# Life cycle assessment of household plastic waste treatment in Norway

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REPORT NO.
OR 07.22

YEAR
2022

| ISBN NO. | ISSN NO. | REPORT TYPE | CONFIDENTIALITY |
| --- | --- | --- | --- |
| 978-82-7520-887-1 | 2703-8610 | Commissioned | Open |

PROJECT TITLE
Life cycle assessment of recycling of plastic waste
PROJECT NUMBER
3155
COMMISSIONED BY
Plastretur, Grønt Punkt Norge
REFERENCE
Kristian Nordby
INTERNAL QUALITY CONTROL
Hanne Lerche Raadal
NUMBER OF PAGES
43
KEY WORDS
Plastic waste, plastic sorting, plastic recycling, life cycle assessment
PHOTO FRONTPAGE
Unsplash, Tanvi Sharma

# Summary

This study was commissioned by Plastretur (Green dot Norway) and was carried out by NORSUS. The overarching goal has been to quantify the environmental impacts of Plastretur's system for collection and material recycling of plastic packaging waste from households in Norway, and to identify factors which have large impacts on the results.

Life cycle assessment (LCA) methodology was applied to calculate the environmental impacts of collection and treatment of plastic waste resources, as well as the avoided emissions when recycled material substitute virgin material, and when energy from waste substitute other energy carriers. The current system of sorting and recycling plastic waste was compared with an alternative with no sorting, where plastic waste goes to incineration with energy recovery together with residual waste. The assessment is made for the treatment of the amount of plastic waste sorted from Norwegian households during a year.

The plastic collection of household plastic waste in Norway consists of three systems, and each system is analysed and summarised to quantify the annual environmental impacts:

- sorted at source versus incineration
- sorting at ROAF sorting facility versus incineration and
- sorting at IVAR sorting facility versus incineration

Note that the results for the three systems are not comparable since different functional units (representing different plastic compositions and quality) have been used for each system.

Specific data were collected, e.g. from Plastretur, ROAF and IVAR, to represent these systems to the extent possible. When specific data were unavailable, generic data were utilized. Four environmental impacts were assessed, including climate change, freshwater eutrophication, fossil resource scarcity and fine particulate matter formation.

The results from the study show that the Norwegian system for sorting and material recycling of plastic waste contributes to a reduction in greenhouse gas emissions of approximately 72 300 tonnes $CO_2$ equivalents compared to the alternative with no sorting where all plastic is incinerated instead. The system for sorting in households contributes to a reduction of approximately 51 000 tonnes $CO_2$ equivalents, and the sorting facilities of ROAF and IVAR contribute to a reduction of approximately 10 500 and 10 800 tonnes $CO_2$ equivalents, respectively, compared to incineration. In municipalities with sorting in households, each kg sorted contributes on average to an emission reduction at 2.0 kg $CO_2$ equivalents compared to the same amount being incinerated.

The results from this study show that sorting and recycling of household plastic waste is preferable to incineration with energy recovery in terms of climate change and fossil resource depletion. In terms of fine particulate matter formation and freshwater eutrophication, on the other hand, incineration with energy recovery gives lower impacts. For fine particulate matter formation, this is a result of higher avoided impacts from incineration compared to avoided impacts from recycling and incineration of plastics in the systems for sorting and recycling of plastics. For freshwater eutrophication, this is due to impacts from the resources needed for recycling processes, such as

electricity, while incineration avoids contributions to freshwater eutrophication when substituting Norwegian district heat generation.

Critical factors affecting the results include:

- Sorting rates for each plastic type
- The quality of the plastic and what it substitutes
- The market for recycled plastics

Transport and energy use have low impacts on the results.

In the future, Plastretur is advised to collect more specific data from the sorting- and recycling facilities, which to various extent had to be modelled using generic data. More information on recycling rates per plastic type, the quality and market of recycled materials and what type of material that is substituted by these recycled materials would be beneficial. Furthermore, Plastretur is advised to select sorting- and recycling facilities that produce high quality recycled material that in turn can substitute virgin plastics.

This project has not included a comparative assessment of the different sorting systems (sorting at source compared with residual waste sorting facilities). In such a study the comparison must be done based on the amount of plastic waste generated in the households. As more data is available for the different systems, it is recommended to set up analyses with the aim of a direct comparison of the different systems to better understand the implications of choosing one system over the other. In such a study, it would be interesting to address under what circumstances that one of these systems becomes preferable to the other. This could be done by, for example, assessing how well consumers need to sort the household plastic waste for the sorted at source system to be environmentally preferable over a sorting facility system where plastics are disposed with the residual waste.

# Sammendrag

Denne studien er gjennomført av NORSUS på oppdrag fra Plastretur (Grønt Punkt Norge). Målet med prosjektet har vært å kvantifisere miljøpåvirkningen fra Plastreturs system for innsamling og materialgjenvinning av plastemballasje fra husholdninger, og å identifisere de faktorene som har størst påvirkning på resultatene.

Studien har benyttet livsløpsvurdering (life cycle assessment – LCA) som metode for å beregne miljøpåvirkninger fra innsamling og avfallshåndtering av plastavfallsressursene, i tillegg til de unngåtte utslippene når gjenvunnet materiale erstatter jomfruelig materiale, og når energi generert fra avfall erstatter andre energibærere. Det nåværende systemet for innsamling og materialgjenvinning er sammenliknet med et alternativ uten utsortering der alt plastavfallet går sammen med restavfallet til energiutnyttelse. Den funksjonelle enheten ble definert som behandling av den årlige utsorterte mengden plastavfall fra norske husholdninger i løpet av et år.

Det norske innsamlingssystemet for husholdningsplast består av tre ulike systemer. Hver av systemene ble analysert og summert sammen for å kvantifisere den årlige miljøpåvirkningen:

- Kildesortering sammenliknet med energiutnyttelse
- Utsortering på ROAFs ettersorteringsanlegg sammenliknet med energiutnyttelse
- Utsortering på IVARs ettersorteringsanlegg sammenliknet med energiutnyttelse

Merk at resultater per mengde utsortert plast ikke er sammenliknbare på tvers av de tre systemene, siden plasten har ulik kvalitet og sammensetning og blir utsortert ulike steder i verdikjeden.

Det er samlet inn spesifikke data blant annet fra Plastretur, ROAF og IVAR for å gi et så representativt resultat som mulig. Der spesifikke data ikke var tilgjengelig er det benyttet generiske data. Fire miljøpåvirkningskategorier har blitt analysert: klimaendringer, ferskvannseutrofiering, fossil ressursbruk og partikkeldannelse (småpartikler).

Resultatene fra studien viser at det norske systemet for utsortering og materialgjenvinning av plastavfall bidrar til en reduksjon i klimagassutslipp på omtrent 72 300 tonn $CO_2$-ekvivalenter/år sammenliknet med å ikke kildesortere og sende plast til forbrenning. Av dette bidrar kildesorteringssystemet med omtrent 51 000 tonn $CO_2$-ekvivalenter, og sorteringsanleggene til ROAF og IVAR med henholdsvis rundt 10 500 og 10 800 tonn $CO_2$-ekvivalenter sammenliknet med ingen utsortering. I kommuner med kildesorteringssystem bidrar hver kg plast som kildesorteres med en utslippsreduksjon på 2.0 kg $CO_2$ ekvivalenter i gjennomsnitt.

Resultatene i denne studien viser at utsortering og materialgjenvinning av plastavfall gir et bedre resultat enn energiutnyttelse når man ser på miljøpåvirkningskategoriene klimaendringer og utarming av fossile ressurser. Dette gjelder både for kildesortert plast og plast utsortert på ettersorteringsanleggene til ROAF og IVAR. For indikatorene ferskvannseutrofiering og partikkeldannelse (småpartikler), derimot, gir energiutnyttelse lavere påvirkning. For partikkelutslipp skyldes dette utslippene som unngås ved å generere energi fra avfallet er større enn de som unngås ved materialgjenvinning. For ferskvannseutrofiering oppnår energiutnyttelse lavere belastning på

grunn av en høyere gevinst ved å erstatte fjernvarmemiks og på grunn av energibehovet knyttet til materialgjenvinning i Tyskland.

Kritiske faktorer som påvirker resultatene har blitt identifisert som:

- Sorteringsgrad for hver plasttype
- Kvaliteten på den utsorterte plasten og hva den erstatter
- Markedet for gjenvunnet plast

Transport og energibruk har ikke stor innvirkning på resultatene.

I fremtiden anbefales det at Plastretur samler inn mer spesifikke data fra sorterings- og gjenvinningsanleggene hvor det i noen tilfeller var nødvendig å bruke generiske data i denne studien. Mer informasjon om gjenvinningsgrader per type plast, kvaliteten og markedet til de resirkulerte materialene og hva slags materialer som erstattes av disse hadde vært ønskelig. Videre oppfordres Plastretur til å velge sorterings- og gjenvinningsanlegg som produserer resirkulert materiale med høy kvalitet som i størst mulig grad erstatter jomfruelig plast.

Denne studien har ikke gjort en komparativ analyse av de ulike sorteringssystemene (kildesortering sammenliknet med sentralsortering). For å kunne gjøre dette, måtte analysen vært gjennomført per mengde plastavfall oppstått i husholdningene. Etter hvert som det finnes representative driftsdata for de forskjellige løsningene, anbefales det at det gjennomføres en sammenlikning av de to løsningene for å forstå bedre styrken og svakheten til de ulike systemene, og når de ulike systemene bør velges. En slik studie vil for eksempel kunne gi svar på hvor gøy kildesorteringsgraden må være for at kildesortering gir en bedre miljøprestasjon enn sentralsortering.

# Contents

# 1 Introduction

NORSUS (previously Østfoldforskning) has formerly conducted Life Cycle Assessments (LCAs) of household plastic recycling in Norway (Lyng & Modahl, 2011; Raadal, Brekke, & Modahl, 2008). These studies were commissioned by Plastretur (Green Dot Norway), which is responsible for financing the return scheme for e.g., plastic packaging for its members in Norway. In the last years, the value chain for recycling of plastic household waste resources has changed (Plastretur, 2021). The composition of the plastic waste is different today and new data have become available as technology and operational practice improves. Furthermore, the previous studies did not include data for washing and granulation of plastic. In addition to the handling of household plastic waste that is sorted at source and sent for further sorting and recycling, the residual waste sorting facilities at ROAF and IVAR have been introduced in 2014 and 2019, respectively. Therefore, Plastretur has commissioned this study to obtain environmental impact results representative for today's recycling system for Norwegian household plastic waste.

The overarching goal with this project has been to quantify the environmental impacts of Plastretur's system for collection and recycling plastic packaging waste from households in Norway. Furthermore, the most important factors in influencing the results were identified, as well as potentials for system improvements.

As Plastretur currently supports three different systems for recycling plastic waste, these have been assessed individually, and are used as a basis for calculating the annual environmental impact of the overall system. The systems studied individually are:

1. ***Sorted at source versus incineration***. The environmental impacts of Plastretur's system for material recycling of collected household plastic waste that has been sorted by Norwegian households compared with incineration of un-collected household plastic in residual waste
2. ***Sorting at ROAF versus incineration***. The environmental impacts of ROAF's system for sorting out plastics from residual waste in a material recovery facility, and then sending these fractions to further material recycling compared with incineration of household plastic in residual waste
3. ***Sorting at IVAR versus incineration***. The environmental impacts of IVAR's system for sorting out plastics from residual waste and then recycling some fractions while others are sent to further material recycling compared with incineration of household plastic in residual waste

The specific goals of the three LCA studies are specified in Section 3.2.1 , 3.3.1 and 3.4.1 , respectively. Results are provided for these three LCAs, specifically, in addition to the annual treatment of household plastic waste in Norway in 2020. The results from these studies can be applied to communicate whether recycling household plastic waste is environmentally preferable to sending household plastic waste to incineration or not. Note that the results from the three LCAs are not comparable as different functional units are applied and thus the results from these LCAs need to be interpreted individually. A comparison of source separation in households versus IVAR/ROAF could, however, be very interesting to conduct in the future. The potentials of, and the potential requirements/suggestions for, such a future study are discussed in Section 5.

Note that this study only covers the sorted waste treated in the three systems described below, which represent most of the plastic sorted in Norway in 2020. There are, however, some smaller amounts which were not covered in this study, for example plastic sent to a chemical recycling plant in 2020 as part of a pilot project.

# 2 Method

Life cycle assessment (LCA) is a methodology that enables quantification of the environmental impacts of products and services throughout their life cycle. The methodology is standardised through the ISO system and can be divided into four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a, 2006b). The methodology applied when assessing the service of collecting and treating waste is typically different from when the life cycle impacts of a physical product is assessed. Therefore, the European Commission Joint Research Centre has developed guidelines for LCA of waste systems, specifically (European Commission Joint Research Centre, 2011). In LCA of waste management services it is common practice to start the study from where the waste occurs, while the impacts from producing and using the products before they became waste is regarded as outside of the system boundaries. The waste treatment phase includes the activities of collection and treatment of the waste until the waste resources are converted into recycled materials and/or energy.

Since the household plastic waste is used as a resource to generate recycled materials and/or energy that can substitute virgin materials and/or energy from other energy carriers, this study has applied the system expansion approach to take this into consideration. The system expansion approach is also referred to as the end of life approach (Ekvall et al., 2020). In this approach, the impacts from extraction and production of virgin materials and the impacts from energy generation that can be avoided due to recycling of waste and/or energy generation from waste is included as negative impacts. Thus, the results include both impacts and avoided impacts which can be summarised into net impacts for different waste treatment scenarios.

The foreground system data for the studied systems were gathered to be representative for the year of 2020 to the degree that this was possible. When data were unavailable for 2020, data were selected to be as up to date as possible. Data were gathered e.g. from Plastretur (2021) and from IVAR and ROAF. The systems studied in the three conducted LCAs on household plastic sorted at source, sent to ROAF and sent to IVAR and the data applied are described in Section 3. The life cycle impact assessment (LCIA) method of ReCiPe version 2016, with the hierarchist perspective, (Huijbregts et al., 2017) was applied focusing on the impact categories of global warming, freshwater eutrophication, fossil resource scarcity and fine particulate matter formation. The modelling was conducted in SimaPro version 9.3 and the ecoinvent database, version 3.8 (Wernet et al., 2016) was applied for background system data.

