Carbon footprint Synova/T.EN technology

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This report was prepared by:
Meis Uijttewaal, Martijn Broeren

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Further information on this study can be obtained from the contact person Martijn Broeren (CE Delft)

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Content

Summary

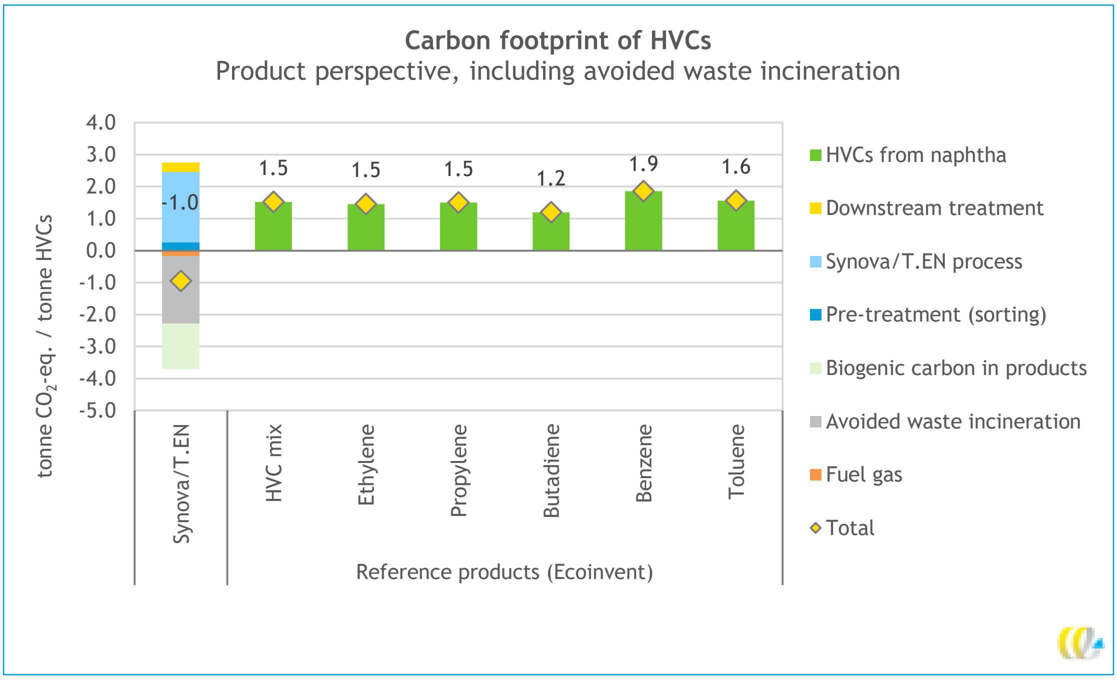
This screening life cycle assessment (LCA) study analyses the carbon footprint performance of a novel chemical recycling technology developed by Synova in cooperation with Technip Energies (T.EN) for downstream purification. The technologies can process a mix of waste plastics and waste biomass, and can thus be used to divert these materials that would otherwise be incinerated. By processing this feedstock mix in Synova/T.EN technologies, high value chemicals (HVCs) are produced. These (partly biobased) HVCs can be further processed into valuable end-products in existing chemical production infrastructure.

The carbon footprint analysis focuses on processing a waste feedstock, consisting of 590 kg waste plastic and 291 kg biomass (dry weights and excluding inert material) per tonne. The analysis uses process data provided by Synova, combined with background data from LCA databases, literature, and internal CE Delft sources.

The screening LCA uses two distinct perspectives:
1. A **product perspective**, focusing on the production of one tonne of separated HVC gases. In this perspective, Synova/T.EN's production process is compared to conventional, virgin production of the same HVCs.
2. A **waste perspective**, focusing on the treatment of one tonne Synova/T.EN feedstock. In this perspective, Synova/T.EN's conversion process is compared to incineration with energy recovery.

The carbon footprint analysis shows that based on the best data currently available, the use of Synova/T.EN technologies results in a carbon footprint reduction compared to reference technologies. This is the case in both the product perspective (carbon footprint per tonne of HVC produced) and the waste perspective (carbon footprint per tonne of waste).

Figure 1 - Carbon footprint comparison of HVC production, Synova/T.EN technology and reference HVC production, tonne CO_2-eq./tonne separated HVCs



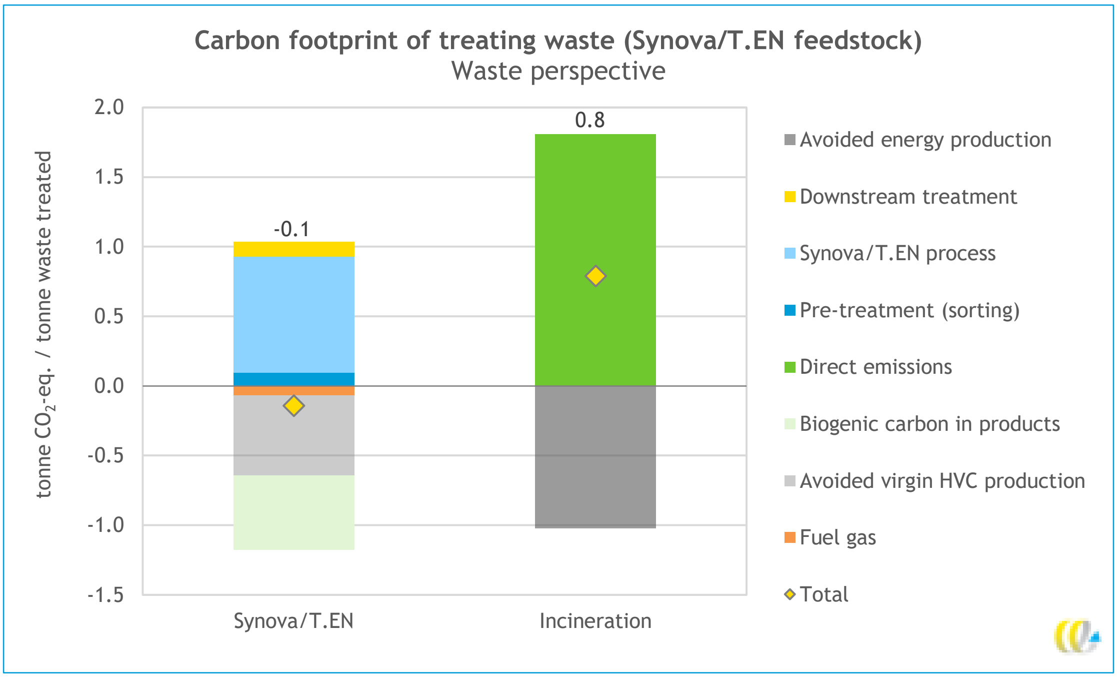
For the product perspective, Figure 1 shows the carbon footprint results of Synova/T.EN technology and reference processes in detail. The carbon footprint of the HVCs produced via Synova/T.EN technology is estimated at -1.0 tonne CO_2-eq./tonne separated HVCs. This result includes a credit for the avoided incineration of the feedstock materials (see discussion at the end of this Summary). The total value is negative because the credits for avoiding emissions are larger than the direct emissions and emissions linked to the energy and materials used.

In comparison, the carbon footprint for conventional fossil fuel-based HVC production amounts to 1.5 tonne CO_2-eq./tonne HVCs. The overall difference is therefore estimated at about 2.5 tonne CO_2-eq./tonne HVC.

For the waste perspective, Figure 2 shows the carbon footprint results for Synova/T.EN and reference treatment in detail. The carbon footprint of treating waste in Synova/T.EN technology is approximately -0.1 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock). The negative value indicates that the credits allocated to the process, due to avoiding virgin HVC production, fuel gas exports and biogenic carbon present in the products, are higher than the direct emissions and emissions linked to energy and material use.

The reference conventional treatment of the waste feedstock is incineration with energy recovery in a municipal solid waste incinerator (MSWI). For the situation in the Netherlands, incineration would result in a carbon footprint of 0.8 tonne CO_2-eq./tonne waste treated. The difference between this reference treatment and Synova/T.EN technology is therefore 0.9 t CO_2-eq./tonne waste (Synova/T.EN feedstock) compared to incineration. Note that this 'waste' is the feedstock for the Synova/T.EN process, which contains 59% plastic and remainder is biogenic residues, inert materials and water.

Figure 2 - Carbon footprint comparison (waste perspective) of Synova/T.EN technology and incineration, tonne CO_2-eq./tonne waste (Synova/T.EN feedstock)



Two sensitivity analyses show that:

- If the expected 2030 electricity mix with a lower carbon intensity is used, the carbon footprint of Synova/T.EN technologies is reduced. The CO_2 emission reductions compared to the reference technologies also increase.

- When operating on a feedstock containing more biomass, the carbon footprint remains roughly equal in the product perspective (expressed per unit of HVC). If the reference treatment of this biomass-rich feedstock was landfilling instead of incineration, a first indicative analysis shows that the CO_2 reduction increases substantially.

Care should be taken when interpreting these results or comparing them to results from other studies. A number of characteristics of the present study should be kept in mind, including:

- As a screening LCA, this analysis quantifies the carbon footprint performance of the technologies based on the current best available data provided by Synova for a plant at 50 kilotonne/year scale. Further research would be required to analyse its performance on other environmental impact indicators, or to verify the carbon footprint performance in practice based on (measured) process data.

- The study has a cradle-to-gate scope, including all steps from the feedstock pre-treatment (i.e. sorting from mixed waste), to Synova technology and finally T.EN treatment to produce separated HVC streams. A credit for biogenic carbon present in the products (at the ‘end’ of this scope) is included in the results (in line with the ‘carbon storage’ approach).

