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Environmental and economic assessment of plastic waste recycling

A comparison of mechanical, physical, chemical recycling and energy recovery of plastic waste

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Contents

Abstract

The present study provides a comparative environmental and economic assessment of plastic waste recycling and energy recovery (incineration) technologies, using actual plant data complemented with external information. The recycling technologies include mechanical, physical and chemical recycling.

The study concludes that the choice of the preferred management option for plastic waste should be based on three main criteria: i) the maximisation of material recovery while minimising processing impacts, principally related to energy consumption (reflecting environmental performance), in line with the waste hierarchy, ii) the specificity of the plastic waste stream and the treatment thereby required (technical feasibility), and iii) the economic feasibility.

A key limitation to the study has been the lack of data available on the characteristics of the waste inputs to recycling, which is needed to understand in which cases physical or chemical recycling and mechanical recycling may compete for similar waste feedstock and in which cases physical or chemical recycling provides an alternative option for processing waste otherwise sent to energy recovery or landfill.

Preliminary economic data suggests that some physical and chemical recycling technologies may be already economically viable without financial support, whereas others might become so in the medium to long term.

As the sectors of physical recycling and chemical recycling are currently experiencing rapid technological developments, the analysis presented in this study should be updated as technologies become more mature, also in view of formulating appropriate and possible policy interventions.

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Executive summary

As part of the EU's transition from a linear to a circular economy, the plastics industry in Europe, and globally, is going through a major transformation. In order to achieve new ambitious recycling targets, existing plastic mechanical recycling technologies are being joined by new technologies. These include physical recycling, also called solvent-based separation or dissolution recycling, and chemical recycling technologies, which include solvolysis, pyrolysis and gasification technologies.

The main aim of this study was to provide a comparative environmental and economic assessment of plastic waste recycling and energy recovery technologies. This main aim was translated into four specific initial objectives: i) determine the criteria and conditions to identify the preferred plastic waste treatment option from a life cycle perspective; ii) quantify the environmental improvements or impacts from mechanical, physical and chemical recycling relative to alternative options; iii) identify the key conditions under which mechanical, physical and chemical recycling can function optimally from a technical point of view; and iv) identify the key conditions under which mechanical, physical and chemical recycling is economically viable without public support.

The scope of the study includes the treatment of plastic waste after collection, including possible sorting and pretreatment technologies, as well as any of the technologies transforming the plastic waste in plastic recyclate, co-products, energy and emissions. Collection of plastic waste and use of the recyclates, co-products or energy are not discussed in this study. Waste generated and collected before end-of-life management was assumed to carry no environmental impacts ("zero-burden" assumption) as these impacts would be exactly the same with any subsequent end-of-life treatment, hence not meaningful for the purpose of comparing between different end-of-life options. Landfilling of plastic waste was not part of the scope as it is being scaled down or phased out in most Member States.

The tools used for this study were Life Cycle Assessment (LCA) and conventional Life Cycle Costing (LCC) methodologies, complemented by an additional economic assessment on the financial viability and by a literature-based operational assessment of chemical recycling technologies.

A life cycle assessment methodology tailored to waste management systems was applied in which the functional unit was the management of 1 tonne of sorted plastic waste, wet weight (i.e. waste that has undergone collection and sorting at appropriate material sorting facility where bales of targeted polymers are produced, e.g. PET or PS). Three types of comparisons were elaborated: i) comparisons focusing on plastic waste streams where mechanical recycling is compared with chemical or physical recycling and with energy recovery; ii) comparisons focusing on plastic waste streams where chemical or physical recycling is compared with energy recovery; and iii) comparisons focusing on plastic waste streams where mechanical recycling is compared with energy recovery. The LCA considered 14 environmental impact categories. For the purpose of presenting the key results of the study, this report focuses on a sub-set of categories namely Climate Change, Particulate Matter, Acidification and Resource Use- Fossils, which typically are the most relevant when focusing on plastic waste management, based on previous studies. Yet, the full results for the remaining 10 categories are available in Annexes 3 and 4.

Primary data on plastic waste treatment processes was collected via an external contractor, following an initial Stakeholder Workshop attended by more than 200 participants. Templates were used to collect waste composition information, life cycle inventory data, economic parameters and information on possible technical or operational issues. A total of 47 fully or partially completed templates were received: 16 templates on mechanical recycling, 4 templates on physical recycling, and 27 templates on chemical recycling. These templates corresponded to a total of 27 different pathways, i.e. combinations of a specific technology and waste stream. Following an assessment of the templates' data, 27 out of the 47 templates received were retained for the study, corresponding to 7 mechanical recycling, 3 physical recycling and 8 chemical recycling pathways. Most of these provided sufficient information to allow for preliminary life cycle inventory of the recycling process. However the level of detail provided was not consistent across all templates and some elements were missing. Therefore, information was complemented with data from literature and, where necessary, assumptions were made based on authors' experience and knowledge. No templates were received on energy recovery. Nonetheless, life cycle inventory data for 9 energy recovery pathways was produced from a dedicated waste incineration model. While the recycling technology templates received provided primary

information on the so-called 'foreground'[1] inventory (for each technology: consumption of electricity, chemicals, generation of outputs, etc.), the study relied on existing datasets to represent the impact of the 'background' processes (e.g. the impact of producing and supplying 1 kWh electricity or 1 kg of a chemical). These datasets were the Environmental Footprint and the ecoinvent dataset, used as a backup. Given the limited input of economic data and no input on technical and operational issues, from stakeholders, a literature study was performed to collect information on costs.

This study concludes that the choice of the preferred management option for plastic waste should be based on three main criteria: i) the maximisation of material recovery while minimising processing impacts, principally related to energy consumption (reflecting environmental performance), ii) the specificity of the plastic waste stream and the treatment thereby required (technical feasibility), and iii) the economic feasibility.

In this perspective, this study yielded a number of main results.

Climate Change: the preferred waste management option from a life cycle perspective is the one maximising material recovery while minimising impacts from waste processing (primarily energy consumption). Recycling (mechanical, physical or chemical) is preferable to energy recovery in all pathways analysed, notably for mixed polyolefin waste currently not mechanically recycled, because the environmental savings from energy recovery are not sufficient to compensate for the environmental impacts from waste incineration and the related CO_2 emissions.

Other environmental categories: For most categories, the abovementioned criterion on maximising material recovery while minimising processing impact still holds true (notably ozone depletion and fossil resource use). For some categories however (notably acidification, particulate matter, ionising radiation, human toxicity non-cancer, and eutrophication), energy recovery can perform better than energy intensive recycling pathways[2]. The main reason is that, for some substances emitted to air such as NOx, SO_2, dust or metal emissions (which largely determine the resulting impact on those abovementioned categories), current incinerators in Europe achieve on average much lower emissions than the EU average energy production mix - which has been used to calculate both the impacts from energy consumption of recycling and the savings/credits from energy recovery.

The current energy production mix (electricity and heat) in Europe has been modelled with a high share of coal, nuclear, and heavy fuel power plants, thus strongly influencing the choice of the preferred waste management option, in two main ways:

1) By increasing the calculated savings/credits for energy substitution; and
2) By increasing the calculated impacts for energy consumption of recycling processes.

As the European energy mix will get cleaner, the gap between recycling and energy recovery will further increase in favour of recycling, thus supporting the validity of the EU waste hierarchy.

A key limitation to the study has been the lack of data available on the characteristics of the waste inputs to recycling (characterisation, origin). For any future follow up, improved information on the waste-feedstock composition will be paramount to understand in which cases physical or chemical recycling and mechanical recycling may compete for similar waste feedstock and in which cases physical and chemical recycling provides an alternative option for processing waste otherwise sent to energy recovery or landfill. Considering the investigated scenarios where mechanical and chemical recycling constitute alternative management options, a clear ranking could not be established.

[1] The foreground system/technology refers to the system/technology on which the operators have full control. An operator typically knows the input-output inventory of the system/technology that it operates (e.g. how much electricity or chemical is used). However, the impact of producing and supplying energy and ancillary materials (e.g. electricity or chemical) to its system/technology or the impacts avoided by replacing in the market virgin materials is typically out of its control and it is thus referred to as 'background' system.

[2] Depolymerisation via alkaline hydrolysis for PET packaging waste, mechanical recycling for PS waste, mechanical recycling and pyrolysis for MPO waste, mechanical recycling and physical recycling for PE film waste, physical recycling for EPS from construction and demolition waste).

It was also not possible to identify the key conditions under which physical and chemical recycling can function optimally from a technical point of view, due to limited stakeholder input and scarce data availability in the literature. Nonetheless, a number of parameters could be identified that affect the operational performance. These include quality issues linked to the presence of heteroatoms in pyrolysis, heterogeneity of the output in case of certain pyrolysis operations without catalysts, catalyst inefficiency, deactivation and loss, as well as inefficient reactor design.

The main parameters that determine the economic viability of physical and chemical recycling are feedstock prices, capital and operational expenditures and output prices. Data provided by stakeholders on these parameters and literature data was scarce and characterized by large variability. Data on (annualised) CAPEX and OPEX was only provided for pyrolysis. The study analysed that dissolution and glycolysis may already have reached break-even status in terms of costs, however this result is driven by unusually high reported revenues in the survey data, and are reversed when using only literature data. Methanolysis, pyrolysis and gasification were found to have negative net incomes. Nonetheless, the current analysis did not account for possible gate fees or other cost correction measures. Furthermore, physical and chemical recycling technologies are still very much under development and costs are projected to decrease in the future, while costs for mechanical recycling are expected to remain stable and costs for virgin plastics production to substantially increase, together with fossil fuel prices. As a result, it is estimated that between 2019 and 2040, all chemical recycling technologies can reach positive net earnings -methanolysis in 2025, pyrolysis in 2033 and gasification by 2040. Due to insufficient data availability on economic parameters, there is a perceived need to update this analysis as technologies become more mature.

Introduction

1.1 Content and policy background

The European Commission's Plastics Strategy is part of its Circular Economy Package. It addresses different topics including reuse and recycling of plastics, alternative feedstock to fossil resources, more sustainable production pathways (e.g., industrial symbiosis), improved design of plastic articles (e.g., new designs, longer life, easy to recycle, biodegradability), more sustainable consumption and use of plastics, and better collection and sorting of plastic waste. The European strategy on plastics aims to address at least three interrelated issues: i) High dependence on fossil feedstock, ii) Low rate of recycling and reuse of plastics, iii) Significant leakage of plastics into the environment.

With respect to point (ii) on plastic waste reuse/recycling, the current performance of the EU27 waste management system is poor. For instance, reported recycling rates for plastics packaging (the largest market sector for this material) are in the range of 38% (EUROSTAT, 2022), which refers to the waste input actually going into recycling operations Therefore, different actions are necessary to achieve the EU27 55% target on recycling rate of plastic packaging waste by 2030. The European strategies for increasing the circularity of plastics involve greenhouse gas (GHG) emission reduction, diversification and security of supply, energy savings, water and material savings, increased recyclability, durability and lifetime of plastic articles, as well as potential reduction of littering and resulting impacts on soils and waters (including marine waters).

Among the different actions available to reach the abovementioned objectives, developing innovative recycling technologies is key to increase recycling rates and potentially improve environmental performance compared with existing technologies and options, while securing the EU supply of material resource. Among these, chemical and combined physical[3] recycling technologies are promising as they are anticipated to play an important role in complementing the more established mechanical recycling technologies by handling challenging waste flows, otherwise sent to disposal or incineration. However, the economic feasibility, the potential environmental impacts, and the operational conditions under which these alternative technologies may perform best are not yet well-understood due to data scarcity alongside the low maturity of some of the technologies.

1.2 Objectives of the study

The objective of this study is to perform a life-cycle-based comparison between chemical, physical recycling, mechanical recycling[4] and energy recovery of plastic waste flows for a number of realistic scenarios, with a view to:

i. Qualify the criteria and conditions which should be considered to identify the most effective options, from a life cycle perspective, for the management of plastic waste.

ii. Quantify the potential environmental impacts and life cycle costs resulting from chemical or physical recycling of plastic waste in comparison with energy recovery and/or mechanical recycling.

iii. Identify the key conditions under which chemical or physical recycling can function optimally from a technical point of view (e.g., safety, yield, predictable quality of output) and from an environmental point of view (e.g., taking into account different impacts related to the process used for plastic structure dismantling, from solvent-based purification over depolymerisation to full feedstock recycling).

iv. Identify the key conditions under which chemical or physical recycling is economically viable without public support (e.g., quality of feedstock, quality requirements on output, price of output).

Based on the above-mentioned analysis, the study aims to provide recommendations on:

- Which plastic waste management options, and under which key conditions, show the greatest potential for environmental improvement through chemical or physical recycling (in comparison with mechanical recycling and/or energy recovery);

[3] For instance, technologies based on solvent-based separation/dissolution of waste pre-treated with conventional mechanical operations (e.g. shredding and density separation). Because of the presence of mechanical and physical operations, we name them 'physical' in the context of this study.

[4] Intended as the established mechanical recycling of plastic waste (i.e. does not include dissolution technologies and chemical recycling).

- Which criteria and conditions should be considered to identify the most effective option between chemical/physical recycling, mechanical recycling and energy recovery from a life cycle perspective, or the most effective combination of these different plastic waste management options.

1.3 Scope of the study

The study addresses plastic waste recycling (mechanical, chemical, and combined physical), as well as energy recovery. Landfilling of plastic waste is not included in the study scope as it is being scaled down or phased out in most Member States. Potential environmental impacts of these technologies are evaluated based on Life Cycle Assessment (LCA), while costs are assessed via Conventional Life Cycle Costing (LCC), which represents a traditional financial cost assessment. These evaluations are complemented by an additional economic assessment looking into financial viability and by a preliminary operational assessment of chemical recycling technologies. The financial costs are estimated based on the data obtained in the data collection exercise (see Section 2), further complemented with relevant scientific and technical literature. Other technical considerations, e.g., safety of operations, yield, quality of outputs, are qualitatively addressed, separately from the conducted LCA studies, and based entirely on scientific and technical literature.

The study scope excludes the collection step and starts instead at the collected plastic waste. Where relevant, sorting and pretreatment technologies are included, as well as any of the technologies transforming the plastic waste in plastic recyclate, co-products, energy and emissions. Use of the recyclates, co-products and energy is not discussed in this study.

1.4 An important note on nomenclature

'Mechanical recycling', 'physical recycling' and 'chemical recycling', or combinations thereof, are concepts for which, at present, no universally agreed definition exists in EU legislation. Hence, several actors in the industry have come up with alternative or specific definitions for some of these processes such as 'feedstock recycling'. Furthermore, as the recycling industry is experiencing substantial growth and transformation, it can be expected that additional technologies to those addressed in this study may emerge in the near future, thus involving the potential need of introducing additional or alternative terminology and definitions.

For the purpose of this study, and without prejudice to any existing or future legal definition, mechanical recycling is defined as an operation aiming to recover plastic waste via mechanical processes, i.e. possible dismantling/disassembling, grinding, washing, separating, drying, re-granulating and compounding, thus producing recyclates that can be converted into new plastics products, often substituting virgin plastics. Physical recycling is a variant of mechanical recycling in which the polymer backbone is recovered in its entirety from the plastics matrix via dissolution in a solvent (Collias et al., 2021). Mechanical as well as physical recycling processes mainly use physical methods to treat and separate different types of plastics and to separate plastics from contaminants like non-plastic materials (e.g. metals, paper, or organic residues), resulting ultimately in a plastic material with specific technical characteristics.

Chemical recycling of plastic waste is understood according to the definition given in recent scientific publications (Delva et al., 2019; Collias et al., 2021) as a process where the polymer chains are converted into its oligomers, monomers or other basic chemicals (such as carbon monoxide, carbon dioxide, methane, and hydrogen) prior to further reprocessing into monomers/polymers. This is different from the "material recycling" technologies of mechanical and physical recycling. Chemical recycling can be subdivided into depolymerisation, pyrolysis and gasification as summarised in Collias et al. (2021). Depolymerisation is also referred to as chemolysis or solvolysis. Since many chemical recycling processes take place at elevated temperatures, they may also be labelled as thermochemical recycling.

All recycling processes can be further addressed as polymer loops, monomer loops, and molecular loops. Material recycling belongs to the polymer loop as the output obtained from this recycling is the purified form of the same input plastic waste that was originally fed into the process. Depolymerisation is classified as a monomer loop as the input plastic waste is converted into its constitutive monomers, while pyrolysis and gasification are classified as molecular loops as the input plastic waste is converted into smaller molecules or group of molecules (e.g. carbon monoxide, carbon dioxide, hydrogen, methane) prior to further reprocessing into monomers or polymers (Collias et al., 2021).

Finally, it should also be noted that losses are inherent to any recycling process. This can be due to pre-treatment losses (e.g. sorting prior to recycling operations that incurs residues composed of non-target polymer), but also due to transformation of material into emissions, reactor deposits (e.g. char) or fuels (gaseous or liquid), which do not contribute to recyclate formation. Hence, the use of the term 'plastic recycling' for the purpose of this

study should be interpreted as any operation that results in at least some new material, product or substance that is not used for fuel or energy production following the definition of recycling in the EU Waste Framework Directive.

2 Methodology

This section describes the life-cycle-based methods used in the study to quantify the potential environmental impacts (savings or burdens) and costs of plastic waste recycling or energy recovery, based on LCA (Section 2.1) and conventional LCC (Section 2.2). The approaches used for further economic assessment and preliminary operational assessment of chemical and physical recycling technologies are also briefly described in Sections 2.3 and 2.4, respectively.

2.1 Potential environmental impacts (LCA)

The quantification of potential environmental impacts was carried out following established practice for waste management LCA (Clift et al., 2000; Finnveden, 1999; Joint Research Centre, 2012) and in accordance with the guidelines of the ISO 14040/14044 standards (ISO, 2006a, 2006b). Specific methodological and modelling rules of the Environmental Footprint (EF) Method (European Commission, 2012) relevant to the goal and scope of the study were also applied. These regard, for instance, the selection of impact categories and Life Cycle Impact Assessment (LCIA) methods, the modelling of relevant background activities and processes involved in the investigated waste management pathways and scenarios (e.g. electricity use, transport and capital goods), handling of any multi-functionality of such background activities and processes, as well as, to the extent possible, the selection of secondary datasets and data for modelling, prioritising the use of EF-compliant datasets. Further detail is provided in Sections 2.1.6 (life cycle impact assessment) and 2.1.7 (life cycle inventory).

2.1.1 Functional unit and key methodological aspects

In order to compare mechanical recycling with chemical recycling or combined physical recycling, or any of the former with energy recovery (e.g., incineration) of a given plastic waste stream, it is necessary to compare the common service provided by each of these alternative waste management technologies (or systems). The appropriate functional unit[5] to enable such comparison is: "*the management (or valorisation) of the same unit-quantity of a specific waste stream with a given material fraction composition and related physico-chemical properties*". By applying this functional unit, it is possible to compare different technologies (or different systems of technologies) that are capable to handle the same input-waste while producing similar or different outputs, as illustrated in Figure 1. This is also known in literature as waste management-LCA whereby the focus is on the management of a specific waste or feedstock, and the co-products generated via the management operations are assumed to replace corresponding market products according to the respective quality and substitutability. Production impacts of the replaced products are then credited to the co-products[6]. It should be noted that this functional unit corresponds to the reference flow[7] of one unit-quantity (1 tonne) of wet waste to be managed, including any impurities[8] contained in the plastic waste stream sent for treatment. In this study, the functional unit of each comparative assessment is thus "*the management of 1 tonne of (sorted or pre-treated) plastic waste, wet weight, containing any impurities embedded in it*", which is represented by the input-waste to the different treatment pathways (or, more broadly, LCA scenarios)[9] considered in a specific comparison, as described in Section 2.1.3 (LCA scenarios) and Table 2 (input-waste). Based on this functional unit, each comparison addresses alternative waste management pathways to handle a same plastic waste stream, but relying on technologies that do not necessarily produce the same end products. This is obviously

[5] The functional unit describes qualitatively and quantitatively the required performance of the service under assessment, to be used as a reference to quantify potential impacts and as a basis for comparison of different management pathways/scenarios.

[6] Impacts from Use and End-of-life stages of the substituted products are not considered, because they are assumed to be the same as those of the recycled or recovered products (in such circumstance, what differs between the two products is only the production stage and, possibly, subsequent transport to downstream users).

[7] The reference flow is the amount of material (i.e. waste) required to fulfil the functional unit of the study, i.e. 1 tonne.

[8] Material/chemical contaminants embedded in the wasted products or resulting from prior waste management operations (e.g. collection and sorting), as well as non-targeted polymers and non-plastic materials still present in the sorted waste stream after any prior sorting operations.

[9] We call 'pathway' the entire set of operations, processes and activities associated with the management of the waste through a specific recycling or energy recovery technology, from transport of the waste to the recycling/energy recovery plant until treatment of all valuable fractions and residues generated during treatment. Beyond the pathway, the LCA 'scenario' also includes all other activities considered to model the system in a life cycle perspective (notably, displacement of market products from products obtained from recycling or energy recovery), according to the system boundary applied in this study (Section 2.1.2). Therefore, each pathway is associated to a scenario that represents an expansion of the pathway to include credits following recycling or recovery.

the case of recycling and energy recovery pathways (with the latter producing energy and the former polymers and/or other materials or products), but can also occur in case of mechanical and chemical recycling pathways producing different outputs (e.g. polymers rather than chemical intermediates or feedstock) from the same input-waste. It is also important to note that individual recycling technologies considered for comparison may not be necessarily capable of processing, *per se*, the same input-waste, while some technologies may require lower levels of impurities (i.e. a certain quality of the feedstock) compared to others. Therefore, when comparing technologies requiring a different quality of the feedstock, we strived to include in the compared pathways any pre-treatment of the input-waste needed to obtain a feedstock suitable for processing through the specific technology. This ensures comparability between the treatment pathways compared.

It should be noticed that the functional unit and LCA approach described above are the only ones that allow evaluating whether chemical recycling can be environmentally preferable to energy recovery for managing difficult plastic waste streams, complementing mechanical recycling by handling sorted waste streams that cannot be processed mechanically and/or rejects from sorting or mechanical recycling, thereby increasing overall recycling rates[10] (Figure 2). Also notice that the waste treatment pathways shown in Figure 1 represent only generic alternative scenarios for the management of unspecified plastic waste via mechanical recycling, chemical or physical recycling, and energy recovery. As such, they do not represent the specific recycling and energy recovery scenarios assessed in this study for defined waste streams, which are described in Section 2.1.3. Similarly, Figure 2 is purely illustrative of hypothetical scenarios where mechanical recycling is complemented by chemical recycling or energy recovery to handle non-mechanically recyclable plastic waste and rejects from sorting and/or mechanical recycling, but such enlarged scenarios are not investigated in this study. Finally, note that multiple recycling and/or cascading cycles (e.g. subsequent uses of the same material after the very first recycling loop, over a given time-period) are not considered in this study, as they require a shift in scope and functional unit (see, for instance, the work from Andreasi Bassi et al., 2022 and Faraca, Tonini, et al., 2019).

[10] Intended here according to the definition in the EU Waste Framework Directive (i.e. any material, product, or substance used for the original or other purposes, excluding fuel or energy use). This means that the recycling rate does not necessarily reflect a closed loop, plastic-to-plastic recycling.

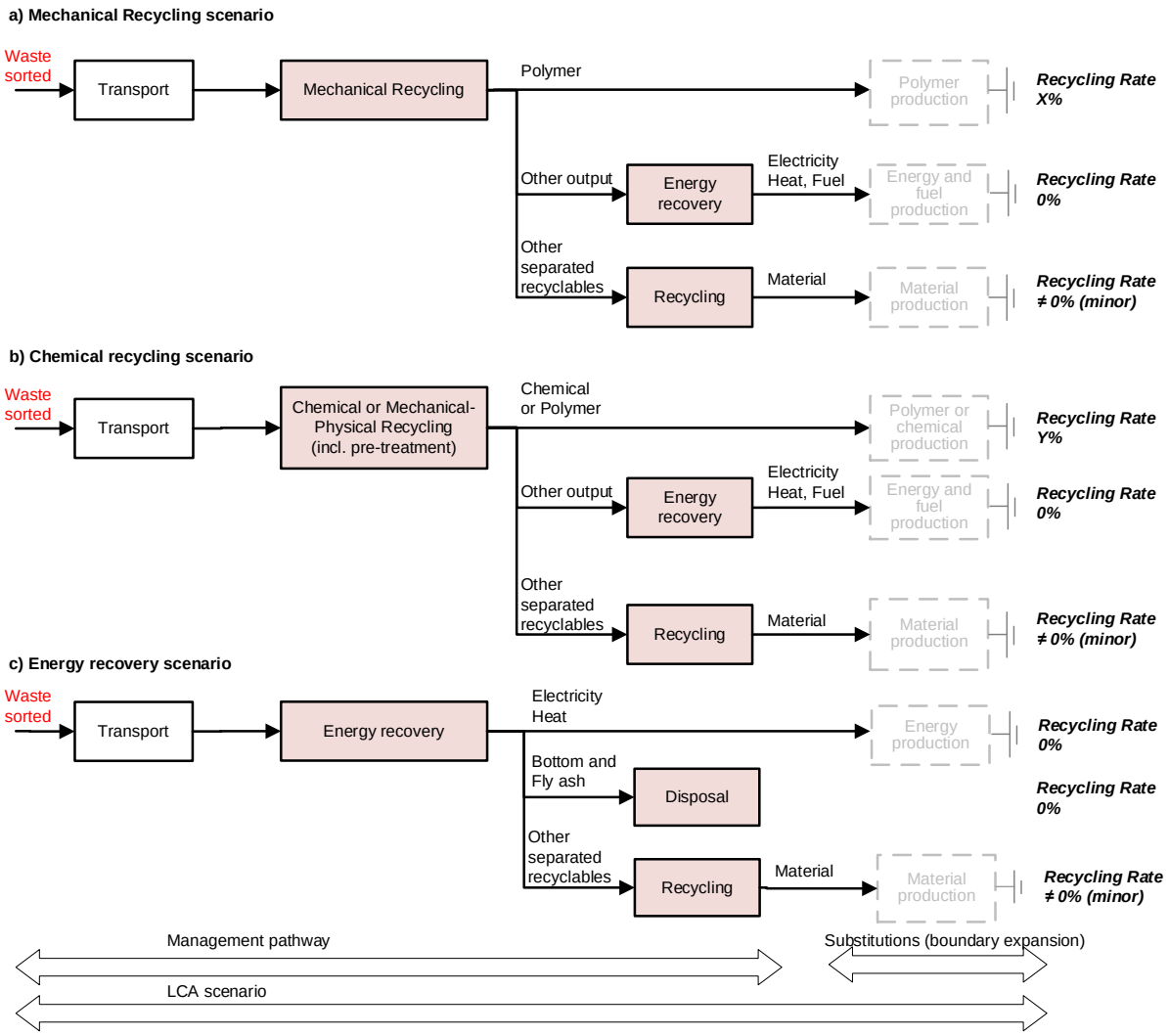


Figure 1. Comparison of mechanical recycling (a) versus chemical or physical recycling (b) versus energy recovery (c) of a same input-waste. While the input-waste is the same in the three generic pathways (in red), the products generated along with treating the input-waste may differ (hypothetical situation in which mechanical recycling and chemical or physical recycling are capable to handle the same feedstock after any required sorting and/or other pre-treatment). Pathways are indicated with black continuous lines and boxes, while substitutions are indicated with grey dotted lines and boxes.

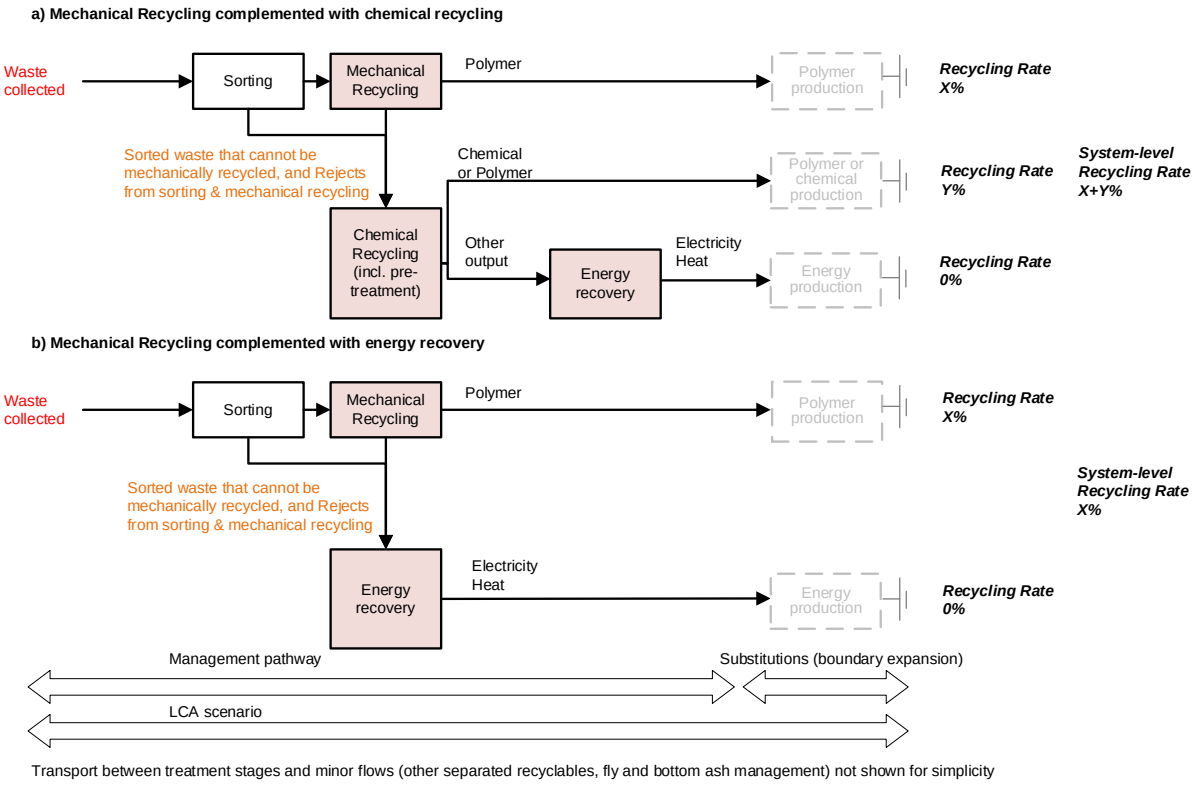


Figure 2. Comparison of a pathway including mechanical recycling and chemical recycling of non-mechanically recyclable waste and of the rejects from sorting and/or mechanical recycling (a) with one including mechanical recycling & energy recovery of the same waste streams (b). While the original input-waste is the same in the two pathways (in red), the input-waste to mechanical and chemical recycling differs and different end products are generated (hypothetical situation in which mechanical and chemical recycling do not handle the same input-waste and chemical recycling complements mechanical recycling by handling plastic waste that cannot be mechanically recycled under current conditions). Pathways are indicated with black continuous lines and boxes, while substitutions are indicated with grey dotted lines and boxes.