# 3 Systems studied

In this chapter, a description of the overall system for treatment of household plastic waste is given and then each of the three sub systems are described.

## 3.1 Annual treatment of household plastic waste in Norway in 2020 versus incineration

The overall goal of the study is to compare the annual environmental impacts of the current system for sorting and material recycling of household plastic waste with incineration of household plastic waste and to identify the environmental hotspots in these systems.

The assessment is made for the treatment of the amount of plastic waste sorted from Norwegian households in 2020, including the necessary collection, sorting and treatment, as well as the avoided emissions due to material recycling and incineration with energy recovery. The impact associated with the annual treatment of household plastic waste in Norway in 2020 was compared with incineration.

The results represent the sum of the LCAs performed for each sorting system presented in Section 3.2 to 3.4. For these calculations, the plastics sorted at source (excluding impurities, such as food waste and metals) and further sent to the three German sorting plants EING, Vogt and Kedenburg, the plastics sorted out at ROAF and the plastics sorted out at IVAR was assumed to have a composition and treatment as described in Section 3.2, Section 3.3 and Section 3.4, respectively.

As shown in Table 1, the amount of separated plastic waste resources sorted at source in Norwegian households was about 26 000 tonnes plastics in 2020 (excluding separated waste not sent to Germany and impurities, such as food waste and metals) (Plastretur, 2021). Furthermore, about 3 400 tonnes plastics were sorted out at IVAR sorting facility in 2020 (Meissner, 2021), while about 3 400 ton plastics were sorted out at ROAF sorting facility in 2019 (Skovly, 2021), assumed to be representative for 2020 as well.

**Table 1** Amount of plastic waste resources sorted in the three different systems in 2020 (excluding impurities)

| System | Tonnes | Comment |
|---|---|---|
| Sorted at source (in households) | 25 675 | Plastic waste bales (excluding impurities) |
| Sorted at ROAFs sorting facility | 3 404 | Excluding non-recyclable mixed fraction |
| Sorted at IVARs sorting facility | 3 438 | Excluding non-recyclable mixed fraction |
| *Total* | *32 517* | |

In the following sub chapters, a description is given of the study goal, functional unit and data collected for each of the three sorting systems.

## 3.2 Sorted at source versus incineration

### 3.2.1 Study goal

The goal of this LCA study is to compare the environmental impacts of Plastretur's system for material recycling of household plastic waste with incineration of household plastic waste and to identify the environmental hotspots in these systems. In Plastretur's system, the household plastic waste that has been sorted at source is collected and then sent to Germany for further sorting and material recycling. In the system of incineration, the household plastic waste is incinerated together with residual waste.

### 3.2.2 Functional unit

The main function of the systems for plastic sorted at source and recycled, and for incineration of plastic in household waste is the waste treatment of discarded household plastic. The functional unit was set to be the annual amount of plastics from households packed in bales and ready to be collected at the municipality collection point for further transport to sorting and recycling (about 26 000 tonnes in 2020). The estimated composition of the collected household plastic waste per functional unit is presented in Table 2.

Note that the sorted plastic also includes some impurities such as residual waste and metal (14%). In this study, however, only the plastics in the household plastic waste was considered in the functional unit while the residual waste and metal fractions in the household plastic waste was excluded. The reason is that the alternative treatment of these impurities can be assumed to be incineration with energy recovery regardless of the scenario. Sensitivity assessments showed that the additional transport and effect of incinerating the impurities in Germany instead of Norway would lead to increased impacts associated with transport. However, the avoided impacts due to the substitution of a less renewable energy mix in Germany would lead to decreased impacts. In total, the inclusion of the impurities would decrease the difference in results between sorting at source and incineration with energy recovery with only about 1%.

**Table 2.** The share of different fractions in the household plastic waste bales and per functional unit based on an estimation of the share of various fractions in collected household plastic waste made by Plastretur. The data has been corrected so that the total sum becomes 100%, and is based on a waste composition study made by Mepex in 2019 (Plastretur, 2021).

| Type of material | Share per household plastic waste | Share per functional unit |
|---|---|---|
| Film (LDPE) | 0.40 | 0.465 |
| Other plastics | 0.20 | 0.233 |
| Polypropylene (PP) | 0.090 | 0.105 |
| PET (trays) | 0.080 | 0.093 |
| High-density polyethylene (HDPE) | 0.060 | 0.070 |
| Polyethylene terephthalate (PET) – bottles | 0.020 | 0.023 |
| Polystyrene (PS) | 0.010 | 0.012 |
| Residual waste (e.g. food waste, paper etc.) | 0.130 | - |
| Metal | 0.010 | - |
| Total sum | 1 | 1 |

## 3.2.3 Systems studied and data sources

A schematic overview of the systems studied is given in Figure 1. The data applied for the related life cycle inventory calculations are summarized in Table 11 in Appendix 1. Specific data were applied when such data was available, e.g. from Plastretur, otherwise generic data from the ecoinvent database (v3.8) were applied.

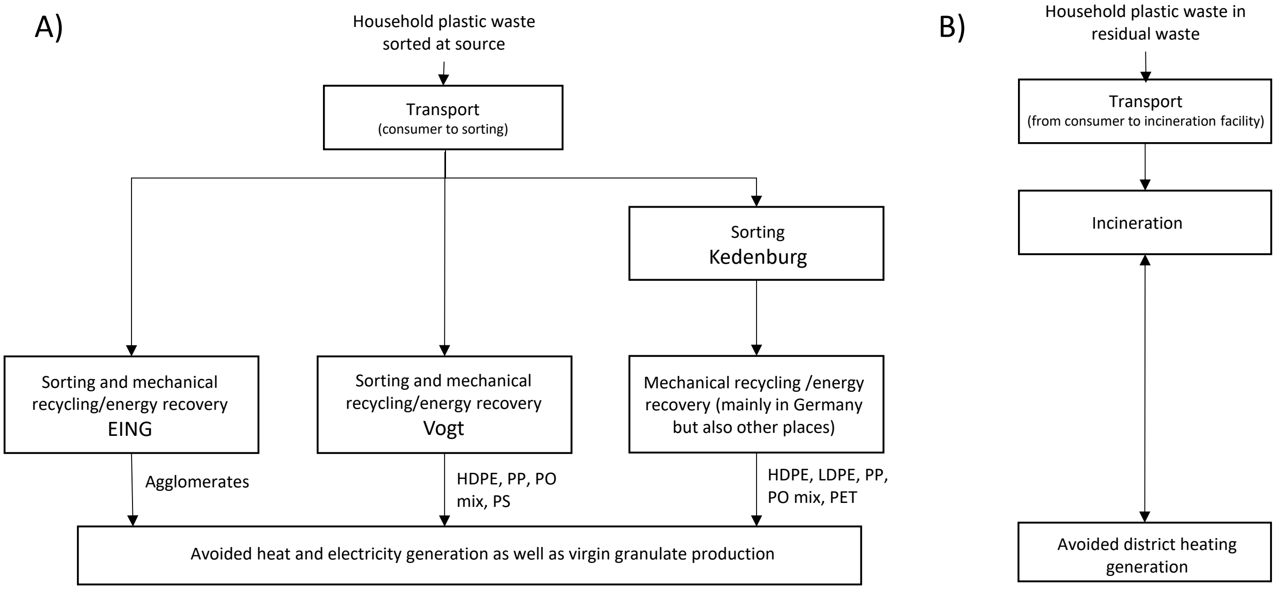


**Figure 1.** Simplified flowchart for the two compared systems A) household plastic waste sorted at source and B) household plastic waste in residual waste sent to incineration with energy recovery

## Household plastic waste sorted at source

### *Collection and transport to sorting*

Household plastic waste that is sorted at source is first collected and then transported to collection points in each municipality. The collection systems and the systems for sorting at source, as well as their efficiency, differs between the municipalities in Norway. The data applied to model the transport from consumers to these collection points were based on Raadal, Modahl, and Lyng (2009). More updated data regarding average distance driven by waste collection vehicles and average distance for further transport to local collection points, as well as the fuel mix used by Norwegian waste collection vehicles would have been preferable. As this was not available, it was assumed that the changes in transport distances between 2009 and 2020 were negligible.

At the collection points, the plastic waste becomes pressed into bales weighting about 300-500 kg each. From there, the plastic waste becomes transported to various sorting facilities in Germany and a large share of this transport is conducted by train. The Norwegian household plastic waste is sent to three sorting facilities in Germany; Vogt, EING and Kedenburg. These sorting facilities apply different technologies for sorting, and some of them are integrated sorting and recycling plants. The plants report data to Plastretur on the amounts of sorted Norwegian household plastic waste as well as where the sorted plastic becomes recycled.

Bring is responsible for the transportation of the household plastic waste sorted at source in Norway to the sorting facilities in Germany. The household plastic waste is collected by Bring from different collection points across Norway and then transported to different railway hubs. From there, the plastic is transported by train to two different railway stations in Germany, depending on the location of the sorting facility. Finally, the plastic is transported from the German railway stations to the specific sorting facilities.

Data from 2020 were used to calculate the average transport distance per kg plastic going to each sorting facility. For each collection point in Norway, data on the amounts of plastic and the route to its destination was collected. The transport route was divided in three phases, lorry transport in Norway (first mile), train transport to Germany and lorry transport in Germany (last mile) and multiplied with the transported amounts of plastic to obtain results for the transported tonne-kilometre (tkm) of plastics yearly. Afterwards, the tkm result for each route going to a specific sorting facility was summarized to calculate the total amount of tkm transported to each individual sorting facility. Finally, this was divided by the total amount of plastic transported to each sorting facility to calculate the average km transported per kg plastic going to each sorting facility.

### *Sorting and material recycling at Vogt*

In 2020, about 41% of the collected Norwegian household waste sorted at source was transported by truck and train to the integrated sorting and recycling facility in Premnitz, which is owned by Vogt-Plastic GmbH (Plastretur, 2021). There, the plastic is shredded, washed, grinded and finally separated by the application of various techniques, such as density and electrostatic separation methods. Plastics not sorted out at Vogt, i.e. losses of plastics or plastic types that do not become sorted out (polyethylene terephthalate (PET) bottles and trays), were assumed to become incinerated with energy recovery, substituting a certain amount of European heat and electricity generation. Data on the overall efficiency of the recycling process was provided by Vogt. However, the main input material in the sorting and recycling facility are yellow bags from the German collection system. Since also metal and cardboard are the targeted fractions in these bags, data on materials flows and overall efficiency were not deemed to be representative for the Norwegian plastic flow, specifically. Hence sorting and recycling efficiencies for each plastic fraction were instead collected from Eriksen, Damgaard, Boldrin, and Astrup (2018). Based on this, an overall efficiency of 51% (including residual waste and metal fraction) was applied for the Premnitz facility. It should be noted that the facility has reported an overall efficiency of 56% for the Norwegian plastic in later communication. Hence, the estimate used in the study (51%) is slightly conservative. Electricity consumption, diesel consumption and losses during electrostatic separation and extrusion, provided from Vogt, were applied for the modelling of the sorting and recycling of plastics at Vogt. However, this data and the processes at Vogt cannot be presented in more detail in this report due to confidentiality.

*Material recycling at EING and avoided production*

In 2020, about 22% of the collected Norwegian household waste sorted at source was transported to EING in Germany. At EING, there is no sorting step for the ingoing household plastic waste, but the household plastic waste is directly used in the mechanical recycling process (Ahaus, 2021). First, the waste is crushed and then it goes through the following process steps; metal separation, wind shifting, dry cleaning, cold washing and finally agglomeration. In the wind shifting step, heavy non-plastic parts like glass, wood, wet paper, organics etc. are removed, while the remainders become further processed. Density separation, via float-sink separation, enables the separation of plastics with a density >1 g/cm³, like PET and polystyrene (PS), and in this way a relatively pure mixture of polyethylene (PE) and polypropylene (PP) can be obtained. Mainly three agglomerate qualities are produced at EING, i) dry-cleaned, no float-sink separation, agglomerate, ii) washed, without float-sink separation, agglomerate and iii) washed, with float-sink separation, agglomerate. During agglomeration, the plastic is heated so that it builds a kind of pellet, but there is no complete melting and filtration. The yield in the mechanical recycling process, estimated by dividing the amount of output agglomerate (e.g. ton) with the amount of input plastic waste (e.g. ton), varies between 45-65% depending on the product produced (Ahaus, 2021). EING reported that they use electricity and cold water (40℃) in their processes but data on the amounts used were not available for this study. No chemicals are reported to be used in the mechanical recycling process by EING. Due to limited data on the use of resources, such as electricity, at EING, generic data for LDPE recycling from Wernet et al. (2016) were used in this study as a proxy for the process at EING (see further Table 11). This since a large share of the plastic bale is low-density polyethylene (LDPE). The dataset was corrected for German electricity mix and the specific yield at EING.

According to EING (2021), the agglomerate types produced at EING include a polyolefin agglomerate, a polyethylene agglomerate and a polypropylene agglomerate. Polyolefin is a name for various plastics, including LDPE, linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE) as well as PP plastics (Plastics Europe, 2021). From the Norwegian plastic waste, EING reported to have produced 50% PO85 and 50% PO95/99. Hence, it was assumed that LDPE, HDPE and PP were the targeted fractions in the recycling process. According to Ahaus (2021), there is a 12.5% loss in the agglomeration process itself (targeted fractions). Remaining losses in the recycling process are assumed to be caused by the non-targeted fraction (PET, PS and other plastics). Applied on the specific waste composition (including residual waste and metal), this results in an overall recycling efficiency of 48%, which lies between the 45% and 65% mentioned earlier. According to Ahaus (2021), materials not sorted out and recycled at EING as well as losses of plastics become used by the cement industry and in incineration with energy recovery. In line with this, remaining plastics in the household plastic waste, i.e. PET, PS and other plastics, as well as losses of LDPE, HDPE and PP, were assumed to become incinerated with energy recovery and thus substituting a certain amount of European heat and electricity generation.