- In the product perspective, we assumed that waste feedstocks were diverted from incineration. However, other treatment options are also possible. For example, plastics could also be sorted out and sent to mechanical recycling (resulting in a lower carbon footprint than incineration). Conversely, biomass could also have been landfilled, leading to methane emissions (potentially resulting in a higher carbon footprint than incineration). These routes were not considered in detail here.

- In the product perspective, the carbon footprint benefits of avoided incineration are included in the results. This shows the overall effect of using Synova/T.EN technology instead of incinerating the feedstock. However, it is not evident that this benefit can be fully allocated to the final HVCs produced by Synova/T.EN, since other parties such as plastic sorters also contribute to avoiding incineration. Care should be taken to explain this when communicating results with downstream customers or other stakeholders.

1 Introduction

Synova is developing a chemical recycling technology to convert a feedstock of waste plastics and biomass into useful chemical products. Technip Energies (T.EN) is developing a purification technology to further treat the Synova product gas and to allow its integration within steam cracking units. By combining their processes, Synova and T.EN transform the material into basic chemicals such as ethylene and propylene. These high value chemicals (HVCs) can be used in existing chemical production infrastructure.

This report describes the method and results of a screening life cycle assessment (LCA), conducted to provide a first order estimate the carbon footprint of Synova's process at roughly 50 kt feedstock/year scale, as well as a comparison to alternative technologies.

The screening LCA uses two distinct perspectives:
1. A **product perspective**, focusing on the production of one tonne of separated HVC gases. In this perspective, Synova/T.EN's production process is compared to conventional, virgin production of the same HVCs.
2. A **waste perspective**, focusing on the treatment of one tonne plastic/biomass waste. In this perspective, Synova/T.EN's conversion process is compared to incineration with energy recovery.

This document describes the screening carbon footprint analysis, covering the LCA methodology (Section 2), results (Section 3) and conclusion/discussion (Section 4). Details for the data and modelling are included in (confidential) Annex B.

2 Methodology

2.1 Synova/T.EN technology summary

In this analysis, Synova/T.EN technology is modelled as three subsequent processes:

- **Pre-treatment**: During pre-treatment, mixed municipal solid waste is sorted into a feedstock mix suitable for the Synova process, containing biomass, plastics, ash and moisture. In this analysis, the mixed waste is assumed to be diverted from incineration in a municipal solid waste incinerator (MSWI).

- **Synova/T.EN process**: The Synova process breaks down the feedstock mix in several steps into HVC gases, using steam and electricity. During a purification step (Technip energy), undesired gases such as CO_2, H_2S and other sulphur compounds, HCN, HCl, NH_3, NO_x and CO are removed from the gas mix. Wastes generated include ash, waste water and flue gases.

- **Downstream processing/separation**: Finally, the mixed HVC gases produced in the Synova/T.EN process are separated to yield pure gas streams. Synova/T.EN can utilise existing infrastructure for this separation step since naphtha-based steam crackers produce comparable mixes of gases. Separation produces the HVCs ethylene, propylene, 1,3-butadiene, benzene and toluene. In addition, fuel gas (exported as a fuel carrier) and ethane (and other paraffins) are produced. The ethane (and other paraffins) can be fed back to an existing steam cracker to yield additional HVCs (so-called *indirect* HVCs).

More details on the models and system boundaries are provided in Section 2.3.

2.2 Goal

The goal of this screening[1] LCA is to provide a first estimate of the carbon footprint performance of the Synova/T.EN chemical recycling process and a comparison to alternative technologies. The carbon footprint measures a product's or process' contribution to global climate change due to the emission of greenhouse gases. It is expressed in tonne (t) CO_2-equivalents (eq.).

Table 1 provides an overview of the Synova/T.EN feedstock composition and the yields of valuable products (i.e. HVCs and fuel gas). Note that an alternative (biomass-richer) feedstock composition is studied in Section 3.3.2.

[1] This analysis is considered a screening LCA, since it considers a single environmental indicator (the carbon footprint, i.e. the contribution to climate change), focuses on the main mass/energy flows and contains simplifications or assumptions where necessary. Overall, a conservative approach is taken to prevent overestimating the environmental benefits of the Synova/T.EN technology.

Table 1 - Feedstock composition and final product yields of HVCs and fuel gas (kg per tonne input)

Synova/T.En feedstock	
Feedstock composition (input)	
Plastic[a]	590
Biomass[a]	291
Ash	109
Moisture	10
HVC and fuel gas production (valuable outputs)	
Ethylene	198
Propylene	70
1,3-Butadiene	26
Benzene	67
Toluene	16
Fuel gas	189

a) Note that 'plastic' and 'biomass' refer to pure, dry materials excluding inert material and moisture.

Product and waste perspective

The screening LCA is conducted using two distinct perspectives: the waste perspective and the product perspective.

The **waste perspective** focuses on the question: *What is the carbon footprint of treating one tonne of plastic-containing waste via different waste treatment routes?* In the waste perspective analysis, the functional unit is *the treatment of one tonne of plastic-containing waste*. This perspective is often used by policymakers focusing on waste, and enables environmental comparisons of different waste treatment options of a particular waste streams (e.g. recycling vs. incineration).

The waste perspective compares the following technologies:
- Synova processing/T.EN purification;
- Incineration with energy recovery.

The **product perspective** is used to answer the following research question: *What is the carbon footprint of one tonne of HVCs produced via different (virgin or recycling) routes?* This analysis enables Synova to understand, compare and communicate the carbon footprints of different HVC production routes. In the product perspective analysis, the functional unit is the *production of one tonne of (separated) HVCs*.

The product perspective compares the following technologies:
- Synova processing/ T.EN purification;
- Virgin HVC production.

What are the similarities and differences between the product and waste perspective?
The product perspective and waste perspective analyses are based on the same underlying data (described in Annex A). In addition, the recycling technologies are analysed using similar system boundaries in both perspectives. For this reason, comparisons between these technologies will lead to similar conclusions, regardless of the perspective used. This means that if one option performs best in a product perspective analysis, it will also perform best in a waste perspective analysis.

However, there are two important differences in the perspectives, corresponding to the different questions and audiences they belong to (discussed above). These can affect how recycling technologies are viewed and what conclusions are drawn.

They are:

- The functional unit is different. Due to losses, one tonne of plastic waste input is not converted into one tonne of HVC output. Therefore, expressing the results per tonne of HVC output (product perspective) or per tonne of plastic waste input (waste perspective) changes the absolute values in the carbon footprint results.
- The reference technologies are different. In both analyses, the reference technology is the ‘conventional alternative’ to recycling; if recycling would not exist, this ‘conventional’ technology would be applied to produce HVCs or dispose of plastic-containing waste. In the product perspective, the reference is the virgin production of HVCs. In the waste perspective, the reference is the incineration (with energy recovery) of plastic waste. Because these two references differ substantially, the product or waste perspective affects how recycling is viewed.

2.3 Scope

The analysis focuses on the carbon footprint performance of the studied technologies when operating in the Netherlands, under current conditions (e.g. regarding the electricity mix).

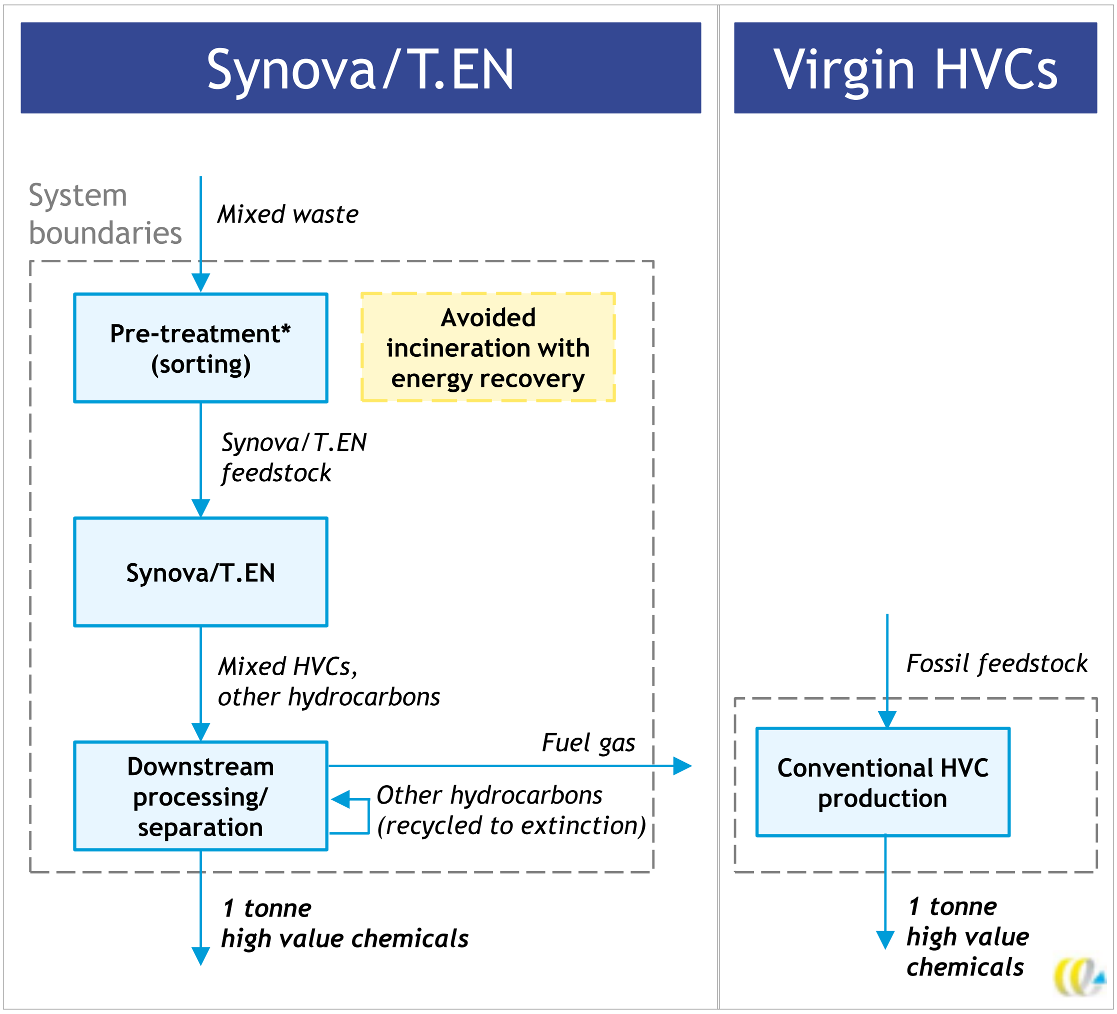
System boundaries

The study has a cradle-to-gate scope. The starting point of the analysis is waste (plastic and biomass) diverted from a MSWI. This waste is considered free of environmental burdens (‘cut-off approach’). All processes up to the production of HVCs is included. The further downstream processing into chemical products (e.g. plastics) and use are not included, since HVCs produced via Synova/T.EN technology are identical to their conventional counterparts. To account for the fact that the HVCs are partly biobased, a credit for biogenic carbon included in the HVCs is taken into account (see details below).