2.1.2 System boundary, geographical and temporal scope and supporting software

The system boundary of each LCA scenario (reflecting a specific waste management pathway and technology for the waste under study) includes all the operations involved in the management of the waste through the specific technology, i.e.: a) transport of the input-waste from centralised sorting facilities or collection centres to treatment facilities; b) recycling or energy recovery of the waste material (depending on the scenario); c) further recycling of any non-targeted material fractions separated/recovered during recycling (e.g. metals, paper/cardboard and rubber) or of materials recovered from treatment of bottom ash from energy recovery (i.e. metals, when included in the input-waste); d) handling of separated non-recyclable material fractions, residues and losses from recycling and residues from energy recovery processes; as well as e) substitution of market materials, products and/or energy from the recovered materials/products and/or energy (via system expansion; the exact quantity and type depend on the scenario). Depending on the material and process, non-recyclable fractions, residues and losses from recycling are assumed to be incinerated with energy recovery, sent to specific thermal treatments, or landfilled. Incineration residues (bottom ash after metal separation and air pollution control residues) are each sent to a specific treatment and fate, i.e. reuse as construction material and disposal in underground deposits, respectively. In case of chemical recycling, any required mechanical pre-treatment of the input-waste is also included (if not already covered in the received process data), to account for the additional burdens associated with possible sorting of any impurities (non-targeted plastic and non-plastic fractions) and non-suitable (targeted or non-targeted) materials, and with any prior shredding of the waste to be fed into the reactor or process.

The input-waste is assumed to carry no environmental burdens from the respective upstream life cycle, following the common "zero-burden" assumption applied in waste management LCA (see, for instance, Ekvall et al. (2007); Finnveden (1999), as the impacts occurring before the waste is generated would be exactly the same across the alternative management scenarios herein compared. Plastic waste in input to a mechanical, chemical, or physical recycling plant is intended as the plastic fraction targeted for recycling and associated

impurities (if any, such as metals, rubber, paper, non-targeted plastics, etc.). Collection, initial transport, and any centralised sorting of the input-waste are also excluded from the system boundary, along with any other activity performed prior to transport of the waste to recycling or energy recovery (e.g. incineration of sorting rejects and residues). While it is acknowledged that these activities are not necessarily the same in the compared recycling and energy recovery pathways -e.g. separate collection and sorting are not needed in case of energy recovery- they are not considered, in order to: i) allow the assessment to focus especially on the impacts and performance of the compared technologies, and ii) to better capture and understand the different contributions to the overall impacts of each technology (which would be more difficult to perform if other activities with relevant contributions were included, such as incineration of sorting rejects/residues). Moreover, this choice is considered to only marginally affect the comparative results, as the burdens from (separate) collection, initial transport and centralised sorting are generally negligible compared to the burdens from actual processing (recycling or energy recovery) of the waste, and to the resulting benefits from material and energy substitution, e.g. see the recent results of Andreassi Bassi et al. (2022). On the other hand, incineration of sorting rejects generally provides larger contributions (see again Andreassi Bassi et al. (2022)), but this process would equally occur also in case of energy recovery (although at a different point of the treatment chain and together with the remaining material fractions in the input-waste), so that no or marginal effects from its exclusion are expected on the ultimate comparative results between recycling and energy recovery pathways.

As mentioned earlier, along with the main service of treating the waste, different co-products are generated in each scenario. This is called 'multi-functionality'. To solve multi-functionality, system expansion via substitution (or avoided burden method) is applied, following common practice in waste LCA. For more information on this methodological approach, the reader is referred to the extensive literature on LCA applied to waste management (e.g. see Ekvall et al., 2007; Finnveden, 1999; Joint Research Centre, 2012; Laurent, Bakas, et al., 2014; Laurent, Clavreul, et al., 2014). Accordingly, the products and co-products generated along with the management of the waste (secondary materials, chemicals, feedstock, electricity, heat, etc.) are credited to the waste management system by assuming the displacement of the corresponding market products obtained from primary/virgin material, or from conventional energy sources or production routes. Notice that this system expansion via substitution approach is similarly applied in the end-of-life modelling approach of the currently recommended EU Environmental Footprint Methods (i.e. the Circular Footprint Formula), although here it is adapted to the specific scope and functional unit of this study, i.e. management of waste. To represent the displaced products, the current market average for those products was used. Possible differences in the relative quality of recycled and replaced virgin/primary products on the market (due to, e.g., downgrading during -mechanical- recycling) were taken into account by applying material-specific or product-specific substitution factors (quality ratios). Further details on replaced products and related modelling and assumptions are provided in Section 2.1.7.5.

The geographical scope of the study is the European Union, represented by the entirety of its Member States, i.e. EU-27. The investigated recycling and energy recovery pathways are thus modelled with reference to this geography, or other enlarged European geographies[11] when no data for EU-27 were available. In a few cases, data for specific Member States were only available and thus used in the assessment. As for the temporal scope, the study reflects current or recent past conditions, depending on available data. This applies both to the foreground system including all activities associated with the specific waste management pathway/ scenario, and to the background system including all ancillary activities such as energy and material supply.

The assessment of the investigated waste management scenarios and technologies is conducted with the support of the LCA software EASETECH v3.4.0 (Astrup et al., 2012; Clavreul et al., 2014) specifically developed to assess waste management technologies and systems. This tool is applied to model the different waste management activities and processes included in each scenario, and to calculate the respective potential environmental impacts and conventional life cycle costs.

2.1.3 Scenarios definition

The assessment considers three classes of comparison among different waste management scenarios relying on alternative pathways and technologies for treatment of specific plastic waste streams (generally sorted and/or pre-treated):

a) Comparisons focusing on plastic waste streams where mechanical recycling is compared with chemical or physical recycling and with energy recovery (i.e., the plastic waste stream can be either mechanically,

[11] For instance, "EU+EFTA+UK" or "Europe without Switzerland".

physically or chemically recycled, or incinerated; shaded in light green in Table 1). A generic system boundary is that previously illustrated in Figure 1 – pathways (a), (b) and (c). Specifically, these comparisons focus on the following services and waste streams:

- Management of sorted *PET packaging (bottles and trays) waste bales* via mechanical recycling, or chemical recycling, or energy recovery;
- Management of sorted *PS packaging waste bales* via mechanical recycling, or chemical recycling, or energy recovery;
- Management of sorted *flexible packaging waste bales made from Mixed Polyolefins (MPOs; i.e. PE and PP)* via mechanical recycling, or chemical recycling, or energy recovery;
- Management of sorted *large-format PE film waste bales* via mechanical recycling, or physical recycling, or energy recovery.

b) Comparisons focusing on plastic waste streams where chemical or physical recycling is compared with energy recovery (i.e. the plastic waste stream cannot -or is difficult or too costly- to be mechanically recycled given current technology development, or no data were received for mechanical recycling of the waste; shaded in light purple in Table 1). A generic system boundary is that previously illustrated in Figure 1 – pathways (b) and (c). These comparisons focus on the following services and waste streams:

- Management of post-industrial *PE/PA multilayer film waste* via physical recycling or energy recovery;
- Management of sorted *EPS construction and demolition waste (CDW)* via physical recycling or energy recovery;
- Management of *used tyre waste* via chemical recycling or energy recovery.

c) Comparisons focusing on plastic waste streams where mechanical recycling is compared with energy recovery (i.e. no alternative chemical/physical recycling technologies are currently available for direct application to the plastic waste stream; shaded in light blue in Table 1). A generic system boundary is that previously illustrated in Figure 1 – pathways (a) and (c). These comparisons focus on the following services and waste streams:

- Management of *mixed plastic-rich waste from shredding of small WEEE* (small domestic and ICT appliances; SAs)[12] via mechanical recycling or energy recovery;
- Management of *mixed plastic-rich waste from shredding of large WEEE* (cooling and freezing appliances; CFAs)[13] via mechanical recycling or energy recovery.

In this last set of comparisons, energy recovery includes not only combustion in a conventional municipal solid waste (MSW) incineration plant, but also hazardous waste incineration (HWI) of brominated and chlorinated plastics assumed to be separated from remaining plastic and non-plastic material fractions in the input-waste, before sending it to energy recovery.

[12] Corresponding to categories number 5 and 6 of the WEEE Directive (2012/19/EU; Annex III), i.e. "*Small equipment*" and "*Small IT and telecommunication equipment (no external dimension more than 50 cm)*".

[13] Corresponding to category number 1 of the WEEE Directive (2012/19/EU; Annex III), i.e. "*Temperature exchange equipment*".

Table 1. Overview of the waste management scenarios and technologies assessed for each plastic waste stream and details of the technology applied and main products obtained in each scenario. Details on the input-waste to each scenario are provided later. CFAs: cooling and freezing appliances; CDW: construction and demolition waste; CHP: combined heat and power; CR: chemical recycling; FPW: flexible packaging waste; FW: film waste; HW: hazardous waste; MPOs: mixed polyolefins; MR: mechanical recycling; MSPs: mixed shredded plastics; MSW: municipal solid waste; PR: physical recycling; PW: packaging waste; SAs: small domestic and ICT appliances; WEEE: waste electrical and electronic equipment. For more information on the main technologies see Glossary.

Input-waste	Functional unit	Scenario name	Type of treatment	Main technology	Main products	Other products
PET packaging (bottles and trays) waste bales	Management of 1 tonne of sorted PET waste bales (semi-rigid packaging) with the composition reported in Table 2	MR-PET-PW	Mechanical recycling[(a)]	Grinding, washing, (density) separation, drying, granulation	PET regranulate – food grade (63%) PET regranulate – non-food grade (37%)	PE and PP regranulate Metals Rubber Paper/cardboard Electricity and heat[(b)]
		CR-PET-PW-(I)	Chemical recycling	Partial glycolysis	PET granulate	N/A
		CR-PET-PW-(II)	Chemical recycling	Methanolysis-Hydrolysis	EG and PTA	N/A
		CR-PET-PW-(III)	Chemical recycling	Alkaline hydrolysis	EG and PTA	Sodium sulphate
		ER-PET-PW	Energy recovery	Incineration (MSW) with CHP generation	Electricity and heat	Metals
PS packaging waste bales	Management of 1 tonne of sorted PS packaging waste bales with the composition reported in Table 2	MR-PS-PW	Mechanical recycling	Size reduction, separation of impurities, heat-based processing, granulation	PS regranulate (non-food grade)	Metals Electricity and heat[(b)]
		CR-PS-PW	Chemical recycling	Pyrolysis-assisted depolymerisation	Styrene	Other styrenics Naphtha Pyrolysis oil
		ER-PS-PW	Energy recovery	Incineration (MSW) with CHP generation	Electricity and heat	Metals
Mixed polyolefins (MPOs) flexible packaging waste bales	Management of 1 tonne of sorted MPO (PE and PP) flexible packaging waste	MR-MPO-FPW-(I)	Mechanical recycling	Shredding, separation of impurities, washing, density separation, drying, granulation	MPO, PP and HD-PE regranulate (non-food grade)	RDF Metals Electricity and heat[(b)]

Input-waste	Functional unit	Scenario name	Type of treatment	Main technology	Main products	Other products
	bales with the composition reported in Table 2	MR-MPO-FPW-(II)	Mechanical recycling	Shredding, sorting of impurities, cleaning (de-dusting)	MPO agglomerate	RDF Metals Electricity and heat[b]
		CR-MPO-FPW-(I)	Chemical recycling	Pyrolysis (including hydro-cracking of pyrolysis oil)[f]	Hydro-treated pyrolysis oil	Pyrolysis gas Carbon black Heavy fuel oil Wax
		CR-MPO-FPW-(II)	Chemical recycling	Pyrolysis (including hydro-cracking of pyrolysis oil)[f]	Hydro-treated pyrolysis oil	Pyrolysis gas Char Tar
		CR-MPO-FPW-(III)	Chemical recycling	Hydrothermal pyrolysis (including hydro-cracking of pyrolysis oil)	Hydro-treated pyrolysis oil	Pyrolysis gas
		ER-MPO-FPW	Energy recovery	Incineration (MSW) with CHP generation	Electricity and heat	Metals
Large-format PE film waste bales	Management of 1 tonne of sorted large-format PE film waste bales with the composition reported in Table 2	MR-PE-FW	Mechanical recycling	Pre-sorting, initial shredding and washing, separation of impurities, shredding (flaking), washing, density separation, drying, granulation	LDPE regranulate (non-food grade)	RDF Metals Electricity and heat[b]
		PR-PE-FW	Physical recycling	Solvent-based separation/ dissolution[c]	R-LDPE granulate (non-food grade)	RDF Metals Electricity and heat[b]
		ER-PE-FW	Energy recovery	Incineration (MSW) with CHP generation	Electricity and heat	Metals
PE/PA multilayer film waste (post-industrial)	Management of 1 tonne of post-industrial PE/PA multilayer film waste with the composition reported in Table 2	PR-PE/PA-FW	Physical recycling	Solvent-based separation/ dissolution[c]	R-LDPE granulate (non-food grade)	R-PA granulate (non-food-grade) Electricity and heat[b]
		ER-PE/PA-FW	Energy recovery	Incineration (MSW) with CHP generation	Electricity and heat	-

Input-waste	Functional unit	Scenario name	Type of treatment	Main technology	Main products	Other products
EPS from CDW	Management of 1 tonne of sorted EPS construction and demolition waste with the composition reported in Table 2	PR-EPS-CDW	Physical recycling	Solvent-based separation/ dissolution[(d)]	R-PS granulate (non-food grade)	Electricity and heat[(b)]
		ER-EPS-CDW	Energy recovery	Incineration (MSW) with CHP generation	Electricity and heat	-
Used tyre waste	Management of 1 tonne of used tyre waste with the composition reported in Table 2	CR-TYR	Chemical recycling	Pyrolysis	Pyrolysis oil	Pyrolysis gas Carbon black Steel
		ER-TYR	Energy recovery	Incineration (MSW) with CHP generation	Electricity and heat	Steel
Mixed shredded plastics (MSPs) from small WEEE (small domestic and ICT appliances; SAs)	Management of 1 tonne of MSPs from SAs with the composition reported in Table 2	MR-MSP-WEEE-SA	Mechanical recycling	Sorting, washing, granulation	ABS, PP and high-impact PS regranulate	Metals RDF Electricity and heat[(b)]
		ER-MSP-WEEE-SA	Energy recovery	Incineration (MSW/HW)[(e)] with CHP generation	Electricity and heat	Metals
Mixed shredded plastics (MSPs) from large WEEE: (cooling and freezing appliances; CFAs)	Management of 1 tonne of MSPs from CFAs with the composition reported in Table 2	MR-MSP-WEEE-CFA	Mechanical recycling	Sorting, washing, granulation	High-impact PS, ABS, and PP regranulate	Metals RDF Electricity and heat[(b)]
		ER-MSP-WEEE-CFA	Energy recovery	Incineration (MSW/HW)[(e)] with CHP generation	Electricity and heat	Metals

([a]) Average process (based on data from 4 different recycling plants) producing both food grade and non-food grade PET regranulate. All necessary steps to achieve food-grade quality (including possible decontamination) are assumed to be included in the process, and covered by the received process-data, although this information was not explicitly provided.
([b]) From incineration of non-recovered material fractions (e.g. non-targeted/non-recyclable plastics, paper and cardboard, other combustible materials, etc.) and/or residual fractions and losses from recycling.
([c]) Combined mechanical and physical recycling including shredding, density separation, selective dissolution, solid/liquid separation, purification of the polymer, and solvent removal and recovery.
([d]) Combined mechanical and physical recycling including shredding, dissolution, separation of solid impurities through filtration, PS separation (precipitation), solvent recovery (distillation), drying, and granulation.
([e]) Includes also hazardous waste (HW) incineration of brominated and chlorinated plastics separated from the remaining plastic and non-plastic material fractions (sent to municipal waste incineration).
([f]) CR-MPO-FPW-(I) and CR-MPO-FPW-(II) scenarios both represent conventional pyrolysis of MPO waste. The final hydrocracking step's input-output data were retrieved from stakeholders differently in both templates, so aggregation was not possible in this case.

2.1.4 Input waste and material fraction composition

The composition of the plastic waste streams (input-waste) to be managed in the investigated scenarios (and considered to define the functional unit of each comparison) is provided in Table 2. This composition is used for modelling purposes, and does not necessarily reflect the exact composition of the waste treated in the specific plants covered by the data collected for this study. In most cases, the input-waste composition was defined based on raw data and information collected for individual recycling plants, especially concerning the feedstock processed, the recycled outputs, and the waste streams generated. These data were generally complemented with a number of assumptions (especially on the type and composition of the reported waste streams) to define the specific material fractions in the input-waste. Where more plant-data were received for the same technology managing a given waste stream (e.g. mechanical recycling of PET), a weighted-average composition was defined, based on the annual treatment capacity of each plant as recalculated for this study. When different recycling technologies were compared (e.g. mechanical recycling versus chemical or physical recycling of PET), the most complex and articulated composition was considered as a common input for modelling purposes. When applying this composition to chemical recycling technologies, a specific sorting step to separate additional impurities and any non-suitable material fractions was considered (see Sections 2.1.2 and 2.1.7.2 for details), if not already covered in the provided process data, to obtain a feedstock suitable for the specific technology. In some cases, collected data were not sufficiently detailed to define a suitable input-waste composition for modelling purposes, so that literature data were used as a basis, complementing them with any missing material fraction identified based on the originally provided data. This was especially the case of flexible packaging waste made of mixed polyolefins and large-format PE film waste, for which the data reported in Lase et al. (2022) were considered as a starting point.

The physico-chemical characteristics used to model the individual material fractions composing the input-waste are based on the analyses performed by Götze et al. (2016). While the study provides chemical composition for both separately and non-separately collected materials, we used the composition for non-separately collected materials (when available). This choice is justified by the fact that the physico-chemical properties of the waste mostly affect the modelling of energy recovery (incineration) processes, which mainly treat non-separately collected waste.

Table 2. Composition of the input-waste (column 2-to-10), as assumed for modelling in this study based on collected plant data and assumptions or literature data. Values are expressed as percentage of total waste (wet weight). CDW: construction and demolition waste; Br-FR: brominated flame retardant; WEEE: waste electrical and electronic equipment.

Material fractions	Input-waste								
	PET packaging (bottles and trays) waste bales	PS packaging waste bales	Mixed polyolefins flexible packaging waste bales	Large-format PE film waste bales	PE/PA multilayer film waste	EPS from CDW	Used tyre waste	Mixed shredded plastics from WEEE (small domestic and ICT appliances)	Mixed shredded plastics from WEEE (cooling and freezing appliances)
PET (packaging)	84.0	-	-	-	-	-	-	-	-
HDPE (packaging – closures)	1.82	-	-	-	-	-	-	-	-
PE (films/rigid)	-	-	35.0	75.5	80	0.0303[e]	-	-	-
PP (packaging – closures)	1.82	-	-	-	-	-	-	-	-
PP (films/rigid)	-	-	25.2	4.80	-	-	-	-	-
PP (non-filled, from WEEE)	-	-	-	-	-	-	-	12.7	4.84
PP (filled, from WEEE)	-	-	-	-	-	-	-	11.5	5.82
PP (with Br-FR, from WEEE)	-	-	-	-	-	-	-	-	4.91
PS (packaging)	-	70.3	-	-	-	-	-	-	-
PS (high-impact, from WEEE)	-	-	-	-	-	-	-	12.4	50.5
EPS (from CDW)	-	-	-	-	-	94.8	-	-	-
ABS (from WEEE)	-	-	-	-	-	-	-	20.7	6.04
ABS (with Br-FR, from WEEE)	-	-	-	-	-	-	-	3.72	-
PC/ABS (from WEEE)	-	-	-	-	-	-	-	10.6	-
PA (films)	-	-	-	-	20.0	-	-	-	-
PA61/PA66 (from WEEE)	-	-	-	-	-	-	-	10.6	-
PVC (rubber, from WEEE)	-	-	-	-	-	-	-	-	4.91
PUR (from WEEE)	-	-	-	-	-	-	-	-	3.72

Other plastic films (monomaterial)	-	-	4.30	3.70	-	-	-	-	-
Multi-material films and metallised PE/PP films	-	-	9.50	6.30	-	-	-	-	-
Unspecified plastic (packaging)	-	3.64	-	-	-	-	-	-	-
Unspecified plastic (non-packaging)	-	-	-	-	-	-	-	6.65	3.72
Metals (with pathway-specific shares of ferrous and non-ferrous)	0.627	0.495	2.00	0.664	-	-	-	0.367	10.7
Steel	-	-	-	-	-	-	15.0	-	-
Paper (e.g., print paper, hygiene and tissue paper) and cardboard	0.00344	9.14	3.70	1.50	-	-	-	-	-
Rubber	0.0116	-	-	-	-	-	40.0	-	-
Organic waste	-	14.6	-	-	-	-	-	-	-
Inert waste (cement, dirt and similar)	-	-	-	-	-	5.00	-	-	-
Carbon black	-	-	-	-	-	-	25.0	-	-
Other combustible materials	11.6[a]	1.82[c]	10.2[d]	3.77[d]	-	0.200[f]	20.0[i]	5.32[g]	2.45[g]
Other non-combustible materials	0.125[b]	-	10.2[d]	3.77[d]	-	-	-	5.32[h]	2.45[h]

([a]) PET residues (e.g. fines and -coloured- rejects), mixed plastic and paper (labels), and unspecified (mixed) materials from pre-treatment (sorting) operations during recycling.
([b]) Unspecified (mixed) materials from pre-treatment (sorting) operations during recycling.
([c]) Other unspecified impurities.
([d]) Residues ("compounds, clogged, others") and fines.
([e]) PE film.
([f]) Other unspecified waste.
([g]) Wood and paper.
([h]) Glass and minerals.
([i]) Fibre, fillers and other additives.

2.1.5 Data collection

2.1.5.1 Interactions with stakeholders and primary data collection

2.1.5.1.1 Data collection process

In order to collect life cycle inventory data, as well as any available economic and operational data on the various plastic waste management technologies/processes, JRC launched a call for tender procedure, with the contract awarded to AIMPLAS.

On 4 March 2021, JRC organised a large workshop addressed to all relevant stakeholders in the field, which was attended by about 200 participants. The aim of the workshop was two-fold, i.e.: providing information on the work that JRC was carrying out on LCA applied to plastic waste treatment, and calling upon stakeholders to assist in the exercise by providing relevant data and information.

AIMPLAS developed a dedicated website where it provided background information on the study and a page where questionnaires and templates for data collection could be downloaded for various plastic waste management processes (see Figure 3). Furthermore, AIMPLAS provided Non-Disclosure Agreements to participating data providers, in order to ensure confidentiality and anonymity towards JRC.

On 28 April 2022, JRC organised a second stakeholder workshop for operators that had participated in the data collection, plastic industry umbrella organisations and Commission colleagues. The aim of this Workshop was to: i) illustrate the work performed so far by JRC, including data collection by AIMPLAS and preliminary LCA results; ii) get feedback from the stakeholders during the same workshop; and iii) prepare the ground for the follow-up written stakeholder consultation where stakeholders had about two months to provide further data and feedback to the study. The information collected has been used to improve the LCA modelling and incorporated in the last version of the report.

Figure 3. Overview of data collection templates for different plastic waste management processes made available on a dedicated website by AIMPLAS to be filled by stakeholders.

2.1.5.1.2 Pathways covered

A total of 47 fully or partially completed templates (datasheets) were received from stakeholders (via AIMPLAS) during the data collection procedure: 16 templates on mechanical recycling, 4 templates on combined physical recycling, and 27 templates on chemical recycling. These templates corresponded to a total of 26 different pathways, intended, in this section, as combinations of a specific technology and waste stream (e.g. mechanical recycling of PET): 9 mechanical recycling, 3 combined physical recycling, and 14 chemical recycling pathways.

No templates were received on energy recovery. Overall, these pathways covered 13 different waste streams[14]. In the case of mechanical recycling, a total of 5 templates concerning treatment of PET packaging (bottles and trays) were received, as well as 4 templates for mechanical recycling of Mixed Polyolefins (MPOs) flexible packaging or unspecified MPO waste. For the other waste streams, which include PS packaging, large-format PE films, MPO (PE/PP) bottles, rejects from treatment of Used Beverage Cartons (UBC) in paper mills, and mixed plastic-rich waste from shredding of three different types of WEEE (unspecified large appliances, small domestic and ICT appliances, cooling and freezing appliances) one mechanical recycling template was received. For combined physical recycling, 2 templates were received for EPS from construction and demolition waste[15] (CDW), as well as one template for large-format PE film and one for post-industrial PE/PA multilayer film. 6 templates were received for different chemical recycling technologies[16] of PET waste (mostly packaging and textiles), 3 for pyrolysis-assisted depolymerisation of PS (packaging) waste (and in one case also EPS waste), 1 for microwave pyrolysis of PS (packaging) waste, 13 for pyrolysis or microwave pyrolysis of MPOs-rich waste (films/packaging including also multilayer/hybrid materials and mixed-plastic waste (MPW) from sorting facilities)[17], 1 for pyrolysis of post-industrial multilayer PE/PA/PET and PE/PA lightweight packaging waste, 1 for glycolysis of post-industrial PUR flexible foams, and 2 for used-tyres pyrolysis.

Only a part of the received templates could be ultimately used in this study, due to different reasons, such as the lack of sufficiently detailed information on the input-waste and/or other relevant flows (especially recycled product outputs and waste flows), the provision of only partial and/or not sufficiently detailed life cycle inventory data, the focus on waste streams outside the scope of this study, as well as the use of non-compliant formats and languages for the template. Table 3 provides a detailed overview of the pathways (i.e. technologies and corresponding waste streams) covered by the templates received, and those considered for investigation in this study (shaded in grey). The number of templates originally received and of those ultimately used for each pathway is also reported, along with the specific reasons for excluding some of the received templates.

[14] Covered waste streams included: PET packaging and textile waste; PS packaging waste; Mixed Polyolefins (MPOs) waste (with different specified or unspecified qualitative characteristics) including in most cases flexible packaging and film waste; large-format PE films waste; MPOs (PE/PP) bottles; rejects from treatment of used beverage cartons in paper mills; post-industrial PE/PA multilayer film waste; post-industrial multilayer PE/PA/PET and PE/PA lightweight packaging waste; EPS from construction and demolition waste (CDW); mixed plastics from shredding of three different types of WEEE (small domestic and ICT appliances, cooling and freezing appliances, and unspecified large appliances); and used tyre waste.

[15] Both templates referred to the same process and technology, but data were reported for different reference periods. The template considering to the longer reference period was considered for the purpose of this study.

[16] Covered technologies included partial glycolysis, methanolysis-hydrolysis, and depolymerisation (selective depolymerisation via alkaline hydrolysis).

[17] Unspecified mixed plastic waste (MPW) or rejected MPW from sorting facilities is considered as "MPO-rich".

Table 3. Overview of the data templates received, used and excluded for each plastic waste treatment pathway, and of the pathways ultimately considered for assessment in this study (in grey), as described in Section 2.1.3. CDW: construction and demolition waste; MPOs: mixed polyolefins; MPW: mixed plastic waste; POs: polyolefins; WEEE: waste electrical and electronic equipment.

Pathway (technology and related waste stream)	Data-templates received	Data-templates used	Reason for excluding any templates
Mechanical recycling			
PET packaging (bottles and trays) waste bales	5	4	Template received beyond the deadline
PS packaging waste bales	1	1	-
Mixed polyolefins (MPOs) flexible packaging waste bales or unspecified MPOs waste bales	4	2	Template using a non-compliant format and language, or not providing sufficiently detailed information on the input waste
Large-format PE films waste bales	1	1	-
MPOs (PE/PP) bottles waste	1	0	Template not providing sufficiently detailed information on the input waste, and very partial LCI data
Rejects from treatment of used beverage cartons in paper mills	1	0	Template referring to a process/technology dealing with a waste stream outside the scope of this study
Mixed shredded plastics from WEEE (3 different types)[(a)]	3	2	Template not providing sufficiently detailed LCI data and information on the input waste[(b)]
Physical recycling			
Large-format PE films waste bales	1	1	-
PE/PA multilayer film waste (post-industrial)	1	1	-
EPS from CDW	2	1	Template referring to the same process and technology, with data reported for a shorter reference period
Chemical recycling			
PET[(c)] partial glycolysis	1	1	-
PET[(c)] methanolysis	1	0	Template not providing sufficiently detailed LCI from a plant already in operation
PET[(c)] methanolysis-hydrolysis	1	1	-
PET[(c)] selective depolymerisation (alkaline hydrolysis)	2	2	-
PET[(c)] enzymatic depolymerisation	1	0	Template not providing sufficiently detailed LCI data and information on the input waste
PS packaging (and EPS) pyrolysis-assisted depolymerisation	3	2	Template not providing sufficiently detailed LCI data and information on the input waste

PS microwave pyrolysis	1	0	Template not providing sufficiently detailed LCI data and information on the input waste
Pyrolysis of (mixed) polyolefins (POs)-rich films/packaging waste (including also or mostly multilayer/hybrid materials)[(d)]	12	6	Templates not providing sufficiently detailed LCI data and information on the input waste
Mixed POs microwave pyrolysis	1	0	Template not providing sufficiently detailed LCI data and information on the input waste
Pyrolysis of post-industrial multilayer PE/PA/PET and PE/PA lightweight packaging waste	1	0	Template not providing sufficiently detailed LCI data and information on the input waste
PUR flexible foams glycolysis (post-industrial)	1	0	Template not providing sufficiently detailed LCI data and information on the input waste
Used tyre waste pyrolysis	2	2	-

([a]) Small domestic and ICT appliances, cooling and freezing appliances, and unspecified large appliances.
([b]) Specifically, the template related to mechanical recycling of mixed shredded plastics from unspecified large appliances was excluded.
([c]) Including, in most cases, packaging (bottles and trays) and textiles.
([d]) This pathway also includes unspecified mixed plastic waste (MPW) or rejected MPW from sorting facilities, which can be categorised as "MPO-rich".

2.1.6 Life cycle impact assessment

The following 14 environmental impact categories included in currently recommended EU methods for Environmental Footprint (EF) (European Commission, 2021) were considered in this study: Climate Change (CC), Ozone Depletion (ODP), Human Toxicity, cancer (Htox_c), Human Toxicity, non-cancer (Htox_nc), Particulate Matter (PM), Ionising Radiation (IR), Photochemical Ozone Formation (POF), Acidification (AC), Eutrophication, terrestrial (TEU), Eutrophication, freshwater (FEU), Eutrophication, marine (MEU), Ecotoxicity, freshwater (Ecotox), Resource Use, minerals and metals (MRU), and Resource Use, fossils (FRU). The EF 3.0 Life Cycle Impact Assessment (LCIA) method, as implemented in the LCA software used to model the investigated waste management scenarios (EASETECH v3.4.0), was applied to calculate the potential environmental impacts of each scenario in these impact categories. The impact categories "Water Use" and "Land Use" originally included in the EF method were not considered in the assessment, due to current absence of regionalised water and land use flows in the EASETECH software, leading to potential discrepancies between regionalised life cycle inventory flows used in the applied background (EF-compliant) datasets and non-regionalised flows currently used for life cycle impact assessment in EASETECH. However, water and land use are not expected to be relevant categories for the waste management scenarios assessed, as waste management activities do not generally involve substantial land use and/or land transformation burdens (no agricultural or forestry activities are normally involved), nor relevant water use burdens relative to virgin production activities. Completeness of results is thus only marginally affected by these exclusions.