The recycled agglomerate can be used to produce new products such as planks, pallets and boxes. The share of recycled plastics in the final products is >90%-100% (Ahaus, 2021). Based on data from 2018, around 40% of the agglomerate goes to products such as pallets and boxes. Another 40% goes to planks, garden furniture, etc. while the remaining 20% goes to multiple different applications. Due to a lack of more detailed data, it was assumed that 50% of the agglomerate is used in planks, garden furniture, etc. while 50% is used for producing pallets and boxes. As pointed out by Huysman et al. (2015), using recycling plastics in outdoor applications, such as street benches, may replace wood or other materials rather than virgin plastic. As a conservative approach, agglomerates used in planks, garden furniture, etc. were assumed to substitute wood planks. Agglomerates used in pallets and boxes, on the other hand, were assumed to substitute virgin plastics.

*Sorting at Kedenburg, further material recycling and avoided production*

About 37% of the collected Norwegian household waste sorted at source was transported to Kedenburg in Germany in 2020. At the Kedenburg facility, household plastic waste is sorted by the the separation of flexible vs. ridged plastics and the application of NIR techniques (Glattowski, 2021). First the material passes a shredder, then it goes through a ferrous metal separation unit and a film separation unit. After that, the material flow passes a double deck ballistic separation unit for separation of 2D vs. 3D plastics and fines. The large sized film flow and the film flow from the film separation unit meet and goes through a manual quality control. Rigid plastics passes a ferrous metal separation station and next the wind shifting unit. Separated films meet the small sized film flow from the ballistic separation. The heavy fraction from the wind shifting unit is split and passes altogether 8 NIRs. Produced single polymer streams are baled and marketed as input material for mechanical recycling facilities. Leftover and fines become used by the cement industry and in incineration with energy recovery. Based on this, it was assumed that all plastic not sorted out and sent to further recycling becomes incinerated.

Data provided from Glattowski (2021) on electricity use, diesel use and losses of plastics during sorting was applied to model the sorting process at Kedenburg. Several plastic fractions become sorted out at Kedenburg, including HDPE, PP, LDPE, PET bottles and a mixed plastics fraction (Plastretur, 2021). Other plastic fractions in the household plastic waste not sorted out at Kedenburg, i.e. PS and PET trays was assumed to become incinerated at Kedenburg. Note that more recently, Kedenburg has started to sort out PS and send it to Vogt for further recycling, however, this was not the case in 2020 and therefore not considered in this study. The plastic fractions sorted out at Kedenburg mainly become transported to different material recycling facilities in Germany but also to facilities in other countries, including Austria, the Netherlands and Bulgaria. According to Plastretur (2021), about 98% of the Norwegian household plastic waste sorted out at Kedenburg, EING and Vogt becomes recycled in Germany. Thus, in this study, it was assumed that all plastics sorted out at Kedenburg become sent to further recycling in Germany. The recycled material substitutes other production of granulates, in this study assumed to be from virgin materials. The mixed plastic fraction is sorted at Kedenburg, but not always recycled. In 2020, approximately 3% (69 ton) of the generated mixed plastic from the Norwegian waste stream at Kedenburg was sent to recycling. The remaining share of the mixed plastics was sent to incineration. Note that the process of further recycling of the mixed plastics fraction from Kedenburg was excluded from the calculations due to limited knowledge on the recycling process and due to the small volume of the material flow.

#### Household plastic waste in residual waste to incineration

Household plastic waste that becomes discarded together with residual waste is first collected and then transported to various incineration plants. In this study, it was assumed that the residual waste was transported in average 19 km by a waste collection truch and further transported 52 km and then another 14 km, based on Raadal et al. (2009). More updated data regarding average distances driven would have been preferable. As this was not available, it was assumed that transportation changes between 2009 and 2020 were negligible. The incineration of the plastic waste generates heat, and this was assumed to substitute a Norwegian district heating mix. The Norwegian district heat production that can be avoided due to the generation of heat from plastic waste incineration was thus estimated. The avoided production was modelled in line with Raadal et al. (2009) while lower heating values for the various plastic types assessed were obtained from Tsiamis and Castaldi (2016).

While most of the residual waste from households is sent to incineration plants in Norway, a small share of the waste is exported and sent to Swedish incineration plants. As the correct share of waste exported was unknown in this project, a sensitivity analysis was performed to assess the importance of export in terms of climate change impacts. Export to Sweden was modelled by adding a transport distance of 400 km (corresponding to the distance between Oslo and Jönköping) and by assuming that energy generated at the incineration plant in Sweden substitute a Swedish district heat mix. The results from the sensitivity analysis showed that incineration in Sweden resulted in higher emissions from transport and reduced benefits associated with substitution of other energy carriers from energy recovery from waste compared with incineration in Norway due to a more renewable district heating mix in Sweden. Incineration in Sweden result in an increase of 0.2 kg CO2 equivalents/kg waste collected compared to incineration in Norway. This implies that if 10% of the household waste is exported to Sweden, the impact of incineration will increase by less than 1% per kg waste collected, while if 20% of the waste is exported the impact will increase by less than 2%. The conclusion was therefore that the results are not sensitive to the assumption regarding what share of residual waste that become exported to Sweden.

## 3.3 Sorting at ROAF versus incineration

### 3.3.1 Study goal

The goal of this LCA study is to compare the environmental impacts of the ROAF system for sorting and further material recycling of household plastic waste with incineration of household plastic waste and to identify the environmental hotspots in these systems. In ROAF's system, household plastic waste, together with residual waste, is collected and transported to ROAF for sorting and then sorted plastic fractions are sent for further material recycling. In the system for incineration of household plastic waste, this waste become incinerated together with residual waste. The data applied represents the ROAF system that has been in operation for about four years, however, the facility is continuously being updated to meet todays' challenges.

### 3.3.2 Functional unit

The functional unit was set to the annual amount of plastic sorted out from the ROAF sorting facility to be sent to further material-recycling (approximately 3 400 tonnes in 2019) and the shares of different plastics sorted out from ROAF per functional unit is shown in Table 3. Only plastics which are sorted for recycling were considered. Hence, the mixed plastic fraction (which currently follows the residual waste steam towards incineration) is excluded from the analysis.

**Table 3.** The amounts of different plastics sorted out at ROAF in 2019 per functional unit, based on data for plastic sorted out from the facility, see Table 12 in Appendix 1. HDPE=high-density polyethylene, LDPE=low-density polyethylene, PET=polyethylene terephthalate, PP=polypropylene

| Plastic type | ROAF [Share/functional unit] |
|---|---|
| PET (mainly bottles) | 0.042 |
| PP | 0.157 |
| HDPE | 0.073 |
| LDPE (film) | 0.728 |
| **Total sum** | 1 |

### 3.3.3 Systems studied and data sources

The systems studied are illustrated in
Figure 2. Please note that incineration of the sorting losses at ROAF is not included in the analysis because the functional unit is only related to a specific amount of plastic waste in the residual waste stream. In addition, including this would not change the results since sorting losses are incinerated in both systems. The data applied for the related life cycle inventory calculations are summarized in Table 12 in the Appendix. Specific data were applied to the extent possible, e.g. using data available from ROAF, otherwise, generic data from Wernet et al. (2016) were applied.

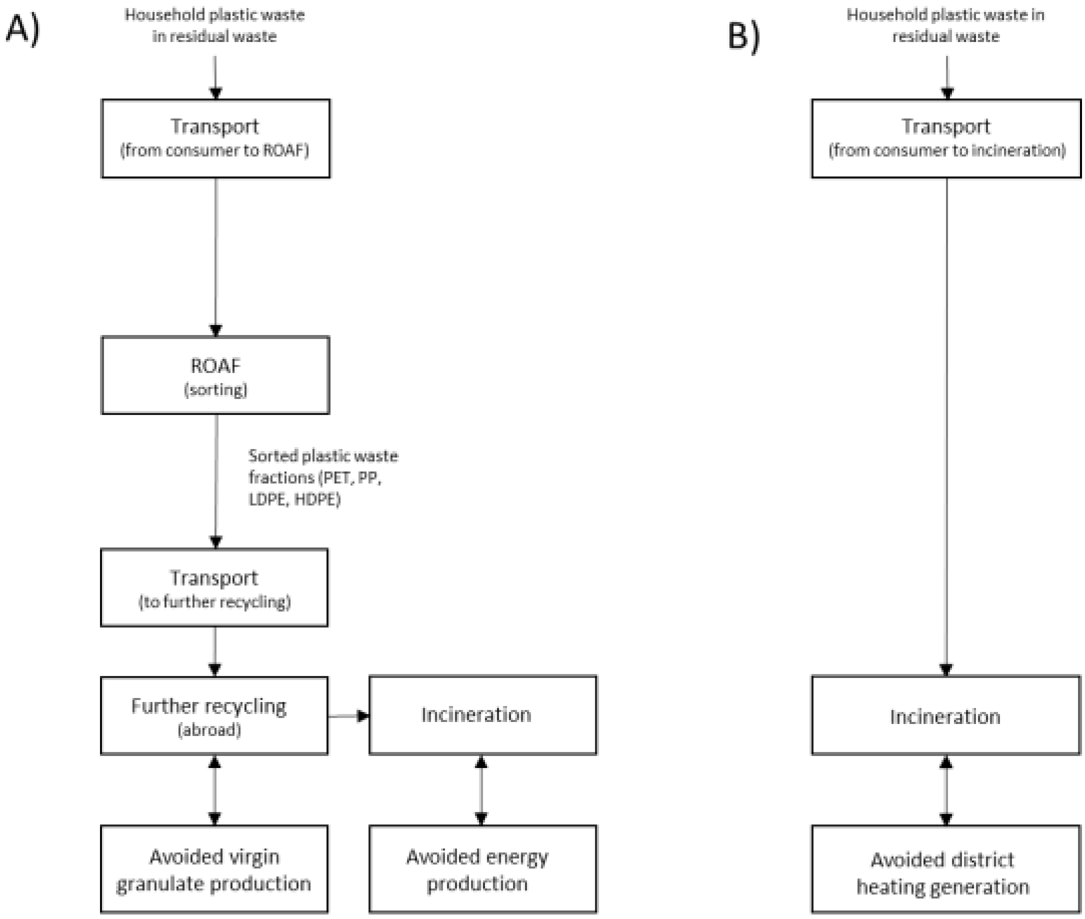


**Figure 2.** Simplified flowchart for the compared systems a) household plastic waste sorted at ROAF and further recycling abroad and b) household plastic waste going to incineration together with the residual waste instead of sorting at ROAF.

## Household plastic waste sorted at ROAF and further recycling

### *Transport from consumer to ROAF*

The household plastic waste first become transported together with the residual waste to ROAF. This transport was modelled using specific data for waste collection at ROAF (NorEnviro database, 2016).

### *Sorting at ROAF*

At the ROAF sorting facility ESAR, located in Nedre Romerike in Norway, the household residual waste is first delivered by waste trucks and fed onto a conveyor, which delivers the waste into the full-automatic sorting plant (ROAF, 2021). Near-infrared (NIR) technology is applied to separate the food waste from other waste bags. The food waste bags are sent to a biogas plant after sorting and transformed into biogas and biofertilizers. The biogas is utilized by the waste trucks at ROAF. The other waste bags, containing the household plastic waste, become opened by a bag opener. Drum and vibration screens are then used to separate the waste according to sizes. Ultimately, the different fractions that become sorted out at ROAF include PET, PP, film (LDPE), HDPE, food waste, paper, metals and residual waste. The plastic fractions become sorted out by first separating the film from the other plastic materials using ballistic separators and then NIR technology is applied to sort out

PET, PP and HDPE. Previously, five plastic fractions were sorted out, as a mixed plastic fraction also were sorted out at ROAF to be sent to further recycling abroad. However, that is not the case anymore due to the limited market for the mixed plastic fraction. This fraction is incinerated instead. A paper and residual waste fraction are also sorted out at this stage. Furthermore, magnetic and non-magnetic metals are also sorted out, using over band magnets and an eddy-current machine, respectively. The sorted plastic fractions become pressed into cubes and sent to further recycling.

***Transport of plastic fractions sorted out at ROAF, recycling and avoided production***
The plastic fractions sorted out at ROAF become transported for further recycling abroad, i.e. to Germany, Lithuania or the Netherlands (Plastretur, 2021). There, the plastic fractions become recycled, and the recycled material then substitutes other production of granulates elsewhere, in this study assumed to be from virgin materials. Due to a lack of specific data from the recycling facilities, generic data from Wernet et al. (2016) have been used. The loss from recycling is assumed to be sent to incineration, where heat and electricity is generated and substitute other energy carriers in the respective countries.

#### Household plastic waste in residual waste to incineration

The household plastic waste discarded together with residual waste is first collected and then transported to various incineration plants in Norway. In this study, the transport between the consumer and incineration and the transport between the consumer and ROAF were assumed to be the same. Thus, the household plastic waste in residual waste becomes transported over approximately the same distance as the collected household waste to ROAF. The incineration of the plastic waste generates heat, and this was assumed to substitute Norwegian district heating mix. The Norwegian district heat production that can be avoided due to the generation of heat from plastic waste was thus estimated. The avoided production was modelled in line with Raadal et al. (2009) while lower heating values for the various plastic types assessed were obtained from Tsiamis and Castaldi (2016).

## 3.4 Sorting at IVAR versus incineration

### 3.4.1 Study goal

The goal of this LCA study is to compare the environmental impacts of the IVAR system for sorting and further material recycling of household plastic waste with incineration of household plastic waste and to identify the environmental hotspots in these systems. In the IVAR system, the household plastic waste is collected and transported to IVAR together with residual waste for sorting and a certain share of some of the sorted plastic fractions become recycled on-site while others are sent to other locations for recycling. In the system for incineration of household plastic waste, plastic waste is incinerated together with residual waste.

### 3.4.2 Functional unit

The main function of the IVAR system for sorting and recycling of household plastic waste and for the system of incineration of plastic in household waste is the waste treatment of discarded household plastic. The functional unit was set to the annual amount of plastic sorted out from the IVAR sorting facility to be further material-recycled at IVAR or sent to further material-recycling elsewhere (3 438 tonnes in 2020). The amounts of different plastics sorted out from the IVAR facility per functional unit is shown in Table 4. To treat ROAF and IVAR equal in the analysis, only plastics sorted for recycling at IVAR were considered. Hence, the mixed plastic fraction is excluded from the analysis.