Figure 3 (product perspective) and Figure 4 (waste perspective) show the compared systems and underlying processes in greater detail. For the processes within the system boundaries, all known inputs and outputs (not shown) are taken into account, i.e. the energy (electricity, steam), auxiliary materials, waste streams and emissions.

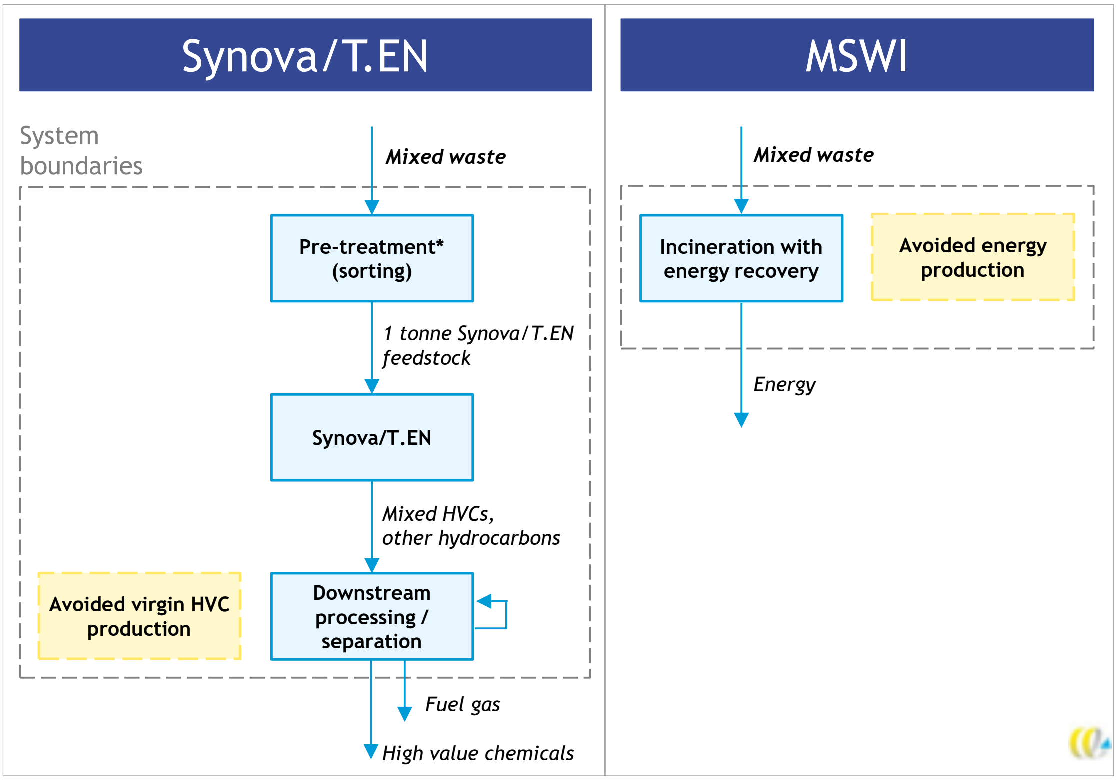
In those cases where the systems perform a useful co-function, we assume a conventional process for the same function is avoided (substitution through system expansion).
These avoided processes are shown in yellow in Figure 3 and Figure 4.

Figure 3 - Flow diagrams for the product perspective analysis. The product perspective analysis compares the production of 1 tonne HVCs via Synova/T.EN technology or via virgin fossil production



* *During pre-treatment, mixed waste is sorted to create Synova/T.EN feedstock. The other materials that are rejected during sorting are sent to incineration. The analysis accounts for the carbon footprint of the pre-treatment of all mixed waste entering the sorting process. The carbon footprint of incinerating the rejects is excluded from the analysis, since this material will be incinerated regardless of whether Synova/T.EN technologies are used. This is further explained in Annex A.*

Figure 4 - Flow diagrams for the waste perspective analysis. The waste perspective analysis compares the carbon footprint of treating the same amount of mixed waste via Synova/T.EN technology or via an MSWI. The amount of mixed waste corresponds to the production of 1 tonne Synova/T.EN feedstock during pre-treatment



* *During pre-treatment, mixed waste is sorted to create Synova/T.EN feedstock. The other materials that are rejected during sorting are sent to incineration. The analysis accounts for the carbon footprint of the pre-treatment of all mixed waste entering the sorting process. The carbon footprint of incinerating the rejects is excluded from the analysis, since this material will be incinerated regardless of whether Synova/T.EN technologies are used. This is further explained in Annex A.*

Assumptions

A number of general assumptions and other remarks regarding the system boundaries and approach should be mentioned here:

- In the product perspective analysis, the Synova process diverts waste from an incinerator. The emissions (and energy production) that would have taken place if the plastics and biomass had been incinerated in a Dutch MSWI are taken into account as avoided emissions. It should be noted here that the avoided incineration is sometimes 'claimed' by different parties (e.g. sorters, users of recycled products or governments providing financial support), potentially leading to double counting of the environmental benefits. The current analysis therefore considers the *overall* carbon footprint effect of the Synova/T.EN process, which includes avoided incineration in full. Care should be taken not to count this benefit a second time.

- The fuel gas produced in the Synova/T.EN process can be sold. It is assumed to replace natural gas, based on an equivalent lower heating value.

- Electricity and natural gas (for steam production) used by Synova/T.EN's process are supplied from the Dutch national grid. Other inputs (e.g. auxiliary materials) are modelled using average European production data, which is considered representative for operation in the Netherlands. Full details are available in Annex A.
- The feedstock used in the Synova/T.EN processes contains biogenic carbon. In this cradle-to-gate study, we apply a 'carbon storage' approach for biogenic carbon (Pawelzik, et al., 2013). This means we provide a carbon footprint credit based on the amount of biogenic carbon present in the feedstocks, while also fully accounting for emissions of biogenic CO_2 in the carbon footprint results. This approach, as well as the alternative 'carbon neutral' approach, is discussed in greater detail below. Note that the term 'carbon storage' used in the results does not imply *permanent* storage of CO_2.

'Carbon storage' approach for biogenic carbon

All carbon in biomass has been captured (relatively recently) from the atmosphere via photosynthesis. If this biogenic carbon is emitted as CO_2, there is therefore no net climate change effect since the removal from and emission to the atmosphere have the same magnitude and cancel each other out.

In LCA studies, there are two approaches on how biogenic carbon can be treated (Pawelzik, et al., 2013):

- '**Carbon storage**': The capture of biogenic CO_2 (via photosynthesis) as well as any emissions of biogenic CO_2 are both taken into account. Capturing CO_2 has a negative carbon footprint impact (reducing climate change), while emissions have a positive carbon footprint (increasing climate change). Emissions of biogenic CO_2 are treated the same way as fossil CO_2 emissions.
- '**Carbon neutral**': Biogenic CO_2 capture *and* emissions are both not taken into account in the carbon footprint. Biogenic CO_2 does not contribute to climate change since an identical amount of CO_2 was recently captured from the atmosphere through photosynthesis, so both the uptake and emissions are not counted in the carbon footprint. This means that the amount of biogenic carbon in a product needs to be tracked across production chains to be properly taken into account at the point where the CO_2 is released (e.g. when a partly biobased plastic is incinerated at end-of-life).

Over the entire life cycle of a product, from cradle-to-grave, both approaches yield the same results. However, the results will differ when a cradle-to-gate scope is used, meaning that care should be taken when interpreting and comparing findings.

This cradle-to-gate study uses the carbon storage approach. A credit based on the amount of biogenic carbon present in the feedstock used is calculated and deducted from the overall carbon footprint of the studied processes. This means that in, for example, the product perspective, the carbon footprints for the HVCs are directly comparable to fossil production of the same HVCs. If the carbon neutral approach were used, the system boundary would need to be expanded to properly account for the biogenic carbon, for instance by including end-of-life where all carbon present in the HVCs is released as CO_2.

It should be noted that the term 'carbon storage' does not imply permanent storage. Finally, some LCA guidelines (e.g. PAS2050) take into account the timing of emissions, since carbon footprints are commonly calculated over a 100 year timespan. These guidelines argue that temporarily storing biogenic CO_2 in products such as plastics delay its release, and that each year of storage reduces the amount of time it will be in the atmosphere (within the 100 year timespan). This effect is not considered here.

2.4 Data gathering and modelling

This section summarises the data gathering and LCA modelling process. Full details on the data used are available in Annex A.