2.1.7 Life cycle inventory modelling

The life cycle inventory of the investigated recycling processes was mostly developed based on primary data and information provided from stakeholders participating to the data collection exercise (Section 2.1.5). Where needed, these data were complemented with additional literature data or specific assumptions, and then combined with secondary data from existing databases to represent the burdens of non-elementary process inputs and outputs, as described in Section 2.1.7.2.

For incineration processes used as main technology in energy recovery scenarios, a dedicated waste incineration model was applied to develop the respective life cycle inventory (Section 2.1.7.3). The modelling was input-specific, taking into account the elemental composition and relevant physical properties (e.g. heating value) of the waste being incinerated.

The other foreground processes and activities of the investigated scenarios, i.e. transport of the input-waste, external recycling of non-targeted material fractions, treatment of some residues, losses or separated non-recyclable fractions, as well as substitution of market products, were modelled based on secondary datasets for current (or recent past) average EU conditions, in line with the geographical scope of the study. If no datasets were available for EU, alternative datasets for single Member States were used as best available proxies. Similarly, proxy datasets were used when no representative datasets were available for the specific process to be modelled. Moreover, the selected datasets were complemented, where needed, with literature data or assumptions (e.g. on transport distances) to determine the specific process quantity. Secondary datasets were generally sourced from the pool of Environmental Footprint (EF)-compliant datasets while, in the absence of representative datasets or suitable proxies among these, alternative datasets from the *ecoinvent* database v3.6 (ecoinvent centre, 2021) were applied for modelling. The same overall approach was applied to model also individual non-elementary inputs and outputs of recycling and energy recovery processes (e.g. energy, fuels, water, chemicals, other ancillary materials and products, wastewater, sludge, and process waste due to material and product use). The detailed modelling of foreground processes and activities other than recycling and incineration is described in Sections 2.1.7.1 (transport of the input-waste), 2.1.7.4 (transport and treatment of non-targeted recyclable materials, separated non-recyclable fractions, residues and losses from recycling and residues from energy recovery), and 2.1.7.5 (substitution of market products). As for background processes and activities, the modelling of energy (electricity and heat) supply is specifically addressed in Section 2.1.7.6.

2.1.7.1 Transport of the input-waste to treatment

Input plastic waste to recycling was assumed to be transported by truck along a distance of 50 km from centralised sorting facilities or collection centres. While longer distances may need to be currently covered in case of chemical and physical recycling, due to lower availability of facilities relying on such emerging or maturing technologies, the same distance as mechanical recycling scenarios was assumed, to allow the assessment to capture differences in the environmental and economic performance of individual recycling technologies, rather than potential differences in infrastructure development. A lorry with a full load mass larger than 32 tonnes was considered for transport, as modelled in the EF-compliant dataset "*[EU+EFTA+UK] Articulated lorry transport, Euro 4, Total weight >32 t; diesel driven, Euro 4, cargo | consumption mix, to consumer | more than 32t gross weight / 24.7t payload capacity*". For transport of plastic waste from the place of origin to energy recovery, the following EF-compliant dataset, referring to a 28-32 tonne fully-loaded lorry, was used: "*[EU+EFTA+UK] Articulated lorry transport, Total weight 28-32 t, mix Euro 0-5; diesel driven, Euro 0 - 5 mix, cargo | consumption mix, to consumer | 28 - 32t gross weight / 22t payload capacity*". According with the reference geography of these aggregated datasets, the diesel mix for countries in EU-27, EFTA and UK is considered as a fuel input to both of them.

2.1.7.2 Recycling (mechanical, physical or chemical)

For each investigated recycling process, raw data collected for individual plants were checked and, in most cases, adjusted to ensure that the mass balance was respected, i.e. to ensure that the amount of input waste (with impurities) was equal to the mass of recovered useful products, other recyclable and non-recyclable material fractions, residues and losses leaving the process. Alignment between the reported amounts of process waste (excluding residues, losses and other separated fractions) and relevant ancillary material and product inputs to the process was also checked and, where needed, such amounts were adjusted to ensure consistency. The quantity of input-waste determined after checking the mass balance was the basis to quantify process inputs (e.g. energy, chemicals and water) and outputs (e.g. air emissions and wastewater) with respect to the reference flow of 1 tonne of waste treated/managed through a specific recycling process. This means that the adjusted amount of input-waste was considered as a reference for quantification, rather than the annual amount of waste treated or the plant capacity declared in the received datasheets (filled templates).

Electricity used in recycling processes was assumed to be entirely sourced from the grid, regardless of any specific energy source reported in the collected data (which refer to particular installations), since the assessment aimed at reflecting average EU conditions and recycling plants, rather than very local situations that would restrict the validity and applicability of the results. For the same reasons, thermal energy requirements of the processes were assumed to be fulfilled by the estimated current EU average mix of thermal energy, regardless of any specific energy source referred to in the collected data. Further details on the modelling of electricity and thermal energy inputs are provided in Section 2.1.7.6.

Where more datasheets were received for the same (or similar) recycling technology, an average process inventory was developed, based on adjusted inputs and outputs per functional unit determined for single processes after checking material balances (as described above). Inputs and outputs of the average process

were determined by combining all relevant inputs and outputs of the individual processes considered as a basis. The amount of each input and output was then calculated as weighted average of the quantities used or generated in the individual processes, considering as weighting factor the adjusted amount of input-waste to each process. For mechanical recycling processes, an average inventory was developed for PET packaging waste (based on 4 templates), while for chemical recycling this was the case of PET alkaline hydrolysis (2 templates), PS packaging depolymerisation (2 templates), MPOs flexible packaging waste pyrolysis (7 templates, including also 3 templates for mixed plastic waste pyrolysis) and used tyre waste pyrolysis (2 templates).

For chemical recycling processes, the burdens associated with possible mechanical pre-treatment of the input waste to sort out any non-targeted and/or non-suitable material fraction, and to possibly shred the waste to be fed into the process, were included in the inventory, unless it was clearly reported that these steps were already covered by the received data. In the absence of specific information, the sorting step was modelled based on average data referring to centralised sorting of mixed plastic waste from municipal and industrial collection in dedicated facilities (Franklin Associates, 2018), as reported in Table 4. Separated fractions were then assumed to be sent either to further treatment in the chemical recycling process (targeted plastic fraction), to recycling in external facilities (recyclable fractions such as metal scrap, waste paper/cardboard and specific non-targeted plastics), or to energy recovery via incineration (other fractions, such as mixed plastics). For shredding, an average electricity consumption of 61.1 kWh per tonne of input waste was estimated, based on the specific demand of plastic granulators with different throughputs (between 12-50 kg/h and 2500-10000 kg/h), as reported in different unit-process datasets available in the GaBi database (Sphera, 2022).

Table 4. Life cycle inventory of possible mechanical sorting of the input-waste to chemical recycling processes to separate any non-targeted and/or non-suitable material fraction (based on Franklin Associates (2018)). Amounts per kg waste treated.

Input	Amount	Dataset name	Dataset source
Electricity	0.0458 MJ	[EU-28+3] Electricity grid mix 1kV-60kV; AC, technology mix | consumption mix, at consumer | 1kV - 60kV {34960d4d-af62-43a0-aa76-adc5fcf57246}	EF 3.0
Natural gas	1.09×10-4 MJ	[EU-28+3] Thermal energy from natural gas, technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency {81675341-f1af-44b0-81d3-d108caef5c28}	EF 3.0
Diesel	0.00153 kg	[GLO] Diesel combustion in construction machine, diesel driven {dae81b4f-688f-44cd-906b-9435d3843e65}	EF 3.0
LPG	0.078 MJ	[GLO] propane, burned in building machine {4dd96eab-d6a2-48d2-a192-ac59e55e0d47}	*ecoinvent*

When the main recycled material or product output(s) declared for a given recycling process were not in a form useful to replace any specific virgin material or product on the market, additional process steps required to enable such replacement were modelled. For instance, when plastic flakes were declared as the main output from mechanical recycling, further conversion (extrusion) into pellets was additionally considered in the inventory, so that replacement of virgin plastic granulate typically available on the market could be assumed. The extrusion process was modelled based on the exchanges reported in the unit-process dataset *"[DE] Pelletizing and compounding; technology mix | production mix, at plant | Pelletizing and compounding*", available in the GaBi database (Sphera, 2022). The process inventory accounted for electricity consumption (1.1 MJ / kg input plastic flakes) and treatment of process losses (incineration was assumed), based on a conversion efficiency equal to 98%.

Suitable EF-compliant datasets or proxy datasets representative of average EU conditions were applied, where available, to model production and supply of the inventoried ancillary inputs (e.g. chemicals, additives, detergents, washing agents, fuels for internal movement) and of process water not directly withdrawn from nature, as well as external treatment of wastewater, sludge and process waste due to material and product use. Alternatively, relevant datasets from the *ecoinvent* database v3.6 (ecoinvent centre, 2021) were used when representative EF-compliant datasets were not available. Treatment (recycling or incineration) and disposal of non-targeted recyclable fractions, separated non-recyclable fractions, residues and losses were modelled as described in Section 2.1.7.4, while recycled and recovered products and resulting substitution of equivalent products on the market were handled as reported in Section 2.1.7.5.

2.1.7.3 Energy recovery (incineration)

Energy recovery of plastic waste (as an alternative to mechanical, physical, or chemical recycling) was modelled by developing waste-specific process inventories for each material fraction in the input-waste to be treated. The same approach was followed also to model energy recovery of most non-recyclable material fractions, residues and losses generated in the investigated recycling processes.

Waste-specific inventories were developed to be representative of average EU technology and conditions in terms of e.g. applied energy recovery and flue gas cleaning systems, with the related energy recovery rates, abatement efficiencies, and resulting process-specific emissions. The modelling was based on thermodynamic-based transfer coefficients to calculate the partitioning of the chemical elements present in the input-waste between the flue gas and solid residues, i.e. bottom ash and air pollution control residues. By doing so, input-specific air emissions are determined on the basis of the specific physico-chemical composition of the input-waste.

Emissions of selected substances (i.e. HCl, HF, NOx, VOC, N_2O, CO, NH_3, SO_2, dust, dioxin, and some heavy metals) are modelled as process-specific (i.e. regardless of the input-waste composition), as mostly depending on the average concentration in flue gas achievable with the applied flue-gas cleaning technology, rather than on the characteristics of the input-waste. Energy recovery is based on the lower heating value of the input-waste and the assumed EU average electricity and heat recovery efficiencies (i.e. 15% and 35%, respectively). According with the applied modelling approach and system boundary, the avoided burdens associated with the substitution of energy (average EU electricity and heat mix) were credited to energy recovery scenarios (where incineration is the main treatment technology) and to recycling scenarios including energy recovery of separated non-recyclable fractions, residues and/or losses. The detailed incineration inventory, including a description of the literature sources used for compiling it, may be found in Table A1-1. Similarly, metal recovery from bottom ash was modelled based on literature, and the associated benefits (avoided virgin material production after recycling of recovered metal scrap) were credited to energy recovery scenarios or recycling scenarios including energy recovery processes. The detailed bottom ash treatment inventory, including literature sources used for compiling it, may be found in Table A1-2. Notice that energy recovery of hazardous waste was modelled by means of existing waste-specific incineration datasets or proxy datasets (EF-compliant or from the *ecoinvent* database v3.6).

2.1.7.4 Transport and treatment of separated materials, residues and losses from recycling and of residues from energy recovery

Outputs from recycling activities generated directly from processing the input-waste[18] and requiring further external treatment or disposal included: i) recyclable non-plastic materials (e.g. metals, paper and cardboard) and non-targeted plastics separated from the input-waste and sent for recycling in external facilities; ii) non-recyclable materials separated, generally as mixed materials, during recycling (e.g. mixtures of non-targeted/non-recyclable plastics, paper/cardboard, and/or other combustible materials, and mixtures of inert materials) sent to energy recovery in municipal or hazardous waste incinerators or to landfilling; as well as iii) non-recyclable process losses (e.g. PET fines and purge) and residues (e.g. filtration residues and sludge) that are sent to energy recovery via incineration, incineration without energy recovery (thermal treatment), or disposal in landfills. For energy recovery processes, outputs sent to further external treatment or disposal were recyclable metals separated from bottom ash (if included in the input-waste composition), and air pollution control residues sent for disposal in underground deposits.

All recoverable and non-recoverable material and waste streams generated from processing the input-waste in a recycling plant were assumed to be transported to further treatment or disposal along a distance of 50 km, covered by lorry (full load mass >32 t; EURO 4 emission class)[19].

External recycling of non-plastic fractions and non-targeted plastics separated during recycling, and of metals recovered from bottom ash, was modelled by means of suitable EF-compliant datasets representing the recycling of the specific material into a finished or semi-finished product in the EU (e.g. graphic paper and metal billets or ingots). Alternative datasets from the *ecoinvent* database v3.6 (ecoinvent centre, 2021) were used when suitable EF-compliant datasets were not available. In a few cases, proxy datasets were used, in the

[18] Thus excluding any waste generated from running the recycling process due to the use of specific products and materials.

[19] Modelled using the EF-compliant dataset: "*[EU+EFTA+UK] Articulated lorry transport, Euro 4, Total weight >32 t; diesel driven, Euro 4, cargo | consumption mix, to consumer | more than 32t gross weight / 24,7t payload capacity*".

absence of representative data for the specific recycling process or for EU as reference geography. For instance, recycling of rubber was approximated with data related to mechanical recycling of generic plastic waste into secondary plastic granulate. Overall, these approximations are considered to only marginally affect the results, as generally applying to minor material streams in terms of quantity produced per functional unit. The substitution of recycled products for equivalent primary products on the market was modelled as described in Section 2.1.7.5.

To model energy recovery of most non-recyclable material fractions, residues and losses generated from recycling processes, material-specific inventories were developed as described in Section 2.1.7.4. However, for some of these waste streams (e.g. filled PP from WEEE recycling), representative data on the respective physico-chemical composition were not available and a proxy composition was thus applied for modelling (e.g. in the case of filled PP, the composition of a combustible waste with high concentration of flame retardant was considered). When energy recovery took place in hazardous waste incinerators, the modelling was based on existing waste-specific datasets from the *ecoinvent* database v3.6 (no models for hazardous waste incineration were available in EASETECH), generally relying on the best available proxy dataset for the specific waste material to be incinerated. Particularly, incineration of brominated and chlorinated plastics (ABS, PP and PVC) and of Cd- and Pb-containing sludge from WEEE recycling was approximated with incineration of average hazardous waste, in the absence of specific datasets for these material fractions.

Landfilling of non-recoverable fractions, residues and losses from recycling was modelled by means of existing waste-specific EF-compliant or *ecoinvent* datasets identified as the most appropriate to represent disposal of each material fraction following this fate. These pre-compiled datasets are developed based on a controlled-landfill model applying element-specific transfer coefficients to calculate the distribution of elements in the input-waste composition between landfill gas and leachate, and their ultimate emission to the environment over a 100-year time horizon. Emissions occurring beyond 100 years from landfilling are not accounted in the model. Site-specific and technology-specific parameters reflect average EU conditions. Also in this case, some approximations were performed. For instance, disposal of sludge containing organic residues and fine fibres originally present in the input-waste as contaminants, or derived from its processing, was approximated with landfilling of average sludge from pulp and paper production.

A particular residual stream was represented by sludge generated during physical recycling of EPS from construction and demolition waste, consisting of the flame retardant Hexabromocyclododecane (HBCD) and degraded PS separated (and lost) in the recycling process. This stream was declared to be sent to thermal treatment in a high-temperature waste incinerator, where HBCD and residual PS are destructed, while elemental Bromine is recovered for possible further use. Since no specific data were provided nor were available for this treatment, the respective process-inventory was approximated with an *ecoinvent* dataset related to municipal incineration of a combustible material with the highest bromine concentration available (i.e. 7%), which is likely lower than the actual (unknown) concentration in the sludge. On the one hand, this approximation may underestimate the burdens of the treatment, as the modelled process deals with a lower Bromine concentration and operates at lower temperatures than those applied in the real process. On the other hand, the modelled benefits may be overestimated, as benefits from energy recovery are likely higher than any benefits associated with Bromine recovery and possible replacement of market Bromine. Therefore, overall, the net impacts from this particular treatment are likely underestimated, although it is acknowledged that they apply to a residual stream accounting for only ca. 4% of total process outputs.

2.1.7.5 Recycled and recovered products and related substitutions

Recycled and recovered products/co-products (e.g. recycled materials and recovered energy or fuels) were identified as those process outputs that can be directly sold on the market and used, as such or after further external processing/conversion, to replace virgin plastic materials, chemical intermediates (e.g. monomers) or feedstock (e.g. naphtha), and/or conventional fuels or energy (electricity and heat). Where relevant, such additional processing and/or conversion steps (e.g. metal or paper recycling) were modelled, as described in Section 2.1.7.4.

According with the applied methodological approach and system boundary (Section 2.1.2), recycled and recovered products/co-products were assumed to replace equivalent primary products on the market, obtained from virgin or conventional production routes. Specific substitution factors (quality ratios) were applied, where relevant, to account for any real or potential difference between the quality of recycled and replaced primary products, as detailed in Table 5. For mechanically recycled polymers (regranulate), substitution factors were determined based on the ratio between the market value of recycled and virgin granulate, assuming that differences in the market value of a given polymer can be used as proxies for any differences in its overall

(technical) quality. Three-year average prices for the period 2019-2021 were considered, for both recycled and virgin polymers, to calculate substitution ratios[20]. In case of market ratios larger than 1, the substitution factor was assumed to be 1:1, as replacement of larger amounts of virgin material from a given amount of recycled material is physically impossible. The same market value-based ratios calculated for mechanically recycled polymers were applied also to polymers from combined physical recycling, following a conservative approach, although their quality may be different from the former. For chemically recycled polymers, a 1:1 replacement was considered, assuming that a quality comparable to that of the displaced virgin polymers is achieved through chemical recycling technologies. For all other products, substitution factors were defined on a case-by-case basis, based on technical (e.g. for metals and paper) or economic considerations.

Cradle-to-gate burdens associated with avoided market-average production of replaced primary/conventional products were modelled based on suitable EF-compliant or *ecoinvent* datasets for each substituted product. Proxy datasets were used for a few process, generally in terms of reference geography. For instance, avoided production of primary cold rolled steel, assumed to be replaced by secondary steel, was modelled using a dataset referring to German and not EU conditions, due to the lack of suitable EF-compliant datasets for this geography. In the case of RDF (refuse-derived fuel) replacing conventional and other alternative fuels used in cement kilns (see Table 5), avoided burdens included not only those from extraction and supply of the specific fuel, but also avoided airborne and waterborne emissions from its combustion in the kiln (estimated based on a dedicated input-specific model for hazardous waste incineration, i.e. Doka (2009). Additional emissions from combustion of RDF, estimated based on the same model, were also taken into account in the scenario, as these emissions differ from those associated with combustion of replaced fuels (and thus were modelled to reflect differences in the burdens resulting from using RDF as a co-product from recycling).

Regarding energy substitution, recovered electricity was assumed to replace average electricity from the EU grid, represented by the residual EU electricity grid mix as of 2020[21], including 31.56% nuclear, 25.5% natural gas, 19.97% lignite, 14.59% hard coal, 3.00% hydro & marine, 2.38% wind, 1.59% biomass, 0.70% oil, 0.66% solar, and 0.05% geothermal (Sphera, 2021). For thermal energy substitution from recovered heat, an average EU thermal energy mix was calculated, as described in Section 2.1.7.6, and considered for replacement. The mix reflects the combination of most relevant heat sources estimated to be currently used in the EU, and includes 43.3% natural gas, 27.3% hard coal, 25.8% biomass, and 3.5% heavy fuel oil.

[20] Annual-average market values were calculated based on (average) monthly prices for primary and secondary plastics provided in the "BvSE Market Reports" available from the website "Plasticker – the home of plastics" (https://plasticker.de/preise/marktbericht_en.php).

[21] As modelled in the EF-compliant dataset: "*[EU-28+3] Residual grid mix; AC, technology mix | consumption mix, to consumer | 1kV - 60kV*".

Table 5. Main assumptions related to the modelling of the substitution of (primary) market products by products obtained from the investigated recycling scenarios: substituted products and corresponding substitution factors.

Input-waste	Technology	Recycled product	Substituted product	Substitution factor
PET packaging (bottles and trays)	MR	PET regranulate (food grade)	Virgin PET granulate (bottle grade)	1:1
		PET regranulate (non-food grade)	Virgin PET granulate (amorphous)	1:0.85
	CR-(I)	PET granulate	Virgin PET granulate	1:1
	CR-(II)	Ethylene glycol (EG)	EG from virgin fossil-based feedstock	1:1
		Purified terephthalic acid (PTA)	PTA from virgin fossil-based feedstock	1:1
	CR-(III)	Ethylene glycol (EG)	EG from virgin fossil-based feedstock	1:1
		Purified terephthalic acid (PTA)	PTA from virgin fossil-based feedstock	1:1
		Sodium sulphate	Sodium sulphate (market-average production)	1:1
	MR CR-(I) CR-(II) CR-(III)	PP regranulate (non-food grade)	Virgin PP granulate	1:0.6
		HDPE regranulate (non-food grade)	Virgin HDPE granulate	1:0.65
		Steel billet (secondary)	Semi-finished steel product (primary)	1:1
		Rubber regranulate	Synthetic rubber	1:1
		Secondary graphic paper	Virgin paper (kraft)	1:1
PS packaging	MR	PS regranulate (non-food grade)	Virgin PS granulate	1:0.65
	CR	Styrene	Styrene from virgin fossil-based feedstock	1:1
	MR / CR	Steel billet (secondary)	Semi-finished steel product (primary)	1:1

Mixed polyolefins (MPOs) flexible packaging	MR-(I)	MPO regranulate (non-food grade)	Virgin HDPE granulate (50%) Virgin PP granulate (50%)	HDPE = 1:0.45 PP = 1:0.4
		PP regranulate (non-food grade)	Virgin PP granulate	1:0.6
		HDPE regranulate (non-food grade)	Virgin HDPE granulate	1:0.65
		RDF	Average fuel mix to cement kilns[(a)]	1:1 (energy-based)
	MR-(II)	MPO agglomerate	Virgin HDPE granulate (50%) Virgin PP granulate (50%)	HDPE = 1:0:15 PP = 1:0.15
		RDF	Average fuel mix to cement kilns[(a)]	1:1 (energy-based)
	CR-(I) CR-(III)	Hydrocarbons (CR-(I) only)	Virgin mixed hydrocarbons (ethylene, propylene, butadiene, benzene, butane and pentane)	1:1
		Naphtha (CR-(III) only)	Virgin naphtha	1:1
		Pyrolysis gas	Average EU heat mix (see Section 2.1.7.5)	1:1 (energy-based)
		Light fuel oil (CR-(III) only)	Virgin light fuel oil	1:
		Heavy fuel oil	Virgin heavy fuel oil	1:1
		Carbon black (CR-(I) only)	Carbon black	1:1
		Wax	Virgin paraffin wax	1:1
	CR-(II)	Hydro-treated pyrolysis oil	Virgin naphtha	1:1
		Pyrolysis gas	Average EU heat mix (see Section 2.1.7.5)	1:1 (energy-based)
		Char	Virgin bitumen	1:1
		Tar	Virgin bitumen	1:1
	MR-(I), MR-(II) CR-(I), CR-(II), CR-(III)	Steel billet (secondary)	Semi-finished steel product (primary)	1:1
		Aluminium ingot (secondary)	Aluminium ingot (primary)	1:1

Large-format PE film	MR PR	LDPE (re)-granulate (non-food grade)	Virgin LDPE granulate	1:0.5
		RDF	Average fuel mix to cement kilns[(a)]	1:1 (energy-based)
		Steel billet (secondary)	Semi-finished steel product (primary)	1:1
		Aluminium ingot (secondary)	Aluminium ingot (primary)	1:1
PE/PA multilayer packaging film	PR	LDPE granulate (non-food)	Virgin LDPE granulate	1:0.5
		PA granulate (non-food grade)	Virgin PA granulate	1:0.5
EPS (CDW)	PR	PS granulate (non-food grade)	Virgin PS granulate	1:0.65
Used tyre waste	CR	Pyrolysis oil	Crude oil	1:1
		Pyrolysis gas	Average EU heat mix (see Section 2.1.7.5)	1:1 (energy-based)
		Carbon black	Carbon black	1:1
		Steel billet (secondary)	Semi-finished steel product (primary)	1:1
Mixed shredded plastics from small WEEE (small domestic and ICT appliances)	MR	ABS regranulate	Virgin ABS granulate	1:1
		PP regranulate (non-food grade)	Virgin PP granulate	1:0.6
		PS (high-impact) regranulate	Virgin PS (high-impact) granulate	1:0.65
		Steel billet (secondary)	Semi-finished steel product (primary)	1:1
		Aluminium ingot (secondary)	Aluminium ingot (primary)	1:1
		RDF	Average fuel mix to cement kilns[(a)]	1:1 (energy-based)
Mixed shredded plastics from large WEEE (cooling and freezing appliances)	MR	PS (high-impact) regranulate	Virgin PS (high-impact) granulate	1:0.65
		ABS regranulate	Virgin ABS granulate	1:1
		PP regranulate (non-food grade)	Virgin PP granulate	1:0.6
		Steel billet (secondary)	Semi-finished steel product (primary)	1:1
		Aluminium ingot (secondary)	Aluminium ingot (primary)	1:1
		RDF	Average fuel mix to cement kilns[(a)]	1:1 (energy-based)

([a]) Including hard coal (30.9%), petroleum coke (30.9%), wood chips (from post-consumer wood; 24.8%), used tyre (6.3%), animal meal (4.1%), and used solvents (3.0%).

2.1.7.6 Electricity and thermal energy generation

Electricity supply from the grid (EU average grid mix) was modelled by means of the EF-compliant dataset *"[EU+EFTA+UK] Electricity grid mix 1kV-60kV; AC, technology mix | consumption mix, at consumer | 1kV - 60kV"*, which is built as combination (weighted average) of the electricity consumption mixes (grid mixes) of single countries contributing to the total mix (i.e., 31 countries overall). For thermal energy generation, an average EU mix was defined for modelling, based on most recent statistics (IEA, 2021), with the aim of reflecting most relevant thermal energy sources used in that region under current conditions. The share of each energy source was calculated as the average value of individual shares determined for the years 2018, 2019 and 2020 based on raw IEA data. Relevant EF-compliant datasets were then used, where available, to represent each source included in the mix, as described in Table 6. To define the mix, small average shares of thermal energy generated from geothermal, nuclear, and solar thermal sources (less than 1% overall) and other unspecified sources (5%) were excluded, in the absence of specific datasets to model the respective process inventory. Thermal energy from waste (11%) was also excluded, in the absence of both specific information on the type of waste used and of suitable datasets to represent this energy source, which accounts for only a moderate share overall.

Table 6. EU-average thermal energy mix defined and used in the study, and datasets applied to model each energy source.

Thermal energy source	Share	Dataset name	Dataset source
Natural gas	43.3%	[EU-28+3] Thermal energy from natural gas; technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency	EF 3.0
Coal	27.3%	[EU-28+3] Thermal energy from hard coal; technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency	EF 3.0
Biomass	25.8%	[EU-28] Thermal energy from biomass (solid); technology mix regarding firing and flue gas cleaning | production mix, at heat plant	GaBi database (Sphera, 2022)
Fuel oil	3.52%	[EU-28+3] Thermal energy from heavy fuel oil (HFO); technology mix regarding firing and flue gas cleaning | production mix, at heat plant | MJ, 100% efficiency	EF 3.0

2.2 Life cycle costing

A conventional LCC[22] (CLCC) focusing on internal costs (budget costs and transfers) and reflecting a traditional financial assessment was performed. The conventional LCC adhered to state-of-the-art LCC methodology as presented in (Hunkeler D. et al., 2008; Martinez-Sanchez et al., 2015). The LCC and LCA share the same object, scope, functional unit, and system boundaries. For the former, differently than the LCA where a zero-burden assumption was taken, the waste was assigned a price to reflect eventually different qualities. Notice that lower quality feedstock, while being cheaper, might require additional cleaning and sorting to be treated by selected technologies (having stricter requirement on input quality), thus overall increasing OPEX. Similarly to the LCA, we strived to take this into account also in the LCC.

The cost assessment includes internal costs (budget costs and transfers); strictly, budget costs are costs incurred by the different actors involved in the management chain of the waste (collectors, operators, transporters, etc.), while transfers refer to money redistributed among stakeholders (taxes, subsidies, value added tax - VAT, and fees). In our analysis, for the purpose of simplicity and the resolution of the data obtained, we will refer only to the aggregated internal costs in general reported as operational expenditures and capital

[22] This is different from a societal LCC (SLCC) that sums the internal to the external costs, both expressed as shadow prices, to quantify the total cost carried by the society, thus reflecting a socio-economic or welfare assessment.

expenditures (sum of OPEX and CAPEX). The CLCC also allows deriving the total employment induced by the waste management system, expressed as full-time equivalent jobs per tonne of waste managed (FTE/tonne). The LCC was implemented using the software EASETECH v3.4.0 (Astrup et al., 2012; Clavreul et al., 2014).

As concerns the data used to represents costs, it should be kept in mind that, due to claimed confidentiality and competitiveness concerns, most stakeholders did not fill in the information on costs in the surveys. Thus, we had to rely strongly on databases and the literature for the economic parameter values. Notably, the data for CAPEX and OPEX of mechanical recycling technologies were not provided and we therefore approximated them using the figures provided in (Andreassi Bassi et al., 2022). These may be well-representative of PET mechanical recycling technologies but less representative of other polyolephines recycling plants such as PE, PP or PS. For chemical recycling technologies, whenever not available from the surveys, CAPEX and OPEX were based on KIDV (2018) and/or Stapf et al. (2018). These data represent technologies under development or with low TRL. On this basis, and similarly to the prices for mechanical technologies other than PET, these data may not be representative of full-scale implementation of these plants. Prices of sorted waste-bales and recycled materials were retrieved from different on-line databases. The remaining information regarding costs of waste transport, incineration, landfill and energy carriers were based on previous work conducted by the JRC in the context of plastic waste management (notably, Andreasi Bassi et al., 2022). All prices were adjusted according to inflation to EUR 2019. More detailed information may be found in Table A2-1.

2.3 Further economic assessment of physical and chemical recycling

2.3.1 Collection of economic data

Very limited economic data was disclosed in the stakeholder surveys, so it had to be complemented with data from the literature and from databases. The data on the prices of the products of the recycling processes are often based on the prices of the corresponding virgin-based products, which might lead to over- or underestimation of the real costs.