**Table 4.** The amounts of different plastics sorted out at IVAR in 2020 per functional unit, based on data for plastic sorted out from the facility, see Appendix 1. Note that values are presented with two significant figures. HDPE=high-density polyethylene, LDPE=low-density polyethylene, PET=polyethylene terephthalate, PP=polypropylene, PS=polystyrene

| Plastic type | IVAR [Shares, including mixed plastics] | IVAR [Share/functional unit] Excluding mixed plastics |
|---|---|---|
| PET (bottles) | 0.017 | 0.043 |
| PP | 0.058 | 0.148 |
| HDPE | 0.041 | 0.104 |
| LDPE | 0.269 | 0.685 |
| PS | 0.008 | 0.020 |
| Mixed plastics to incineration with energy recovery | 0.61 | - |
| **Total sum** | 1 | 1 |

### 3.4.3 Systems studied and data sources

The system for sorting and further recycling of household plastic waste at IVAR and the system for household plastic waste sent to incineration in Norway together with residual waste are illustrated in
Figure 3. The data applied for the related life cycle inventory calculations are summarized in Table 13 in Appendix 1. Specific data were applied to the extent possible, e.g. using data available from IVAR. Otherwise, generic data from Wernet et al. (2016) were applied.

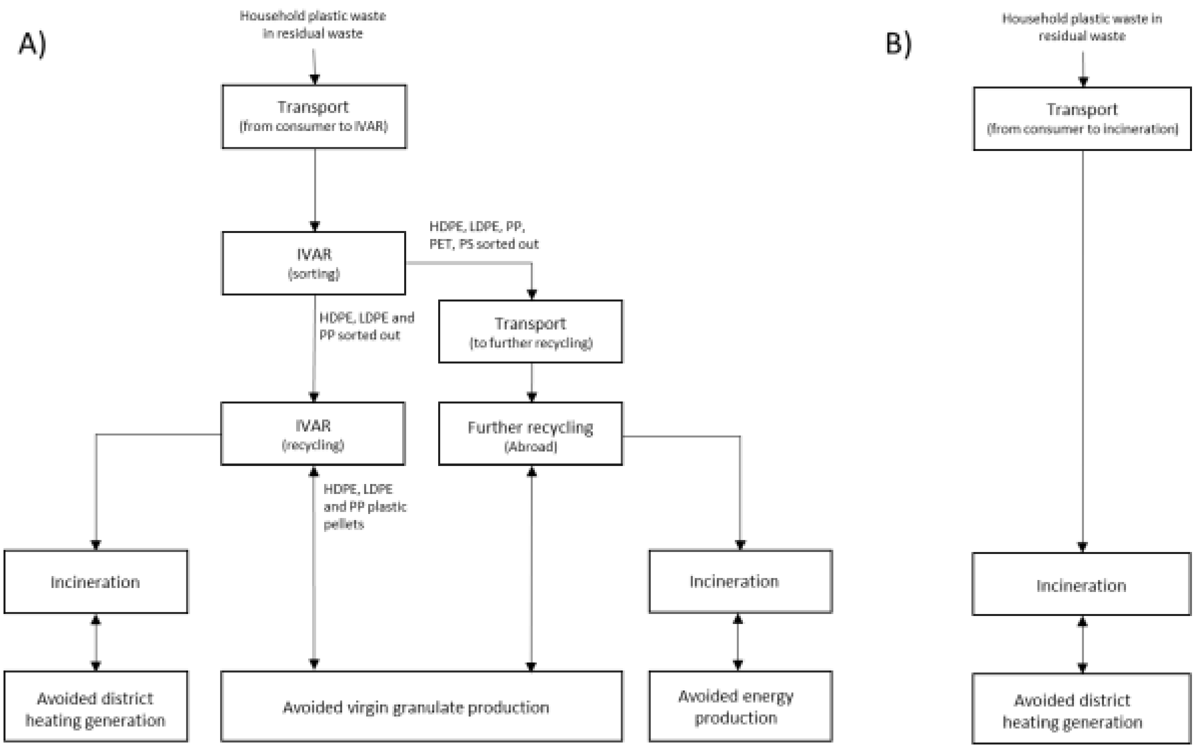


**Figure 3.** Simplified flowchart for a) household plastic waste sorted and recycled at IVAR and b) household plastic in residual waste going to incineration instead of sorting and recycling at IVAR.

## Household plastic waste sorted at IVAR and further recycling

### *Transport from consumer to IVAR*

The household plastic waste first become transported together with the residual waste to IVAR. The transport was modelled using data from the NorEnviro database (2016), assuming a similar transport system as for ROAF.

### *Sorting and recycling at IVAR and avoided production*

At the sorting and recycling facility IVAR, located in Stavanger in Norway, the household residual waste becomes sorted into a number of fractions (IVAR, 2021). The residual waste, which should not contain food or paper waste, is delivered to IVAR by waste trucks and the waste bags is fed onto a transport band and opened by a bag opener. The waste then becomes sorted according to size in a trommel screen. NIR technology is applied to separate the plastic waste from other types of waste, i.e. paper and metals. The plastic waste is sorted mechanically and with the aid of NIR technology further sorted into five plastic fractions; PET, PP, HDPE, LDPE and PS. Certain shares of the PP, HDPE and LDPE plastic fractions are taken to the washing and recycling facility at IVAR where they become treated separately. The plastic is first chopped into smaller pieces and then washed and dried to be prepared for further recycling. These smaller pieces of plastic then become smelted and filtrated to remove impurities from the plastic. The final recycled products are plastic pellets, which are sold on the market to be used as a raw material by the plastics industry in the production of new products.

The recycled granulates substitutes other production of granulates, in this study assumed to be from virgin materials. The impurities from incineration are assumed to be incinerated. The generated heat was assumed to substitute a Norwegian district heating mix.

*Transport of plastic fractions sorted out at IVAR, recycling and avoided production*
Certain shares of the LDPE, HDPE, PP, PET and PS sorted out at IVAR become transported to other locations, i.e. to Germany, Lithuania, Poland, Czech Republic, Bulgaria or the Netherlands (Meissner, 2021; Plastretur, 2021), for recycling. There, the plastic fractions become recycled, and the recycled material then substitutes other production of granulates elsewhere, in this study assumed to be from virgin materials. Due to a lack of specific data from these recycling facilities, generic data from Wernet et al. (2016) have been used. The loss from recycling is assumed to be sent to incineration, where heat and electricity is generated and substitute other energy carriers in the respective countries.

### Household plastic waste in residual waste to incineration

The household plastic waste discarded together with residual waste is first collected and then transported to various incineration plants in Norway. In this study, the transport between the consumer and incineration and the transport between the consumer and IVAR were assumed to be the same. Thus, the household plastic waste in residual waste was considered to be transported over approximately the same distance as the collected household waste to IVAR. The incineration of the plastic waste generates heat, and this was assumed to substitute Norwegian district heating mix. The Norwegian district heat production that can be avoided due to the generation of heat from plastic waste was thus estimated. The avoided production was modelled in line with Raadal et al. (2009) while lower heating values for the various plastic types assessed were obtained from Tsiamis and Castaldi (2016).

# 4 Results

The climate change impact results for the annual treatment of household plastic waste in Norway compared to incineration with energy recovery are presented in Section 4.1. The results from the three specific LCAs are addressed in more detail and presented in Section 4.2-4.4. In addition to climate change, results for freshwater eutrophication, fossil resource scarcity and fine particulate matter formation are also presented. Note that the results from the three LCAs cannot be compared since different functional units have been applied.

## 4.1 Annual treatment of household plastic waste in Norway versus incineration

The results for the climate change impacts associated with the annual treatment of household plastic waste resources sorted at source and the annual amounts of plastics sorted out at ROAF and IVAR in 2020 compared to incineration are presented in Figure 4. These results shows that it is clearly preferable, from a climate change perspective, to send household plastic waste to sorting and further recycling rather than sending it to incineration. The results show that the sorting and recycling system for plastic waste resources from households represent a reduction of approximately 72 300 tonnes $CO_2$ equivalents per year compared with incineration (difference between "Annual treatment" and "Incineration"). The system for sorting in households contribute to a reduction of 51 000 tonnes $CO_2$ equivalents, and the sorting facilities of ROAF and IVAR contribute to reductions of 10 500 and 10 800 tonnes $CO_2$ equivalents respectively.

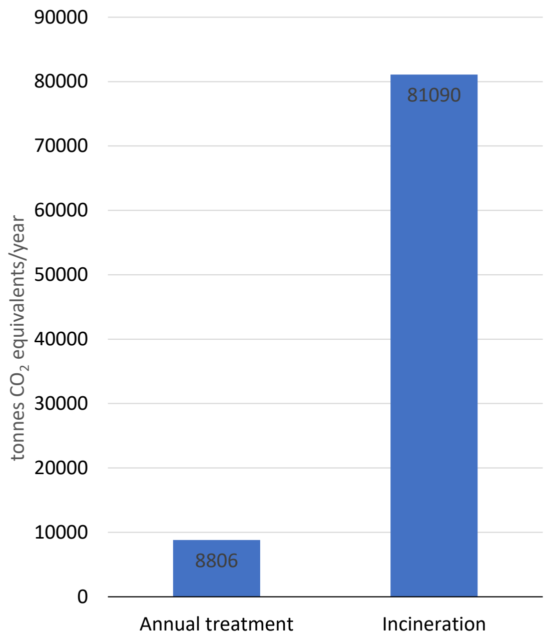


**Figure 4.** Climate change impacts associated with the annual treatment of household plastic waste sorted at source and the annual amounts of plastics sorted out at ROAF and IVAR in 2020 compared to incineration (in total approx. 32 500 ton plastic waste excluding impurities). See further Section 3.1 for details on the calculations behind these results.

## 4.2 Sorted at source versus incineration

In this chapter, the results for the amounts of plastic sorted at source are presented for the annual amount of plastic waste collected and treated and, in addition, per kg sorted waste.

### 4.2.1 Results per year

The resulting climate change impacts per life cycle process are shown in Figure 5. Resulting values per process are also provided in Table 5. The main contributor to the climate change impacts of plastic treatment via sorted at source is the incineration of plastics that do not become sorted out and further recycled. Figure 6 shows the net results for climate change impacts.

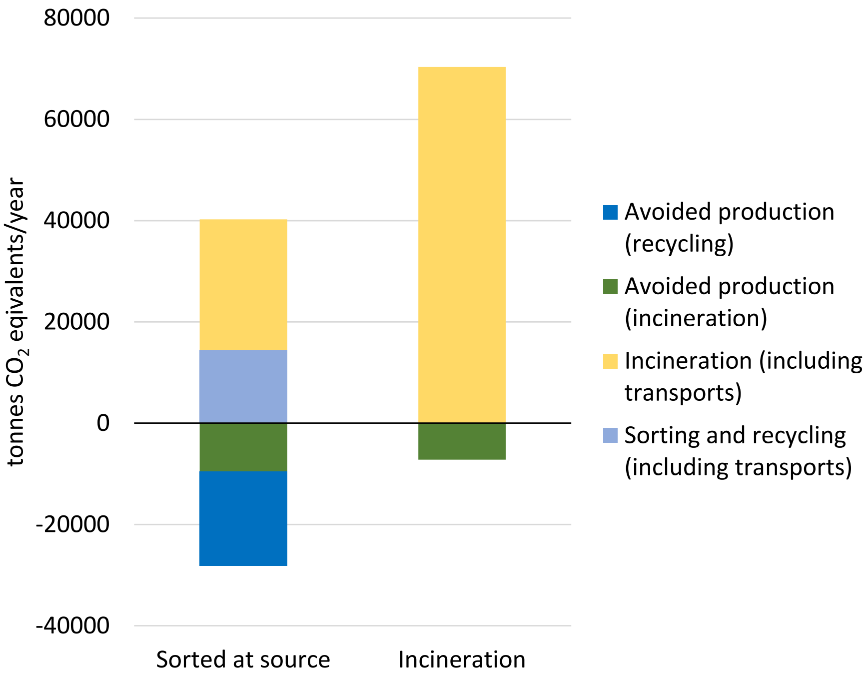


**Figure 5.** Climate change impacts per life cycle process for the system of sorted at source for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic waste that is packed in bales and ready to be collected at the local municipality collection point for further transport to sorting and recycling.

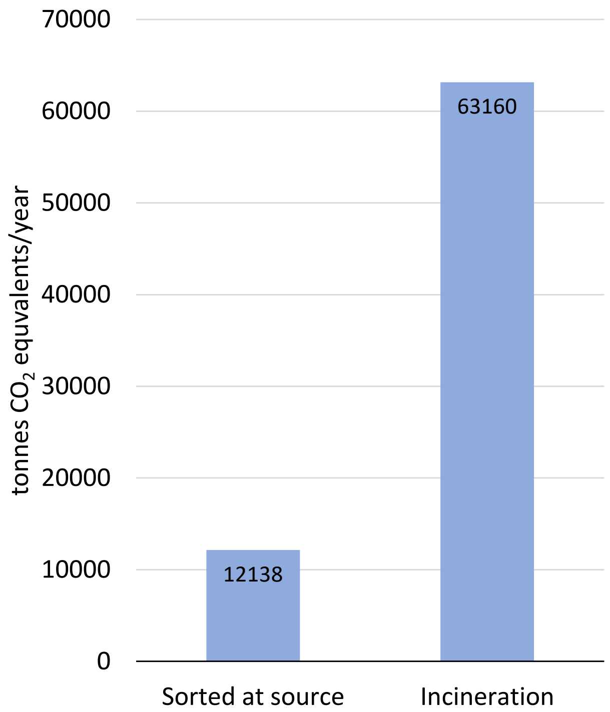


**Figure 6.** Net climate change impacts for the for the system of sorted at source for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amounts of household plastic waste that is packed in bales and ready to be collected at the local municipality collection point for further transport to sorting and recycling.

The results in Figure 6 shows that if household plastic waste becomes sorted at source and further treated, the climate change impacts are reduced by approximately 51 000 tonnes $CO_2$ equivalents per year compared with incineration.