Synova process

The foreground data for this LCA was provided by Synova. This includes for instance:
- composition and characteristics of the feedstock (e.g. lower heating values used to determine carbon footprint of incineration in MSWI);
- energy and material inputs and outputs for Synova/T.EN processes;
- energy use for feedstock pre-treatment (sorting).

The foreground process data is combined with background data from the Ecoinvent (v3.6; cut-off system model) LCA database (Ecoinvent, 2016), public literature, and internal CE Delft data. Most notably, downstream processing/separation is based on Ren et al. (2006).

Reference processes

The references to which Synova/T.EN technology is compared are modelled using various sources. In the product perspective, virgin HVC production data is taken from the Ecoinvent database (v3.6; cut-off system model), representing average European production from fossil feedstocks.

In the waste perspective, the carbon footprint of incineration with energy recovery is modelled based on the carbon content of the Synova/T.EN feedstock (Synova information), accounting for biogenic and fossil carbon[2]. Energy recovery efficiency is based on average Dutch waste incinerators, i.e. 15% net electrical efficiency and 28% thermal efficiency. The replacement of conventional electricity and heat production are taken into account.

Modelling

The SimaPro 9.1 software is used to model the processes and generate carbon footprint results. The carbon footprint results are calculated using the IPCC 2013 GWP 100a (v1.03) method in SimaPro, taking a 100 year perspective.

[2] Note that no carbon storage credit is required here since all biogenic carbon is released as CO_2 within the system boundaries (i.e. the system does not produce outputs containing biogenic carbon).

3 Carbon footprint results

The carbon footprints in the product perspective analysis (Section 3.1) and waste perspective analysis (Section 3.2) are shown below. In both perspectives, we first consider a detailed breakdown of Synova/T.EN's carbon footprint and then compare Synova/T.EN to the reference processes. Everywhere, lower values indicate a lower environmental impact.

3.1 Product perspective

Figure 5 shows the carbon footprint of producing 1 tonne HVCs using Synova/T.EN technology. The analysis covers both the production of HVCs from waste (diverted from MSWI) as well as the biogenic carbon stored in the HVCs.

The carbon footprint is estimated at -1.0 tonne CO_2-eq./tonne separated HVCs. This result includes a credit for the avoided incineration of the feedstock materials (see also discussion in Section 2.3). The carbon footprint can be split in three parts: the HVC production process (from feedstock pre-treatment to downstream separation), the credit received for avoiding incineration, and the credit received for biogenic carbon present in the products. The value is negative because the credits for avoiding emissions are larger than the direct emissions and emissions linked to the energy and materials used.

Within the processes under Synova/T.EN's direct control, the largest contributions come from flue gas emissions, CO_2 emissions from CO_2 removal, and energy use (electricity, steam). Note that waste treatment (wastewater treatment and ash transportation) is not visible in Figure 5 (and subsequent graphs) due to its small contribution.

Figure 5 - Carbon footprint of HVC production using Synova/T.EN technology, tonne CO_2-eq./tonne separated HVCs

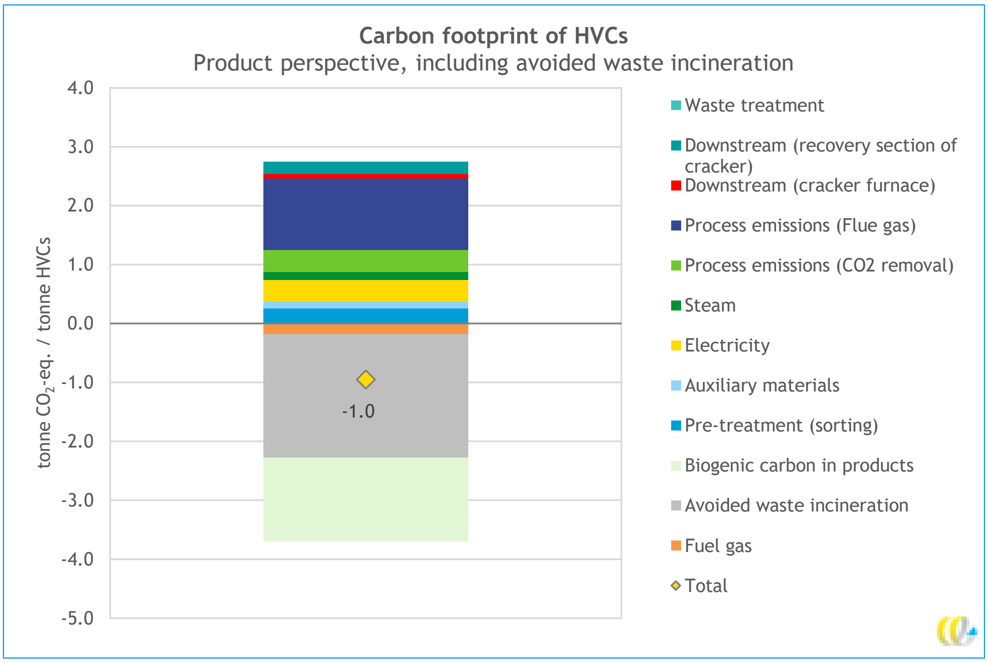
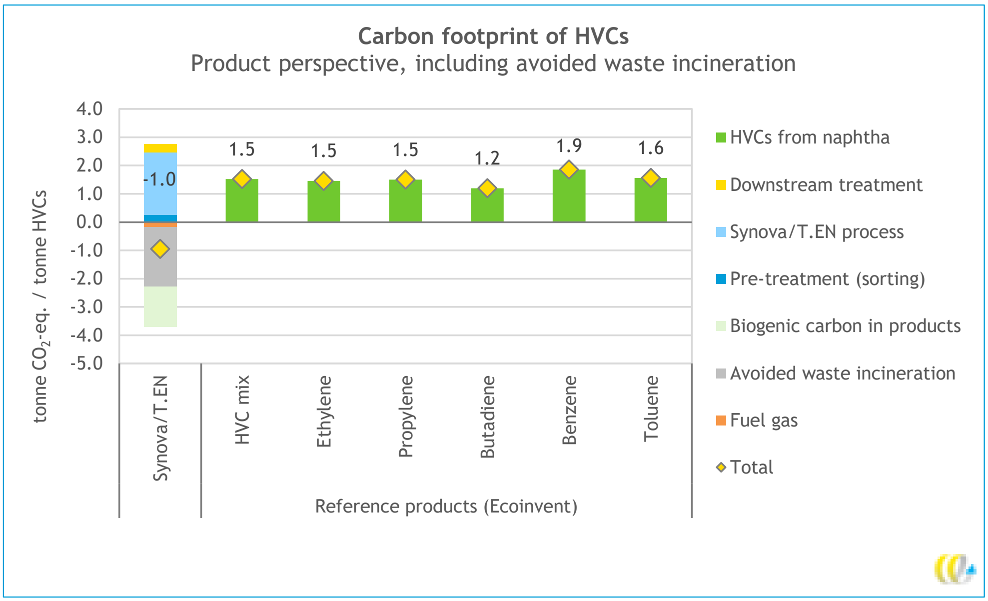


Figure 6 compares Synova/T.EN's (product perspective) carbon footprint to reference products, based on Ecoinvent data (cradle-to-gate production). For the reference products, the HVC mix produced in the Synova/T.EN process is shown on the left. The total (cradle-to-gate) carbon footprint for reference HVC production amounts to 1.5 tonne CO_2-eq./tonne HVCs. While the Synova/T.EN production process itself has a higher carbon footprint than virgin production, it benefits from three key factors: co-production of fuel gas, avoided waste incineration credits, and biogenic carbon present in the products. The net reduction amounts 2.5 kg CO_2-eq./tonne HVCs.

Figure 6 - Carbon footprint comparison of HVC production, Synova/T.EN technology and reference HVC production, tonne CO_2-eq./tonne separated HVCs



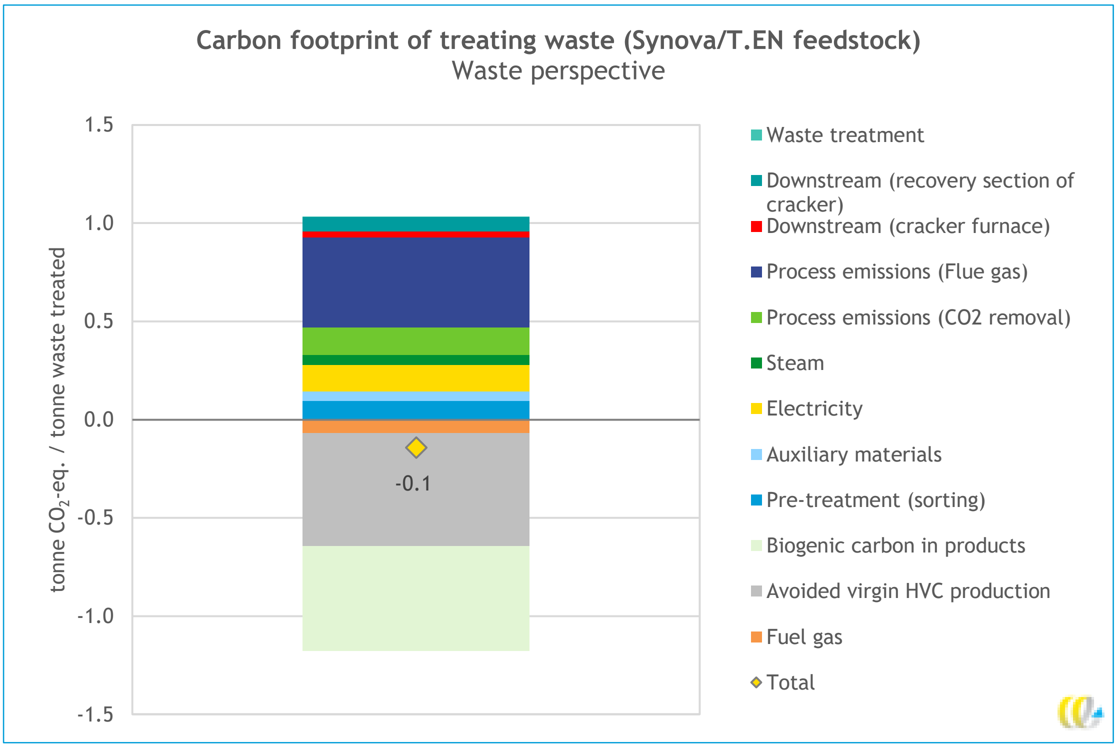
3.2 Waste perspective

The carbon footprint breakdown for Synova/T.EN technology in the waste perspective analysis is shown in Figure 7. The carbon footprint of treating waste using Synova/T.EN technology is approximately -0.1 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock)[3]. The negative value indicates that the credits allocated to the process, due to avoiding virgin HVC production, fuel gas exports and biogenic carbon present in the products, are higher than the emissions.