Regarding the prices of feedstock, we supplemented the survey data with price overviews from the Plasticker material exchange,[23] trade data from EUROSTAT COMEXT,[24] and trade data from the UN COMTRADE database[25]. Data from the Plasticker material exchange are based on offers made on the exchange. Data on the actual transactions are not reported, just on offers. Prices are calculated monthly and consider all offers which were made at any given time of that month (and which were within the interval of two times the standard deviation).

Data on (annualised) CAPEX and OPEX of CR pathways was particularly scarcely reported in the survey, with either only one respondent (which we cannot report here due to confidentiality reasons) or no respondent at all for most pathways, except for the case of pyrolysis (with three respondents for pyrolysis of MPW). It is equally scarcely reported in the literature: nevertheless, we found estimates for pyrolysis, gasification, dissolution, methanolysis and glycolysis in Carducci et al. (2020), Faraca et al. (2019), KIDV (2018) and Stapf et al. (2018).

Output prices, that is the prices of the different recycled materials, were retrieved from various commercial sites[26] whenever they were not available from the surveys. All data are reported in Section 3.3.

2.3.2 Methodology

In the following, we define a chemical recycling technology as "economically viable" if its net income in a given year is greater than zero. Similar to Ghodrat et al. (2019), we define net income (NI) as the revenues minus the costs, both given in € per tonne of waste treated.

The main determinants of the costs of different chemical recycling (CR) technologies are the price of the feedstock as well as other operational and capital costs. The main determinant of the revenue (per tonne of waste) is the price at which the recycled goods are sold, which can be influenced by the quality of the recycled output[27].

[23] https://plasticker.de/recybase/index_en.php
[24] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=546683#Average_prices_and_trade_volumes
[25] https://comtrade.un.org/
[26] https://shipandbunker.com, https://www.chemanalyst.com, https://www.recyclingpyrolysisplant.com, https://3mgas.vn , https://www.made-in-china.com and https://www.finanzen.net/rohstoffe/.
[27] Further conditions include government regulations and policies such as the provision of pre-sorted, pre-cleaned plastic waste, as well as taxes and subsidies.

The costs of treating one unit of plastic waste with technology X are given by $C^X = CAPEX^X + OPEX^X$, where $OPEX^X = f(C^X_{feedstock}, C^X_{transport}, \dots)$. Each technology X produces different goods g^X_n which are sold at prices p_n. Revenues are hence given by $R^X = \Sigma^{k^X}_{n=1} g^X_n p_n$, where $k^X$is the number of goods produced by technology X.

Due to the large volume of virgin fuel, polymer and chemical production and assuming a well-functioning market, the prices of the goods will depend only on the cost of virgin production, i.e. $p_n = f(C^{VG})$. Net Income (NI) from treating one unit of plastic waste with technology X is given as: $NI^X = R^X - C^X$.

If there is a difference (real or perceived) in the quality of the recycled output compared to the virgin output, there will be a price markdown ("discount"), which is accounted for in the data collection whenever possible. Conversely, if the recycled product is valued higher than the virgin-based product, e.g. as a consequence of a recycled content policy (or 'green premium'), recycled product prices can exceed those of virgin based products. Due to a lack of price data provided by the stakeholders, we can assess this effect only for a limited number of products.

Regarding the quality of the input, feedstock quality is reflected in the price: lower quality feedstock is cheaper, but might need additional cleaning and sorting, which increases OPEX. The economic analysis in Section 3.3.3 then uses empirical data to determine the costs and the revenues from CR technologies in order to assess their economic viability.

2.4 Operational assessment of chemical recycling

The case of operational data collection is very similar to the one of economic data collection. Despite repeated attempts at obtaining survey-based information from operators, which could help identify the key conditions under which chemical recycling can function optimally from a technical point of view (e.g. safety, yield, predictable quality of output), no such input was received. For this reason, a literature review was conducted, specifically aimed at chemical recycling technologies. Physical recycling technologies were not included in this review due to the very limited information available.

There may be various reasons for the lack of stakeholder and operator input, particularly linked to the fact that many operations constitute advanced pilot plants or small-scale commercial installations. Chemical recycling of plastic waste is an emerging technology field, featured by rapid technological developments and fierce competition. Furthermore, identifying possible operational issues may hamper operators' efforts to secure investment for expanding their business or create an obstacle in the growth of chemical recycling in general.

The field of plastic chemical recycling thus contrasts largely with comparable fields like mechanical recycling of plastics or petrochemical activities for which possible operational issues and challenges have been well documented, and where solutions are available. This may also explain why some important players in the plastic waste management and recycling sector have expressed reluctance to entering the field of chemical recycling (Hugo, 2022).

Nonetheless, section 3.4 highlights and discusses operational aspects of chemical recycling, based on the scarce information that could be found in the more recent scientific literature. It should be stressed that most of the literature is based on laboratory or pilot scale information, with very little literature referring to full scale plants.

3 Results

In the following sections, the potential environmental impacts of the investigated mechanical recycling, physical recycling, chemical recycling, and energy recovery scenarios are presented for a subset of impact categories, namely: Climate Change, Particulate Matter, Acidification, and Resource Use, fossils (Section 3.1.2). These impact categories were selected as the most relevant in the context of plastic waste management, based on previous evaluations, notably Andreassi Bassi et al. (2022). For an overview of the results for the remaining ten impact categories, please refer to Annex 3, which also includes numerical results for the four categories addresses in this section. Conventional life cycle costs of the investigated scenarios are also presented (Section 3.2.2), as well as the results of further economic assessment and preliminary operational assessment of chemical and physical recycling technologies (Section 3.3 and 3.4, respectively). Overall coverage and quality of the data received and applied for life cycle assessment and further economic assessment are also discussed in the corresponding section.

3.1 Life cycle assessment of recycling and energy recovery scenarios

3.1.1 Data coverage and quality

Primary data and information on the investigated recycling technologies, received from stakeholders in the data collection exercise, covered relevant inputs and outputs of the specific recycling process, including: plastic waste streams used as feedstock; recycled and recovered products (materials, chemical intermediates and feedstock, fuels, etc.); inputs of energy (electricity and heat), fuels, water and ancillary materials/products (e.g., chemicals, additives and detergents); as well as wastewater outputs, waste flows (non-recyclable fractions, process residues, losses and other waste), and direct emissions to air and water. For each of these inputs and outputs, quantitative information on the amount used or generated in the process during the chosen reporting period (generally one year) was provided, and possibly complemented by more or less detailed qualitative information describing the type and nature of the specific input or output. This additional information included, for instance, the general characteristics of the incoming plastic waste (e.g. according to specific national recycling standards), final market applications for the recycled product(s), the use of any specific energy sources, the intended use of ancillary inputs (e.g., water and chemicals), the fate of generated waste and wastewater flows (e.g., internal or external treatment of wastewater), and the overall material composition of certain (complex) waste streams.

In most of the data templates (datasheets) used in the study, the information and data provided were complete and detailed enough to develop a preliminary life cycle inventory of the recycling process. However, the level of detail of the information and descriptions provided was not consistent across the different datasheets, and in most of them relevant aspects and/or elements were missing. These included, for instance, the specific characteristics of the input-waste, the detailed composition and/or fate of the generated residues, losses and other waste streams, as well as data on particular treatments of such residues, losses and waste. Therefore, collected data and information had to be generally complemented with a number of assumptions (based on authors' experience and knowledge), and with additional data from the literature and existing databases, to develop suitable and final process inventories (as described in Section 2.1.7). Moreover, declared quantities of the main material inputs and outputs of the recycling processes, in terms of waste input, recycled or recovered product/material outputs, and -where reported- residues, losses and other waste, were often not fully consistent, i.e. mass balances did not fully close. Further interpretation, elaboration and amendment of the collected raw data was thus generally required to adjust inconsistencies and ensure fulfilment of mass balances (see Section 2.1.7.2).

One of the most important gaps was generally related to the specific characteristics of the input waste (e.g. detailed composition and possible classification according to existing recycling standards or schemes), as well as to its nature (e.g. post- or pre-consumer waste) and origin. In most cases, these aspects were not reported or not sufficiently specified, while only generic descriptions were provided without additional information (e.g., "mixed household post-consumer packaging waste", "mixed lightweight packaging waste", or "mixed plastics after shredding of small appliances"). Alternatively, impurities and any other waste flows beyond those intended for recycling were not reported or not quantified. The composition of the input waste had thus to be generally inferred or estimated based on available information on the processed feedstock, as well as on reported outputs of recycled product(s)/material(s) and process residues, losses and waste. Moreover, several specific assumptions had normally to be made (especially on the type and composition of the reported residual and waste streams, as discussed below) to identify and differentiate the specific material fractions in the input waste. In a few cases, such additional specific assumptions could be cross-checked with stakeholders, although this could not be consistently performed across all the investigated recycling processes. For some processes

(i.e. mechanical recycling of flexible packaging made of mixed polyolefins and large-format PE film), the data and information provided was not sufficiently detailed and literature data had to be used as a basis to define a suitable input-waste composition (as described in Section 2.1.4).

The specific type and composition of non-recyclable materials, residues, losses and/or other possible waste streams generated from recycling processes was also frequently not reported, while they were either: i) defined only generically (e.g. "-sorting- reject bales", "waste to incineration", "filtration residue to incineration", "other solid waste arising to incineration", "fluff for RDF production"); ii) defined based on a very generic EWC[28] code (e.g. "other wastes -including mixtures of materials- from mechanical treatment of wastes"); iii) defined considering only the machinery or process flow generating the waste, while providing a possible generic description (e.g. "flex sorter", "PET purge", "heavy fraction from wind shifter", "sludge from the separator"); iv) described only in terms of fate/destination (e.g. "incineration with energy recovery" or "hazardous waste incineration"); or v) defined by providing only a qualitative composition (e.g. "mixed rigid plastic, paper/cardboard, plastic films and other undesirable") with no indication of the relative share of each component. In some cases, no specific residual/waste flows were reported at all, although these were expected to be generated in the process. The fate (destination) of the reported waste flows was also often not specified. To fill these different gaps, any available literature on the process was consulted or, when possible, additional information was requested to stakeholders, which in some cases provided further detail. However, in most cases, different assumptions had to be necessarily performed. These assumptions were generally applied to waste streams accounting for a maximum of 5-10% of total process outputs, with no ultimate relevant effects on the results. In a few cases, the affected waste streams were more considerable (accounting for ca. 25-50% of total process outputs) and results therefore need to be interpreted and used more carefully in this case, especially where the impact contributions from treating such residual and waste flows is not marginal (e.g. for mixed shredded plastics from small WEEE).

3.1.2 Life cycle impact assessment results

This section presents the results of the environmental life cycle assessment, which are expressed per functional unit, i.e. management of one tonne (t) of plastic waste input to each of the compared set of scenarios (i.e. mechanical recycling, physical recycling, chemical recycling and energy recovery) including any impurities[29]. Positive impact contributions represent burdens to the environment, while negative impact contributions represent savings to the environment. The total net impact of the management of the waste at the level of individual scenarios is calculated as the difference between the burdens of the management pathway and the savings from the substituted products and co-products arising from that pathway, and it is referred to as "total" in the discussion of the results. The "total" impact is thus a 'net saving' when negative or a 'net burden' when positive. The results regarding potential impacts on Climate Change, Particulate Matter, Acidification, and Resource Use, fossils, with a breakdown of the contribution of each sub-process/activity, are presented herein, while the results related to the ten remaining environmental impact categories considered in this study can be found in Annex 3. For the entire set of fourteen categories, the latter provides detailed results tables with a breakdown of the contributions to the total impact of the different management scenarios investigated for a given plastic waste stream. A comparison of total scenario impacts across the different impact categories is also reported in

[28] EWC: European waste catalogue

[29] Material/chemical contaminants embedded in the wasted products or resulting from prior waste management operations (e.g. collection and sorting) as well as non-target polymers and non-plastic materials still present in the sorted waste stream after any prior sorting operations.

Annex 4. Note that the plastic waste input was considered to enter each scenario as "burden-free", i.e. free of any upstream environmental impact (as the upstream impacts of generating the waste would be the same across all the scenarios handling such waste). The impact contributions were aggregated into seven categories, representing the main processes and activities of the investigated scenarios:

Transport: it includes the impacts (burdens) from transport of the input-waste from centralised sorting facilities or collection centres to recycling or energy recovery, and transport of recovered non-targeted material fractions, separated non-recyclable fractions, residues and losses from recycling, as well as residues from energy recovery, to further treatment (recycling, incineration, thermal treatment or combustion in cement kilns) or disposal.

Processing – Energy: it includes the impacts (burdens) due to electricity and heat consumption from recycling.

Processing – Non Energy: it includes the impacts (burdens) associated with all non-energy inputs to recycling (e.g., fuels for internal transport/movement[30], water, chemicals, etc.), and with the external treatment or disposal of outputs generated from process operation, i.e. wastewater, sludge, and other waste streams due to material and product use to run the process.

Incineration: this category applies only to energy recovery pathways/scenarios, and includes the impacts (burdens) associated with the treatment (combustion) of the input-waste in the modelled energy recovery plant, including treatment of process residues (bottom ash and air pollution control residues).

Treatment of residues: it includes the impacts (burdens) associated with the external treatment or disposal of all material fractions, residues and losses generated, beyond the targeted plastic material(s), from handling the input-waste via recycling . This category thus includes the burdens from: (a) external recycling of non-targeted material fractions recovered in the process (e.g. metals and paper/cardboard); (b) combustion of RDF in cement kilns; (c) energy recovery or landfilling of (mixed) non-recyclable fractions separated during recycling (e.g. -mixtures of- non-targeted/non-recyclable plastics, paper/cardboard, and/or other combustible materials sent to incineration, and -mixtures of- inert materials sent to landfill); as well as (d) energy recovery, thermal treatment or landfilling of recycling residues (e.g. specified or unspecified fractions included in filtration residues or sludge) and losses (e.g. fines and purge).

Substitution of energy: it includes the savings due to the substitution of market energy from heat and electricity generated from incineration of the input-waste in energy recovery scenarios, or from incineration of non-recyclable material fractions, residues and losses from recycling. Where relevant, it also includes the savings associated with the combustion of RDF in cement kilns (i.e. with avoided fuel extraction and combustion).

Substitution of materials: it includes the savings due to the products and co-products substituted from the (secondary) materials and products derived from recycling, including separated non-targeted plastic and non-plastic materials present in the input-waste and recycled outside the process, such as metals and paper. In case of energy recovery, this category includes the savings from the substitution of metals following the recovery of ferrous and non-ferrous scrap from bottom ash (when relevant to the specific input-waste composition).

Across all scenarios investigated, the most important contribution to the burdens from recycling is provided by processing (energy and chemicals) and treatment of the residues generated within the processing itself, while the most important contribution to the savings is substitution of materials via recycling. In selected recycling pathways also substitution of energy via energy recovery becomes important owing to mass losses during recycling and the consequent diversion to incineration of a significant portion of the input-waste treated (e.g. as RDF).

For energy recovery, the most important contribution to the burdens is the incineration process itself (combustion and related emissions), while the most important contribution to the savings is energy substitution. Notice that for Climate Change, the burdens from incineration are always larger than the savings obtained via energy recovery and substitution (i.e. incineration burdens are much larger than energy substitution

[30] Impacts due to the use of fuels for internal transport and/or movement are included under the "Processing – Non energy" category as they are a material input to the process, in contrast to electricity and heat, which are energy inputs (and thus included under "Processing – Energy").

savings, leading to a net burden on Climate Change). This is not the case in the remaining categories (i.e. energy substitution savings are much larger than incineration burdens).

3.1.2.1 Comparison between mechanical recycling, chemical recycling, physical recycling and energy recovery

3.1.2.1.1 Sorted PET packaging waste (bottles and trays)

Figure 4 shows that the management of PET packaging waste results in:

Climate Change: Net savings for all recycling scenarios and net burdens for energy recovery. Mechanical recycling achieves the largest net savings (-1933 kg CO_2-eq./t PET waste) followed closely by Chemical recycling via partial glycolysis (CR-I) with comparable net savings (-1711 kg CO_2-eq./t PET waste). Chemical recycling via hydrolysis-methanolysis (CR-II) and alkaline hydrolysis (CR-III) achieve lower net savings, but still better than energy recovery, which incurs a net burden (1241 kg CO_2-eq./t PET waste, i.e. incineration burdens are much larger than energy substitution savings).

Particulate Matter: Net savings for all scenarios investigated except for chemical recycling via alkaline hydrolysis (CR-III), which results in a net burden due to a significant impact from consumption of sodium hydroxide. Chemical recycling via hydrolysis-methanolysis (CR-II) achieves the largest net saving, but it is comparable to partial glycolysis (CR-I) and mechanical recycling. Energy recovery via incineration also achieves a net saving, albeit lower. .

Acidification: Net savings for all scenarios investigated except for chemical recycling via alkaline hydrolysis (CR-III), due to the relevant burden from consumption of sodium hydroxide. Chemical recycling via hydrolysis-methanolysis (CR-II) achieves the largest net saving, followed by partial glycolysis (CR-I) and mechanical recycling (which are comparable) and energy recovery, while alkaline hydrolysis (CR-III) incurs a net burden.

Resource Use, fossils: Net savings for all scenarios investigated. Mechanical recycling and chemical recycling via partial glycolysis (CR-I) achieve the largest savings with similar magnitude, followed by the remaining chemical recycling technologies, i.e. hydrolysis-methanolysis (CR-II) and alkaline hydrolysis (CR-III). Energy recovery incurs the worst performance, but still achieving environmental savings overall.

Impact contributions: In chemical recycling via hydrolysis-methanolysis (CR-II), the processing of the waste incurs a higher Climate Change impact relative to mechanical recycling and chemical recycling via partial glycolysis (CR-I) due to higher energy consumption (heat and electricity) and lower credits from recycled material substitution. Similarly, in chemical recycling via alkaline hydrolysis (CR-III) waste processing has a (substantially) higher contribution across the four discussed impact categories, due to higher energy use and consumption of other inputs (notably sodium hydroxide) compared to the other recycling technologies.

The material substitution savings are maximised either in mechanical recycling (Climate Change and Resource Use, fossils) or in alkaline hydrolysis (CR-III; Particulate Matter and Acidification), due mostly to higher yields (i.e. higher production of recycled material) compared to the other recycling processes. However, mechanical recycling generally provides comparable or similar savings to partial glycolysis (CR-I), as both processes have similar yields (i.e. 88% and 86%, respectively). Moreover, in Particulate Matter all recycling technologies show comparable or similar savings, especially mechanical recycling and hydrolysis-methanolysis (CR-II). Similarly, in Acidification, the savings from hydrolysis-methanolysis (CR-II) are not substantially different from the largest one of alkaline hydrolysis (CR-III).

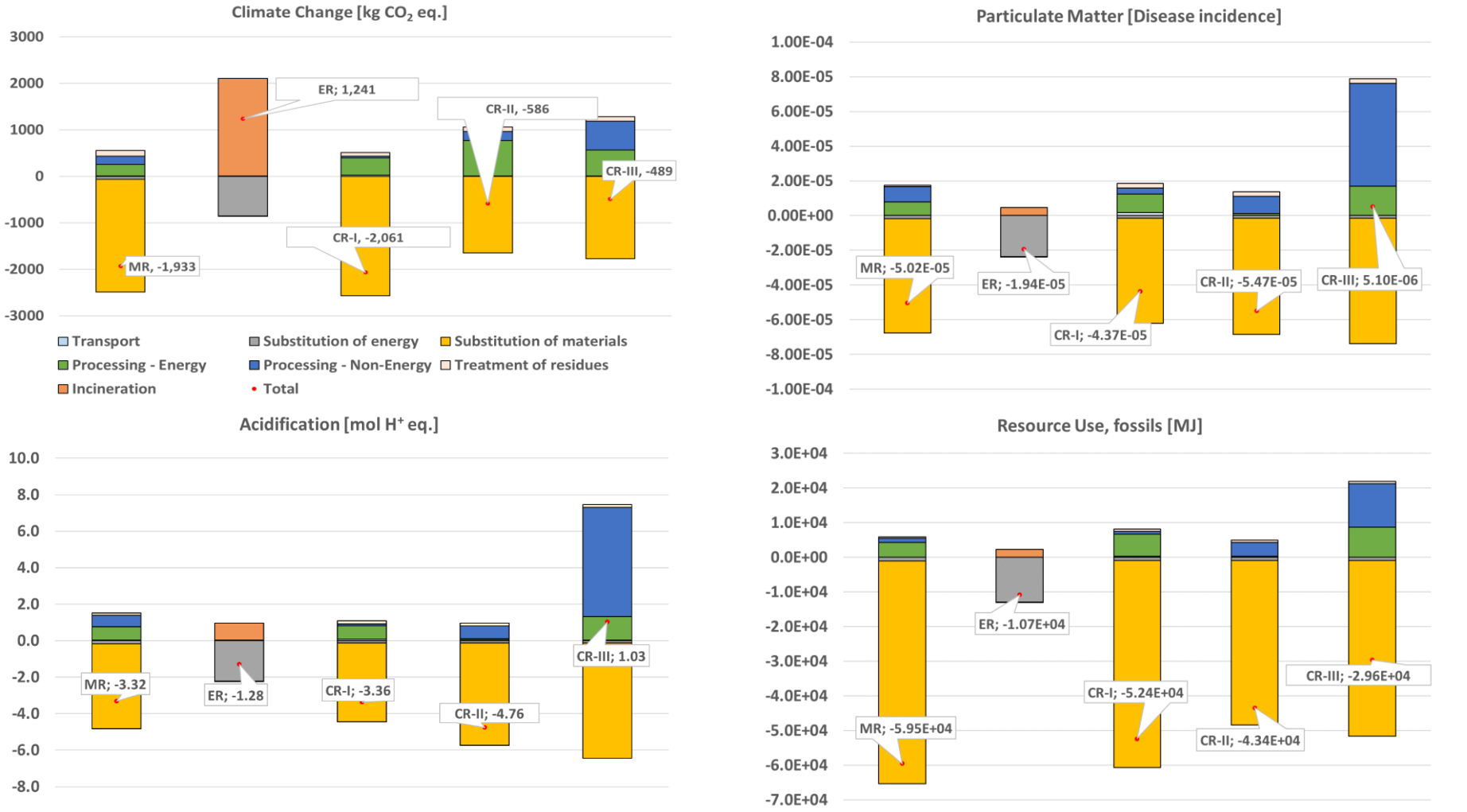


Figure 4. Management of 1 tonne of sorted PET packaging waste (bottles and trays) through mechanical recycling (MR; PET regranulate production), energy recovery (ER; incineration), and chemical recycling via partial glycolysis (CR-I), hydrolysis-methanolysis (CR-II), and alkaline hydrolysis (CR-III): Climate Change, Particulate Matter, Acidification, and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.1.2 Sorted PS packaging waste

Figure 5 shows that the management of PS packaging waste results in:

Climate Change: Net savings for both mechanical and chemical recycling, while energy recovery results in net burdens (1114 kg CO_2-eq./t PS waste, i.e. incineration burdens are much larger than energy substitution savings). Chemical recycling via pyrolysis-assisted depolymerisation results in the largest net saving, followed by mechanical recycling (-667 and -438 kg CO_2-eq./t PS waste, respectively).

Particulate Matter, Acidification and Resource Use, fossils: Net savings for all scenarios analysed. Chemical recycling via pyrolysis-assisted depolymerisation results in the largest net savings, followed by energy recovery and mechanical recycling. This ranking is only different in 'Resource Use, fossils', where mechanical recycling performs better than energy recovery, while chemical recycling still has the best performance (largest net savings).

Impact contributions: Material substitution savings are (much) higher in chemical recycling via pyrolysis-assisted depolymerisation relative to mechanical recycling, due to the higher yield (47% vs 70%) and 1:1 replacement of virgin styrene monomer rather than substitution of virgin PS granulate at a ratio of 0.65 (which explains the lower savings of mechanical recycling despite a polymer being replaced rather than a monomer). The contribution of the burdens from processing and treatment of the (process) residues are generally comparable in both recycling scenarios, while being moderately higher for chemical recycling in Climate Change.

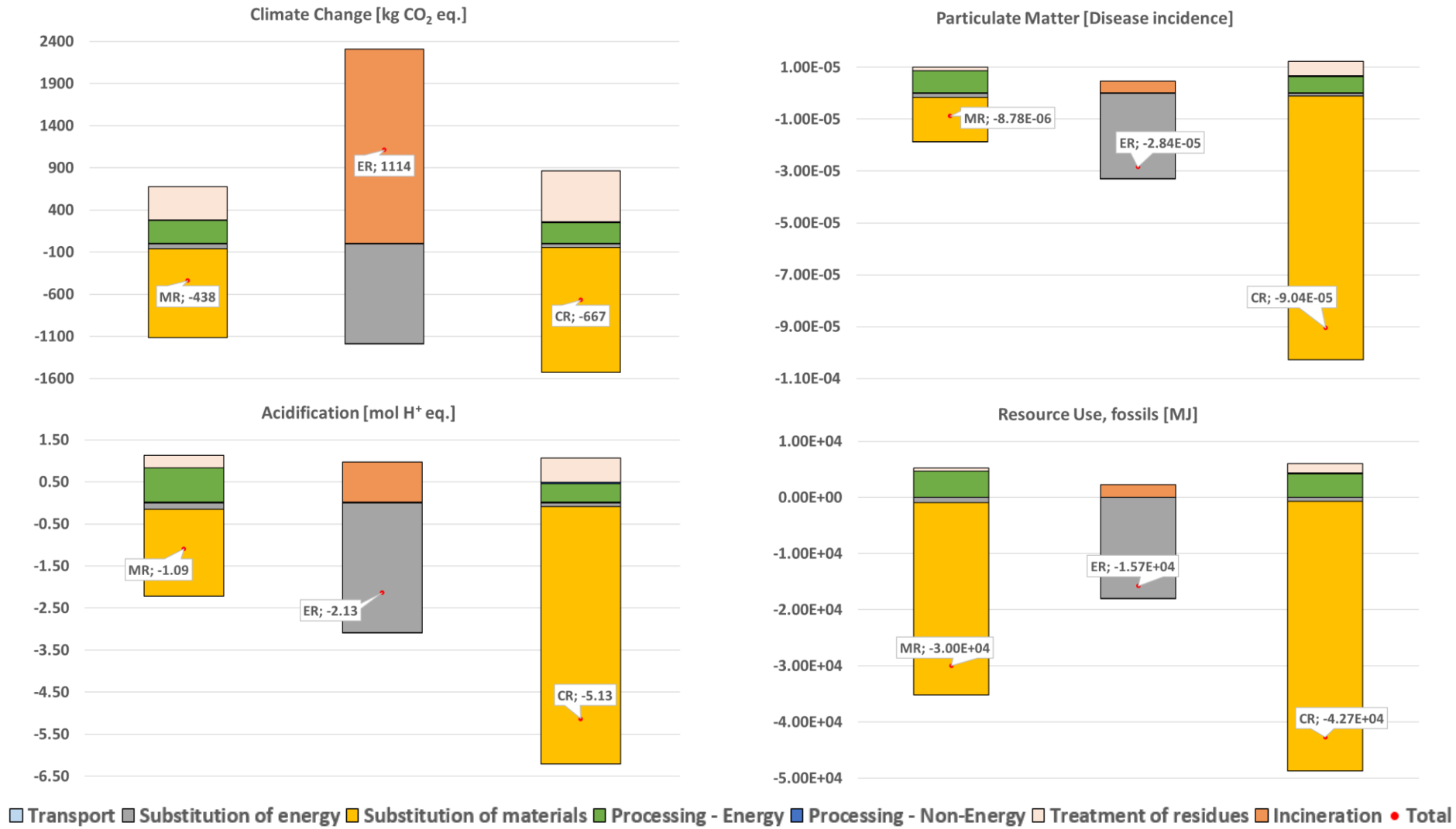


Figure 5. Management of 1 tonne of sorted PS packaging waste through mechanical recycling (MR; PS regranulate production), energy recovery (ER; incineration), and chemical recycling (CR; pyrolysis-assisted depolymerisation): Climate Change, Particulate Matter, Acidification, and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.1.3 Sorted MPO flexible packaging waste

Figure 6 shows that the management of 1 tonne of sorted MPO flexible packaging waste results in:

Climate Change: Net savings for mechanical recycling scenarios (both MR-I and MR-II; -209 and -56 kg CO_2-eq./t MPO waste, respectively). However, for MR-II (MPO agglomerate production), the net saving is limited as the savings from material and energy substitution are almost entirely balanced by the burdens from processing the waste and treatment of the residues. All chemical recycling scenarios incur a net burden, likewise energy recovery.

Particulate Matter, Acidification and Resource Use, fossils: Net savings for all pathways investigated. CR (III), i.e. chemical recycling via hydro-thermal pyrolysis, has the highest net savings in the Acidification and Resource Use, fossils impact categories, although for Acidification the savings are comparable to those from energy recovery. Energy recovery results in the highest net saving in the Particulate Matter category, followed by pyrolysis (CR-I), while the other chemical and mechanical recycling scenarios have lower and comparable net savings. MR-II (MPO agglomerate production) provides the lowest net savings, albeit in Acidification and Particulate Matter it is comparable to most (Particulate Matter) or part (Acidification) of the other investigated recycling scenarios.

Impact contributions: in Climate Change, chemical recycling scenarios (I, II, III) incurs higher burdens due to energy consumption for processing the waste relative to mechanical recycling (I and II). In the other impact categories, this is mostly the case of CR-I (pyrolysis), while CR-II (pyrolysis) and CR-III (hydrothermal pyrolysis) provide a burden comparable to that of mechanical recycling scenarios, particularly MR-II. Burdens from treatment of residues and non-energy process inputs and outputs are also in most cases comparable across the different mechanical and chemical recycling scenarios investigated. Savings from material substitution show different magnitudes and trends depending on the impact category, with the highest savings being in most cases associated with specific chemical recycling technologies, albeit also MR-I (regranulate production) provides substantial savings. The lowest material substitution savings are generally associated with MR-II (agglomerate production), due to the low substitution factor applied when replacing recycled for virgin material (as discussed below). Energy substitution savings associated with the production of RDF in mechanical recycling and its subsequent utilisation (substituting for fuels otherwise used in cement kilns) is also an important contribution. This is because the process losses are significant when recycling MPO, since a portion (ca. 15%) of the MPO waste bale consists of multi-material films (e.g. metal and paper laminate) and other films (e.g. nets, foamed) that are not recycled but recovered as RDF-bale, along with a share of various types of PE and PP films not retained for recycling (ca. 18-19%), and sent to combustion in cement kilns.