**Table 5.** Detailed results for climate change impacts for the system of sorted at source for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic in household plastic waste that is packed in bales and ready to be collected at the local municipality collection point for further transport to sorting and recycling.

| Climate change impact [tonnes $CO_2$-eq per functional unit] | | |
|---|---|---|
| Process contribution | Sorted at source | Incineration |
| Sorting and recycling (including transports) | 14 474 | - |
| Incineration (including transports) | 25 773 | 70 341 |
| Avoided production (incineration) | -9 506 | -7 181 |
| Avoided production (recycling) | -18 603 | - |
| **Net result** | **12 138** | **63 160** |

The net results for fossil resource scarcity shows, in line with the climate change results, that sorting of plastic is preferable compared to incineration (Table 6). However, the net results for fine particulate matter formation are lower for plastic treatment via incineration compared to treatment via sorted at source. The reason for this is that the avoided production processes applied in the systems are different. Fine particulate matter formation is avoided to a higher degree when plastic is incinerated and substitutes Norwegian district heat generation, including e.g. the generation of heat from bioenergy. While fine particulate matter formation is avoided to a relatively lower degree when plastic is recycled and substitutes e.g. European electricity generation in the system for sorted at source. In terms of freshwater eutrophication, sorting at source results in net positive impacts while the impacts are net negative for incineration. This is due to the use of electricity at the German sorting and recycling plants and German electricity mix's relatively high impact on eutrophication, which is caused by mining of lignite.

**Table 6.** Net results for climate change, freshwater eutrophication, fossil resource scarcity and fine particulate matter formation for the system of sorted at source for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste. The functional unit is the annual amount of plastic in household plastic waste that is packed in bales and ready to be collected at the local municipality collection point for further transport to sorting and recycling.

| Net results per functional unit | | |
|---|---|---|
| Impact assessment category | Sorted at source | Incineration |
| Climate change [tonnes $CO_2$ eq] | 12 138 | 63 160 |
| Freshwater eutrophication [kg P eq] | 5.0 | 6.8 |
| Fossil resource scarcity [kg oil eq] | -13 568 | -1 690 |
| Fine particulate matter formation [kg PM2.5 eq] | -22 | -28 |

### 4.2.2 Results per kg

The results in Figure 7 show that for each kg sorted in the households the climate change impact is in average reduced by 2.0 kg $CO_2$ equivalents.

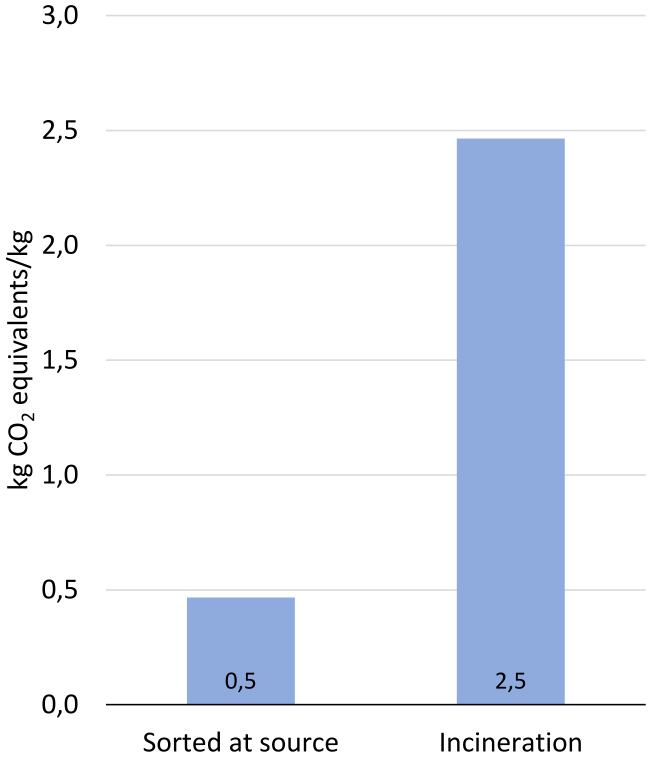


**Figure 7.** Net climate change impacts for the for the system of sorted at source for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per kg plastic in household plastic waste that is packed in bales and ready to be collected at the local municipality collection point for further transport to sorting and recycling.

## 4.3 Sorting at ROAF versus incineration

In this chapter, the results for the amounts of plastic sorted at ROAF are presented for the annual amount of plastic waste collected and treated.

### 4.3.1 Results per year

The resulting climate change impacts per life cycle process for the amount of plastic waste sorted for material recycling in ROAF waste sorting facility in 2020 (approximately 3 400 tonnes) are shown in Figure 8. Resulting values per process are also provided in Table 7.

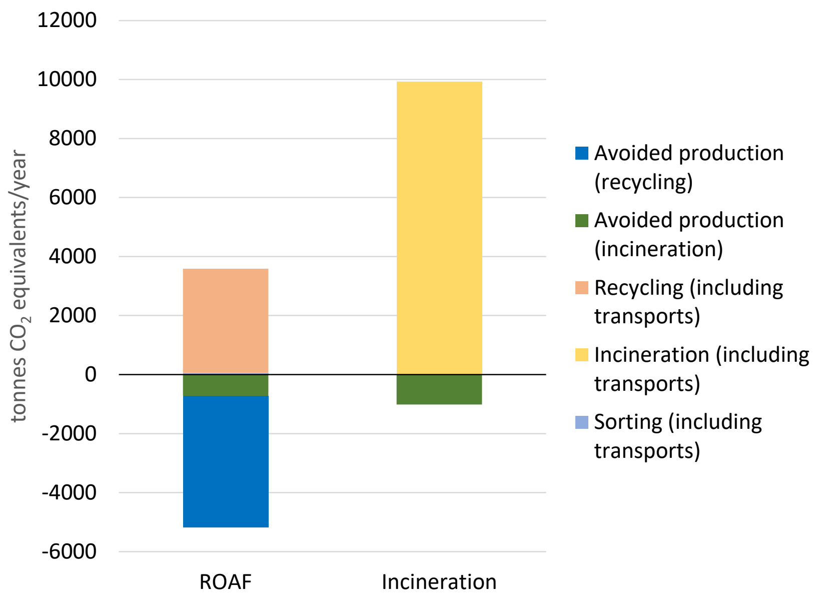


**Figure 8.** Climate change impacts per life cycle process for the ROAF system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic sorted out from the ROAF sorting facility.

For the ROAF system, the main contributors to the climate change impact are transport to recycling and energy use and incineraton of losses in the recycling process. For the incineration system, the main contributor is the emission of $CO_2$ from incineration of plastic waste. The resulting climate change impacts in terms of net results are shown in Figure 9.

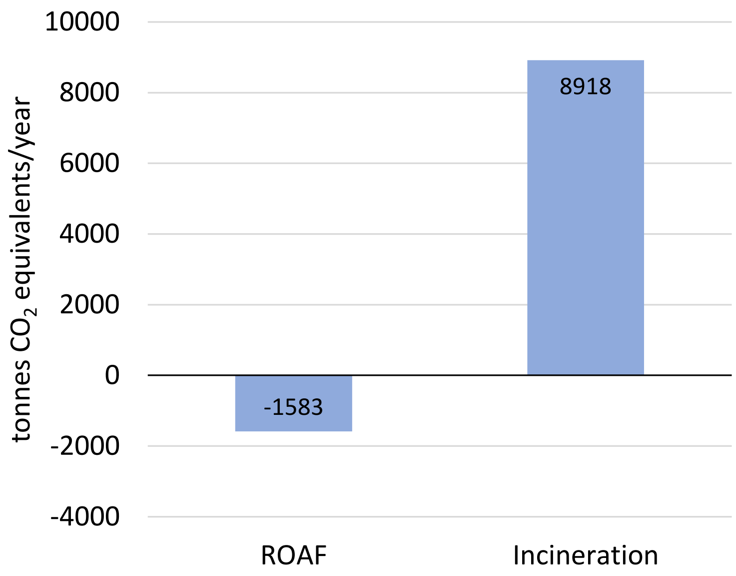


**Figure 9.** Net climate change impacts for the ROAF system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic sorted out from the ROAF sorting facility.

Figure 9 shows that the annual amount of plastic waste that becomes separated and treated in the ROAF sorting facility contribute to a reduction in climate change impact of approximately 10 500 tonnes $CO_2$ equivalents, compared to if the waste was not sorted but instead sent to incineration with energy recovery together with the residual waste.

**Table 7.** Detailed results for climate change impacts for the ROAF system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic waste sorted out from the ROAF sorting facility.

| Climate change impact [tonnes $CO_2$-eq per functional unit] | | |
|---|---|---|
| Process contribution | ROAF | Incineration |
| Sorting (including transports) | 50 | 0 |
| Incineration (including transports) | 0 | 9 933 |
| Recycling (including transports) | 3 534 | - |
| Avoided production (incineration) | -723 | -1 015 |
| Avoided production (recycling) | -4 445 | 0 |
| Net result | **-1 583** | **8 918** |

The net results for fossil resource scarcity shows, in line with the climate change results, that sorting of plastic at ROAF is preferable compared to incineration (Table 8). However, the net results for freshwater eutrophication and fine particulate matter formation are lower for treatment via incineration compared to treatment at ROAF. In terms of freshwater eutrophication, the sorting at ROAF is associated with a net positive impact. The recycling of plastics, sorted out at ROAF, and further recycled in Germany is associated with the mining of lignite (later used in the German electricity generation), which contributes to this impact. Incineration of plastics, on the other hand, is associated with a net negative impact due to avoided Norwegian district heat production in turn contributing to freshwater eutrophication. The reason why fine particulate matter formation impacts are lower for treatment via incineration compared to treatment at ROAF is due to the larger share of avoided Norwegian district heat generation in the system for incineration compared to the system for sorting at ROAF.

**Table 8.** Net results for climate change, freshwater eutrophication, fossil resource scarcity and fine particulate matter formation for the ROAF system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste. The functional unit is the annual amount of plastic sorted out from the ROAF sorting facility.

| Net results per functional unit | | |
|---|---|---|
| Process contribution | ROAF | Incineration |
| Climate change [tonnes $CO_2$-eq] | -1 583 | 8 918 |
| Freshwater eutrophication [kg P eq] | 0.5 | 0.7 |
| Fossil resource scarcity [kg oil eq] | -2 862 | -275 |
| Fine particulate matter formation [kg PM2.5 eq] | -2.7 | -4.1 |

## 4.4 Sorting at IVAR versus incineration

In this chapter, the results for the amounts of plastic sorted at IVAR are presented for the annual amount of plastic waste collected and treated.

### 4.4.1 Results per year

The resulting climate change impacts per life cycle process for the amount of plastic waste sorted for material recycling by IVAR waste sorting facility in 2020 (approximately 3 400 tonnes, excluding the amounts of mixed plastics sent to incineration with energy recovery) are shown in Figure 10. The resulting climate change impacts in terms of net results are shown in Figure 11. Resulting values per process are also provided in Table 9.

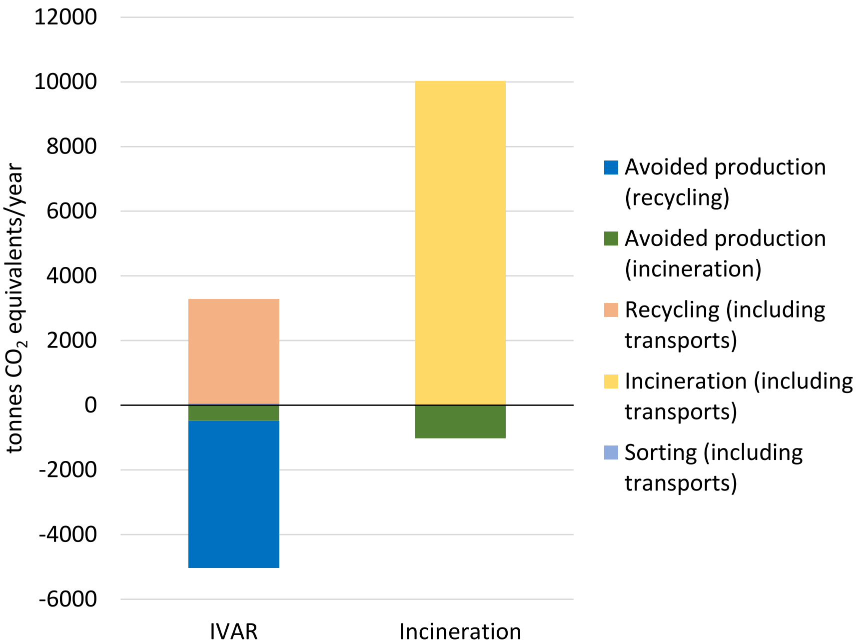


**Figure 10.** Climate change impacts per life cycle process for the IVAR system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic sorted out from the IVAR sorting facility.

The main contributors to the climate change impact for the IVAR system are transport to recycling and energy use and incineration of losses in the recycling process. In the incineration system, the main contributor is the emission of $CO_2$ from incineration of plastic waste. The resulting climate change impacts in terms of net results are shown in Figure 11.

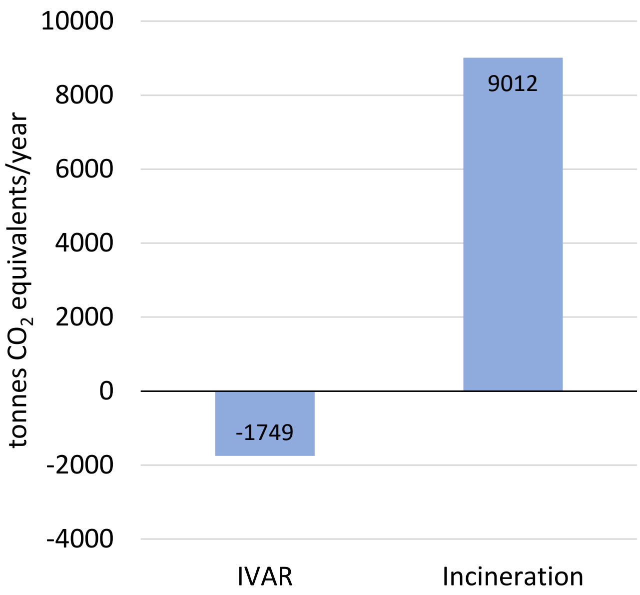


**Figure 11.** Net climate change impacts for the IVAR system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic waste sorted out from the IVAR sorting facility.