The relative contributions of the different processes to the carbon footprint are the same as in the product perspective analysis (although the absolute values are different due to the different unit). However, the credits for avoided processes differ; in the waste perspective, HVC production is viewed as a co-function of waste treatment, meaning that credits are provided for avoiding virgin HVC production from fossil feedstocks.

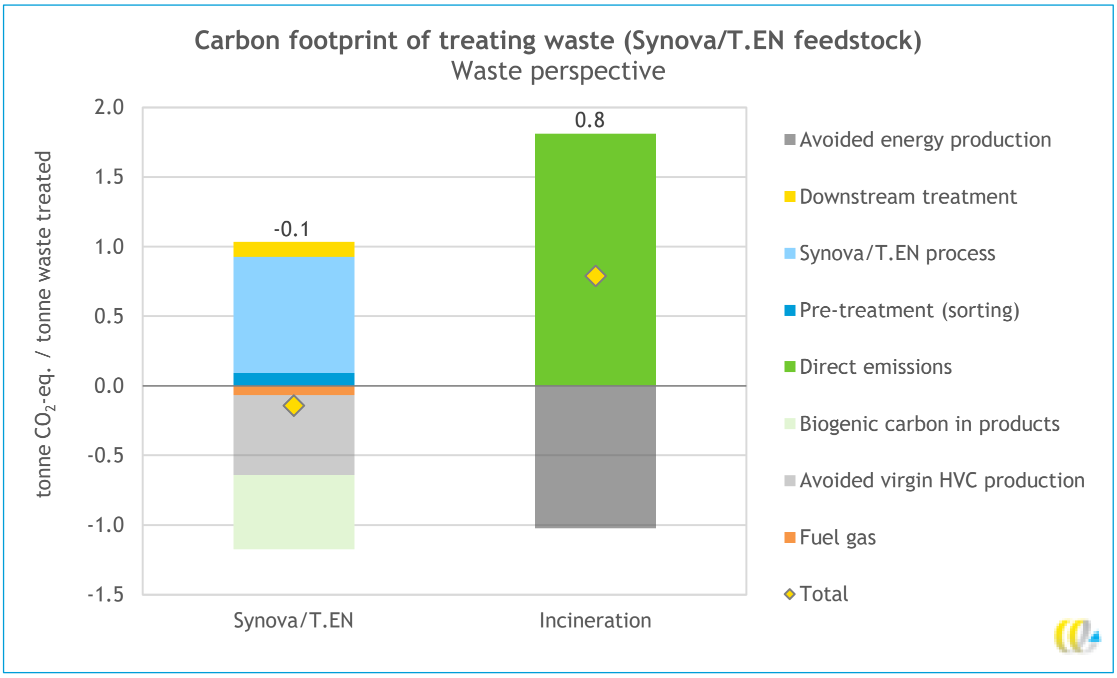
[3] As clarified in Section 2.3/Annex A, the waste perspective focuses on 1 tonne Synova/T.EN feedstock produced from mixed waste. The carbon footprint of the pre-treatment (sorting) required to produce the Synova/T.EN feedstock is included, since this is required to use Synova/T.EN technologies but not for the reference (incineration).

Figure 7 - Carbon footprint (waste perspective) of Synova/T.EN technology, tonne CO_2-eq./tonne waste (Synova/T.EN feedstock)



In Figure 8, the Synova/T.EN (waste perspective) carbon footprint is compared to the reference process for waste treatment: incineration with energy recovery in a Dutch MSWI. Incineration results in direct CO_2 emissions, but also avoids conventional electricity and heat production. The carbon footprint of incineration of the feedstock is approximately 0.8 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock). Treating waste in the Synova/T.EN processes results in a lower carbon footprint, since avoiding HVC production saves more CO_2 emissions than avoiding energy production. The overall carbon footprint reduction amounts to 0.9 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock) compared to incineration. Note that this “waste” is the feedstock for the Synova/T.EN process, which contains 59% plastic with the remainder being biogenic residues, inert materials and water.

Figure 8 Carbon footprint comparison (waste perspective) of Synova/T.EN technology and incineration, tonne CO_2-eq./tonne waste (Synova/T.EN feedstock)



3.3 Sensitivity analyses

In this section, two additional analyses are carried out. We first study the effect of using the expected 2030 electricity mix, which will have a lower carbon footprint due to the increased share of renewable electricity (Section 3.3.1). Then, we estimate the carbon footprint of Synova/T.EN technologies if an alternative, biomass-rich feedstock were to be used (Section 3.3.2). In this second sensitivity analysis, landfilling is added as an additional reference treatment in the waste perspective. Both sensitivity analyses are conducted using the product and waste perspectives.

3.3.1 Carbon footprint of 2030 electricity mix

In the main model we have made the assumption that the current electricity mix is used by the Synova/T.EN technology as well as in the reference systems. However, the electricity mix and associated carbon footprint are changing over time due to the increase of renewables. Once Synova/T.EN technology enters operation the carbon footprint of the electricity system is likely lower than the carbon footprint of the current electricity system.

In this sensitivity analysis we estimate how the 2030 Dutch electricity mix (with an increased share of renewables), affects the carbon footprint of the Synova/T.EN process and the reference processes.

The carbon footprint of the Dutch electricity mix in 2030 is predicted to be 0.14 kg CO_2-eq./kWh (PBL, 2020)[4], against 0.48 kg CO_2-eq./kWh for the current Dutch electricity mix. In the model we have made the following changes:

- In the Synova/T.EN system, including pre-treatment(sorting) and avoided processes, the current Dutch electricity mix is replaced by the expected Dutch electricity mix in 2030 for all processes.
- In the incineration model, the avoided current electricity production is replaced by the avoided 2030 electricity production.
- The carbon footprint of virgin HVC production is reduced by 4.2%, since these processes also benefit from a lower carbon footprint of electricity. This is an estimation[5].

The modelling remains otherwise unchanged.

Product perspective results

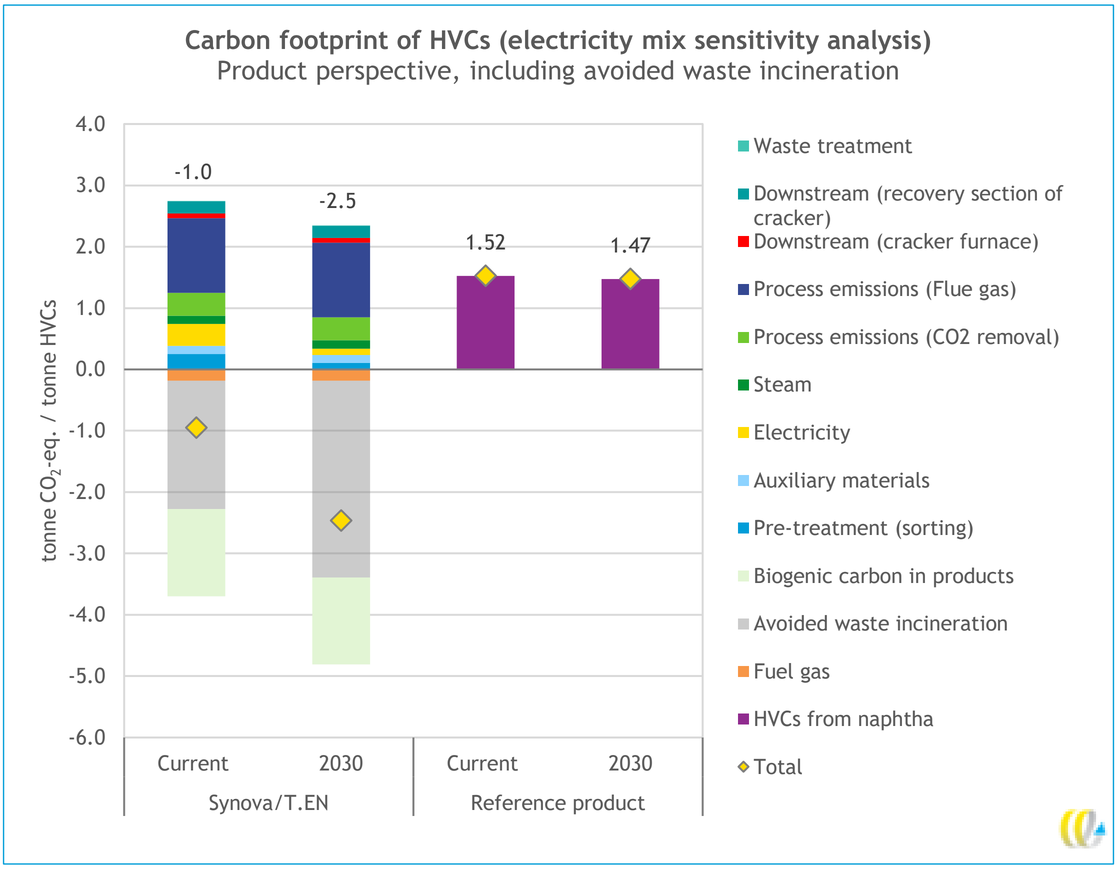
Figure 9 shows the results of this sensitivity analysis for the product perspective. The carbon footprint of the Synova/T.EN HVC production (on the left) is more strongly affected by a more renewable electricity mix than the carbon footprint of the virgin HVC production (on the right). The Synova/T.EN carbon footprint is reduced by 1.5 tonne CO_2-eq./tonne HVCs, whereas the carbon footprint of the virgin HVCs is reduced by only 0.05 tonne CO_2-eq./tonne HVCs (not visible in the graph due to rounding).