The two mechanical recycling technologies achieve different overall performances because of the different processing applied and recycled products obtained, with MR-I (regranulate production) performing significantly better than MR-II (agglomerate production) in Climate Change and Resource Use, fossils, as well as to a lower extent in Particulate Matter and Acidification. This is because the savings from virgin material substitution are (much) higher for MR-I relative to MR-II, and compensate for the increased burdens occurring in MR-I from more intensively processing the waste and treating process residues. In MR-I, different types of virgin plastic granulate are produced (MPO, PP and HDPE) with a substitution ratio relative to their virgin counterpart ranging from 1:0.4 to 1:0.65 (Table 5). In contrast, the MPO agglomerate produced in MR (II) is assumed to replace virgin granulate at a ratio of 1:0.15 (based on market values), thus resulting in lower savings from material substitution.

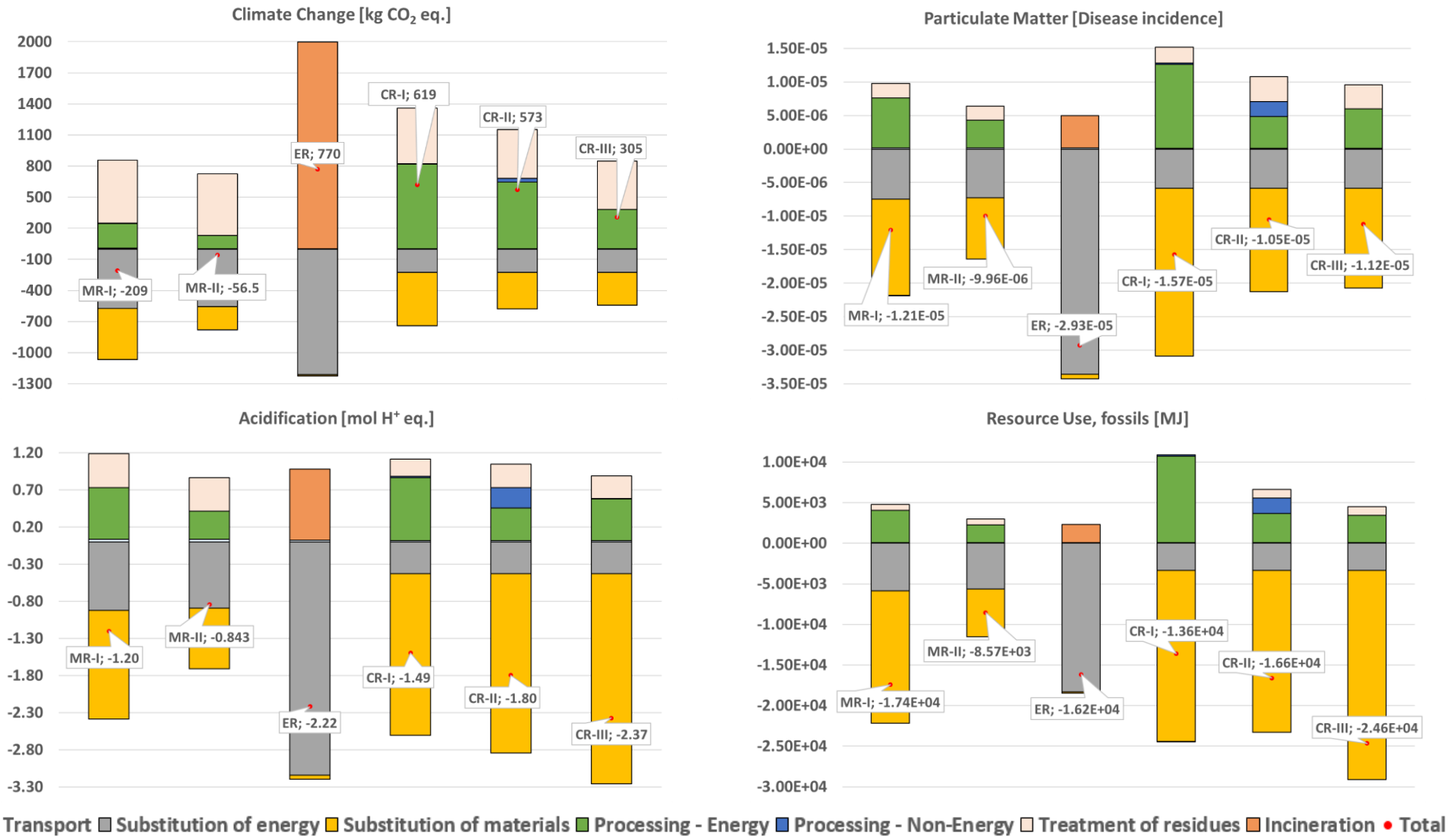


Figure 6. Management of 1 tonne of sorted mixed polyolefins (MPOs) flexible packaging waste through mechanical recycling via regranulation (MR-I; MPO, PP and HDPE regranulate production), mechanical recycling via MPO agglomerate production (MR-II), energy recovery (ER; incineration), and chemical recycling via pyrolysis (CR-I), pyrolysis (CR-II), and hydrothermal pyrolysis (CR-III): Climate Change, Particulate Matter, Acidification, and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.1.4 Sorted large-format PE film waste

Figure 7 shows that the management of 1 tonne of sorted large-format PE film waste results in:

Climate Change: Net savings for mechanical and physical recycling and net burdens for energy recovery. Physical recycling achieves the largest net savings compared to mechanical recycling, thanks to lower burdens from processing and treatment of residues.

Particulate Matter, Acidification and Resource Use, fossils: Net savings for all pathways investigated. Energy recovery performs best in Acidification and Particulate Matter, where mechanical and physical recycling provide similar net savings. In 'Resource Use, fossils', a comparable performance is observed for the three pathways investigated.

Impact contributions: Mechanical recycling and physical recycling achieve comparable impact contributions in terms of processing, i.e., they have similar impacts from energy use and non-energy process inputs and outputs. Conversely, physical recycling results in lower burdens from treatment of residues (especially in Climate Change), as a lower share of the input-waste is used for RDF production (i.e. 25% vs 37%) and less emissions are generated from its subsequent combustion in cement kilns. The material substitution savings are moderately larger for physical recycling, reflecting its higher overall yield (65%) compared to mechanical recycling (53%). On the other hand, savings from energy substitution are larger in the case of mechanical recycling, because of the higher RDF production and subsequent replacement of conventional and alternative fuels otherwise used in cement kilns.

It is important to keep in mind that the results presented for physical recycling are affected by the low operational treatment capacity of the investigated recycling plant (ca. 7000 t/year), and by the relatively low technology maturity. This leaves room for future potential improvement of the environmental performance thanks to technology optimisation and upscaling. On the other hand, the burdens associated with solvent use for physical recycling via dissolution were not considered in this study as no data were provided, potentially underestimating the total impact. However, partial solvent recovery may ultimately reduce the burdens from solvent use in the process.

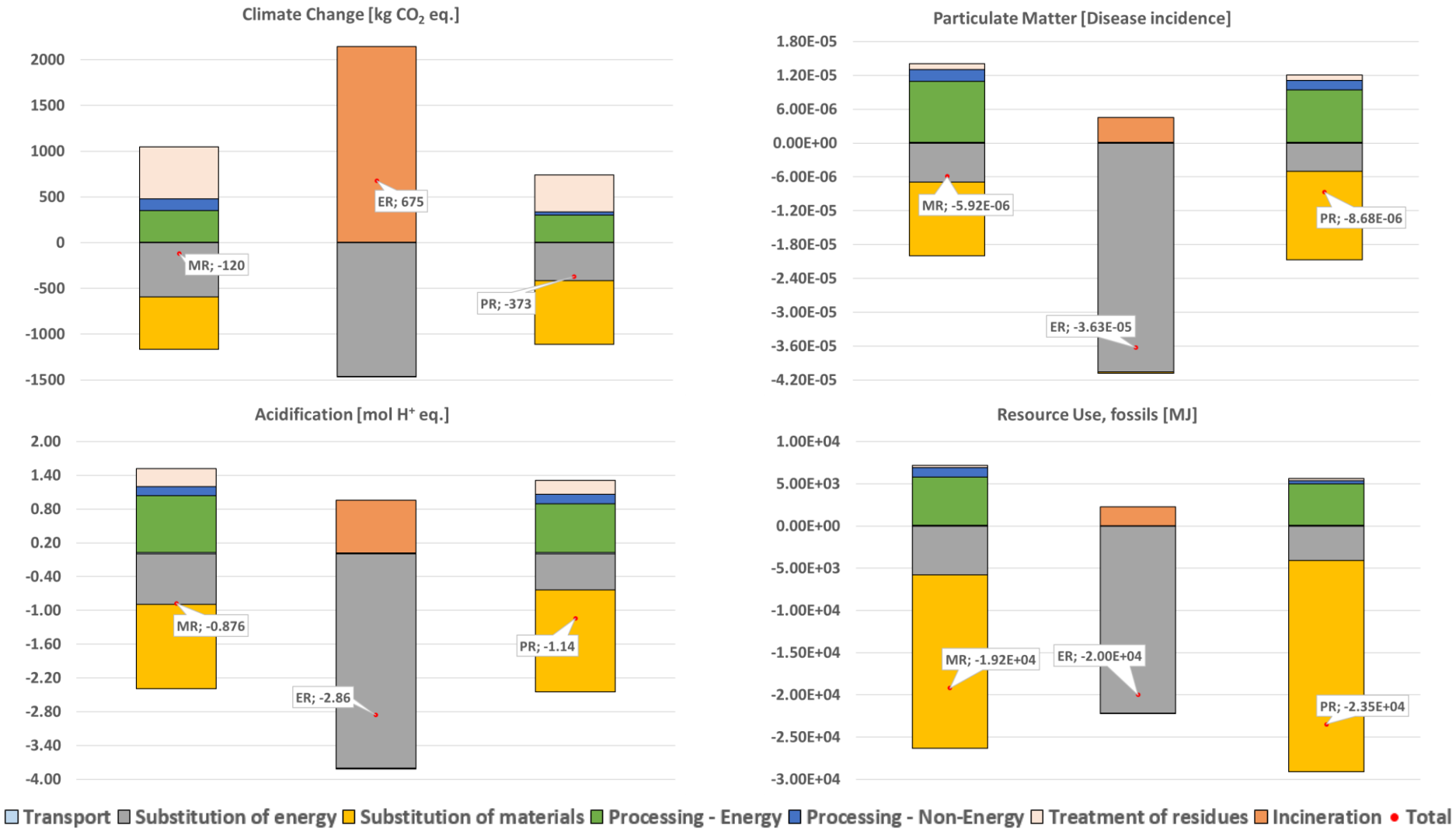


Figure 7. Management of 1 tonne of sorted large-format PE film waste through mechanical recycling (MR; LDPE regranulate production), energy recovery (ER; incineration), and physical recycling (PR; solvent-based separation/dissolution and subsequent production of LDPE granulate): Climate Change, Particulate Matter, Acidification, and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.2 Comparison between chemical recycling, physical recycling and energy recovery

3.1.2.2.1 Post-industrial PE/PA multilayer film waste

Figure 8 shows that the management of 1 tonne of post-industrial PE/PA multilayer film waste results in:

Climate Change: Net burdens for both physical recycling and energy recovery, although for the latter the burdens are one order of magnitude larger.

Particulate Matter, Acidification and Resource Use, fossils: Net savings for both physical recycling and energy recovery. The recycling scenario results in larger net savings than energy recovery in Acidification, while energy recovery outperforms recycling in Particulate Matter and Resource Use, fossils.

Impact contributions: Material recovery and resulting substitution savings from physical recycling are dominated by replacement of virgin PE and PA granulate. Processing burdens are driven by the energy consumption of the recycling process, including both electricity (3.69 MWh/t input-waste) and heat (6.75 GJ/t input-waste).

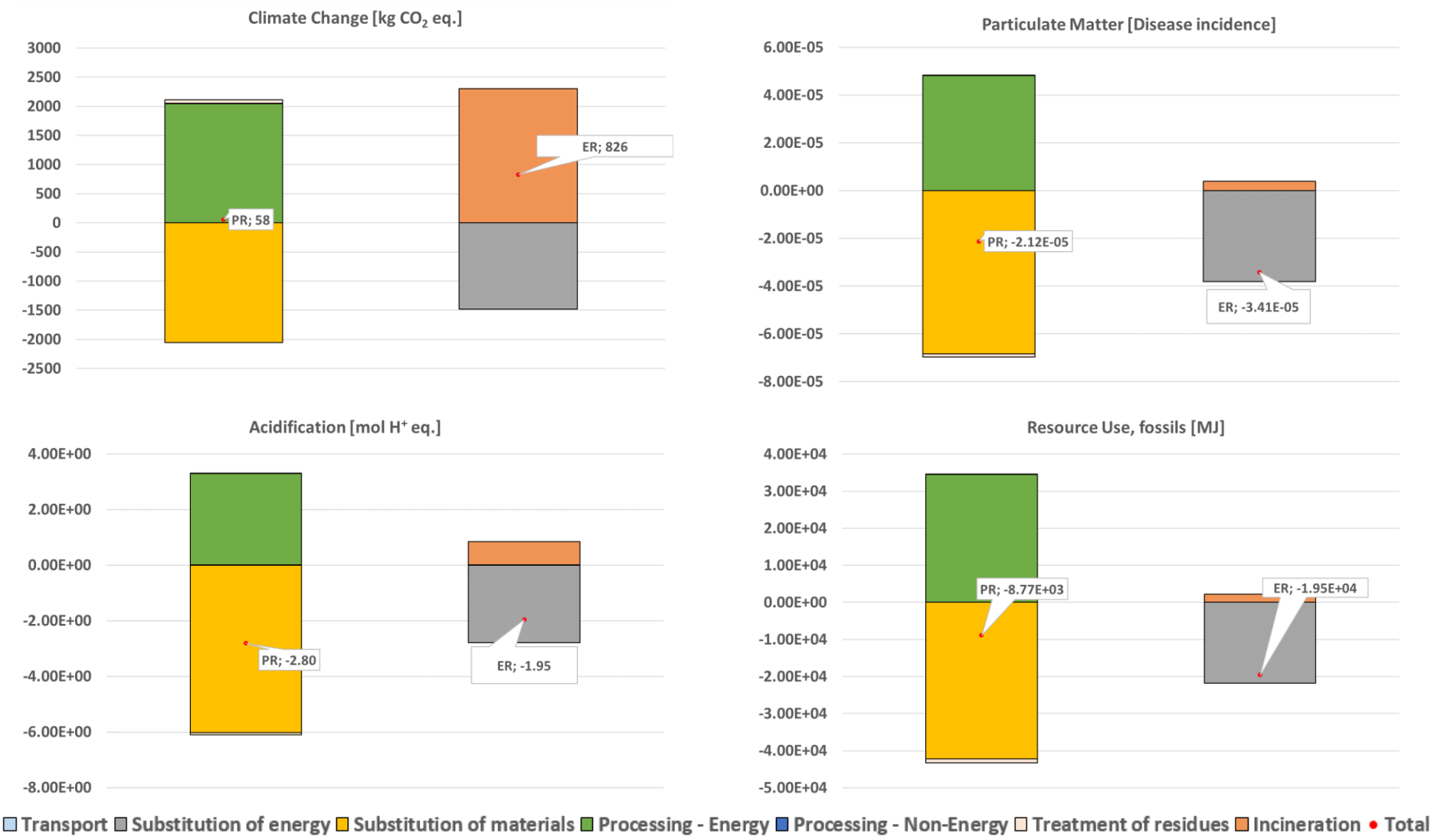


Figure 8. Management of 1 tonne of post-industrial PE/PA multilayer film waste through physical recycling (PR; solvent-based separation/dissolution and subsequent production of LDPE and PA granulate) and energy recovery (ER; incineration): Climate Change, Particulate Matter, Acidification and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.2.2 EPS construction and demolition waste (CDW)

Figure *9* shows that the management of 1 tonne of EPS construction and demolition waste (CDW) results in:

Climate Change: Net burdens for both physical recycling and energy recovery, meaning that overall GHG emissions are (much) larger than total GHG savings. However, physical recycling performs largely better than energy recovery, since the impact of treating 1 tonne of EPS waste is equal to 340 kg CO_2-eq. for recycling and 1773 kg CO_2-eq. for energy recovery.

Particulate Matter and Acidification: Net savings for energy recovery, contrasting with net burdens for physical recycling.

Resource Use, fossils: Net savings for both physical recycling and energy recovery, with the magnitude of these savings being comparable.

Impact contributions: The most important contribution to the burdens from physical recycling is provided by energy used for processing ('Processing – Energy'), which reflect the electricity consumption of the investigated recycling plant (no thermal energy is used). Based on the received plant data, a significantly higher electricity consumption was estimated per unit of waste treated (ca. 3800 kWh/tonne), relative to the other analysed mechanical and physical recycling technologies (mostly demanding between ca. 300 and 700 kWh/tonne). However, this high consumption can be a result of the small treatment capacity of the plant (ca. 3000 t/year), of its recent starting up (mid 2021), and of using a relatively new technology (solvent-based separation or dissolution). Further technology optimisation and upscaling are thus likely to reduce the energy demand of the process and the associated burdens, significantly improving the overall environmental performance of the scenario.

Treatment of residues and provision/treatment of non-energy inputs and outputs of the physical recycling process provide negligible burdens across the four discussed impact categories. However, it should be kept in mind that the assessment: i) did not take into account the burdens of the solvent used for physical recycling via dissolution (no data were provided), and ii) performed some approximations in the modelling of thermal treatment of HBCD-containing sludge generated in the process[31] and of the associated bromine recovery (see Section 2.1.7.4). The contributions from 'Processing – non-energy" and "Treatment of residues" could thus be higher if the modelling was improved and such simplifications were removed. On the other hand, this is not expected to change the results significantly since the solvent may be partially recovered, thus reducing its total consumption per unit of waste treated, while the modelling approximations performed for the sludge treatment only affect a small residual flow corresponding to ca. 4% of total process outputs.

[31] A residual stream of the physical recycling process is represented by sludge containing HBCD (Hexabromocyclododecane, a flame retardant) and degraded PS, which is sent to a Bromine Recovery Unit (BRU), where HBCD is destructed in a high-temperature waste incineration, while elemental bromine is recovered for possible further use.

Figure 9. Management of 1 tonne of EPS construction and demolition waste through physical recycling (PR; solvent-based separation/dissolution and subsequent PS granulate production) and energy recovery (ER; incineration): Climate Change, Particulate Matter, Acidification, and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.2.3 Used tyre waste

Figure 10 shows that the management of 1 tonne of used tyre waste results in:

Climate Change: Net savings for chemical recycling via pyrolysis and net burdens for energy recovery (since incineration burdens are larger than energy substitution savings).

Particulate Matter, Acidification and Resource Use, fossils: Net savings for both chemical recycling via pyrolysis and energy recovery via incineration. Chemical recycling is always better than energy recovery across the three impact categories, providing the highest net savings.

Impact contributions: The burdens from chemical recycling are relatively small or negligible as processing and treatment of process residues provide limited contributions compared to the savings from material substitution due to relatively low GHG emissions from energy consumption compared with other pyrolysis pathways. This is due to the tyre pyrolysis process not requiring a final hydro-treatment step, as opposed to MPO pyrolysis which employs hydro-treatment to upgrade raw pyrolysis oil. The material recovery and related substitution credits are dominated by the savings from carbon black and steel. Note that some categories show "Treatment of residues" as net savings, which is the result of using an aggregated EF dataset to model the incineration of generic plastic waste. Due to the aggregated nature of the dataset, no differentiation between burdens and credits could be made in this case.

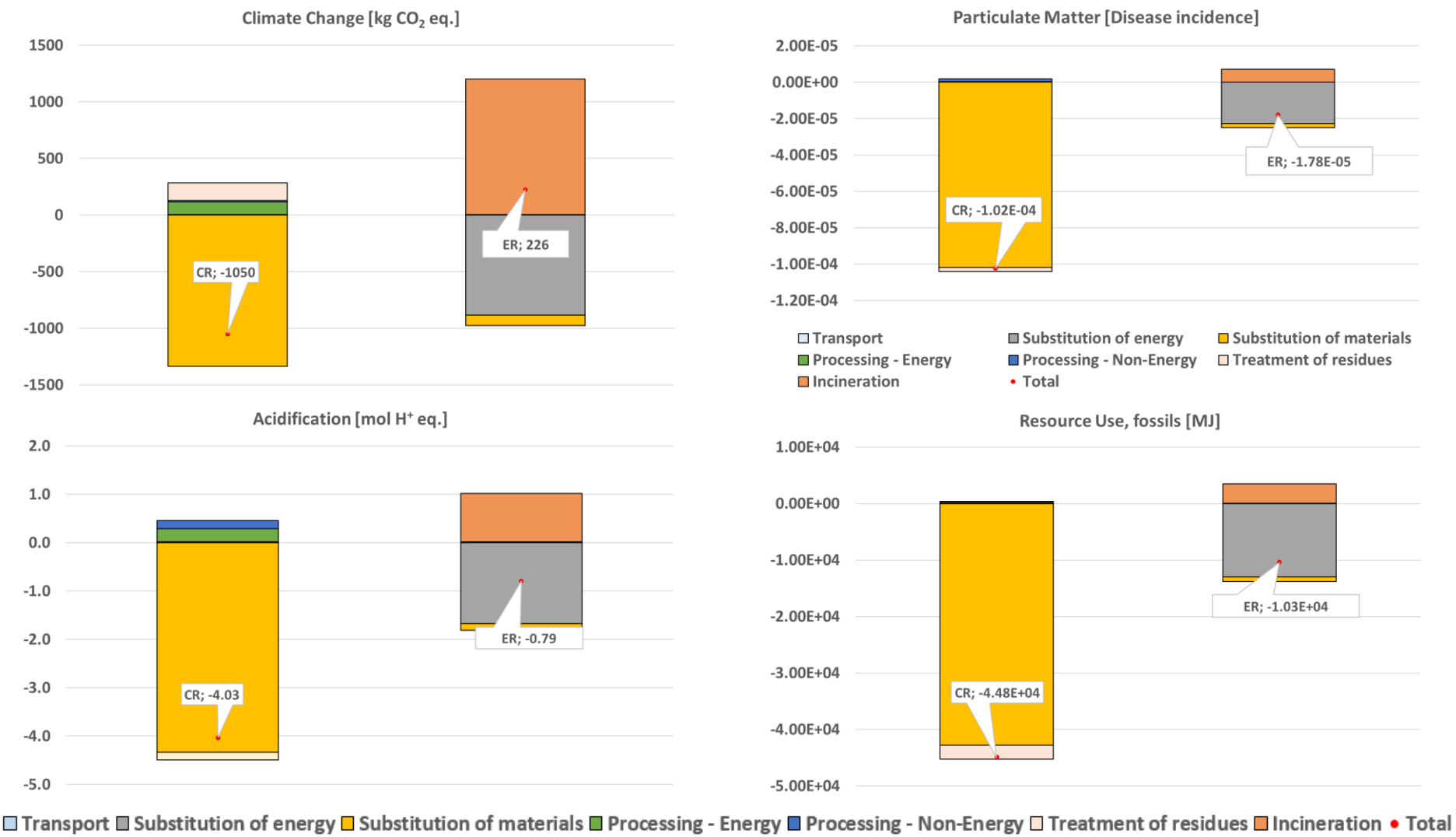


Figure 10. Management of 1 tonne of used tyre waste through chemical recycling (CR; pyrolysis) and energy recovery (ER; incineration): Climate Change, Particulate Matter, Acidification, and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.3 Comparison between mechanical recycling and energy recovery

3.1.2.3.1 Mixed shredded plastics from small WEEE (small domestic and ICT appliances)

Figure 11 shows that the management of 1 tonne of mixed shredded plastics from small WEEE (small domestic and ICT appliances) results in:

Climate Change: Net savings for mechanical recycling (-830 kg CO_2-eq./t) and net burdens for energy recovery via incineration (901 kg CO_2-eq./t; i.e. incineration burdens are larger than energy substitution savings).

Particulate Matter, Acidification and Resource Use, fossils: Net savings for both mechanical recycling and energy recovery via incineration. Mechanical recycling performs always better than energy recovery across the three impact categories, providing considerably larger net savings (2-3.5 times larger).

Impact contributions: The burdens from mechanical recycling are driven by those associated with the treatment of residues, which account for a considerable portion of total process outputs (53%), and include non-recyclable plastic and non-plastic fractions (PC/ABS, filled PP, PA-61 and PA-66, paper, wood, glass and minerals) sent to municipal waste incineration (43%), brominated plastics (ABS) and sludge sent to hazardous waste incineration (7.5%), and dust sent to combustion in cement kilns as RDF (3%). However, the contribution from treatment or residues is relevant only in the Climate Change category, because of the associated GHG emissions, especially those from municipal incineration of non-recyclable plastic and non-plastic fractions. In this respect, it must be noted that the composition of the waste sent to incineration is based on assumptions, in the absence of specific information (see Section 3.1.1), and this affects the resulting GHG emissions. In the other impact categories, the burdens due to treatment of residues are marginal or negligible compared to the other contributions (both positive and negative).

The most important contribution to the savings from mechanical recycling is the substitution of virgin materials, especially virgin ABS granulate, which is responsible for between 62% and 86% of the savings from material substitution, depending on the impact category. This is a consequence of the relatively larger quantity of secondary ABS produced compared to the other recycled polymers (PP and high-impact PS), and also of the higher substitution factor recycled-to-virgin material applied (1:1 for ABS vs 1:0.6 for PP and 1:0.65 for high-impact PS). Energy substitution provides a lower but still important contribution, mainly due to the savings from energy recovery of non-recyclable plastic and non-plastic materials generated in the recycling process and sent to municipal waste incineration. Notice that also these savings are affected by the assumptions on the quantitative composition of the waste leaving the recycling process and sent to incineration, as discussed above.

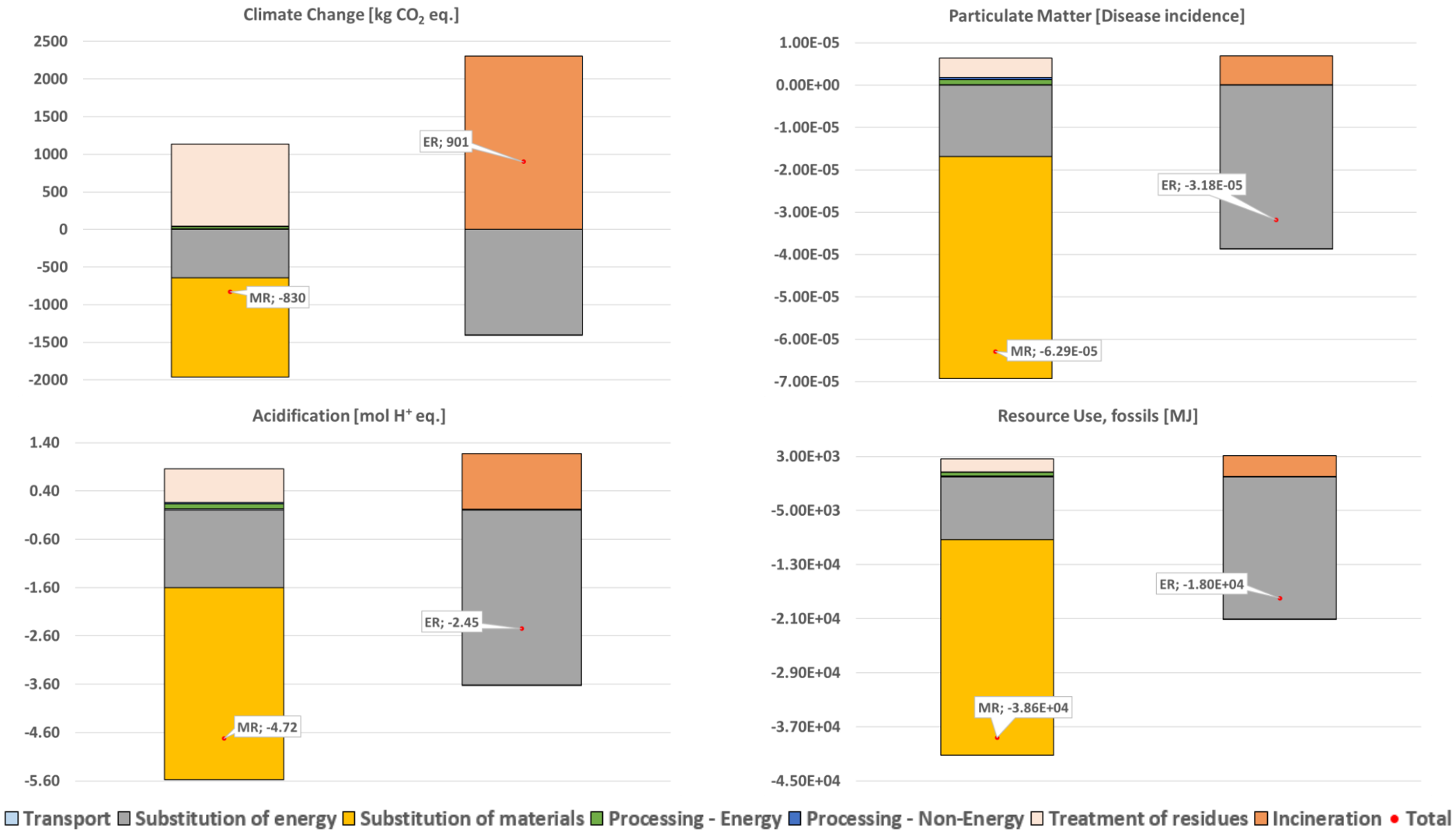


Figure 11. Management of 1 tonne of mixed shredded plastics from small WEEE (small domestic and ICT appliances) through mechanical recycling (MR; production of ABS, PP and high-impact PS regranulate) and energy recovery (ER; incineration): Climate Change, Acidification, Particulate Matter and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.1.2.3.2 Mixed shredded plastics from large WEEE (cooling and freezing appliances)

Figure 12 shows that the management of 1 tonne of mixed shredded plastics from large WEEE (cooling and freezing appliances) results in:

Climate Change: Net savings for mechanical recycling (-1522 kg CO_2-eq./t) and net burdens for energy recovery via incineration (1095 kg CO_2-eq./t; i.e. incineration burdens are much larger than energy substitution savings).

Particulate Matter, Acidification and Resource Use, fossils: Net savings for both mechanical recycling and energy recovery via incineration. Mechanical recycling performs always better than energy recovery via incineration, with savings that are 2.5 times larger than the latter.

Impact contributions: Processing impacts associated with mechanical recycling are negligible, so that the main contribution to the burdens of this scenario is represented by the treatment of the process residues via municipal or hazardous waste incineration, or their use as alternative fuel (RDF) in cement kilns. However, the overall burdens of the recycling scenario are marginal relative to the total savings from material and energy substitution.

The largest contribution to the savings from mechanical recycling is the substitution of virgin materials, particularly the replacement of recycled high-impact PS granulate, which represents 50% of the total process output, for virgin PS granulate of the same grade. Recovery of non-ferrous and ferrous metals (present in the input-waste as impurities), and the resulting substitution of primary metals, provides another important contribution to the savings from material substitution. In selected categories, such as Particulate Matter and Acidification, also the replacement of virgin ABS on a 1:1 basis contributes to a certain extent to the material substitution savings, although recycled ABS represents only 6% of the total output. Compared with these savings, the savings from energy recovery and substitution provide a lower contribution to the overall savings from mechanical recycling, i.e. 11% on average across the four discussed impact categories, with a maximum of 16% in Climate Change.