Figure 11 shows that the annual amounts of plastic waste sorted and treated in the IVAR system for sorting and further recycling result in a reduction of climate change impacts of 10 800 tonnes $CO_2$ equivalents compared to if the waste is not sorted and is sent to incineration with energy recovery together with residual waste.

**Table 9.** Detailed results for climate change impacts for the IVAR system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste per functional unit, i.e. the annual amount of plastic sorted out from the IVAR sorting facility.

| Climate change impact [tonnes $CO_2$-eq per functional unit] | | |
|---|---|---|
| Process contribution | IVAR | Incineration |
| Sorting (including transports) | 50 | - |
| Incineration (including transports) | 0 | 10 032 |
| Recycling (including transports) | 3 223 | - |
| Avoided production (incineration) | -482 | -1 020 |
| Avoided production (recycling) | -4 541 | - |
| **Net result** | **-1 749** | **9 012** |

The net results for fossil resource scarcity shows, in line with the climate change results, that sorting of plastic at IVAR is preferable compared to incineration (Table 10). However, the net results for freshwater eutrophication and fine particulate matter formation are lower for plastic treatment via incineration compared to treatment at IVAR. In terms of freshwater eutrophication, the sorting at IVAR is associated with a net positive impact. The recycling of plastics, sorted out at IVAR, is associated with the mining of lignite (later used in e.g. German and Czech Republic electricity generation), which contributes to this impact. Incineration of plastics, on the other hand, is associated with a net negative impact by the avoidance of contributions to freshwater eutrophication from substituting Norwegian district heat production. The reason why fine particulate matter formation impacts are lower for treatment via incineration compared to treatment at IVAR is due to the larger share of avoided Norwegian district heat generation compared to the IVAR system, where less plastics become incinerated and thus less district heat generation becomes substituted.

**Table 10.** Net results for climate change, freshwater eutrophication, fossil resource scarcity and fine particulate matter formation for the IVAR system for sorting and recycling of household plastic waste and for the system for incineration of plastic in household waste. The functional unit is the annual amount of plastic sorted out from the IVAR sorting facility.

| Net results per functional unit | | |
|---|---|---|
| Process contribution | IVAR | Incineration |
| Climate change [tonnes $CO_2$-eq] | -1 749 | 9 012 |
| Freshwater eutrophication [kg P eq] | 1.6 | 0.7 |
| Fossil resource scarcity [kg oil eq] | -2 847 | -284 |
| Fine particulate matter formation [kg PM2.5 eq] | -2.9 | -4.2 |

# 5 Concluding discussion

The results from this study show that sorting and recycling of household plastic waste is preferable to incineration in terms of climate change impacts and fossil resource scarcity. The results for freshwater eutrophication and fine particulate matter formation show that incineration has lower impacts compared to sorting and further recycling of plastics (see Section 4). The reason for this is that the avoided impacts due to energy recovery in the system for incineration are relatively higher compared to the avoided impacts from energy recovery and recycling of plastics in the systems for sorting and recycling of plastics. Thus, the selected processes to model the avoided production from energy recovery and from recycling of plastics influence the results for these impact categories. Furthermore, resources needed for recycling processes might be associated with certain impacts, such as the freshwater eutrophication associated with the electricity mix used for recycling of plastics sorted, to a higher degree compared to if the plastics are incinerated. This highlights the need to improve processes, to use less resources, or to select other type of resources, e.g. electricity generated from other sources.

Collection of representative data for the systems assessed in this study is an important part in describing these systems. Data on the efficiency of the sorting facilities in Germany influences the results to a high degree and it is important to get up-to-date, comparable, and realistic data for these parameters.

Further developments of this study could be to conduct a LCA study comparing the system for sorting at source with sorting of residual waste, containing plastic waste, at a sorting facility. In the sorted at source system, the consumer sorts out household waste that then become collected and sent to further sorting and recycling. In the other system, all waste is disposed together and then sent to the sorting facility, such as ROAF or IVAR. It would be interesting to compare these systems and in addition address aspects of consumer behaviour and how well consumers need to sort the household plastic waste for the sorted at source system to be environmentally preferable over a system where everything is disposed together and then sorted. In such a study, it would be important to have comparable data for sorting but also for recycling of plastics, which typically have been modelled with generic data in this study due to limited data. Specific data on both sorting and recycling, as well as on the type of plastics and the quality of the plastics that becomes sorted out would be important to acquire for such a study.

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# Appendix 1

**Table 11.** Summary of the data applied in the life cycle inventory calculations related to the systems sorted at source versus incineration. Note that values are presented with two significant figures. HDPE=high-density polyethylene, LDPE=low-density polyethylene, PET=polyethylene terephthalate, PP=polypropylene, LHV=lower heating value, GPN=Green Dot Norway.

| Parameter [unit] | Value | Source | Comment |
|---|---|---|---|
| **Household plastic waste sorted at source** | | | |
| **Transport of collected household plastic waste** (from consumer to sorting) | | | |
| Average distance transported by waste collection vehicle [km] | 19 | Raadal et al. (2009) | Average distance for residual and plastic packaging waste transported by waste collection vehicle based on benchmarking data for Norway in 2006. Transport type: Municipal waste collection service by 21 metric ton lorry (GLO)\| market for \| Cut-off, U |
| Average distance between waste collection and incineration plant | 52 + 14 | Raadal et al. (2009) | Average transport distance after waste collection vehicle to incineration plant based on benchmarking data for Norway in 2006. |
| Average distance between waste collection and baling [km] | 50 | Raadal et al. (2009) | Average transport distance for plastic packaging waste from consumer to local collection point based on benchmarking data for Norway in 2006. |
| Transport (Norway to Beckum, Kedenburg) [tkm/ton plastic waste] | 141 | Plastretur (2021) | Truck, Norway, data from 2020 |
| | 1 287 | | Train, data from 2020 |
| | 144 | | Truck, Germany, data from 2020 |
| Transport (Norway to Gescher, EING) [tkm/ton plastic waste] | 66 | | Truck, Norway, data from 2020 |
| | 1 156 | | Train, data from 2020 |
| | 12 | | Truck, Germany, data from 2020 |
| Transport (Norway to Premnitz, Vogt) [tkm/ton plastic waste] | 90 | | Truck, Norway, data from 2020 |
| | 976 | | Train, data from 2020 |
| | 123 | | Truck, Germany, data from 2020 |
| Truck | Ecoinvent process | - | Transport, freight, lorry 16-32 metric ton, euro6 (RER)\| market for transport, freight, lorry 16 - 32 metric ton, EURO6 \| Cut-off, U |
| Train | Ecoinvent process | - | Transport, freight train (RER)\| market group for transport, freight train \| Cut-off, U |
| Household plastic waste sent to Kedenburg [ton/year] | 11 000 | Plastretur (2021) | In 2020. Thus, about 37%, 22% and 41% of the household plastic waste sorted at source in Norway were sent to Kedenburg, EING and Vogt, respectively, in that year. Based on the composition of the household plastic waste (about 86% is plastics), about 9 500 ton, 5 500 ton and 10 000 ton plastics, in household plastic waste, was sent to Kedenburg, EING and Vogt in 2020, respectively. |
| Household plastic waste sent to EING [ton/year] | 6 400 | | |
| Household plastic waste sent to Vogt [ton/year] | 12 000 | | |
| Composition of household plastic waste (film, LDPE) [weight-%] | 40 | Plastretur (2021) | In 2019. Note that only the plastic fractions were considered in this study |
| Composition of household plastic waste - mixed plastics [weight-%] | 20 | | |

| | | | |
|---|---|---|---|
| Composition of household plastic waste (PP) [weight-%] | 9 | | |
| Composition of household plastic waste (PET trays) [weight-%] | 8 | | |
| Composition of household plastic waste (HDPE) [weight-%] | 6 | | |
| Composition of household plastic waste (PET bottles) [weight-%] | 2 | | |
| Composition of household plastic waste (PS) [weight-%] | 1 | | |
| Composition of household plastic waste - waste (e.g. food waste, paper etc.) [weight-%] | 13 | | |
| Composition of household plastic waste – metal [weight-%] | 1 | | |
| **Sorting and material recycling** (at Vogt Plastics) | | | |
| The data applied for the sorting and material recycling of plastics at Vogt cannot be presented here due to confidentiality. | | | |
| Recycling efficiency, Film (LDPE) [weight-%] | 76% | Eriksen et al. (2018) | Based on table S3 in the supplementary information and table 1 in the article. Average values are used. LDPE is assumed to be recycled to the PO mix fraction only. Remaining share is incinerated. Efficiency factor does not include extrusion losses. |
| Recycling efficiency, PP [weight-%] | 81% | | Based on table S3 in the supplementary information and table 1 in the article. Average values are used. PP is assumed to be recycled to the PP/PE fraction only. Remaining share is incinerated. Efficiency factor does not include extrusion losses. |
| Recycling efficiency, HDPE [weight-%] | 83% | | Based on table S3 in the supplementary information and table 1 in the article. Average values are used. PE is assumed to be recycled to the PP/PE fraction only. Remaining share is incinerated. Efficiency factor does not include extrusion losses. |
| Recycling efficiency, Other plastics [weight-%] | 39% | | Based on table S3 in the supplementary information and table 1 in the article. Average values for "Other" are used. Other plastics are assumed to be recycled to the PO mix fraction only. Remaining share is incinerated. Efficiency factor does not include extrusion losses. |
| Recycling efficiency, PS plastics [weight-%] | 65% + 20% | | Based on table S3 in the supplementary information and table 1 in the article. Average values for PS are used. PS is assumed to be recycled to the PS fraction (65%) and PO mix fraction (20%). Remaining share is incinerated. Efficiency factor does not include extrusion losses. |
| Recycling efficiency, PET [weight-%] | 0% | Vogt (2021) | PET is not sorted / recycled at the Premnitz plant. |

| | | | |
|---|---|---|---|
| **Sorting and material recycling** (at EING) | | | |
| Process used as proxy for sorting and recycling at EING | Ecoinvent process | | Since no data was provided from EING on e.g. electricity use, and since LDPE constitutes a larger share of the plastic bales, this process was applied as a proxy for the process at EING: The dataset for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U, was applied but corrected using data from COWI (2019) to represent average energy use in LDPE recycling, specifically. The process was also modified for the electricity mix, Germany, and corrected for the specific yield at EING. |
| Yield of LDPE, PP, HDPE fractions [weight-%] | 87.5% | Ahaus (2021), EING (2021) | Only LDPE, HDPE and PP in household plastic waste was recycled into agglomerates at EING. Losses at the agglomeration process are stated to be 12.5% and hence, applied on the LDPE, PP and HDPE fraction. Other plastic types in the household plastic waste, i.e. PET, PS and mixed plastics, was assumed to become incinerated together with losses of LDPE, HDPE and PP at EING. |
| **Sorting** (at Kedenburg) | | | |
| Electricity use [kWh/ton input to sorting] | 44 | Glattowski (2021) | In 2020. |
| Diesel use [liter/ ton input to sorting] | 1 | | In 2020. |
| Sorting losses [weight-%] | 5-10 | | In 2020. Average over all sorted fractions. Based on this, a loss at 7.5% was assumed for all plastic fractions in the calculations |
| Energy content, diesel [MJ/liter] | 38.6 | | |
| **Transport of sorted plastics at Kedenburg to material recycling** (in Germany) | | | |
| Share of sorted Norwegian household plastics that become recycled in Germany [%] | 100 | Assumption based on Plastretur | In 2020, 98% of the sorted plastics at Kedenburg, EING and Vogt was recycled in Germany while the remaining 2% become recycled in Austria, Bulgaria and in the Netherlands. Based on this, it was assumed that 100% of the plastics become recycled in Germany in the calculations |
| Distance (average) from sorting in Kedenburg to recycling in Germany [km] | 500 | Assumption by the authors | |
| Truck | Ecoinvent process | | Type of transport assumed to be truck: Transport, freight, lorry 16-32 metric ton, euro6 (RER)\| market for transport, freight, lorry 16-32 metric ton, EURO6 \| Cut-off, U |
| **Material recycling** (of plastic fractions sorted out from Kedenburg) | | | |
| Process for HDPE recycling | Ecoinvent process | | Ecoinvent processes but modify for the electricity mix, Germany.<br>Ecoinvent process: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U |

| | | | |
|---|---|---|---|
| Process for LDPE recycling | Ecoinvent process | | A dataset for recycled LDPE was unavailable in Ecoinvent. The dataset for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U, was applied but corrected using data from COWI (2019) to represent average efficiency and energy use in LDPE recycling, specifically. Modified this process for the electricity mix, Germany. |
| Process for PET recycling | Ecoinvent process | | Ecoinvent processes but modify for the electricity mix, Germany.<br>Polyethylene terephthalate, granulate, amorphous, recycled (Europe without Switzerland)\| polyethylene terephthalate production, granulate, amorphous, recycled \| Cut-off, U |
| Process for PP recycling | Ecoinvent process | | A process for PP recycling were unavailable in Ecoinvent. Instead, the Ecoinvent process for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U, was applied as a proxy for PP recycling, but modified for yield in PP recycling at 85% based on Syversen et al. (2018) and also modified for the electricity mix, Germany. |
| **Material recycling at EING or elsewhere (avoided production)** | | | |
| LDPE, HDPE and PP agglomerate production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Wood pellet, measured as dry mass (RER)\| wood pellet production \| Cut-off, U |
| HDPE production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene, high density, granulate (RER)\| production \| Cut-off, U |
| LDPE production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene, low density, granulate (RER)\| production \| Cut-off, U |
| PP production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polypropylene, granulate (RER)\| production \| Cut-off, U |
| PS production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polystyrene, general purpose (RER)\| production \| Cut-off, U |
| PET production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene terephthalate, granulate, amorphous (RER)\| production \| Cut-off, U |
| Substitution factor for agglomerate and PO granulate [-] | 0.5 | Assumption by the authors | Reasoning described in chapter 3.2.3. Agglomerate and PO mix are used in similar products, hence this substitution factor is also used for the PO granulate produced by Vogt. |
| Substitution factor, HDPE [-] | 0.9 | Zampori and Pant (2019) | Values represent the difference in quality of recycled materials compared to virgin materials. The value for PET is for mechanical PET recycling. |
| Substitution factor, LDPE [-] | 0.75 | | |
| Substitution factor, PP [-] | 0.9 | | |
| Substitution factor, PET [-] | 0.9 | | |
| Substitution factor, PS [-] | 0.9 | Assumption by the authors | |
| **Incineration of plastic residues at Vogt, EING, Kedenburg** | | | |
| Incineration process for HDPE and LDPE [-] | Ecoinvent process | Assumption by authors | Process for incineration of HDPE and LDPE. |

