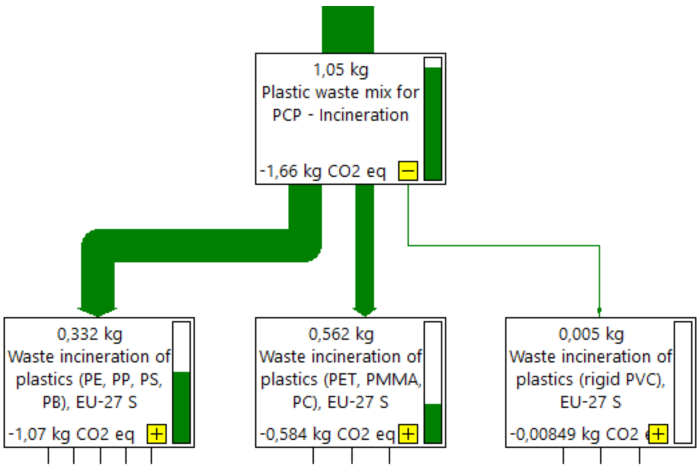
Appendix A: MPW Incineration – Comparison data from literature

Appendix A Literature overview 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 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.
Ecoinvent	NA	NA	1,66	SimaPro Waste scenario – 3 plastic mix waste streams. Waste-to-energy plants. Area: Europe. (SimaPro inputs: *Waste incineration of plastics PE, PP, PS, PB) EU-27 - Waste incineration of plastics (PET, PMMA, PC) EU-27 - Waste in incineration of plastics (rigid PVC) EU-27)*

* *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 for 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.*



Appendix A Screenshot from Network diagram SimaPro 9.1.1 giving an overview of the avoided MPW incineration

Appendix B: B,T,X Eco-profiles

Appendix B Environmental impact data B, T and X – source: PlasticsEurope 2013

B,T and X Ecoprofiles – PlasticsEurope, 2013						
Indicator	*Unit*	*Benzene*	*Toluene*	*p-Xylene*	*o-Xyxlene*	*Mixed Xylenes*
GWP	*Kg CO_2-eq*	1.86	1.22	1.43	1.45	0.79
ODP	*g CFC-11 eq*	5.2E-04	4.1E-04	5.6E-04	5.7E-04	2.7E-04
AP	*g SO_2-eq*	6.12	4.75	5.70	5.80	3.23
POCP	*g Ethene eq*	0.40	0.28	0.29	0.29	0.18
EP, terrestrial	*g PO_4-eq*	0.42	0.33	0.37	0.38	0.25
EP, aquatic	*g PO_4-eq*	0.84	0.73	0.77	0.77	0.66
Dust/particulate matter (2)	*g PM10*	0.27	0.24	0.24	0.25	0.18
Total particulate matter (2)	*g PM10 eq*	5.12	4.01	4.69	4.77	2.87
Waste	*kg*	4.3E-05	4.9E-05	5.7E-05	5.7E-05	5.1E-05
(2) Including secondary PM10						

Appendix B Manual calculations environmental impact data B, T, and X

GWP in relation to content ratio 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		

Appendix C: Additional sorting Mixed Plastic Waste

Source: Jeswani et. al. (2021)

Appendix C Additional impact data of sorting and additional sorting steps of Mixed Plastic Waste

Energy use for sorting of mixed plastic waste (MPW)		
Process	*Electricity (MJ/t MPW)*	*Source*
Sorting	250	Estimated based on data from Kaitinnis (2019) using economic allocation of energy between waste groups. The market values of waste fraction are provided in Table S1 in Supplementary Information
Additional sorting	58	Estimated using data from Kaitinnis (2019)

Appendix D: Detailed overview LCA system boundaries