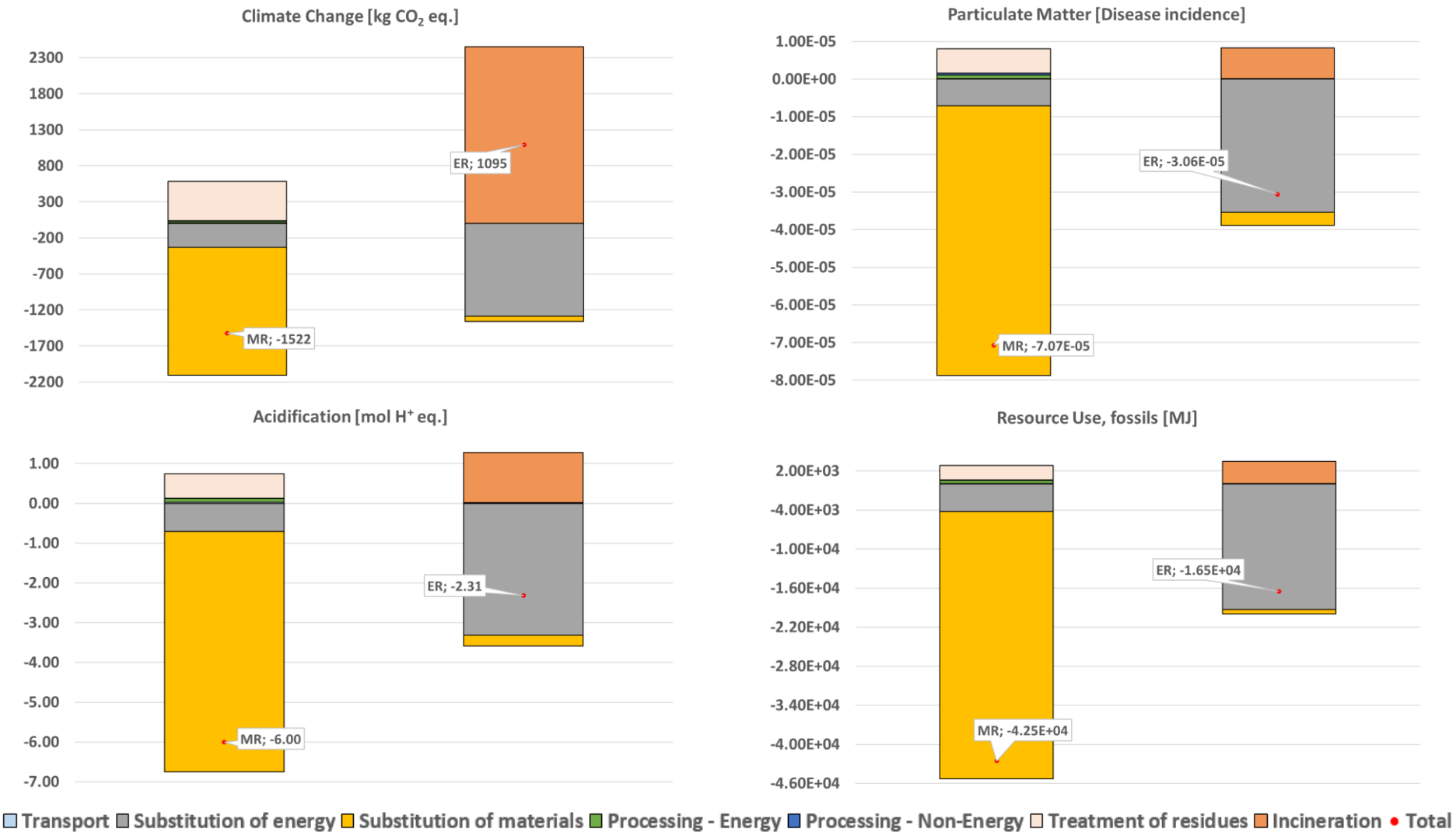


Figure 12. Management of 1 tonne of mixed shredded plastics from large WEEE (cooling and freezing appliances) through mechanical recycling (MR; production of high-impact PS, ABS and PP regranulate) and energy recovery (ER; incineration): Climate Change, Particulate Matter, Acidification and Resource Use, fossils impact indicators. Negative values represent savings, while positive ones represent burdens. See Table 1 for a description of the different treatment scenarios and technologies.

3.2 Life cycle costing of recycling and energy recovery scenarios

3.2.1 Data coverage and quality

As indicated in Section 2.2, very little primary data on costs were received via the dedicated data collection and subsequent stakeholder consultations. This was especially the case for CAPEX, OPEX and labour incurred by the technologies investigated. Therefore, we relied on secondary data (i.e. from scientific and technical literature) to develop the inventory for the conventional life cycle costing of each scenario. While these data are transparently reported in Annex 2, costs for emerging technologies, notably chemical recycling and some physical recycling technologies, are likely to reduce in the future following optimisation of the process. Similarly, market prices for secondary and primary plastics have proved to be very fluctuating and volatile in the last decade, and particularly during the period 2020-2022. Altogether, this means that LCC results should be seen as preliminary and uncertain. We thereby invite the reader to interpret and use the results with much care and in the light of the secondary data used and reported in this document.

3.2.2 Life cycle costing results

This section presents the results of the conventional life cycle costing (CLCC), which are expressed in EUR2020 (€) per functional unit, i.e. one tonne (t) of plastic waste input (i.e. sent to each of the mechanical recycling, chemical recycling, physical recycling and energy recovery scenarios) including any impurities[32]. Positive contributions reflect financial costs, while negative contributions reflect revenues. The total cost of the management of the waste at the scenario level is calculated as the difference between the sum of the costs associated to the management pathway and the revenues obtained from selling any products and co-products arising from that pathway. This is referred to as "total" in the discussion of the results, and can be a "net cost" when positive or a "net saving (or income)" when negative. Cost contributions were aggregated into six categories, representing the main processes and activities of the investigated scenarios:

Transport: it includes the costs from transport of the input-waste from centralised sorting facilities or collection centres to recycling or energy recovery, and transport of recovered non-targeted material fractions, separated non-recyclable fractions, residues and losses from recycling, as well as residues from energy recovery, to further treatment (recycling, incineration, thermal treatment or combustion in cement kilns) or disposal.

Processing: it includes all the costs associated with CAPEX and OPEX from recycling, with OPEX covering the costs due to consumption of electricity, heat, fuels, chemicals etc., and to the external treatment or disposal of outputs from the process, such as wastewater, sludge and waste due to material and product use to run the process.

Incineration: this category applies only to energy recovery pathways/scenarios, and includes the CAPEX and OPEX costs associated with the treatment (combustion) of the input-waste in the modelled energy recovery plant, including treatment of process residues (bottom ash and air pollution control residues).

Treatment of residues: it includes the costs associated with the external treatment or disposal of all material fractions, residues and losses generated, beyond the targeted plastic material(s), from handling the input-waste via recycling, similarly to what done for the LCA results (see Section 3.1.2).

Substitution of energy: it includes the revenues due to energy recovery, i.e. heat and electricity generated from incineration of the input-waste in energy recovery scenarios, or from incineration of non-recyclable material fractions and residues from recycling. Likewise, it also includes any revenue generated from fuel produced at recycling (e.g. chemical recycling). Where relevant, it also includes the revenues associated with the combustion of RDF in cement kilns.

Substitution of materials: it includes the revenues due to the products and co-products derived from recycling, including separated non-targeted plastic and non-plastic materials present in the input-waste and recycled outside the process, such as metals and paper. In case of energy recovery, this category

[32]Material/chemical contaminants embedded in the wasted products or resulting from their waste management as well as non-targeted polymers and non-plastic materials still present in the sorted stream after any prior sorting operations.

includes the revenues from the recovery of ferrous and non-ferrous metals from bottom ash (when relevant to the specific input-waste composition).

Typically, the most important contribution to the costs of recycling scenarios is the processing stage, while the savings are associated with the revenues from material recovery. For energy recovery, the most important contribution to the costs is the incineration process itself, while the revenues come from electricity and heat recovery. The higher the calorific value of the input-waste (per unit of waste), the larger are the revenues.

3.2.2.1 Comparison between mechanical recycling, chemical recycling, physical recycling and energy recovery

3.2.2.1.1 Sorted PET packaging waste (bottles and trays)

Highlights: Chemical recycling via alkaline hydrolysis (CR-III) provides the largest net savings (Figure 13), followed by mechanical recycling and chemical recycling via partial glycolysis (CR-I). Both energy recovery and chemical recycling via hydrolysis-methanolysis (CR-II) result in net costs.

Key Cost Contributions: Material substitution savings are larger for chemical recycling via partial glycolysis (CR-I) and alkaline hydrolysis (CR-III), thanks to larger revenues from commercialisation of recovered products compared to mechanical recycling and chemical recycling via hydrolysis-methanolysis (CR-II). This is due to the higher selling prices of recovered products from CR-I (producing PET granulate) and lower processing costs of CR-III, compared to CR-II (recovering PET monomers with lower prices and incurring in higher processing costs). Material substitution savings are also larger for CR-I than for mechanical recycling, which produces 40% non-food grade PET with a reduced value. On the other hand, CR-I and CR-II incur higher processing costs, due to increased CAPEX and OPEX compared to the other recycling scenarios. For energy recovery, the overall balance shows a net cost (costs > revenues) because the revenues associated with energy recovered from PET packaging waste (calorific value ca. 20 GJ/t) does not exceed the expected costs of treating the waste.

3.2.2.1.2 Sorted PS packaging waste

Highlights: Energy recovery results in the largest net savings across all scenarios considered for PS packaging waste management (Figure 13), followed by mechanical recycling. Chemical recycling (pyrolysis-assisted depolymerisation) results in net costs.

Key Cost Contributions: Mechanical recycling incurs moderately lower costs for processing relative to chemical recycling, while it achieves larger revenues from material substitution. This is due to the higher yield (70%) achieved for the main product from mechanical recycling, i.e. PS regranulate, compared to styrene produced via the chemical recycling route (47%), and also due to the higher selling price of the PS regranulate compared to styrene. . For energy recovery, the overall balance shows a net saving (revenues > costs) because the revenues associated with energy recovered from PS packaging waste (calorific value ca. 28 GJ/t) outweigh the costs of treating the waste (169 €/t), as assumed for this study.

3.2.2.1.3 Sorted MPO flexible packaging waste

Highlights: Energy recovery results in net savings (Figure 13), while the remaining management scenarios via both mechanical and chemical recycling result in net costs. Chemical recycling scenarios show lower net costs than scenarios based on mechanical recycling.

Key Cost Contributions: All mechanical and chemical recycling scenarios incur significant costs for processing, due to operational costs (between 21-157 €/t), albeit also capital costs are relevant (95-141 €/t). Such costs are not balanced by the revenues from material and energy recovery, thus incurring a net cost. The recycling scenarios that incur the lowest net costs overall are CR-I (conventional pyrolysis) and CR-III (hydrothermal pyrolysis), because of the larger revenues from material recovery and substitution relative to the other recycling pathways. For instance, material substitution revenues from mechanical recycling are lower than CR-I and CR-III due to the modest yield in terms of material recovery (41-42%), the comparatively lower prices of the main recycled materials (180-525 €/t), and the limited savings from substitution of RDF (32-43% of total process output) for other fuels used in cement kilns (i.e. 82 €/t_{RDF}). In contrast, for energy recovery the overall balance shows a net saving (revenues > costs), because the revenues associated with energy recovered from MPO flexible packaging waste (calorific value ca. 28 GJ/t) outweigh the costs of treating the waste (169 €/t), as assumed for this study.

3.2.2.1.4 Sorted large-format PE film waste

Highlights: Energy recovery results in net savings (Figure 13), while both mechanical recycling and physical recycling via solvent-based separation/dissolution result in net costs. The highest net costs are associated with mechanical recycling.

Key Cost Contributions: Both mechanical and physical recycling scenarios incur significant costs for processing, especially due to operational costs (174 €/t, i.e. 65% of total costs), while capital costs are less relevant (95 €/t, 35% of total costs). As for other recycling scenarios (e.g. mechanical and chemical recycling of MPO flexible packaging waste), these costs are not balanced by the revenues from material recovery, thus incurring a net total cost of recycling. Also in this case, recycling revenues are affected by modest material recovery yields (53-65%) and resulting production of a relevant portion of RDF (25-37% of total process output) with limited revenues from its use as alternative fuel in cement kilns (82 €/t_{RDF}). For energy recovery, the overall balance shows a net saving (revenues > costs) because the revenues associated with energy recovered from PE film waste (calorific value ca. 34 GJ/t) exceed the costs of treating the waste (169 €/t), as assumed for this study.

3.2.2.2 Comparison between chemical recycling, physical recycling and energy recovery

3.2.2.2.1 Post-industrial PE/PA multilayer film waste

Highlights: Physical recycling of PE/PA multilayer film waste via solvent-based separation/dissolution results in net costs compared to energy recovery, which shows net savings (Figure 14).

Key Cost Contributions: For physical recycling (solvent-based separation), the processing costs outweigh the revenues from material recovery. This is due to the relatively high CAPEX and OPEX of physical recycling (183 and 375 €/t plastic waste, respectively) and also due to applications of a substitution factor=0.5 for PE and PA, which reduces the revenues from material recovery. For energy recovery, likewise, the overall balance shows a net saving (revenues > costs) because the revenues associated with energy recovered from PE/PA film waste (calorific value ca. 37 GJ/t) exceed the costs of treating the waste (169 €/t), as assumed for this study.

3.2.2.2.2 EPS construction and demolition waste

Highlights: Physical recycling of EPS construction and demolition waste via solvent-based separation/dissolution results in larger net savings than energy recovery (Figure 14).

Key Cost Contributions: For physical recycling (solvent-based separation), the revenues outweigh the processing costs, albeit operational costs are represented by an average value[33] (159 €/t) that do not take specifically into account the relatively high electricity consumption of the investigated process (ca. 3800 kWh/t, based on the received plant data) compared to the other mechanical and physical recycling technologies considered in this study (ca. 300-700 kWh/t). Therefore, higher total costs may be actually associated with physical recycling of EPS waste under current conditions. For example, assuming an average electricity cost of 0.2 €/kWh (for industrial users) would lead to 760 €/t in place of the 159 €/t assumed, without accounting for the remaining operational expenditures (total OPEX would be even higher). Such high electricity consumption is also responsible for a relevant share of the potential environmental impacts of this technology, as discussed in Section 3.1.2.2.2. On the other hand, revenues from material recovery and substitution are also substantial for physical recycling, and this can be considered a consequence of the relatively higher price of recycled PS granulate (909 €/t) compared to most of the other polymers obtained from the investigated mechanical and physical recycling technologies (250-850 €/t). For energy recovery, the overall balance shows a net saving (revenues > costs), because the revenues associated with energy recovered from EPS construction and demolition waste (calorific value ca. 29 GJ/t) exceed the costs of treating the waste (169 €/t), as assumed for this study.

[33] Calculated based on operational cost data related to mechanical recycling of different polymers and waste streams (PET, HDPE, PP, films and MPOs), in the absence of specific data for physical recycling of EPS construction and demolition waste. An alternative would be to estimate OPEX based on the electricity consumption (around 3800 kWh/t) and labour required. For example, assuming an average electricity cost of 0.2 €/kWh (in EU27 in the first half of 2022 the price ranged from 0.08 to 0.3 €/kWh for industrial users; https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics) would lead to 760 €/t, only accounting for electricity cost.

3.2.2.2.3 Used tyre waste

Highlights: Energy recovery of used tyre waste via incineration results in net savings, contrary to chemical recycling via pyrolysis, which results in net costs (Figure 14).

Key Cost Contributions: Pyrolysis processing costs due to CAPEX (87% of processing costs) and, to a lower extent OPEX (13% of processing costs) are not compensated by the revenues from moderately low yield recovery and substitution of materials such as pyrolysis oil, carbon black and steel, among others. In contrast, for energy recovery the overall balance shows a net saving (revenues > costs) because the revenues associated with energy recovered from tyre waste (calorific value ca. 22 GJ/t) exceeds the costs of treating the waste (169 €/t), as assumed for this study.

3.2.2.3 Comparison between mechanical recycling and energy recovery

3.2.2.3.1 Mixed shredded plastics from small WEEE (small domestic and ICT appliances)

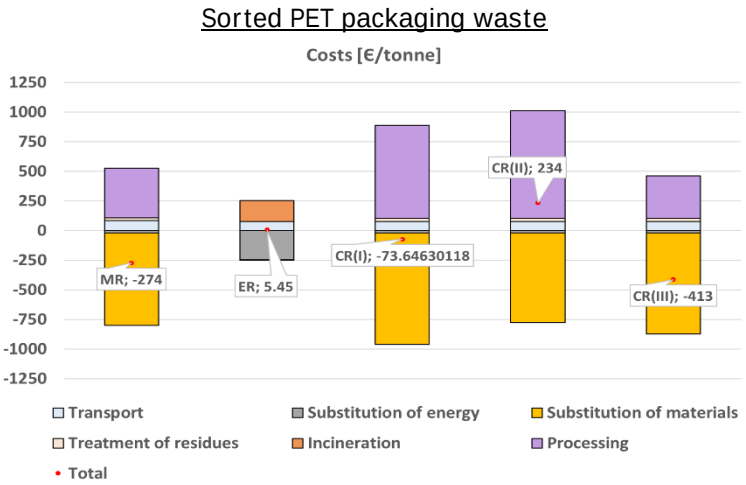
Highlights: Management of mixed shredded plastics from small WEEE via energy recovery (incineration) results in net savings, in contrast to mechanical recycling, which results in net costs (Figure 15).

Key Cost Contributions: Mechanical recycling shows a positive net balance close to zero, i.e. revenues from material and energy recovery balance out the costs from processing, treatment of residues and transport. Processing costs are mainly associated with operational costs (OPEX; 57% of processing costs), although also the contribution of capital costs (CAPEX) is relevant (43% of processing costs). However, operational costs are calculated as the average of cost data related to mechanical recycling of different polymers and waste streams (PET, HDPE, PP, films, MPOs) and hence do not reflect actual costs for WEEE plastics recycling, which may be higher due to the use of more complex/articulated processes to separate and recover multiple polymer streams. Revenues are driven by those associated with material recovery, especially ABS regranulate (42% of total revenues from material substitution) and high-impact PS regranulate (40% of the revenues). For energy recovery, the overall balance shows a net saving (revenues > costs) because the revenues associated with energy recovered from shredded plastics from small WEEE (calorific value ca. 33 GJ/t) exceeds the costs of treating the waste (169 €/t), as assumed for this study.

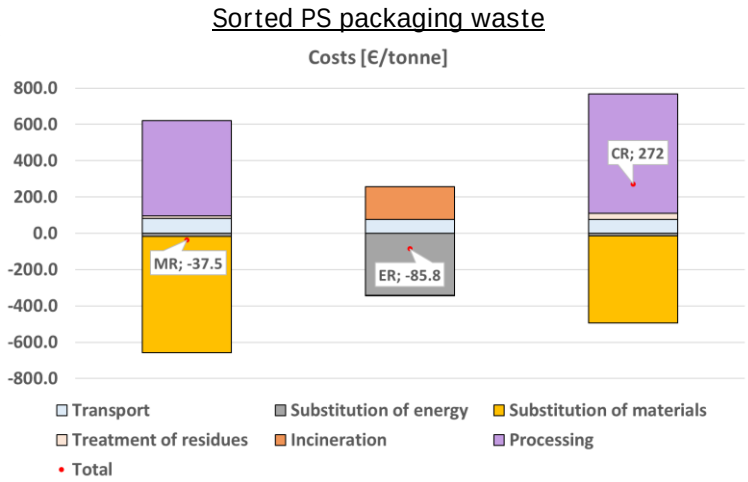
3.2.2.3.2 Mixed shredded plastics from large WEEE (cooling and freezing appliances)

Highlights: Management of mixed shredded plastics from large WEEE via both mechanical recycling and energy recovery results in net savings (Figure 15). Savings form mechanical recycling are larger than energy recovery.

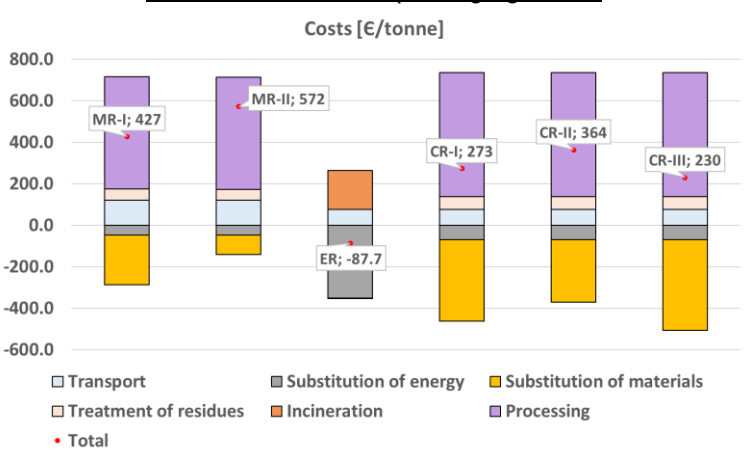
Key Cost Contributions: Processing costs of mechanical recycling are almost evenly due to operational costs (OPEX; 48% of processing costs) and capital costs (CAPEX; 52% of processing costs), in contrast to mechanical recycling of small WEEE. However, as for the latter, operational costs may be underestimated compared to actual costs for recycling of multiple polymers from mixed shredded plastics from (large) WEEE. Revenues from material recovery are in this case higher than costs, especially thanks to the contribution from recovering high-impact PS regranulate (70% of total revenues from material substitution) and non-ferrous metals (17% of the revenues). Similarly, for energy recovery the overall balance shows a net saving (revenues > costs) because the revenues associated with energy recovered from shredded plastics from large WEEE (calorific value ca. 30 GJ/t) exceeds the costs of treating the waste (169 €/t), as assumed for this study.



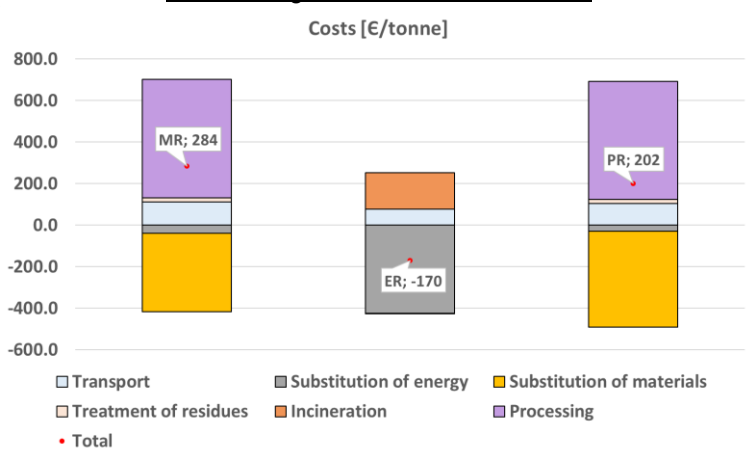
MR: PET regranulate production; ER: incineration; CR-I: partial glycolysis; CR-II: hydrolysis-methanolysis; CR-III: alkaline hydrolysis



MR: PS regranulate production; ER: incineration; CR: pyrolysis-assisted de-polimerisation

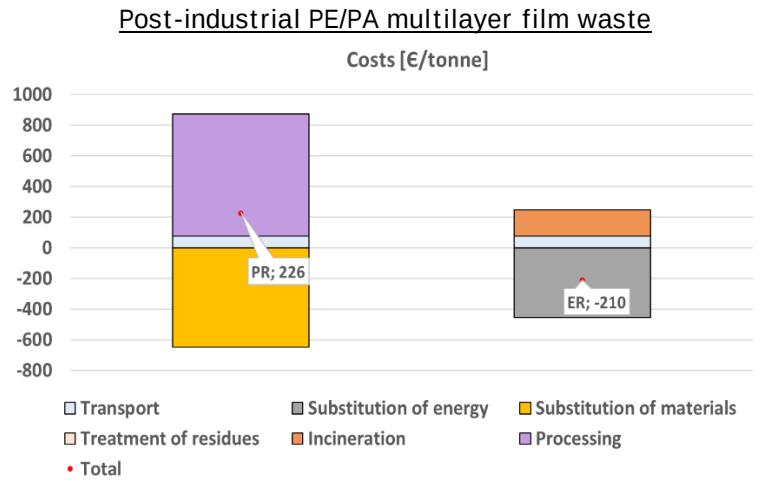


MR-I: MPO, PP and HDPE regranulate production; MR-II: MPO agglomerate production; ER: incineration; CR-I: conventional pyrolysis; CR-II: conventional pyrolysis; CR-III hydrothermal pyrolysis

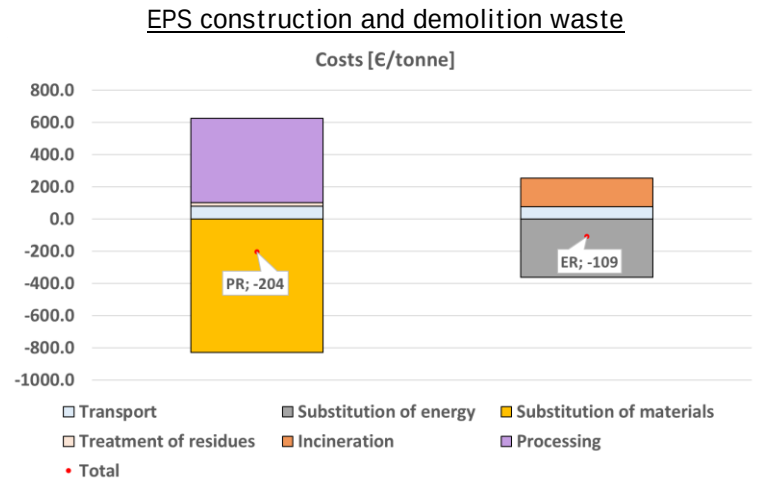


MR: LDPE regranulate production; ER: incineration; PR: solvent-based separation / dissolution and LDPE granulate production

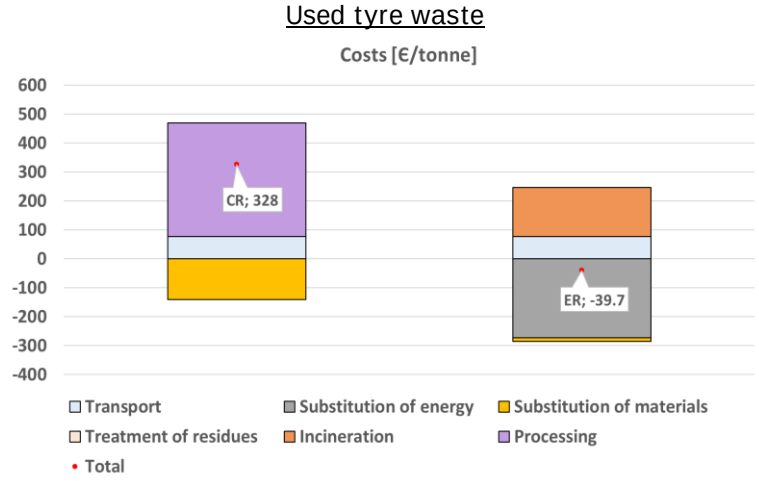
Figure 13. Conventional life cycle costs for the management of 1 tonne of sorted PET packaging waste, sorted PS packaging waste, sorted MPO flexible packaging waste, and sorted large-format PE film waste via mechanical recycling (MR), chemical or physical recycling (CR / PR), and energy recovery (ER). Negative values represent revenues, while positive ones represent costs. Refer to Table 1 for a description of the different treatment scenarios and technologies.



PR: solvent-based separation / dissolution and production of LDPE and PA granulate; ER: incineration



PR: solvent-based separation / dissolution and PS granulate production; ER: incineration



CR: pyrolysis; ER: incineration

Figure 14. Conventional life cycle costs for the management of 1 tonne of post-industrial PE/PA multilayer film waste, EPS construction and demolition waste, and used tyre waste via chemical or physical recycling (CR / PR) and energy recovery (ER). Negative values represent revenues, while positive ones represent costs. Refer to Table 1 for a description of the different treatment scenarios and technologies.

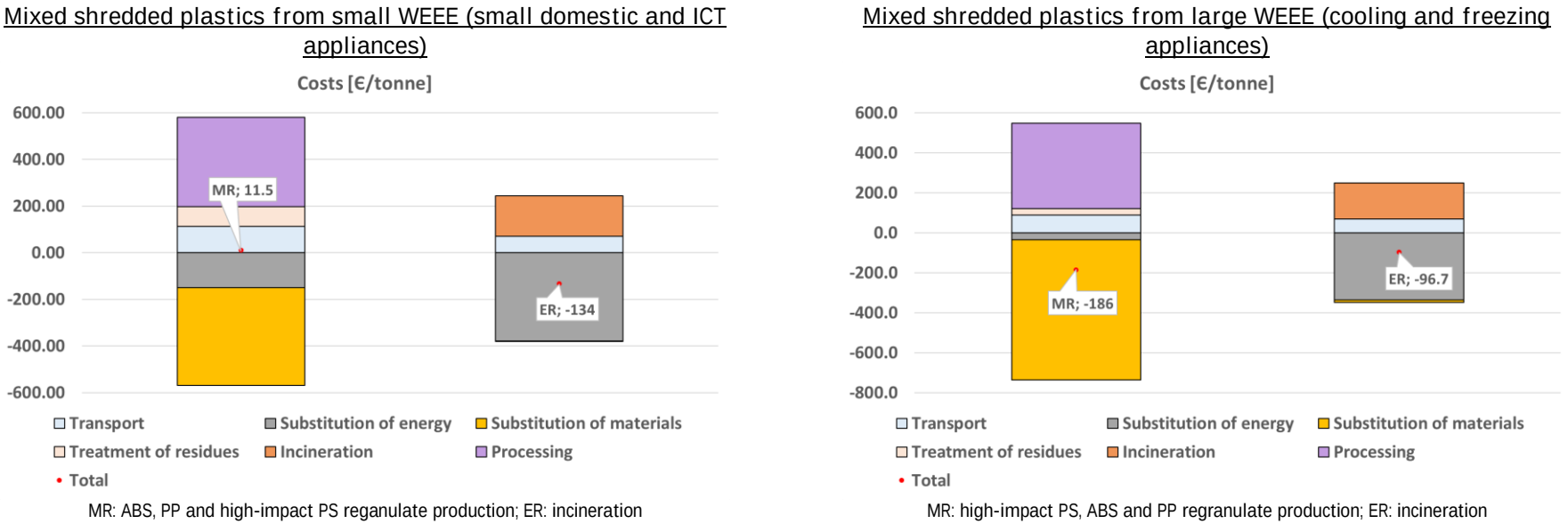


Figure 15. Conventional life cycle costs for the management of 1 tonne of mixed shredded plastics from small WEEE (small domestic and ICT appliances) and mixed shredded plastics from large WEEE (cooling and freezing appliances) via mechanical recycling (MR) and energy recovery (ER). Negative values represent revenues, while positive ones represent costs. See Table 1 for a description of the different treatment scenarios and technologies.