| | | | |
|---|---|---|---|
| | | | Ecoinvent process: Waste polyethylene (RoW)\| treatment of waste polyethylene, municipal incineration \| Cut-off, U |
| Incineration process for PET [-] | Ecoinvent process | Assumption by authors | Process for incineration of PET. Ecoinvent process: Waste polyethylene terephthalate (CH)\| treatment of waste polyethylene terephthalate, municipal incineration \| Cut-off, U |
| Incineration process for PP [-] | Ecoinvent process | Assumption by authors | Process for incineration of PP. Ecoinvent process: Waste polypropylene (CH)\| treatment of, municipal incineration \| Cut-off, U |
| Incineration process for PS [-] | Ecoinvent process | Assumption by authors | Waste polystyrene (CH)\| treatment of, municipal incineration \| Cut-off, U |
| Incineration process for mixed plastics [-] | Ecoinvent process | Assumption by authors | Waste plastic, mixture (CH)\| treatment of, municipal incineration \| Cut-off, U |
| **Incineration of plastic residues at Vogt, EING, Kedenburg (avoided production)** | | | |
| LHV (PET) [MJ/kg] | 23.8 | Tsiamis and Castaldi (2016) | |
| LHV (PP) [MJ/kg] | 41 | | |
| LHV (HDPE) [MJ/kg] | 37.1 | | |
| LHV (LDPE) [MJ/kg] | 40.8 | | |
| LHV (PS) [MJ/kg] | 38.6 | | |
| LHV (Mixed plastics) [MJ/kg] | 35.7 | | |
| Efficiency of incineration process in Europe | 0.3 | Swedenergy (2021) | |
| Share of incinerated plastics that substitutes European electricity generation (rest substitutes European heat generation) [%] | 52 | Eurostat (2021a), Eurostat (2021b) | Municipal and industrial waste is the fuel for 52% electricity and 48% heat (reference year 2018). Ecoinvent processes: Electricity, medium voltage (RER)\| market group for \| Cut-off, U Heat, district or industrial, other than natural gas (RER)\| market group for \| Cut-off, U |
| **Household plastic waste in residual waste to incineration** | | | |
| **Transport of household plastic waste in residual waste** (from consumer to incineration plant) | | | |
| Distance (average) [km] | 19 | Raadal et al. (2009) | Average transport distance for plastic packaging waste from consumer to local collection point based on benchmarking data for Norway in 2006. Transport type: Municipal waste collection service by 21 metric ton lorry (GLO)\| market for \| Cut-off, U Assumed to be similar to the distance between consumers and ROAF. |
| **Incineration of household plastic waste in residual waste** | | | |
| This was modelled in a similar manner as the incineration of plastic residues at Vogt, EING, Kedenburg. The same values for LHVs, efficiency, degree of energy utilization and the share of incinerated plastics that substitutes a Norwegian district heating mix were applied. | | | |

**Table 12.** Summary of the data applied in the life cycle inventory calculations related to the system of ROAF versus incineration. Note that values are presented with two significant figures. HDPE=high-density polyethylene, LDPE=low-density polyethylene, PET=polyethylene terephthalate, PP=polypropylene, LHV=lower heating value

<table>
<tr><th>Parameter [unit]</th><th>Value</th><th>Source</th><th>Comment</th></tr>
<tr><td colspan="4">Household plastic waste sorted at ROAF</td></tr>
<tr><td colspan="4">Transport of collected household plastic waste (from consumer to ROAF)</td></tr>
<tr><td colspan="4">Specific dataset for waste collection at ROAF from NorEnviro database (2016).</td></tr>
<tr><td colspan="4">Sorting at ROAF</td></tr>
<tr><td>Electricity input [kWh/kg output]</td><td>0.189</td><td rowspan="3">Skovly (2021)</td><td>In 2019. This electricity input was allocated equally to all the output fractions, excluding the residual waste output fraction. That is, electricity use per kg output (excluding the residual waste fraction) was calculated to be 189 kWh/ton output by dividing the total electricity use per year (2 944 835 kWh) with the total output of PET, PP, PE, film, food waste, paper and metals for 2019 (about 16 000 ton).</td></tr>
<tr><td>District heating input [kWh/kg output]</td><td>0.014</td><td>In 2019. This district heating input was allocated equally to the output fractions, excluding the residual waste output fraction. That is, use of district heating per kg output (excluding the residual waste fraction) was calculated to be 14 kWh/ton output by dividing the total district heating input per year (221 510 kWh) with the total output of PET, PP, PE, film, food waste, paper and metals for 2019 (about 16 000 ton).</td></tr>
<tr><td>Diesel use [liter/kg output]</td><td>0.001</td><td>The total diesel use for ROAF was assumed to be 8 212 liter/year based on data on diesel consumption for digger from 2016 (0.13 liter/ ton residual waste, Callewaert (2017)), which was assumed to also be valid for 2019. The diesel use per kg output (excluding the residual waste fraction) was calculated to be 1 liter/ton output by dividing the total diesel use per year with the total output of PET, PP, PE, film, food waste, paper and metals for 2019 (about 16 000 ton). Ecoinvent process: Diesel, burned in building machine (GLO)| market for | Cut-off, U</td></tr>
<tr><td>Energy content, diesel [MJ/liter]</td><td>38.6</td><td></td><td></td></tr>
<tr><td>Output PET [ton/year]</td><td>130</td><td rowspan="8">Skovly (2021)</td><td rowspan="8">In 2019. The total amount of residual waste input to ROAF was 63 000 ton in 2019.<br>The outputs sorted out from ROAF include, PET, PP, PE, film (LDPE), paper, metals and residual waste. Note that the residual waste contains fractions of the other outputs as all do not become sorted out. Only considering the amount of plastic sorted out from ROAF (in total 3 400 ton in 2019), about 3.9% were PET, 14% were PP, 8.5% were HDPE and the remaining 74% were film (LDPE). Note that the percentages presented here do not sum up to 100% since the data are rounded.</td></tr>
<tr><td>Output PP [ton/year]</td><td>480</td></tr>
<tr><td>Output HDPE [ton/year]</td><td>290</td></tr>
<tr><td>Output Film (LDPE) [ton/year]</td><td>2 500</td></tr>
<tr><td>Output Food waste [ton/year]</td><td>11 000</td></tr>
<tr><td>Output Paper [ton/year]</td><td>680</td></tr>
<tr><td>Output Metals [ton/year]</td><td>920</td></tr>
<tr><td>Output Residual waste (sent to incineration) [ton/year]</td><td>47 000</td></tr>
</table>

<table>
<tr><td colspan="4">Transport of sorted plastics at ROAF (from ROAF to further recycling)</td></tr>
<tr><td>Share of sorted LDPE sent to Folldal, Norway [%]</td><td>1.5</td><td rowspan="8">Plastretur (2021)</td><td rowspan="8">In 2020. Shares of plastic fractions sorted out at ROAF and sent to recycling facilities in various countries.</td></tr>
<tr><td>Share of sorted LDPE sent to Schwerin, Germany [%]</td><td>60</td></tr>
<tr><td>Share of sorted LDPE sent to Vilnius, Lithuania [%]</td><td>32</td></tr>
<tr><td>Share of sorted LDPE sent to Skaidiškės, Lithuania [%]</td><td>6</td></tr>
<tr><td>Share of sorted HDPE sent to Bernburg, Germany [%]</td><td>51</td></tr>
<tr><td>Share of sorted HDPE sent to Skaidiškės, Lithuania [%]</td><td>49</td></tr>
<tr><td>Share of sorted PET sent to Spijk, Netherlands [%]</td><td>100</td></tr>
<tr><td>Share of sorted PP sent to Skaidiškės, Lithuania [%]</td><td>100</td></tr>
<tr><td>Distance (average) [km]</td><td>300</td><td rowspan="6">Google maps</td><td>ROAF (Bølerveien 93, 2020 Skedsmokorset), Norway to Folldal, Norway.</td></tr>
<tr><td>Distance (average) [km]</td><td>970</td><td>ROAF (Bølerveien 93, 2020 Skedsmokorset), Norway to Schwerin, Germany.</td></tr>
<tr><td>Distance (average) [km]</td><td>1 300</td><td>ROAF (Bølerveien 93, 2020 Skedsmokorset), Norway to Bernburg, Germany.</td></tr>
<tr><td>Distance (average) [km]</td><td>2 400</td><td>ROAF (Bølerveien 93, 2020 Skedsmokorset), Norway to Vilnius, Lithuania.</td></tr>
<tr><td>Distance (average) [km]</td><td>2 400</td><td>ROAF (Bølerveien 93, 2020 Skedsmokorset), Norway to Skaidiškės, Lithuania.</td></tr>
<tr><td>Distance (average) [km]</td><td>1 400</td><td>ROAF (Bølerveien 93, 2020 Skedsmokorset), Norway to Spijk, Netherlands.</td></tr>
<tr><td>Truck</td><td>Ecoinvent process</td><td></td><td>Type of transport assumed to be truck: Transport, freight, lorry 16-32 metric ton, euro6 (RER)| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U</td></tr>
<tr><td colspan="4">Recycling of plastics sorted out at ROAF</td></tr>
<tr><td>Process for HDPE recycling</td><td>Ecoinvent process</td><td></td><td>Ecoinvent processes but modify for the electricity mix, Germany or Lithuania.<br>Ecoinvent process: Polyethylene, high density, granulate, recycled (Europe without Switzerland)| polyethylene production, high density, granulate, recycled | Cut-off, U</td></tr>
<tr><td>Process for LDPE recycling</td><td>Ecoinvent process</td><td></td><td>A dataset for recycled LDPE was unavailable in Ecoinvent. The dataset for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)| polyethylene production, high density, granulate, recycled | Cut-off, U, was applied but corrected using data from COWI (2019) to represent average efficiency and energy use in LDPE recycling, specifically. Electricity mix modified to Germany, Lithuania or Norway.</td></tr>
</table>

| | | | |
|---|---|---|---|
| Process for PET recycling | Ecoinvent process | | Ecoinvent processes but modify for the electricity mix, Germany or Lithuania.<br>Polyethylene terephthalate, granulate, amorphous, recycled (Europe without Switzerland)\| polyethylene terephthalate production, granulate, amorphous, recycled \| Cut-off, U |
| Process for PP recycling | Ecoinvent process | | A process for PP recycling were unavailable in Ecoinvent. Instead, the Ecoinvent process for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U, was applied as a proxy for PP recycling, but modified for yield in PP recycling at 85% based on Syversen et al. (2018) and also modified for the electricity mix, Lithuania. |
| **Recycling of plastics sorted out at ROAF (avoided production)** | | | |
| HDPE production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene, high density, granulate (RER)\| production \| Cut-off, U |
| LDPE production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene, low density, granulate (RER)\| production \| Cut-off, U |
| PET production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene terephthalate, granulate, amorphous (RER)\| production \| Cut-off, U |
| PP production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polypropylene, granulate (RER)\| production \| Cut-off, U |
| Substitution factor, HDPE [-] | 0.9 | Zampori and Pant (2019) | Values represent the difference in quality of recycled materials compared to virgin materials. The value for PET is for mechanical recycling |
| Substitution factor, LDPE [-] | 0.75 | | |
| Substitution factor, PET [-] | 0.9 | | |
| Substitution factor, PP [-] | 0.9 | | |
| **Transport of residual waste sorted out at ROAF** (from ROAF to incineration plant Klemetsrud) | | | |
| Distance [km] | 30 | Google maps | Approximate distance between ROAF and the incineration plant Klemetsrud. Transport, freight, lorry 16-32 metric ton, euro6 (RER)\| market for transport, freight, lorry 16-32 metric ton, EURO6 \| Cut-off, U |
| **Incineration of plastics in residual waste sorted out at ROAF** | | | |
| Incineration process for HDPE and LDPE [-] | Ecoinvent process | Assumption by authors | Process for incineration of HDPE and LDPE.<br>Ecoinvent process: Waste polyethylene (RoW)\| treatment of waste polyethylene, municipal incineration \| Cut-off, U |
| Incineration process for PET [-] | Ecoinvent process | Assumption by authors | Process for incineration of PET.<br>Ecoinvent process: Waste polyethylene terephthalate (CH)\| treatment of waste polyethylene terephthalate, municipal incineration \| Cut-off, U |
| Incineration process for PP [-] | Ecoinvent process | Assumption by authors | Process for incineration of PP.<br>Ecoinvent process: Waste polypropylene (CH)\| treatment of, municipal incineration \| Cut-off, U |
| **Incineration of plastics in residual waste sorted out at ROAF (avoided production)** | | | |
| LHV (PET) [MJ/kg] | 23.8 | Tsiamis and Castaldi (2016) | |
| LHV (PP) [MJ/kg] | 41 | | |
| LHV (HDPE) [MJ/kg] | 37.1 | | |
| LHV (LDPE) [MJ/kg] | 40.8 | | |
| Efficiency [%] | 85 | Raadal et al. (2009) | The amount of energy generated compared to the energy content of the fuel. |
| Degree of energy utilization [%] | 75 | | The amount of energy that becomes utilized compared to the amount energy that is generated. |

| | | | |
|---|---|---|---|
| Share of incinerated plastics that substitutes a Norwegian district heating mix [%] | 100 | | Assumption. |
| **Household plastic waste in residual waste to incineration** | | | |
| **Transport of household plastic waste in residual waste** (from consumer to incineration plant) | | | |
| Specific dataset for waste collection at ROAF from NorEnviro database (2016). | | | |
| Distance [km] | 30 | Google maps | Approximate distance between ROAF and the incineration plant Klemetsrud. Transport, freight, lorry 16-32 metric ton, euro6 (RER)\| market for transport, freight, lorry 16-32 metric ton, EURO6 \| Cut-off, U |
| **Incineration of household plastic waste in residual waste** | | | |
| This was modelled in a similar manner as the incineration of plastics in residual waste sorted out at ROAF when it comes to LHVs, efficiency, degree of energy utilization and the share of incinerated plastics that substitutes a Norwegian district heating mix. | | | |