The change in carbon footprint of the Synova/T.EN system is partly caused by the use of electricity in their own process and the pre-treatment (sorting). The largest change, however, is caused by the avoided waste incineration. With a more renewable electricity mix the carbon footprint of waste incineration increases, because avoiding conventional electricity production results in a lower credit (see also Figure 10). When the carbon footprint of waste incineration increases, the credit for avoiding this waste incineration increases as well.

4 The 2030 Dutch carbon footprint expected by PBL is 0.12 kg CO_2-eq./kWh (determined using the integral method). This value refers only to the carbon footprint of the direct emissions of power plants (PBL, 2020). Currently, these direct emissions make up 85% of the total carbon footprint of electricity, which also including the supply chain emissions (CO2emissiefactoren, 2020). We assume that the ratio between the direct emissions and supply chain emissions remains the same in 2030.

5 The exact amount of electricity used in HVC production is unknown. However, according to the Eco-profiles of PlasticsEurope the electricity used in the production of HVCs contributes 5.9% to the total carbon footprint (PlasticsEurope, 2012). The carbon footprint of the 2030 electricity mix is 71% lower than the carbon footprint of the current electricity mix. With these two values combined the carbon footprint of producing HVCs with the 2030 electricity mix is 95.8% of the carbon footprint of producing HVCs with the current electricity mix.

Figure 9 - Sensitivity analysis: Carbon footprint comparison of HVC production, using the current electricity mix and expected 2030 electricity mix, tonne CO_2-eq./tonne separated HVCs



Waste perspective results

The results of this sensitivity analysis for the waste perspective are shown in Figure 10. Also in this perspective, the carbon footprint of the Synova/T.EN process decreases with a more renewable electricity mix. The reduction is 0.2 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock).

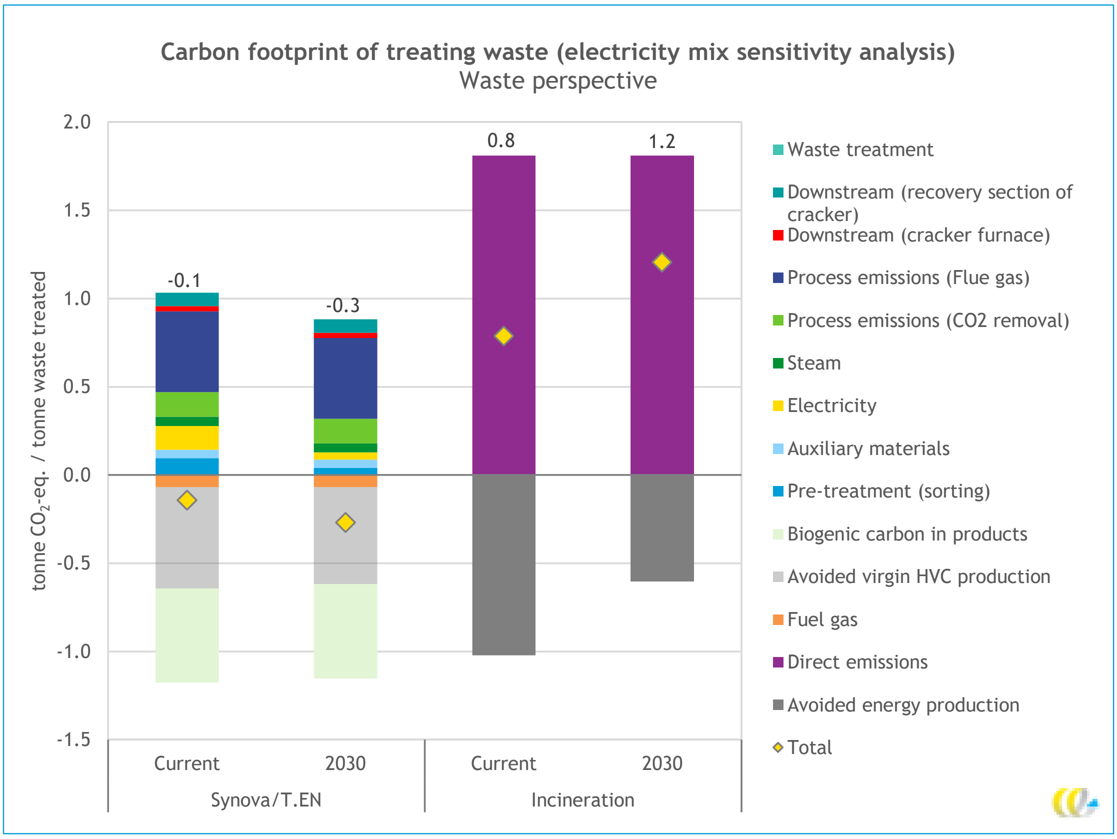
In the waste perspective the lower carbon footprint is only caused by the decreased carbon footprint of the electricity used in the Synova/T.EN system (including pre-treatment). The credit for avoided virgin HVC production decreases slightly, as the carbon footprint of producing virgin HVCs decreases with a more renewable electricity mix (as shown in Figure 9).

The carbon footprint of waste incineration increases by 0.4 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock) with a more renewable electricity mix. When the electricity mix becomes more renewable, the credit resulting from avoiding the production of conventional electricity decreases.

From this sensitivity analysis it can be concluded that in both the product perspective and the waste perspective the difference in carbon footprint between the Synova/T.EN system and the reference system increases when a more renewable electricity mix is used.

Therefore, the Synova/T.EN system still results in a lower carbon footprint than the reference systems.

Figure 10 - Sensitivity analysis: Carbon footprint comparison of waste treatment, using the current electricity mix or expected 2030 electricity mix, tonne CO_2-eq./tonne waste (Synova/T.EN feedstock)



3.3.2 Biomass-rich feedstock and landfilling

The Synova/T.EN process can also process feedstocks with higher biomass contents. The purpose of this analysis is to provide a first assessment of how a switch to biomass-rich feedstock is expected to affect the carbon footprint.

Depending on the geographical region where the process is located, landfilling could represent a more appropriate reference process than incineration. Since this can result in methane emissions (with a high global warming potential), landfilling is added as an additional reference (waste perspective only).

Table 2 shows the feedstock composition in the main analysis on the left (corresponding to the results in Section 3.1 and 3.2) and the biomass-rich composition used for this sensitivity analysis on the right. In addition, the following changes are made to the model (all based on information provided by Synova):
- product yields are changed (Table 2);
- the biogenic carbon credit is higher due to a higher biogenic carbon content in the biomass-rich feedstock;
- the amounts of utilities, auxiliary materials, etc. used are changed (not shown).

To evaluate the carbon footprint of landfilling the biomass-rich feedstock, background LCA data from the Ecoinvent database is used (*Municipal solid waste {CH}| treatment of, sanitary landfill*). It can be noted that the biomass composition in the Ecoinvent dataset (60.4% biogenic carbon, LHV of 11.7 MJ/kg) differs from the biomass-rich feedstock defined in Table 2 (59.7% biogenic carbon, LHV of 14.5 MJ/kg). Therefore, the results for landfilling only provide a first, rough estimation of the carbon footprint that would occur in practice.

Table 2 - Feedstock composition and final product yields of base feedstock (shown in main analysis and Table 1) and alternative biomass-rich feedstock (kg per tonne input)

	Synova/T.EN feedstock (main analysis)	Biomass-rich feedstock (sensitivity analysis)
Feedstock composition (input)		
Plastic	590	182
Biomass	291	424
Ash	109	94
Moisture	10	300
HVC and fuel gas production (valuable outputs)		
Ethylene	198	84
Propylene	70	9
1,3-Butadiene	26	2
Benzene	67	29
Toluene	16	6
Fuel gas	189	178