3.3 Economic viability of physical and chemical recycling

This analysis complements the LCC results by calculating the economic viability of physical and chemical recycling. The same set of data of the LCC were used, wherever possible, in most cases complemented with values from the literature. It should be kept in mind that, due to claimed confidentiality and competitiveness concerns, most stakeholders did not fill in the information on costs in the surveys, so this study had to rely strongly on databases and the literature for the economic parameter values. Nevertheless, not enough evidence is available to draw definite conclusions regarding the economic viability of physical and chemical recycling.

3.3.1 Data coverage and quality

3.3.1.1 The cost of feedstock

Price information on the feedstock for recycled plastics production was not obtained from the recycled plastics producers directly. There are, however, ways to get an idea of the price when analysing trade data. Our main sources are price overviews from the Plasticker material exchange, trade data from EUROSTAT [DS-645593] and trade data from the UN COMTRADE database. The latter two, however, only report price aggregates over different polymers.

Data from the Plasticker material exchange are based on offers made on the exchange. Data on the actual transactions are not reported, just on offers. Prices are calculated monthly and consider all offers which were made at any given time of that month (and which were within two standard deviations). A total of 60 months of data are available for PET, PE-LD and PP (see Figure 16). More recent data on a wider range of plastics is available from (Plasticker, 2022).

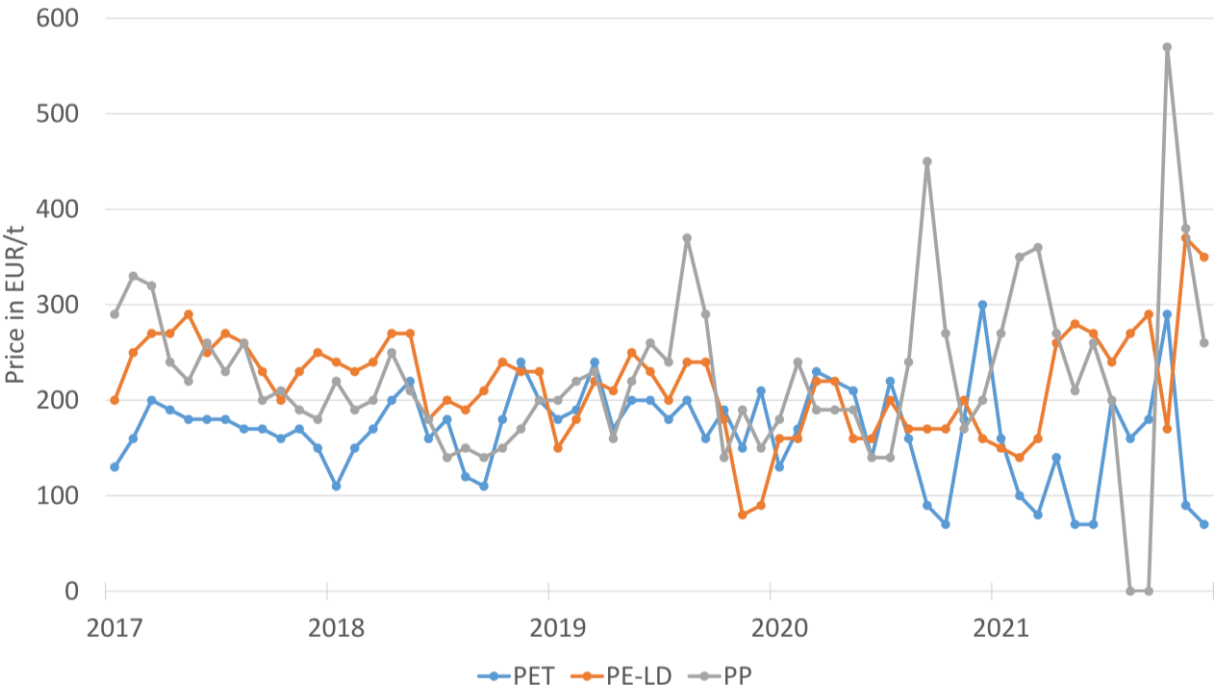


Figure 16. Monthly feedstock prices by material for bales of one tonne of plastic waste (source: Plasticker).

Aggregate trade data from EUROSTAT COMEXT (EUROSTAT, 2021) on plastic waste in general (i.e. aggregated over polymer types) paints a similar picture, with prices ranging from 220 to 360 €/t between the years 2013 and 2020. In the last available year, the average price for one tonne of plastic waste in the EU was 293 (± 19) €. These prices are supplemented by trade data from UN COMTRADE for BE, IT and PT. Here, the weighted average price is 362 € (2020) per tonne of plastic waste, which appears to be on the higher end of the price range.

Anecdotal data from e-mail exchanges between AIMPLAS and different recyclers point to lower prices per tonne. One chemical recycler mentions a price of one tonne of plastic conglomerate after pre-treatment of 100-200 €. Two mechanical recyclers quote prices between 0 and 120 € plus transport costs.

In sum, feedstock prices range from 0 to 362 € per tonne, depending on market conditions, type of material and quality. Based on these numbers, for all feedstock types, we look at two scenarios: the prices in Table A2-1 represent an upper bound and hence the prices for the high-price scenario; for the low-price scenario, the price is assumed to be at 50% of the value given in Table A2-1.

3.3.1.2 CAPEX and OPEX

Data on (annualised) CAPEX and OPEX was particularly scarcely reported, with either only one or two respondents, which cannot be reported here due to confidentiality reasons, or no respondent at all for most pathways. The only exception is pyrolysis of mixed plastic waste, for which a sample of three respondents can be used (see Table 7). For all other pathways, we relied either partially or fully on literature data (see Table 8). Comparing the values from Table 7 and Table 8 shows that the CAPEX values for pyrolysis from the survey are markedly above literature values.

Table 7. CAPEX and OPEX and revenue for pyrolysis of mixed plastic waste (survey data from 2021). The values are reported in Euro per tonne of feedstock. The average capacity of the pyrolysis plants is 56.7 kt/year.

	Mean	Standard deviation	Number of observations
CAPEX (€/t)	1075	124	3
OPEX (€/t)	218	40	3

Table 8. CAPEX, OPEX and plant capacities: average values between survey data and the literature (Carducci et al., 2020; Faraca et al., 2019; KIDV, 2018; Stapf et al., 2018). For Pyrolysis, only literature values are reported due to the unexpectedly high values reported in the surveys. Note that in the LCC in some cases, only survey values are used, instead of averages with the literature. Due to confidentiality reasons, however, we cannot show these values if they are not averaged over several sources. na: not available.

	Dissolution	Glycolysis	Methanolysis	Pyrolysis	Gasification
Material	EPS	PET	PET	MPW	MPW
Capacity (kt waste/y)	0.0112	0.0223	0.0770	na	0.122
CAPEX (EUR/t waste)	190	94	147	na	187
OPEX (EUR/t waste)	489	560	473	na	31
CAPEX+OPEX (EUR/t waste)	679	654	620	193	218

3.3.2 Revenues

3.3.2.1 Output prices

Market prices were obtained for some of the outputs from the surveys and supplemented with market prices of (usually) virgin products whenever there were data gaps (see Table A2-1)[34]. Comparing the prices of recyclates from Table A2-1 with virgin prices shows that, except for recycled PET, which is sold at roughly the same price as virgin PET and sometimes at a mark-up of up to 17%, other recycled materials such as styrene,

[34] Prices for pyrolysis oil from plastic chemical recycling were not received from the data collection, so these were substituted with data on virgin-based pyrolysis oil. Note, however, that in certain markets, customers are willing to pay a premium to be able to claim recycled feedstock content. This means that under certain circumstances, pyrolysis oil from chemical recycling can sell at a higher price than its virgin-based counterpart.

PS and LDPE are sold at prices 10 to 47 % lower than virgin prices. This might be related to an objectively lower quality of the recycled products, but also to the buyers' mere perception of a lower quality. In any case, these numbers have to be taken with a pinch of salt, as they are based on very few data points.

3.3.3 Economic analysis: results

Based on the previous sections on costs and revenues, a tentative estimation can be made of the net income (as defined in Section 2.3.2) for the pathway pyrolysis of mixed plastic waste based on the data collected in the survey. For the same pathway, as well as for gasification, dissolution, glycolysis and methanolysis, net income is estimated based on literature values. It should be noted that there are few reliable sources on cost data, and feedstock as well as output prices are constantly changing. Furthermore, physical and chemical recycling technologies are still under development and costs are projected to decrease in the future, improving the economic performance. For these reasons, this analysis is rather a preliminary indicator than a definite conclusion regarding the economic viability of chemical recycling.

When relying solely on survey data regarding CAPEX and OPEX, it is observed that net income for pyrolysis of mixed plastic waste is negative - with a significant margin - in all feedstock price scenarios (see Table 9). If we instead use values from the literature, net income of pyrolysis is still negative, albeit to a lesser account (see

Table *10*).

Table 9. Net income for pyrolysis of mixed plastic waste for different price scenarios based on data from the surveys. Negative net income values refer to costs, while positive ones refer to benefits.

Feedstock price scenario	Cost of feedstock **(€/t)**	Net Income (**€/t**)
Low	144	-1045
High	288	-1189

In other words, when using only survey data, pyrolysis of mixed plastic waste does not appear economically viable. Using literature values instead of (or combined with) survey data, we can analyse a broader range of pathways, ranging from pyrolysis to gasification, dissolution, glycolysis and methanolysis. Except for pyrolysis, where we consider CAPEX values to be unexpectedly high, and for gasification, for which we do not have survey data, the values reported for all other technologies are averages between survey and literature data.

The results are summarised in Table 10. In the first column, net income of the different pathways is shown for the low feedstock price scenario. The second column reports net income for the high feedstock price scenario and the third column for the values used in the LCC (which draws from fewer sources). The pathways can be ranked by their net income: Ranging from dissolution of EPS with the highest net income, over glycolysis, methanolysis, pyrolysis to Gasification, with the lowest net income. This ranking is stable across the low and high feedstock price scenarios, but not for the case of the LCC values, where glycolysis and dissolution of EPS swap places, as well as pyrolysis and methanolysis. As expected, net income for pyrolysis is higher than when only using survey values (due to lower CAPEX and OPEX values) but still negative.

Pyrolysis, as well as methanolysis and gasification have negative net incomes in all scenarios. Glycolysis and dissolution, by contrast, always have a positive net income, except for glycolysis in the high feedstock price scenario, where the net income is negative (but its absolute value is comparatively low). This result, however, has to be taken with a pinch of salt, as it is driven by the high revenue reported in the surveys for dissolution and glycolysis. The gap between literature and survey values is much bigger for these two pathways than for the other pathways. Therefore, when using exclusively literature data, both dissolution and glycolysis have negative net incomes. The negative earnings can be interpreted as the level of government support necessary to make each of these technologies economically viable.

Table 10. Net income of different chemical recycling pathways calculated using averages of survey and literature data on costs and prices. Regarding the prices of the feedstock, we look at a low- and a high-price scenario. For MPW the low,

and high prices correspond to 144 and 288 €/t, respectively. For all other feedstock types, low prices are at 50% of the prices reported in Table A2-1. Instead of taking averages of survey and literature values, the last column uses the exact same values as the LCC in the previous section. All values in €/t of waste. Positive values refer to net income and negative values to net costs (contrary to the LCC).

Pathway	Net income (low feedstock price) **(€/t)**	Net income (high feedstock price) **(€/t)**	Net income (LCC values, high feedstock price) **(€/t)**
Dissolution (average)	184	100	305
Glycolysis (average)	87	-21	403
Methanolysis (average)	-63	-171	-223
Pyrolysis (partial average[35])	-161	-305	-92
Gasification (literature)	-357	-501	-501

One further consideration to take into account, is that chemical recycling is a term used for a heterogeneous group of relatively recent technologies that are still under development, while mechanical recycling and virgin production of plastics are mature technologies. Werner et al. (2022) estimate that between 2019 and 2040, chemical recycling technologies will experience an average reduction in cost of 37.5%, while costs for mechanical recycling technologies stay roughly the same and virgin plastics production is projected to face increased costs by 71% (largely due to increased fossil fuel prices). As recyclers are price takers and virgin producers determine the prices of most products, in the following we assume that revenues increase similarly to virgin plastic costs.

Increasing revenues and falling costs implies that eventually, all chemical recycling technologies might reach the point at which net earnings become positive. Applying the changes in costs by Werner et al. (2022), to the more optimistic low-feedstock-price scenario, we estimate that methanolysis reaches the point of positive net earnings in 2024 and pyrolysis in 2033.[36] Dissolution and glycolysis have already reached this point in the present (but see the caveat on high reported revenues in the paragraph just above in Table 10). The remaining pathway, gasification, does not reach it before 2040 without additional support (such as subsidies). This is summarised in Figure 17.

[35] Partial average means that in the case of pyrolysis we excluded the survey values on CAPEX and OPEX from the average, but still use other survey information.

[36] The curves would look similar in the high feedstock price scenario and simply would be shifted downwards by the additional feedstock cost.

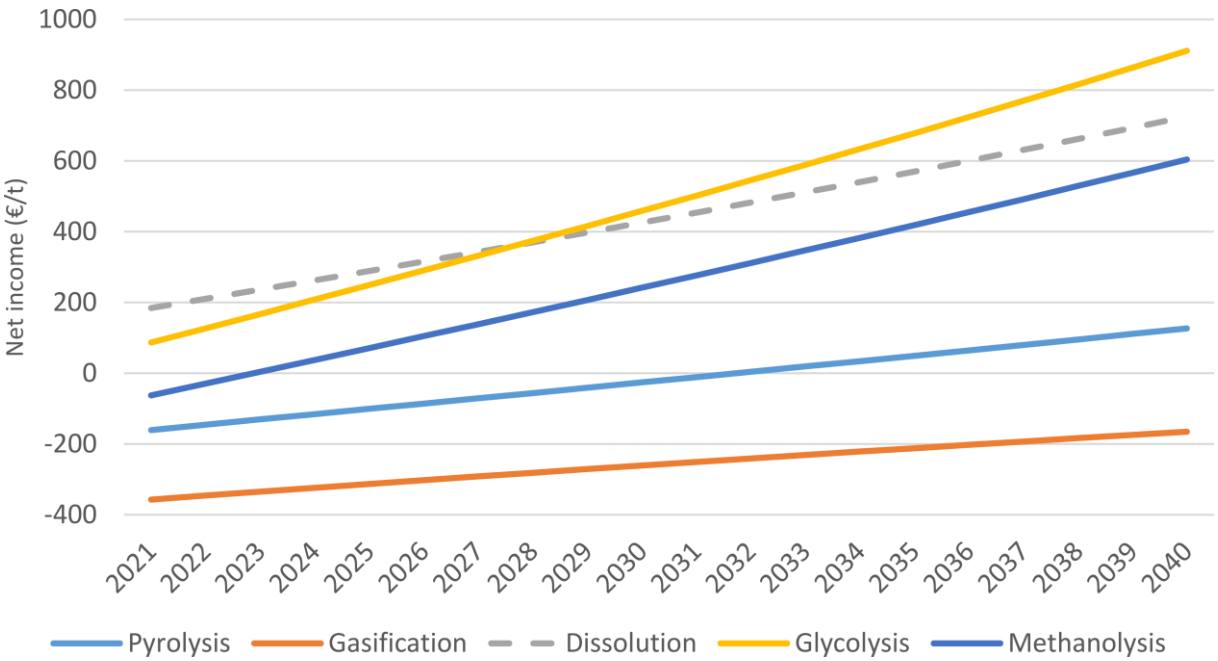


Figure 17. Net income projections until 2040 for different chemical (solid lines) and physical (dashed line) recycling technologies based on (Werner et al., 2022). The starting values in 2021 correspond to the low-feedstock-price scenario.

The gap between costs and revenues of different chemical and physical recycling technologies can also be closed by increasing revenue streams. So, in the following, we estimate by how much revenue per tonne must increase to reach positive net income, assuming that costs stay fixed.[37] While the revenue for gasification would need to increase by 510%, for pyrolysis this number is 67% and for methanolysis 9%. Put differently, costs would need to decrease by 84%, 40% and 9% for gasification, pyrolysis and methanolysis, respectively, to reach a positive net income. We find dissolution and glycolysis to already have a positive net income, so they are not included here. Note that we assume that we are in the low feedstock price scenario. Assuming a higher price per tonne of feedstock would increase the gap between costs and revenues even more for pyrolysis, gasification and methanolysis and shrink net income for dissolution and glycolysis.

Looking at the relationship between the price of crude oil and the price of naphtha, which is one of the main outputs from pyrolysis, we can estimate the increase in crude oil prices at which net income from pyrolysis becomes positive under the assumption that the costs remain unaffected by this price increase.[38] Based on (Gjolberg & Johnsen, 1999), we assume that a 1% price increase in crude oil translates into a 0.96% price increase in naphtha (in the long run). As the revenues from pyrolysis would need to increase by 75% (see previous paragraph), the associated increase in crude oil prices would be 78.1%. Taking the average BRENT crude oil price in 2021 as a basis, the crude oil price at which pyrolysis reaches a positive net income is around 126 USD/barrel.[39]

With synthesis gas being the main output from gasification pathways, a similar estimate can be made for this technology, assuming that syngas prices and natural gas prices move in unison.[40] The break-even natural gas price in the EU would be 510% above the 2021 average and would amount to 0.184€/kWh (price for non-household consumers, excluding taxes).[41] Calculating this relationship for other pathways is less straightforward

[37] The revenue increase we discuss here does comes about via increased output prices (not via increased quantities). But since most processes produce a variety of outputs in different quantities, an increase in revenue could be the result of different combinations of price increases. To keep it simple, we therefore just discuss increases in revenue in general.

[38] This might be a relatively strong assumption, as, for instance, the prices of feedstock might also react to the price of crude oil, albeit less so than the prices of the outputs.

[39] A 2018 article by Hundertmark et al. (2018) estimates that "plastic waste–based feedstocks could be highly competitive with oil refinery–based feedstocks at crude-oil prices of $75 per barrel".

[40] Although syngas can be used for the synthesis of new chemicals, its price will most likely be determined by its predominant use as fuel (i.e. energy recovery).

[41] This is far above average European gas prices observed over the last decade, but below the unusual price peak observed since the onset of Russia's war against Ukraine. It is not possible to say whether prices will eventually return to their historical levels or whether this change is permanent.

due to their large variety of outputs and the less clear-cut relationship between this output and oil or gas prices. However, plastic prices are also directly affected by the price of crude oil: Weinhagen (2006), for instance, shows that an 8.2% increase in the price of crude oil leads to a 0.6% increase in the price of plastic products over the course of 14 months.

3.4 Operational considerations of chemical recycling

As stated in the methodology section of this report, very little information on operational aspects was provided by stakeholders and hence the information in this section is compiled from literature data. Moreover, this analysis is restricted to chemical recycling as information on physical recycling is even scarcer.

A good starting point for the operational analysis of plastic waste chemical recycling is Manžuch et al. (2021), who provide an overview of advantages and disadvantages of the major chemical recycling technologies for plastic waste, see Table 11. In the sections below, operational issues linked to chemical recycling are discussed in more detail.

Table 11. Advantages and disadvantages of commercially applied chemical recycling processes (Jiang et al., 2022; Manžuch et al., 2021; Ragaert et al., 2017; Solis & Silveira, 2020).

Technology	Advantages	Disadvantages
Solvolysis	• Lower energy input than other established chemical recycling processes • Produces pure value-added products, in particular plastic monomers	• Suitable for homogeneous plastics only and mainly condensation polymers (e.g. PET, PU, PC) • Susceptible to process contaminants such as heavy metals or additives • Requires high feedstock volumes to be economically viable
Pyrolysis	• Suitable for difficult to depolymerise plastic waste and mixed plastics	• High energy and temperature requirements • Low tolerance to PVC • Products may need upgrading before further use • Requires high feedstock volumes to be economically viable • Formation of solid residue affects operation
Catalytic pyrolysis	• Compared to regular pyrolysis: • Lower temperature and energy requirements • Higher yields • Optimised product distribution and selectivity	• Compared to regular pyrolysis: • Higher sensitivity to feedstock contamination • Possible catalyst blockage or deactivation • Absence of suitable reactor technology
Gasification	• Advanced polymer breakdown and possibility of hydrogen production • Suitable for mixed plastic waste	• High energy and temperature requirements • Sensitive to some contaminants • Produced syngas requires upgrading before further use

		• Requires high feedstock volumes to be economically viable • Formation of solid residue affects operation and produced gas quality

3.4.1 Presence of heteroatoms

Heteroatoms are atoms in plastics other than carbon and hydrogen. They may be part of the polymer backbone, like nitrogen in PA, oxygen in PET or chlorine in PVC. Heteroatoms may also be part of the additives or contaminants (e.g. residues on packaging materials). Both coke formation and fouling have been put in relation with heteroatoms (Kusenberg, Eschenbacher, et al., 2022), and metal contaminants present in the pyrolysis oils derived from plastic waste. During the thermochemical processing of mixed plastic waste, or of plastics containing heteroatoms, the heteroatoms will not only decrease the quality of the products but also harm the catalyst performance (Huang et al., 2022; Yang et al., 2022; Kusenberg et al., 2022). Heteroatoms are also one of the reasons why PVC, PU, PET and PA should be avoided in pyrolysis or the plastic stream has to be pre-treated, if the pyrolysis oil is to be fed to a steam-cracker (Vollmer et al., 2020; Ragaert et al., 2017; Kusenberg, Roosen, et al., 2022). A typical scenario in practice is to dilute plastic waste pyrolysis oil with fossil fuel feedstock (naphtha) as input for the steam cracker, using an amount in the range of 5–20 % ((Kusenberg, Roosen, et al., 2022). Yet, even in this case, the only contaminants which most likely do not require additional treatment are sulphur, sodium and silicon due to the fact that the dilution factor is sufficiently large. All other contaminants such as nitrogen, chlorine, calcium, iron and lead are exceeding the feedstock specifications for steam crackers to such an extent that additional upgrading technologies such as hydro-treatment are needed, which, of course, challenge the economic potential, and potentially the environmental performance, of plastic waste pyrolysis oil as steam cracking feedstock (Kusenberg et al., 2022).

3.4.2 Yield and heterogeneity of output products

Whereas solvolysis reactions provide monomers or a rather predictable distribution of output chemicals, pyrolysis results in a more heterogeneous chemical distribution. Relatively high monomer recovery rates can be achieved for PMMA (>95%), PS (up to 85%), but this is much less the case for PP (up to 45%) or PE (up to 40%), which have the tendency to randomly fragmentize (Vollmer et al., 2020; Ragaert et al., 2017). For PVC and PET, single stage thermal pyrolysis cannot produce any relevant quantity of monomers. Compact, yet sufficiently detailed kinetic models that have been validated with reliable experimental data are still lacking for plastic waste pyrolysis, and this leads to scale-up problems, which is therefore one of the key difficulties to improve the flexibility of the process. In general, olefins inhibit the cracking of paraffins while paraffins accelerate cracking of olefins (Kusenberg, Roosen et al., 2022). Catalysts have the potential to both reduce pyrolysis temperatures and narrow the product distribution (Lopez et al., 2017). Apart from the pyrolysis conditions, the catalyst properties, especially acidity and pore structure, play a significant role in the product distribution obtained.

3.4.3 Catalyst inefficiency and loss

Catalysts are extremely useful at steering chemical reactions towards a desired output and are encountered in all types of chemical recycling processes, from solvolysis over pyrolysis to gasification, although not all companies use catalysts (Yang et al., 2022). Depending on the type of feedstock and reaction process, challenges may be encountered related to the functionality of the catalyst and recovery from the reaction products.

In solvolysis, one of the main challenges is linked to the recovery of the catalyst (Vollmer et al., 2020; Yang et al., 2022). Although zinc acetate or other heavy metal salts have shown high activity for glycolysis of PET, these homogeneous catalysts are known to exhibit issues with toxicity and difficult recovery. Further investigations were proposed to develop efficient catalysts such as nanocomposites, zeolite, nanoparticles, ionic liquids, protic ionic salt, and deep eutectic solvents (Vollmer et al., 2020; Yang et al., 2022). Despite previous research efforts to improve the efficiency of PET glycolysis, separating nanomaterials after the reaction by centrifuge or membrane filtration consumes additional energy. Therefore, easily recoverable catalysts for PET glycolysis have been studied recently. Materials with magnetic properties can be an elegant alternative to vacuum distillation, cumbersome filtration, or centrifugation because they can be magnetically separated in a timely and cost-effective manner.

In high temperature applications, like in pyrolysis, high viscosity, low thermal conductivity, and relatively long molecular polymer chains may lead to a small catalyst/polymer contact area, as well as inhibit heat and mass transfer (Vollmer et al., 2020). Catalyst sintering is another influential factor for catalyst deactivation at high temperatures. Sintering of Ni species can take place during the steam reforming and the catalyst regeneration by air combustion for coke removal, resulting in lower activity due to the loss of active sites (Huang et al., 2022). Carbonaceous deposits, being Cl and N components present in the raw waste stream, can also rapidly deactivate the catalyst in catalytic pyrolysis (Ragaert et al., 2017). Furthermore, inorganic materials tend to block the pores of the catalyst, which sometimes results in a permanent deactivation of a large number of active sites. Therefore, harsh pre-treatment steps are quite often required to protect the catalyst. Sometimes light pyrolysis of the feed as pre-treatment allows dealing with highly contaminated feeds or feeds containing significant amounts of heteroatoms. In conclusion, in order to develop suitable catalysts for the thermochemical recycling processes, there are several criteria for the catalyst design: (i) highly active in the thermal processes, (ii) appropriate porous structure for optimal mass diffusion and activity, (iii) good stability of catalyst composition and structure under the harsh reaction conditions, (iv) high chemical resistance against coking and sintering, (v) high resistance to deactivation from catalyst poisoning by Cl-, Br- and S-containing impurities, and (vi) low cost or regenerable to be more economical and environmentally favourable (Huang et al., 2022).

3.4.4 Reactor design

The reactor in which waste polymer conversion takes place is the central and crucial element of the chemical recycling process. The design of the reactor and peripheral equipment is subject to various challenges, in particular for full-scale applications. Given the fact that plastics usually have low thermal conductivity and high viscosity, the continuous feeding and pumping mechanism represents a first challenge (Yang et al., 2022). Clogging and reactor fouling are another challenge. Due to the fact that the walls of the heat transfer surface are typically at higher temperatures than the bulk flow, chemical reactions might be catalyzed by the wall material yielding insoluble deposits at the inner walls (Kusenberg, Roosen et al., 2022). Finally, corrosion of the reactor by the presence of halogenated plastics (e.g. PVC) or additives (e.g. brominated flame retardants) may be another major challenge for certain input streams.

Lopez et al. (2017) discuss advantages and disadvantages of different technologies used in plastic waste pyrolysis. These include fixed beds, fluidized beds, spouted beds, screw kilns, microwave, molten bath and circulating spheres. Problems with the possibility to scale up is the most recurring issue for most of the technologies, except for fluidized beds and screw kilns. The use supercritical steam is also possible, which may help overcoming the scaling issued (Viveros et al., 2022).

3.4.5 Safety

Hazard Identification and Human Health Risk Assessment (HHRA) must be carried out before installing any new industrial plant, and these studies are expressly required by European and national legislation (Paladino & Moranda, 2021). The Hazard and Operability (HAZOP) approach, which involves a rigorous review of newly designed processes in order to uncover potential risks and deviations from the original design, may be carried out too (Xu et al., 2016). Unfortunately, obligations regarding such studies are usually much less restrictive, if not absent, in the case of installation of pilot plants, due to their reduced power and their expected period of operation, usually lasting a few years.

Yet, hazards of a pilot plant can be greater than those of a production plant, since pilot plants are operated to test different process conditions, far from the optimized ones. Results from an analysis by Paladino and Moranda (2021) on a pilot-plant for catalytic pyrolysis of mixed plastic waste, calculated as global Hazard Index and global Cancer Risk, showed that the population is not at risk for both dioxins and PCBdl in all their considered scenarios and for both ingestion and inhalation, while attention must be devoted to un-condensable gas releases, containing VOCs. Results also showed that for short operation periods, the classical exposure assessment procedure can highlight its lack of reliability in risk calculation.

4 Discussion: comparative analysis of scenarios and interpretation of results

In this section we discuss the following objectives of the study, earlier introduced in section 1.2:

- Criteria and conditions that should be taken into account to identify the most effective options, from a life cycle perspective, for the management of plastic waste;
- Environmental improvement or impacts resulting from chemical recycling of plastic waste in comparison with energy recovery and/or mechanical recycling;
- Key conditions under which chemical recycling is economically viable without public support.

4.1 Criteria and conditions to be considered to identify the preferred waste management option

4.1.1 Criterion I: Material recovery maximisation

Focusing on the climate change effects, the preferred waste management option from a life cycle perspective is the one maximising recovery of materials (incurring environmental savings) while minimising impacts of the waste processing itself, primarily related to energy consumption (incurring environmental burdens). All in all, any scenario (technology or combination of technologies) leading to combustion of the waste is less preferable to alternative mechanical, physical or chemical recycling, notwithstanding the recovery of electricity and heat, incurring environmental savings. The environmental savings associated with energy recovery from waste are indeed not enough to compensate for the environmental burdens associated with the combustion of the fossil carbon in the plastic waste and subsequent fossil CO_2 emissions. It is anticipated that the environmental savings associated with energy recovery will further decrease under future EU low-fossil carbon energy systems (Keramidas et al. 2021). This will further increase the gap between material- and energy-focused recovery technologies while supporting the validity of the EU waste hierarchy.

Focusing on the effects on the environmental categories other than climate change, it is more challenging to clearly identify preferred management options for plastic waste. For most categories, the abovementioned criterion on maximising material recovery while minimising processing impact still holds true (notably ozone depletion and fossil resource use). However, there are some pathways, e.g. sorted mixed polyolefins (MPOs) flexible packaging waste, sorted large-format PE film waste, post-industrial PE/PA multilayer film waste and EPS construction and demolition waste, and some categories (notably acidification, particulate matter, ionising radiation, human toxicity non-cancer, and eutrophication) where energy recovery can perform better than recycling under the current EU energy system, for instance . The reason is that, for selected emissions, e.g. NO_X, SO_X, particulates, radioactive isotopes, heavy metals, phosphorus, etc., affecting the earlier mentioned categories, incinerators achieve on average lower emissions than the (current) EU energy production mix, where there is still a high share of coal and other heavy fuel oil power plants and higher emission limits at the stack. However, similarly to what is argued above for climate change, it is anticipated that the EU energy system will become less polluting in the near future (Keramidas et al. 2021). This in turn will reduce the environmental savings associated with energy recovery from plastic waste on the abovementioned categories (similarly to climate change) while further increasing the overall gap between material- and energy-focused recovery technologies, thus supporting the validity of the EU waste hierarchy.