**Table 13.** Summary of the data applied in the life cycle inventory calculations related to the system IVAR versus incineration. Note that values are presented with two significant figures. HDPE=high-density polyethylene, LDPE=low-density polyethylene, PET=polyethylene terephthalate, PP=polypropylene, PS=polystyrene, LHV=lower heating value

| Parameter [unit] | Value | Source | Comment |
|---|---|---|---|
| **Household plastic waste sorted at IVAR** | | | |
| **Transport of collected household plastic waste** (from consumer to IVAR) | | | |
| Assumed similar collection system as ROAF. Data retrieved from NorEnviro database (2016). | | | |
| **Sorting at IVAR** | | | |
| Electricity input [kWh/ton output] | 237 | Meissner (2021) | In 2020. In total, ESA Forus sorting facility used 294 877 kWh of electricity in December 2020 (corresponding to 3 538 524 kWh in a year). The operations manager estimated that 75-80% of this electricity can be allocated to the residual waste sorting facility, also sorting out plastics. The electricity input to the residual waste sorting facility was allocated equally to all the output fractions, excluding the residues (rest > 60 mm) and residues (fines < 60 mm) fractions. That is, electricity use per kg output, excluding the residues fractions, was calculated to be 237 kWh/ton output by dividing the total electricity use per year (3 538 524 kWh and assuming that 77.5% of this electricity can be associated with residual waste sorting at IVAR) with the total expected output of PET, PP, HDPE, LDPE, PS, mixed plastics, paper and metals for 2020 (about 12 000 ton). |
| Machine operation, wheel loader [ton residual waste/hour] | 55 | | The capacity of the wheel loader is 55 ton/h. The Ecoinvent process: "Machine operation, diesel, >= 74.57 kW, high load factor (GLO)\| market for \| Cut-off, U" |
| Output LDPE [ton/year] | 2355.3 | | Annual expected outputs based on a total input of residual waste at 37 405 ton in 2020. This data was furthermore based on technical investigations of what the sorting facility can obtain at normal operation and a sorting analysis in week 19, 2019 at ESA Forus. Residues (rest > 60 mm and fines < 60 mm) and mixed plastics fractions become sent to incineration. Note that currently, the output of mixed plastics become sent to incineration, but this might perhaps not be the case in the future. Thus, only considering the amount of plastic sorted out from IVAR (in total 8 700 ton in 2020), about 30% were LDPE, 4.1% were HDPE, 5.8% were PP, 0.8% were PS, 1.7% were PET (bottles) and 61% were mixed plastics. |
| Output HDPE [ton/year] | 357.5 | | |
| Output PP [ton/year] | 504.7 | | |
| Output PS [ton/year] | 73.6 | | |
| Output PET (bottles) [ton/year] | 147.2 | | |
| Output mixed plastics [ton/year] | 5303.6 | | |
| Output residues (rest > 60 mm) [ton/year] | 13 118.1 | | |
| Output residues (fines < 60 mm) [ton/year] | 12 706 | | |
| Output Metals (ferrous and non-ferrous) [ton/year] | 1 493.1 | | |
| Output mixed paper [ton/year] | 1345.9 | | |
| **Transport of sorted plastics at IVAR** (from sorting at IVAR to recycling at IVAR or further recycling elsewhere) | | | |
| Share of sorted LDPE recycled at IVAR [%] | 14 | Plastretur | In 2020. Shares of plastic fractions sorted out at IVAR and either recycled at IVAR or sent to recycling facilities in various countries. |
| Share of sorted LDPE sent to Skaidiškės, Lithuania [%] | 0.35 | Plastretur | |

| | | | |
|---|---|---|---|
| Share of sorted LDPE sent to Schwerin, Germany [%] | 32 | Plastretur | |
| Share of sorted LDPE sent to Vilnius, Lithuania [%] | 6.0 | Plastretur | |
| Share of sorted LDPE sent to Bytom, Poland [%] | 7.0 | Plastretur | |
| Share of sorted LDPE sent to Otrokovice, Czech Republic [%] | 19 | Plastretur | |
| Share of sorted LDPE sent to Skřivany, Czech Republic [%] | 7.0 | Plastretur | |
| Share of sorted LDPE sent to Varna, Bulgaria [%] | 15 | Plastretur | |
| Share of sorted HDPE recycled at IVAR [%] | 98 | Plastretur | |
| Share of sorted HDPE sent to Toruń, Poland [%] | 2 | Plastretur | |
| Share of sorted PP sent to Enschede, Netherlands [%] | 100 | Plastretur | |
| Share of sorted PS sent to Koblenz, Germany [%] | 100 | Assumption based on Meissner (2021) | According to Meissner (2021), PS becomes sent to a washing facility near Koblenz, Germany. |
| Share of sorted PET sent to Koblenz, Germany [%] | 100 | | According to Meissner (2021), PET (consisting of at least 70% transparent PET bottles and the rest being various PET-products (colored PET, PET-trays) is sent to various locations, e.g. Netherlands, Germany and/or Poland. In this study, it was assumed that all PET becomes sent to Koblenz, Germany as for PS. |
| Distance [km] | 1 800 | Google maps | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Skaidiškės, Lithuania. |
| Distance [km] | 1 400 | Google maps | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Schwerin, Germany. |
| Distance [km] | 2 900 | Vilnius, Lithuania | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Vilnius, Lithuania. |
| Distance [km] | 2 400 | Bytom, Poland | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Bytom, Poland. |
| Distance [km] | 2 400 | Otrokovice, Czech Republic | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Otrokovice, Czech Republic. |
| Distance [km] | 2 300 | Skřivany, Czech Republic | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Skřivany, Czech Republic. |
| Distance [km] | 3 900 | Varna, Bulgaria | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Varna, Bulgaria. |
| Distance [km] | 1 900 | Google maps | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Toruń, Poland. |
| Distance [km] | 1 700 | Google maps | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Enschede, the Netherlands. |

| | | | |
|---|---|---|---|
| Distance [km] | 1 400 | Google maps | IVAR (Forusbeen 198, 4313 Sandnes), Norway to Koblenz, Germany. |
| Truck | Ecoinvent process | | Type of transport assumed to be truck: Transport, freight, lorry 16-32 metric ton, euro6 (RER)\| market for transport, freight, lorry 16-32 metric ton, EURO6 \| Cut-off, U |
| **Recycling of plastics sorted out at IVAR** (recycling of LDPE, HDPE and PP at IVAR) | | | |
| Recycling yield, sorted LDPE [weight-%] | 69 | Meissner (2021) | Meissner (2021) assumes that 1 ton input of sorted LDPE (also containing some water and various residues including other plastics) gives gives 680-700 kg output of LDPE pellets. Based on this, a recycling yield at 69 weight-% was assumed. |
| Recycling yield, sorted HDPE and PP [weight-%] | 76.5 | | Meissner (2021) assumes that 1 ton input of sorted HDPE or PP (also containing some water and various residues including other plastics) gives about 750-780 kg output of HDPE or PP pellets. Based on this, a recycling yield at 76.5 weight-% was assumed. Note that no PP was recycled at IVAR in 2020 according to the data from Plastretur. |
| Process for LDPE recycling at IVAR | Ecoinvent process | | Representative data on the recycling process at IVAR was not available since the facility has not been tested over a longer period yet (Meissner, 2021). Therefore, instead, an Ecoinvent process was applied but corrected for electricity mix, Norway and the recycling yield for LDPE at IVAR was also corrected based on data from Meissner (2021). A dataset for recycled LDPE was unavailable in Ecoinvent. The dataset for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U, was applied but corrected using data from COWI (2019) to represent average efficiency and energy use in LDPE recycling, specifically. |
| Process for HDPE recycling at IVAR | Ecoinvent process | | Representative data on the recycling process at IVAR was not available since the facility has not been tested over a longer period yet (Meissner, 2021). Therefore, instead, an Ecoinvent process was applied but corrected for electricity mix, Norway and the recycling yield for HDPE at IVAR was also corrected based on data from Meissner (2021). Ecoinvent process: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U |
| **Recycling of plastics sorted out at IVAR** (recycling of LDPE, HDPE, PET, PP and PS elsewhere than at IVAR) | | | |
| Process for LDPE recycling | Ecoinvent process | | A dataset for recycled LDPE was unavailable in Ecoinvent. The dataset for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U, was applied but corrected using data from COWI (2019) to represent average efficiency and energy use in LDPE recycling, specifically. Electricity mix modified to Lithuania, Germany, Poland, Czech Republic or Bulgaria. |
| Process for HDPE recycling | Ecoinvent process | | Ecoinvent processes but modify for the electricity mix, Poland. Ecoinvent process: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U |
| Process for PET recycling | Ecoinvent process | | Ecoinvent processes but modify for the electricity mix, Germany. Polyethylene terephthalate, granulate, amorphous, recycled (Europe without Switzerland)\| polyethylene terephthalate production, granulate, amorphous, recycled \| Cut-off, U |

| | | | |
|---|---|---|---|
| Process for PP recycling | Ecoinvent process | | A process for PP recycling were unavailable in Ecoinvent. Instead, the Ecoinvent process for HDPE recycling: Polyethylene, high density, granulate, recycled (Europe without Switzerland)\| polyethylene production, high density, granulate, recycled \| Cut-off, U, was applied as a proxy for PP recycling, but modified for yield in PP recycling at 85% based on Syversen et al. (2018) and also modified for the electricity mix, the Netherlands. |
| Process for PS recycling | Ecoinvent process | | An Ecoinvent process was used as proxy for the PS recycling, the process was modified for the electricity mix, Germany. Ecoinvent process: Polystyrene foam slab (CH)\| production, 100% recycled \| Cut-off, U |
| **Recycling of plastics sorted out at IVAR (avoided production)** | | | |
| HDPE production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene, high density, granulate (RER)\| production \| Cut-off, U |
| LDPE production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene, low density, granulate (RER)\| production \| Cut-off, U |
| PP production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polypropylene, granulate (RER)\| production \| Cut-off, U |
| PS production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polystyrene, general purpose (RER)\| production \| Cut-off, U |
| PET production (avoided) [-] | Ecoinvent process | | Ecoinvent process: Polyethylene terephthalate, granulate, amorphous (RER)\| production \| Cut-off, U |
| Substitution factor, HDPE [-] | 0.9 | Zampori and Pant (2019) | Values represent the difference in quality of recycled materials compared to virgin materials. The value for PET is for mechanical PET recycling. |
| Substitution factor, LDPE [-] | 0.75 | | |
| Substitution factor, PP [-] | 0.9 | | |
| Substitution factor, PET [-] | 0.9 | | |
| Substitution factor, PS [-] | 0.9 | Assumption by the authors | |
| **Transport of residual waste sorted out at IVAR** (from IVAR to incineration plant) | | | |
| Distance (average) [km] | 0 | | Note that the residual waste from IVAR is incinerated in a facility located just besides the sorting and recycling facility. Therefore, no transport was assumed between IVAR and the incineration plant since it is located just beside the IVAR facility. |
| **Incineration of plastics in residual waste and mixed plastics sorted out at IVAR** | | | |
| Incineration process for HDPE and LDPE [-] | Ecoinvent process | Assumption by authors | Ecoinvent process: Waste polyethylene (RoW)\| treatment of waste polyethylene, municipal incineration \| Cut-off, U |
| Incineration process for PET [-] | Ecoinvent process | Assumption by authors | Ecoinvent process: Waste polyethylene terephthalate (CH)\| treatment of waste polyethylene terephthalate, municipal incineration \| Cut-off, U |
| Incineration process for PP [-] | Ecoinvent process | Assumption by authors | Ecoinvent process: Waste polypropylene (CH)\| treatment of, municipal incineration \| Cut-off, U |
| Incineration process for PS [-] | Ecoinvent process | Assumption by authors | Waste polystyrene (CH)\| treatment of, municipal incineration \| Cut-off, U |
| Incineration process for mixed plastics [-] | Ecoinvent process | Assumption by authors | Waste plastic, mixture (CH)\| treatment of, municipal incineration \| Cut-off, U |
| **Incineration of plastics in residual waste and mixed plastics sorted out at IVAR (avoided production)** | | | |
| LHV (PET) [MJ/kg] | 23.8 | | |

| | | | |
|---|---|---|---|
| LHV (PP) [MJ/kg] | 41 | Tsiamis and Castaldi (2016) | |
| LHV (HDPE) [MJ/kg] | 37.1 | | |
| LHV (LDPE) [MJ/kg] | 40.8 | | |
| LHV (PS) [MJ/kg] | 38.6 | | |
| LHV (Mixed plastics) [MJ/kg] | 35.7 | | Average of the LHV values for PET, PP, HDPE, LDPE and PS. |
| Efficiency [%] | 85 | Raadal et al. (2009) | The amount of energy generated compared to the energy content of the fuel. |
| Degree of energy utilization [%] | 75 | | The amount of energy that becomes utilized compared to the amount energy that is generated. |
| Share of incinerated plastics that substitutes a Norwegian district heating mix [%] | 100 | | Assumption. |
| **Household plastic waste in residual waste to incineration** | | | |
| **Transport of household plastic waste in residual waste** (from consumer to incineration plant) | | | |
| Assumed similar collection system as ROAF. Data retrieved from NorEnviro database (2016). | | | |
| **Incineration of household plastic waste in residual waste** | | | |
| This was modelled in a similar manner as the incineration of plastics at IVAR. The same values for LHVs, efficiency, degree of energy utilization and the share of incinerated plastics that substitutes a Norwegian district heating mix were applied. | | | |

Norwegian Institute for Sustainability Research

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