Product perspective results

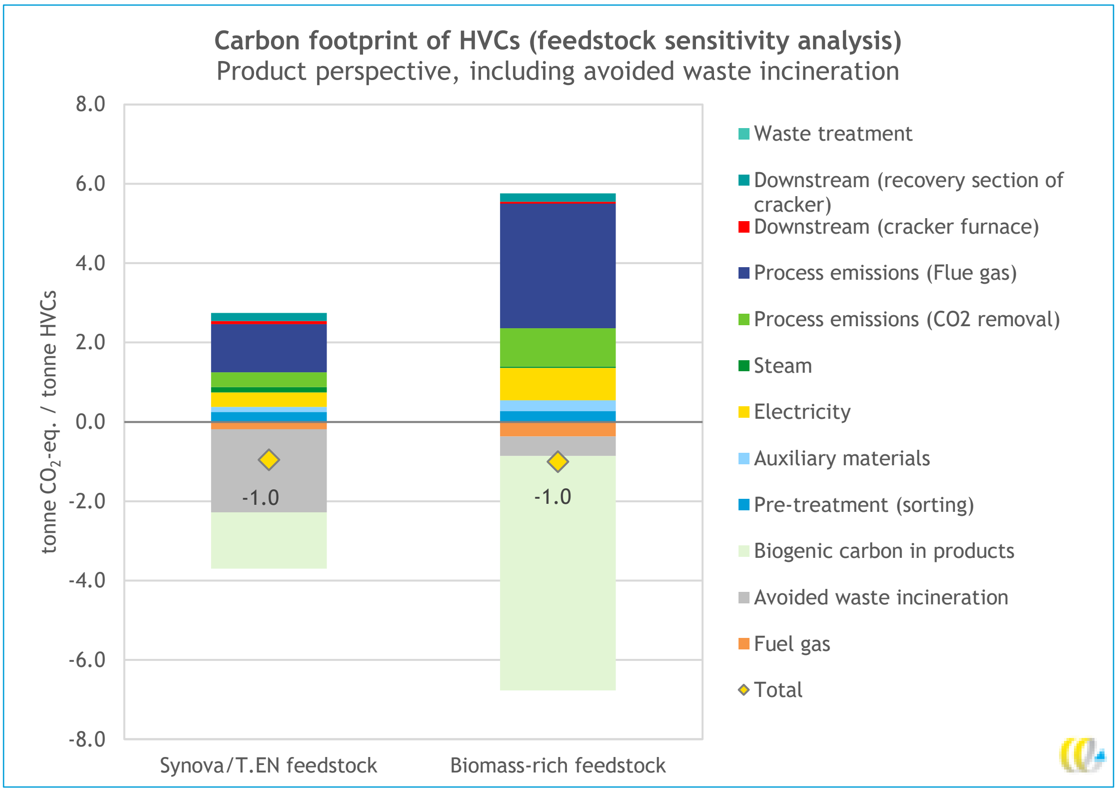
The results of this sensitivity analysis in the product perspective are shown in Figure 11. The carbon footprint of the HVCs using the Synova/T.EN feedstock (on the left) is the same as in Figure 5 (-1.0 tonne CO_2-eq./tonne HVCs). The total carbon footprint of the HVCs using biomass-rich feedstock (on the right) is -1.0 tonne CO_2-eq./tonne HVCs. These two total carbon footprints are almost equal, but the breakdown of the carbon footprints shows large differences.

The carbon footprint of the Synova/T.EN process is higher when using a biomass-rich feedstock. Using biomass-rich feedstock results in a lower HVC yield (as indicated in Table 2). Therefore, more waste must be treated per tonne of HVC yield, which results in a higher energy consumption and process emissions.

Furthermore, the credit for avoided waste incineration is smaller. The incineration of the biomass-rich feedstock results in a low carbon footprint, due to the high biogenic carbon content. Therefore, the credit of avoiding this incineration is low as well.

Finally, the credit for biogenic carbon stored in the HVCs is larger when using a biomass-rich feedstock. The biomass-rich feedstock contains a larger fraction of biogenic carbon, and as a consequence the products also contain more biogenic carbon.

Figure 11 - Sensitivity analysis: Carbon footprint comparison of HVC production, using the default Synova/T.EN feedstock and the biomass-rich feedstock, tonne CO_2-eq./tonne separated HVCs



Waste perspective results

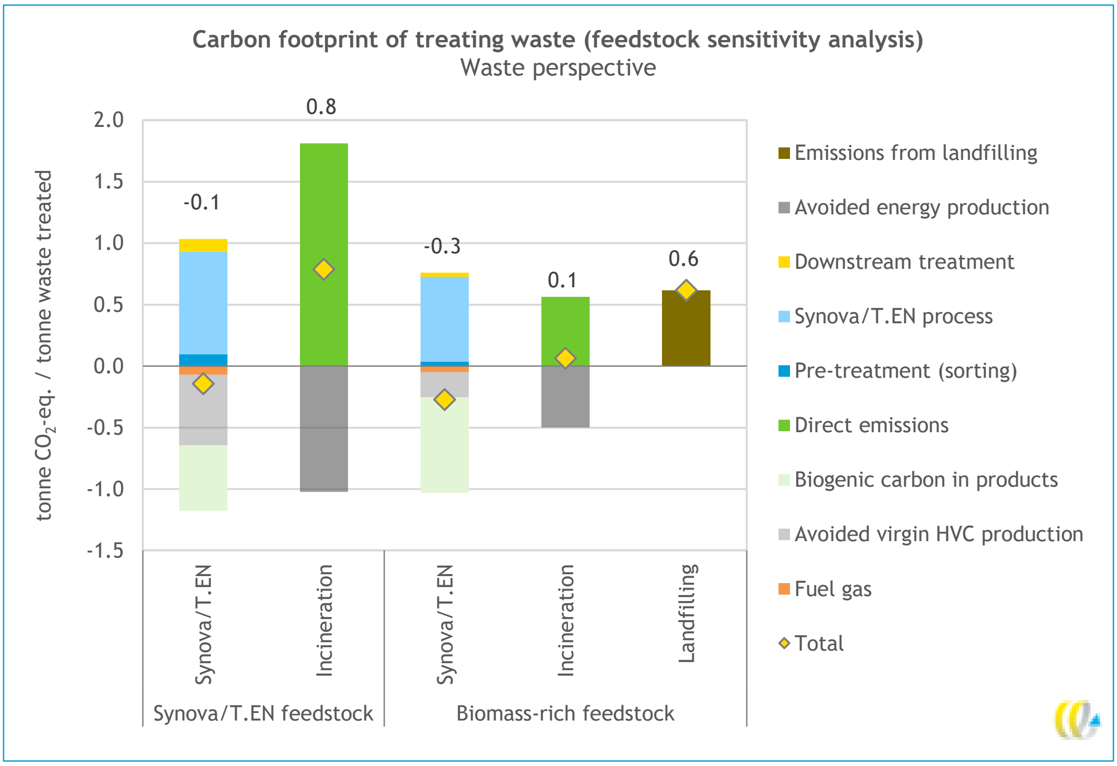
The results of this sensitivity analysis in the waste perspective are shown in Figure 12. The carbon footprint of treating the biomass-rich feedstock with Synova/T.EN process is -0.3 tonne CO_2-eq./tonne waste (biomass-rich feedstock). This is comparable to the carbon footprint of treating the Synova/T.EN feedstock with the Synova/T.EN process, but as in the product perspective there are differences in the carbon footprint breakdown.

The carbon footprint of the Synova/T.EN process itself is smaller when treating the biomass-rich feedstock, because the amount of steam needed and the process emissions are smaller. Also the credit for avoided virgin HVC production is smaller, as the amount of HVCs produced per tonne of biomass-rich feedstock is smaller. On the other hand, the credit for biogenic carbon stored in the products is larger, because the feedstock contains more biogenic carbon.

The carbon footprint of incinerating the biomass-rich feedstock is 0.1 tonne CO_2-eq./tonne waste (biomass-rich feedstock), which is lower than the carbon footprint of incinerating the Synova/T.EN feedstock. The biomass-rich feedstock contains more biogenic carbon, which does not contribute to the direct emissions. However, also the credit for avoided energy production is lower when incinerating biomass-rich feedstock as the heating value of this feedstock is lower. The net reduction amounts 0.4 tonne CO_2-eq./tonne waste (biomass-rich feedstock). Note that this “waste” is the feedstock for the Synova/T.EN process, which contains 18% plastic and remainder is biogenic residues, inert materials and water.

The carbon footprint of landfilling the biomass-rich feedstock is estimated to be 0.6 tonne CO_2-eq./tonne waste (biomass-rich feedstock). That means that the net reduction becomes 0.9 tonne CO_2-eq./tonne waste. As mentioned above, this is a rough estimate of the carbon footprint of landfilling, as the composition of the landfilled waste analysed differs from the composition of the biomass-rich feedstock.

Figure 12 - Sensitivity analysis: Carbon footprint comparison of waste treatment, using the Synova/T.EN feedstock and the biomass-rich feedstock, tonne CO_2-eq./tonne waste



4 Conclusion and discussion

This screening life cycle assessment (LCA) study analyses the carbon footprint performance of a novel chemical recycling technology developed by Synova in cooperation with Technip Energies (T.EN) for downstream purification. The technologies can process a mix of waste plastics and waste biomass, and can thus be used to divert these materials that would otherwise be incinerated. By processing this feedstock mix in Synova/T.EN technologies, high-value chemicals (HVCs) are produced. These (partly biobased) HVCs can be further processed into valuable end-products in existing chemical production infrastructure.

The carbon footprint analysis focuses on processing a waste feedstock, consisting of 590 kg waste plastic and 291 kg biomass (dry weights) per tonne, with the remainder being inert material and moisture. The analysis shows that Synova/T.EN technologies result in a carbon footprint reduction compared to reference technologies. This is the case both when considering a product perspective (carbon footprint per tonne of HVC produced) and a waste perspective (carbon footprint per tonne of waste treated).

The conclusions drawn here are based on the currently best available process data supplied by Synova and only reflect the carbon footprint results. Care should be taken when interpreting the results or comparing them to results from other studies.

Product perspective results

The carbon footprint of the HVCs produced via Synova/T.EN technology is estimated at -1.0 tonne CO_2-eq./tonne separated HVCs (product perspective). The value is negative because the credits for avoiding emissions are larger than the direct emissions and emissions linked to the energy and materials used.

In comparison, the carbon footprint for conventional fossil fuel-based HVC production amounts to 1.5 tonne CO_2-eq./tonne HVCs. The overall CO_2 reduction is therefore estimated at about 2.5 tonne CO_2-eq./tonne HVC.

Waste perspective results

The carbon footprint of treating waste in Synova/T.EN technology is approximately -0.1 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock). The negative value indicates that the credits allocated to the process, due to avoiding virgin HVC production, fuel gas exports and biogenic carbon present in the products, are higher than the direct emissions and emissions linked to energy and material use.

The reference conventional treatment of the waste feedstock is incineration with energy recovery in a municipal solid waste incinerator (MSWI). For the situation in the Netherlands, incineration would result in a carbon footprint of 0.8 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock). The CO_2 reduction of the Synova/T.EN technology compared to this reference treatment is therefore 0.9 tonne CO_2-eq./tonne waste (Synova/T.EN feedstock) compared to incineration.

Interpretation and limitations

Two sensitivity analyses show that:

- If the expected 2030 electricity mix with a lower carbon intensity is used, the carbon footprint of Synova/T.EN technologies is reduced. The CO_2 emission reductions compared to the reference technologies also increase.

- When operating on a feedstock containing more biomass, the carbon footprint remains roughly equal in the product perspective (expressed per unit of HVC). If the reference treatment of this biomass-rich feedstock was landfilling instead of incineration, a first indicative analysis shows that the CO_2 reduction increases substantially.

Care should be taken when interpreting these results or comparing them to results from other studies. A number of characteristics of the present study should be kept in mind, including:

- As a screening LCA, this analysis quantifies the carbon footprint performance of the technologies based on the current best available data provided by Synova for a plant at 50 kilotonne per year scale. Further research would be required to analyse its performance on other environmental impact indicators, or to verify the carbon footprint performance in practice based on (measured) process data.

- The study has a cradle-to-gate scope, including all steps from the feedstock pre-treatment (i.e. sorting from mixed waste), to Synova technology and finally T.EN treatment to produce separated HVC streams. A credit for biogenic carbon present in the products (at the ‘end’ of this scope) is included in the results (in line with the ‘carbon storage’ approach).

- In the product perspective, we assumed that waste feedstocks were diverted from incineration. However, other treatment options are also possible. For example, plastics could also be sorted out and sent to mechanical recycling (resulting in a lower carbon footprint than incineration). Conversely, biomass could also have been landfilled, leading to methane emissions (potentially resulting in a higher carbon footprint than incineration). These routes were not considered in detail here.

- In the product perspective, the carbon footprint benefits of avoided incineration are included in the results. This shows the overall effect of using Synova/T.EN technology instead of incinerating the feedstock. However, it is not evident that this benefit can be fully allocated to the final HVCs produced by Synova/T.EN, since other parties such as plastic sorters also contribute to avoiding incineration. Care should be taken to explain this when communicating results with downstream customers or other stakeholders.

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A Modelling pre-treatment (sorting)

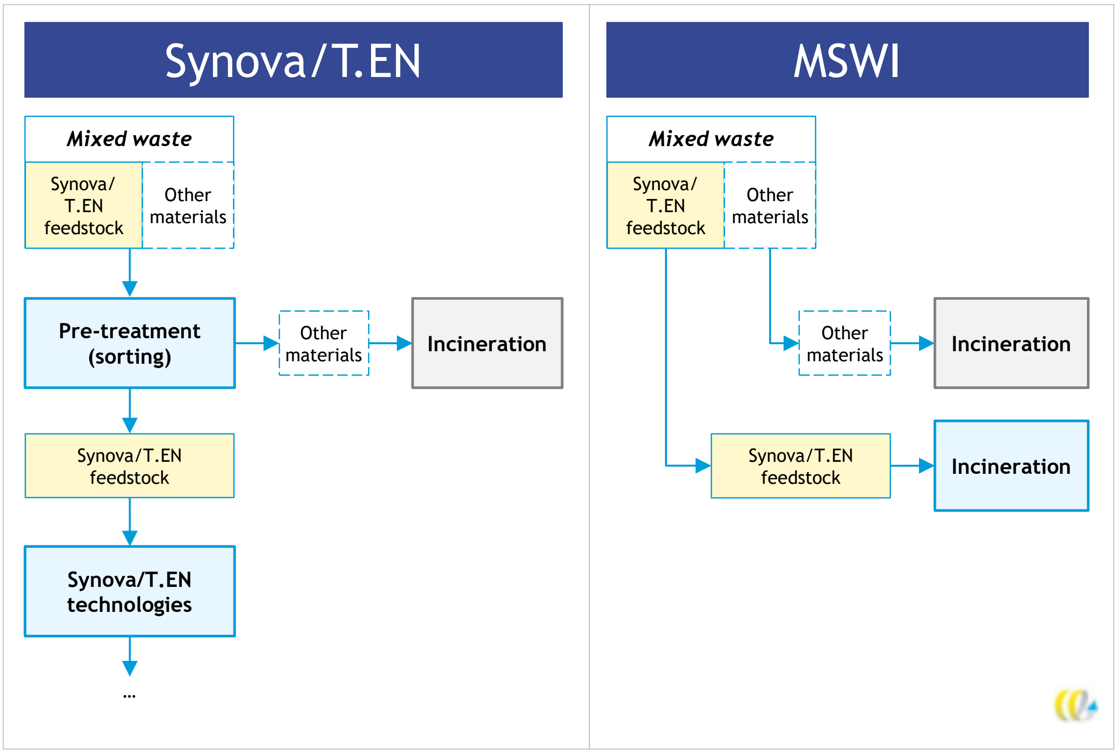
Figure 13 provides a schematic overview of the modelling approach taken for pre-treatment (sorting) when comparing Synova/T.EN technologies (left) and the reference/MSWI system (right) in the waste perspective analysis. Only the processing steps shown in blue are included in the analysis.

In both systems the same function is fulfilled: processing a specific amount of mixed waste. The mixed waste consists of various materials, a part of which are suitable for processing as Synova/T.EN feedstock (as defined in Table 1).

To use Synova/T.EN technologies, the feedstock first needs to be sorted out using a pre-treatment step. The carbon footprint of this sorting step is included when analysing the Synova/T.EN system and accounts for the sorting of all mixed waste going through pre-treatment (see details in Annex B). This pre-treatment is not necessary when applying incineration, so it is not shown in the reference system on the right and not included in the analysis.

Finally, note how the other materials in the mixed waste (i.e. materials that do not end up in Synova/T.EN feedstock) are excluded from the analysis. Regardless of the system applied, these materials end up in incineration.

Figure 13 - Modelling pre-treatment (sorting)



B Data and modelling details

This Annex describes how the LCA models for Synova and the reference processes are set up. We first describe the Synova models, including feedstock preparation (Section B.1), the Synova/T.EN process itself (Section B.2), and downstream processing (Section B.3). Subsequently, the reference systems are discussed (Section B.4).

B.1 Pre-treatment (sorting)

It is assumed that the feedstock is obtained from mixed waste streams like municipal solid waste (MSW). The MSW undergoes several treatment steps to produce refuse-derived fuel (RDF) from the MSW. The RDF is transported to Synova and used as feedstock.

The sorting of MSW requires 25 kWh of electricity per tonne of MSW (Synova information). MSW typically contains 15% plastic and 60% of this plastic ends up in the RDF. Hence, per tonne of plastic in the RDF 278 kWh of electricity is needed for the feedstock preparation. The feedstock contains 0.59 tonne of plastic per tonne, so 164 kWh of electricity is needed for its preparation.

In both the waste perspective and the product perspective analyses, incineration of the feedstocks is included, either as a reference process or as avoided process. Therefore, the lower heating value (LHV) of the feedstock is required to determine the amounts of electricity and heat generated when the feedstocks are burned (see also Section B.4). The LHV of the feedstock, as determined by Synova, is 29.8 MJ/kg.

Table 3 Characteristics of Synova/T.EN feedstock

	Synova/T.EN feedstock
Electricity for sorting (kWh/tonne)	164
Composition (kg/tonne)	
Plastic	*590*
Biomass	*291*
Ash	*109*
Moisture	*10*
LHV (MJ/kg)	29.8
Carbon content (kg/tonne)	
Fossil	479
Biogenic	146

B.2 Synova/T.EN process

The Synova/T.EN process (including MILENA, OLGA and purification units) is modelled as a single unit process. Feedstock, energy and auxiliary materials are used as input to the process and emissions, fuel gas and HVCs are outputs of the process.

Table 4 shows the input and outputs per tonne of feedstock input (waste perspective) to Synova/T.EN, as well as the carbon footprint modelling details. Note that the product perspective model is based on the same data are derived from the values in Table 4.

Table 4 - Synova/T.EN process inventory data, expressed per tonne of feedstock input (waste perspective)

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B.3 Downstream processing

Downstream processing includes HVC gas separation and recycling the ethane fraction back to a nearby steam cracker. The carbon footprint is based on information provided by Synova, based on industry information and literature sources including Ren et al. (2006).

B.4 Reference systems

Virgin HVC production (product perspective)

In the product perspective, virgin HVC production data is taken from the Ecoinvent database (v3.6; cut-off system model), representing average European production. The following datasets are used:

- Ethylene, average {RER}| production | Cut-off;
- Propylene {RER}| production | Cut-off;
- Butadiene {RER}| production | Cut-off;
- Benzene {RER}| production | Cut-off;
- Toluene, liquid {RER}| production | Cut-off.

Incineration with energy recovery (waste perspective)

In the waste perspective, the carbon footprint of incineration with energy recovery is modelled based on the carbon content of the feedstocks (Synova information), accounting for biogenic and fossil carbon.

Energy recoveries are based on average Dutch waste incinerators, meaning 15% of the feedstock's LHV is converted into electricity and 28% into recovered heat. These net efficiencies are used to calculate the amount of exported electricity and heat, which are assumed to replace conventional Dutch electricity and European heat production are avoided. For heat, Ecoinvent information is used (Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Cut-off). For electricity, an internal CE Delft model corresponding to CO2emissiefactoren.nl is used. Note that the Dutch electricity carbon footprint of about 0.48 g CO_2-eq./kWh is close to the European average of about 0.42 g CO_2-eq./kWh (Ecoinvent: Electricity, low voltage {RER}| market group for | Cut-off).