4.1.2 Criterion II: Waste material specificity and treatment required

Since plastic is a generic term that comprehends a multiple set of different materials (polymers, e.g. PET, PE, PP, etc.), which could also be further sub-divided (e.g. PE could be LDPE and HDPE), it is of utmost importance to consider in the analysis of recycling technologies the specificity of the waste-feedstock and thereby the recycling technologies that are capable to handle such specific waste material, to ensure a proper comparison. In this study, we strived to address this aspect of technical feasibility by, in a first instance, requesting specific information from the data providers and, secondly, by complementing it whenever the information provided was deemed not sufficient to compare alternative technologies.

When multiple products are generated (multi-output technologies), as is often the case with waste management facilities, the assessment shall credit such outputs considering their quality and effective substitution of corresponding market products. Having this in mind, it should also be noted that assessing the performance of recycling specific waste streams is different from assessing the performance of a specific recycled material or

product. In the latter case, the focus is on a specific product or material (thereby the functional unit being e.g. 1 kg of a very specific material or product), regardless of the waste-feedstock. This shifts the focus from the recycling or valorisation process and its specificity (also in relation to the complexity of the input-waste to be managed) to a particular product to be *a priori* defined.

While both perspectives may be relevant depending on the question to be answered, it should be noted that a product-perspective does not allow to compare energy recovery to chemical recycling. The implication of this could be exemplified as follows: a product-oriented analysis could conclude that making a product from virgin feedstock is better than making the same product via chemical recycling of waste. While this may be an angle of perspective, it does not capture the full picture. After all, it may occur that such chemical recycling is still better than the bottom-line alternative energy recovery for that particular waste, since waste treatment cannot be ignored in the overall assessment. With this in mind, a decision based only on a product-perspective would ultimately generate suboptimal benefits at a system level, as chemical recycling should be compared to the alternative treatment of that waste (as the baseline is that waste, once generated, needs to be treated).

4.2 Environmental improvements resulting from physical and chemical recycling relative to alternative options

A ranked overview of climate change impacts for all 27 scenarios investigated in this study is given in Figure 18. Climate change was selected as the most relevant impact category in the context of plastic waste management, based on previous evaluations (notably Andreasi-Bassi et al., 2022). As mentioned above, plastic is a generic term that groups a multiple set of different materials (e.g. PET, PE, PP). Hence, the following discussion will take into account the specificity of the waste feedstock.

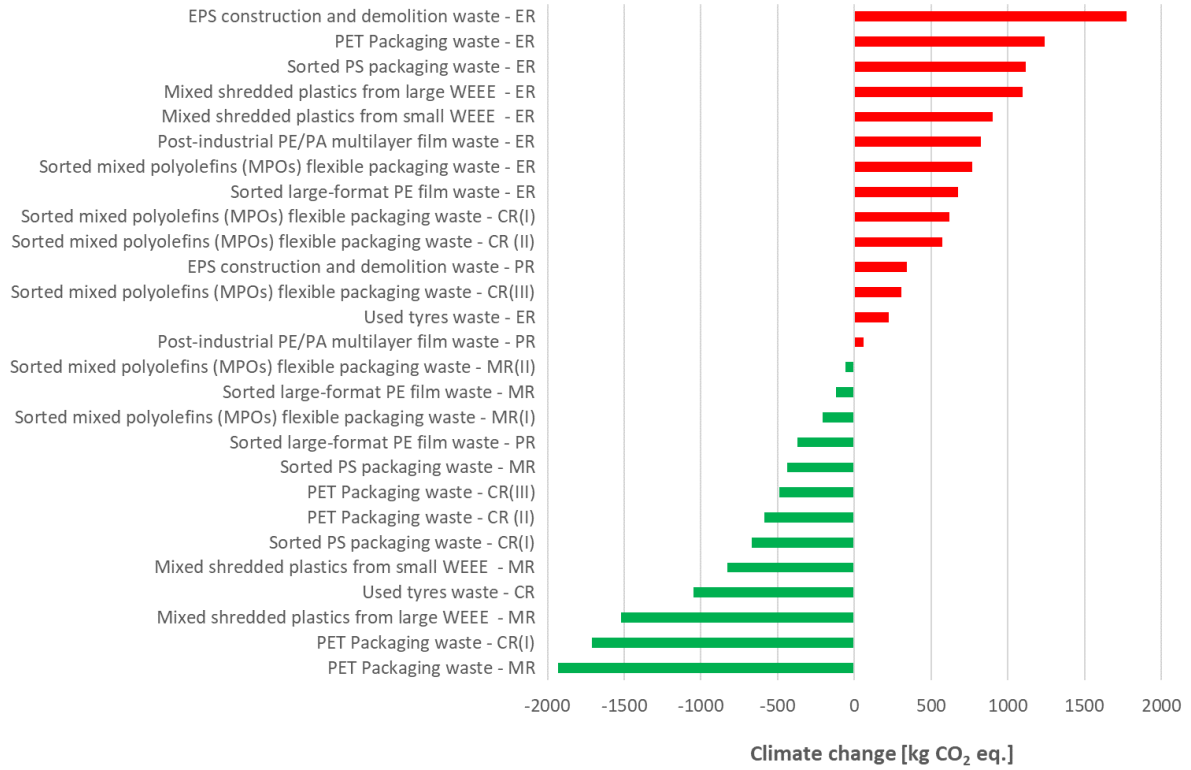


Figure 18. Summary overview of climate change associated with the management of 1 t of various plastic wastes. Negative values (green bars) represent net GHG savings, while positive ones (red bars) represent net GHG burdens. See Table 1 for a description of the different treatment scenarios/technologies. CR: chemical recycling; ER: energy recovery; MR: mechanical recycling; PR: physical recycling.

4.2.1 Mechanical, physical and chemical recycling versus energy recovery

For climate change effects (see Figure 18), across all waste streams investigated (PET, EPS packaging, EPS CDW, MPO, tyres), mechanical, physical and chemical recycling appears always preferable to energy recovery. Energy recovery is a net burden to climate change because of CO_2 emissions following fossil carbon combustion,

which is not compensated by GHG savings from energy recovery and substitution of conventional energy production means. In contrast, recycling incurs net GHG savings following substitution of virgin material production, which more than compensates any GHG burden associated with recycling operations. Relative to energy recovery, the additional savings (i.e. the net delta) on climate change equalled 1777 (PS), 151-465 (MPO), 1729-3300 (PET), 1430 (EPS CDW) kg CO_2-eq. per tonne of waste treated (Figure 18). The gap between chemical recycling and energy recovery is anticipated to become larger under the future (low-fossil carbon) EU energy systems, as climate change benefits incurred by energy recovery from plastic waste will gradually become less prominent. Considering that the future capacity of chemical recycling can be up to 3 Mt by 2030 as suggested by (Systemiq, 2022), this could roughly mean annual additional GHG savings in the order of 0.5-10[42] Mt CO_2-eq. at EU level, if waste otherwise incinerated was treated via chemical recycling instead. For the remaining impact categories, and under the current EU energy system conditions, the performance of physical and chemical recycling was not always superior to energy recovery, especially for pyrolysis technologies. The reason for this lies on the fact that incinerators, for selected substances emitted to air, achieve on average much lower emissions than the (average) EU energy production mix, where there is still a high share of coal and other heavy fuel oil power plants and typically higher emission limits at the stack. This incurs important environmental savings in impact categories such as acidification (related to SO_2, NOx), ionizing radiation, particulate matter (dust and NOx), human toxicity non-cancer (related to metal emissions). However, similarly to what argued earlier for climate change, it is anticipated that the EU energy system will become less polluting in the next future (Keramidas et al., 2021). This in turn will reduce the environmental savings associated with energy recovery from plastic waste on these categories similarly to climate change, while further increasing the overall gap between material- and energy-focused recovery technologies.

4.2.2 Physical and chemical recycling versus mechanical recycling

For a number of waste streams (i.e. PET waste, EPS packaging waste, MPO waste, PE/PA waste), mechanical and physical or chemical recycling could be directly compared as the input-waste treated was considered to be the same. A clear ranking of the scenarios involving these technologies could not be derived as one performed better in some impact categories and worse in others.

4.3 Key conditions under which physical and chemical recycling is economically viable without public support

Building on the same cost-parameters as in the LCC, in section 3.3 this study looked at the determinants of the economic viability of physical and chemical recycling: feedstock prices, capital and operational expenditures and output prices. The following five pathways were analysed: dissolution, glycolysis, methanolysis, pyrolysis and gasification. The pathways were assessed using harmonised survey and literature data, or literature data exclusively (as in the case of gasification).

The main outcome is that under current conditions methanolysis, pyrolysis and gasification have negative net incomes and are thus not economically viable in all analysed scenarios. Dissolution achieves a positive net income in all three analysed scenarios and glycolysis in two of the three, but these results are driven by exceptionally high values for revenues reported in the survey data and are reversed when using only literature data. Further, high electricity consumption for the dissolution processing may significantly increase overall costs, as illustrated in the LCC. However, due to the limitations of the data on which the analysis is based, this does not represent a definite conclusion regarding the economic viability of the abovementioned pathways, but rather a preliminary exploration. In the following paragraphs conditions are discussed under which some or all of the chemical recycling technologies could become economically viable.

The analysis presented here does not account for gate fees or government policies such as subsidies. It might well be that the existing gap between costs and revenues that is found for most chemical recycling technologies could be reduced or eliminated by the introduction of public support measures. Similarly, gate fees could fill this gap. The level of support policies or gate fees necessary to achieve positive net incomes would be 63 €/t waste for methanolysis, 160 €/t waste for pyrolysis and 357 €/t waste for gasification.[43]

[42] Roughly calculated using the range of savings between 151 (MPO) and 3300 (PET) kg CO_2-eq. per tonne of waste treated via chemical recycling instead of energy recovery, and assuming 3 Mt annual chemical recycling capacity.

[43] These numbers are not too far from existing gate fees for landfilling, at least in some European countries: https://www.eea.europa.eu/data-and-maps/figures/typical-charge-gate-fee-and

Furthermore, physical and chemical recycling technologies are still under heavy development and costs are projected to decrease in the future, improving their economic performance. Using projections of technical advances in chemical recycling technologies and increased costs of virgin production, we estimate whether and when different chemical recycling technologies would become economically viable before 2040. Based on these scenarios, all chemical recycling pathways except gasification would be expected to achieve positive net incomes within the next two decades.

Another key factor is the price of crude oil, which is directly coupled with the price of virgin products and the price of natural gas. For instance, the long-run price of naphtha is coupled to the price of crude oil in an almost one to one fashion (Gjolberg & Johnsen, 1999). This is particularly relevant for pyrolysis pathways, for which naphtha is one of the major outputs. A similar logic applies to products derived from other pathways, although their relationships with the price of crude oil are less well-established. A quantification of the relationship between crude oil prices and the economic viability of some chemical recycling pathways is given in Section 3.3.3.

5 Conclusion

5.1 Chemical and physical recycling: When can the case be made from an environmental point of view?

In this section we intend to provide recommendations on when chemical and physical recycling can be an option from an environmental perspective. As preliminary recommendations we anticipate the following:

- Considering climate change effects, the management of plastic waste via chemical and physical recycling appears to be preferred to energy recovery (here modelled as incineration with combined heat and power), notably for mixed polyolefins waste bales currently produced by sorting plants in the EU and not mechanically recycled. The same is valid for other plastic waste streams.
- Considering impact categories other than climate change, the management of plastic waste via chemical or physical recycling can be at times less performing than energy recovery, albeit still overall generating environmental savings, as the savings generated from treatment are considerably larger than the burdens generated from treatment. The reason for this result lies in the significant savings generated via energy recovery thanks to the substitution of energy otherwise produced via the current EU energy mix. However, such energy-related savings are anticipated to be significantly reduced in the future when the EU energy mix will become cleaner. In such scenario, material recovery-focused technologies will rank best also on categories other than climate change.
- Considering the scenarios where mechanical and chemical or physical recycling constitute alternative management options, a clear ranking could not be established.
- Improved information on the waste-feedstock composition is important to understand whether chemical or physical recycling and mechanical recycling may end up competing for similar high-quality waste or whether chemical recycling could realistically be integrated with mechanical recycling by processing waste otherwise sent to energy recovery or landfill.

5.2 How to choose between mechanical, physical, chemical recycling and energy recovery?

The choice of the preferred management option for plastic waste should be based on three main criteria, of which two relate to techno-environmental performance and feasibility and one strictly to economic feasibility: i) the maximisation of material recovery while minimising processing impacts, principally related to energy consumption (reflecting environmental performance), ii) the specificity of the plastic waste stream and the treatment thereby required (technical feasibility), and iii) the economic feasibility.

With respect to the first criterion, we observe that waste treatment performances (notably climate change savings) are typically proportional to the material recovery and this trend will become even more evident in the future low-fossil carbon EU energy system. From a waste hierarchy perspective, energy recovery is the least preferred option, achieving net climate change impacts (i.e. GHG emissions released from the energy recovery treatment are considerably larger than GHG savings generated from substitution of conventional market energy). For categories other than climate change, energy recovery is at times comparable or better than chemical, physical or mechanical recycling because of the important savings associated with substitution of energy otherwise produced via the current EU energy mix. However, such energy-related savings are anticipated to be significantly reduced in the future when the EU energy mix will become progressively cleaner. In such scenario, material recovery-focused technologies will rank best also on categories other than climate change.

With respect to the second criterion, we stress the importance of factoring in the waste composition/quality when comparing management options. Plastic waste is a heterogeneous and challenging flow, and the composition/quality is a determining factor for the operations to be undertaken. Improved information on the waste-feedstock composition is crucial also to understand in which cases chemical recycling and mechanical recycling may end up competing for similar waste feedstock or in which cases chemical could really be integrated with mechanical recycling.

With respect to the third criterion, we indicate that economic viability is a function of OPEX, CAPEX, waste-feedstock and recyclate price. Another factor at play is the price of crude oil, which appears to be directly coupled with the price of virgin products, and in particular plastic. Increasing crude oil prices could thus positively influence the economic viability of physical and chemical recycling. Due to a lack of data, we only analysed the pathway pyrolysis of mixed polyolefin (MPO). The main outcome is that this pathway is economically viable

when the sum of OPEX and CAPEX is below 350 €/t and feedstock prices are at ca. 100€/t. The results of the LCC, while indicating the same overall trend in terms of costs and savings, also highlighted that for selected feedstock (e.g. MPO) mechanical recycling technologies may also need fees to be financially viable.

5.3 Perspectives and future research

This section describes the main limitations associated with this study and how further research could improve the robustness of results and recommendations:

- The low maturity of some of the technologies studied, and therefore the representativeness of the related inventory data, especially in terms of energy consumption. This was especially the case for some technologies such as dissolution (solvent extraction), for which data showed an unusually high electricity consumption for processing. The same issue may as well apply to other inventories. While such limitation is inevitable given the status of development of some technologies, a future second iteration of this LCA using updated data may be a possible way forward to derive more robust results and recommendations.
- The poor information collected and available in the scientific and technical literature about costs of the physical and chemical recycling technologies. This prevents from having a clear picture on the (life cycle) economics of the investigated waste management pathways as well as on their economic viability. This applies also to some mechanical recycling pathways (e.g. MPO) for which the life cycle costing indicated net costs (negative income), which is somehow an unexpected result. Similarly to the point above, a second iteration of this LCC using updated data may be a possible way forward to derive more robust results in terms of economics.
- While the JRC repeatedly insisted on receiving additional and more detailed information on the input-waste composition treated by the technologies investigated, the level of information received was not always sufficient to properly describe the input-waste composition, especially in terms of impurities. To circumvent this issue and ensure a fair comparison between technologies that may require different quality of the feedstock, the authors adjusted the received inventory data by: i) implementing rigorous mass-balances to match input to output material flows; ii) adding additional pre-treatment steps (sorting, shredding, etc. including related energy consumption and losses) wherever in the originally provided datasets it was not transparently documented that such pre-treatments had been included to prepare the feedstock for the subsequent recycling (this mainly applies to some chemical recycling technologies for which higher quality is required). Future studies should focus on collecting more detailed information on the specific quality of the feedstock used for chemical recycling (quality requirement, level of acceptable impurities, pre-treatment required, etc.) in order to better assess to what extent these technologies can complement mechanical recycling by handling challenging plastic waste streams.

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Glossary

Depolymerisation	A general term that includes different ways to convert a polymer into a monomer or a mixture of monomers.
Glycolysis	Depolymerisation reaction through which molecular degradation of PET polymer by glycols occurs, in the presence of trans-esterification catalysts, where ester linkages are broken and replaced with hydroxyl terminals.
Hydro-cracking	The process whereby complex organic molecules such as long-chain hydrocarbons are broken down into simpler molecules such as light hydrocarbons, by the breaking of carbon-carbon bonds in the precursors and assisted by a catalyst in the presence of hydrogen gas.
Hydrolysis	Depolymerisation reaction carried out in the presence of a catalyst, usually a metallic salt soluble in water that decomposes PET into dimethyl terephthalate and ethylene glycol.
Methanolysis	Depolymerisation catalytic process that employs high-temperature and high-pressure methanol to decompose PET into dimethyl terephthalate and ethylene glycol.
Polymer dissolution	A process that involves the dissolution of a physical mixture of polymers into a solvent at a low temperature. This yields both a solid phase containing polymers which are insoluble in the solvent (at the initial temperature) and a solution phase.
Pyrolysis	Thermal decomposition of materials, usually containing carbon, at elevated temperatures in the absence of air.

List of abbreviations and definitions

CAPEX	Capital expenditure
CDW	Construction and demolition waste
CLCC	Conventional life cycle costing
CR	Chemical recycling
EG	Ethylene glycol
EPS	Expanded polystyrene
ER	Energy recovery
GHG	Greenhouse gas
HBCD	Hexabromocyclododecane (flame retardant)
HDPE	High-density polyethylene
HFO	Heavy fuel oil
LCA	Life cycle assessment
LCC	Life cycle costing
LDPE	Low-density polyethylene
LFO	Light fuel oil
LIA	Life cycle inventory
MPO	Mixed polyolefin
MPW	Mixed plastic waste
MR	Mechanical recycling
OPEX	Operational expenditure
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate
PO	Polyolefin
PP	Polypropylene
PPW	Plastic packaging waste
PR	Physical recycling
PS	Polystyrene
PTA	Purified terephthalic acid
RDF	Refuse Derived Fuel
SLCC	Societal life cycle costing
TRL	Technology readiness level
WEEE	Waste electrical and electronic equipment
XPS	Extruded polystyrene

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Annex 1. Inventory tables of the modelled energy recovery processes

Table A1-1. Inventory of the waste-to-energy process used to model energy recovery from plastic waste and treatment of most non-recyclable material fractions, residues and losses arising from the investigated recycling processes.

Inventory flow	Amount (per 1 tonne of waste incinerated)	Unit of measure	Dataset geography	Comment
Inputs				
Plastic waste	1000	kg	-	Input waste
Electricity	251.7	kWh	EU+EFTA+UK	Value taken from[1]
Heat	54.0	MJ	EU+EFTA+UK	Value taken from[1]
Sodium hydroxide	0.65	kg	EU+EFTA+UK	Value taken from[1]
Active carbon	0.78	kg	EU+EFTA+UK	Value taken from[1]
Lime	7.2	kg	EU+EFTA+UK	Value taken from[1]
Steam	100.8	MJ	EU+EFTA+UK	Value taken from[1]
Ammonia	2.0	kg	EU+EFTA+UK	Value taken from[1]
Rain water	52.0	kg	-	Process water; BREF[2]; Table 3.31, pp. 264
Tap Water	36.0	kg	EU+EFTA+UK	Process water; BREF[2]; Table 3.31, pp. 264
Outputs				
Carbon monoxide, fossil	0.165	kg	-	10-50 mg/Nm3; BREF[2]; Table 5.6 pp. 496

Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	2.5E-07	kg	-	0.01-0.08 ng/Nm3; BREF[2]; Table 5.7 pp. 497
Hydrogen chloride	0.028	kg	-	2-8 mg/Nm3; BREF[2]; Table 5.5 pp. 495
Hydrogen fluoride	0.0055	kg	-	<1 mg/Nm3; BREF[2]; Table 5.5 pp. 495
Nitrogen oxides	0.550	kg	-	50-150 mg/Nm3; BREF[2]; Table 5.6 pp. 496
Sulphur dioxide	0.123	kg	-	5-40 mg/Nm3; BREF[2]; Table 5.5 pp. 496
Particulates, > 10 um	0.020	kg	-	2-5 mg/Nm3; BREF[2]; Table 5.4 pp. 494
Dinitrogen monoxide	0.008	kg	-	1-2 mg/Nm3; IPCC; pp. 460; https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf
VOC, volatile organic compounds, unspecified origin	0.036	kg	-	3-10 mg/Nm3; BREF[2]; Table 5.7 pp. 497
C, As, Hg, Cd, Cu, Cr, Ni, Sb, Pb	See note[3]	%substance in waste	-	Based on substance balance (Astrup et al., 2011)
Electricity efficiency	15	%LHV wet waste	-	Average EU efficiency as given in EF incineration dataset
Heat efficiency	35	%LHV wet waste	-	Average EU efficiency as given in EF incineration dataset
Bottom ash	87.4	%ash in waste	-	Based on substance balance (Astrup et al., 2011)
Fly ash	12.6	%ash in waste	-	Based on substance balance (Astrup et al., 2011)

(1) Waste incineration of municipal solid waste; waste-to-energy plant with dry flue gas treatment, including transport and pre-treatment; production mix, at consumer; municipal solid waste. The incineration is done in waste-to-energy plants (WtE) for the thermal treatment of municipal waste with dry flue gas cleaning and selective catalytic reduction (SCR), or selective non-catalytic reduction (SNCR), for NOx-removal to meet the legal requirements. Transport of the waste is included in the data set. The modelled plant consists of an incineration line fitted with a grate and a steam generator.

(2) (JRC, 2015) – BREF incineration; to convert BREF values expressed per Nm^3 flue gas to emission factors expressed per tonne of waste incinerated, a volumetric air flow of 5,500 Nm^3/tonne waste incinerated was considered, as suggested for the calculation of waste incineration emission factors by IPCC (IPCC, 2012).

(3) The partitioning of C and metals to air, bottom ash, fly ash, or other flue-gas cleaning residues is based on mass balances on incinerators (emission to air, as % of the substance in the input-waste: C 100, As 0.012, Hg 0.75, Cd 0.0064, Cu 0.0026, Cr 0.039, Ni 0.033, Sb 0.12, Pb 0.0008); after (Astrup et al., 2011).

Table A1-2. Inventory of the recovery process used to model ferrous and non-ferrous metal recovery from incineration bottom ash. Notice that the inventory is provided per tonne of bottom ash sent to treatment. Data are taken from the work of Allegrini et al. (2014, 2015).

Inventory flow	Amount (per 1 tonne of bottom ash for treatment)	Unit of measure	EF/*ecoinvent* dataset	Dataset geography	Comment
Inputs					
Bottom ash	1000	kg	-	-	Input bottom ash
Electricity	0.24	kWh	Electricity grid mix 1kV-60kV, technology mix, consumption mix, to consumer, 1kV - 60kV	EU+EFTA+UK	Fe and NFe sorting
Electricity	1.1	kWh	Electricity grid mix 1kV-60kV, technology mix, consumption mix, to consumer, 1kV - 60kV	EU+EFTA+UK	NFe upgrading
Diesel in machine	0.3	kg	Diesel_combustion_in_construction_machinediesel_drivenproduction_mix_at_plant_6f06614d-fd12-4072-89ff-909caf1d744	EU+EFTA+UK	Fe sorting
Diesel in machine	0.181	kg	Diesel_combustion_in_construction_machinediesel_drivenproduction_mix_at_plant_6f06614d-fd12-4072-89ff-909caf1d744	EU+EFTA+UK	Fe upgrading
Diesel in machine	0.469	kg	Diesel_combustion_in_construction_machinediesel_drivenproduction_mix_at_plant_6f06614d-fd12-4072-89ff-909caf1d744	EU+EFTA+UK	NFe sorting
Diesel in machine	0.016	kg	Diesel_combustion_in_construction_machinediesel_drivenproduction_mix_at_plant_6f06614d-fd12-4072-89ff-909caf1d744	EU+EFTA+UK	NFe upgrading
Transport	1.92	t*km	Articulated_lorry_transport_Total_weight_20-26_t_mix_Euro_0-5diesel_driven_Euro_0_-_5_mix_cargoconsumption_mix_to_consumer_2a2b6056-87fe-4bc4-bcc6-c4c684b36a0	EU+EFTA+UK	NFe transport to upgrading
Outputs					
Fe metal	80	%Fe in Fe-waste	(1) Steel cold rolled coil <1,5mm, BF route, production mix, at plant, <1,5mm (2) Recycling of steel into steel billet, collection, transport, pretreatment, remelting, production mix, at plant, steel waste, efficiency 95%	(1) DE (2) EU+EFTA+UK	The dataset used to model includes the recycling process and the associated credits.
NFe metal	50	%Al in Al-waste	(1) Recycling of aluminium into aluminium ingot - from post-consumer, collection, transport, pretreatment, remelting, production mix, at plant, aluminium waste, efficiency 90% (2) Aluminium ingot mix, primary production, consumption mix, to consumer, aluminium ingot product	(1) EU+EFTA+UK (2) EU+EFTA+UK	The dataset used to model includes the recycling process and the associated credits.

Annex 2. Inventory data used as input for the conventional life cycle costing and the economic analysis

Table A2-1. Input data for the conventional life cycle cost analysis of mechanical and chemical recycling pathways. The data for CAPEX and OPEX of mechanical recycling technologies are mostly based on Andreassi Bassi et al. (2020), while those for chemical recycling technologies are based on information collected from the survey (see Section 2.1.5) and the literature (Carducci et al., 2020; KIDV, 2018; Stapf et al., 2018). Waste-bales and recycled materials prices were retrieved from different on-line sources such as Plasticker (2022), EUROSTAT (2021) and www.chemanalyst.com, the literature, the survey, or from other recycling plant operators. The remaining information regarding waste shipment, incineration, landfill and energy carriers' prices are based on previous work conducted by the JRC in the context of plastic waste management, notably Andreassi Bassi et al. (2022). All prices are given in EUR 2020. Due to confidentiality reasons, only ranges are provided for data supplied via the survey. However, JRC used the actual values for the calculation.

Price/cost category	Affected process/ input-waste/ recycled/recovered product	Price/Cost	Unit	Source
CAPEX	MR-PET-PW	57.04	EUR/t	Andreasi Bassi et al. (2020). Average of values for MR of clear, light-blue, and mixed-coloured PET
CAPEX	CR-PET-PW-(I)	1-500	EUR/t	Survey
CAPEX	CR-PET-PW-(II)	1-500	EUR/t	Survey
CAPEX	CR-PET-PW-(III)	75.00	EUR/t	Carducci et al. (2020)
CAPEX	MR-PS-PW	76.02	EUR/t	Andreasi Bassi et al. (2020). Average of data for MR of PET, HDPE, PP, film, and MPO
CAPEX	CR-PS-PW	1-500	EUR/t	Survey
CAPEX	MR-MPO-FPW-(I) MR-MPO-FPW-(II)	95.02	EUR/t	Andreasi Bassi et al. (2020)
CAPEX	CR-MPO-FPW-(I) CR-MPO-FPW-(II) CR-MPO-FPW-(III)	141.10	EUR/t	KIT (2018)
CAPEX	MR-PE-FW PR-PE-FW	94.94	EUR/t	Andreasi Bassi et al. (2020)
CAPEX	PR-PE/PA-FW	183.32	EUR/t	KIDV (2018)
CAPEX	PR-EPS-CDW	76.02	EUR/t	Andreasi Bassi et al. (2020). Average of data for MR of PET, HDPE, PP, film, and MPO
CAPEX	CR-TYR	141.10	EUR/t	KIT (2018)
CAPEX	MR-MSP-WEEE-SA	122.00	EUR/t	Plant operators
CAPEX	MR-MSP-WEEE-CFA	170.00	EUR/t	Plant operators
OPEX	MR-PET-PW	145.27	EUR/t	Andreasi Bassi et al. (2020). Average of values for MR of clear, light-blue, and mixed-coloured PET
OPEX	CR-PET-PW-(I)	560.0	EUR/t	KIDV (2018)
OPEX	CR-PET-PW-(II)	500-1000	EUR/t	Survey
OPEX	CR-PET-PW-(III)	93.00	EUR/t	Carducci et al. (2020)
OPEX	MR-PS-PW	159.40	EUR/t	Andreasi Bassi et al. (2020). Average of data for MR of PET, HDPE, PP, film, and MPO
OPEX	CR-PS-PW	500-1000	EUR/t	Survey

Price/cost category	Affected process/ input-waste/ recycled/recovered product	Price/Cost	Unit	Source
OPEX	MR-MPO-FPW-(I) MR-MPO-FPW-(II)	157.40	EUR/t	Andreasi Bassi et al. (2020)
OPEX	CR-MPO-FPW-(I) CR-MPO-FPW-(II) CR-MPO-FPW-(III)	21.00	EUR/t	KIT (2018)
OPEX	MR-PE-FW PR-PE-FW	173.61	EUR/t	Andreasi Bassi et al. (2020)
OPEX	PR-PE/PA-FW	1-500	EUR/t	Survey
OPEX	PR-EPS-CDW	159.40	EUR/t	Andreasi Bassi et al. (2020). Average of data for MR of PET, HDPE, PP, film, and MPO
OPEX	CR-TYR	21.00	EUR/t	KIT (2018)
OPEX	MR-MSP-WEEE-SA MR-MSP-WEEE-CFA	159.40	EUR/t	Andreasi Bassi et al. (2020). Average of data for MR of PET, HDPE, PP, film, and MPO
Waste/feedstock price (bales)	Input-waste to: MR-PET-PW CR-PET-PW-(I) CR-PET-PW-(II) CR-PET-PW-(III)	215.00	EUR/t	Plasticker (2022). Average of the minimum and maximum price of "PET bale goods" for the period Dec. 2021-Apr. 2022 (70-360 EUR/t)
Waste/feedstock price (bales)	Input-waste to: MR-PS-PW CR-PS-PW	288.54	EUR/t	Plasticker (2022). Average of calculated average prices for PET, HDPE, LDPE, and transparent/commercial film waste
Waste/feedstock price (bales)	Input-waste to: MR-MPO-FPW-(I) MR-MPO-FPW-(II) CR-MPO-FPW-(I) CR-MPO-FPW-(II) CR-MPO-FPW-(III)	288.54	EUR/t	Plasticker (2022). Average of calculated average prices for PET, HDPE, LDPE, and transparent/commercial film waste
Waste/feedstock price (bales)	Input-waste to: MR-PE-FW PR-PE-FW	300.00	EUR/t	Plasticker (2022). Average of calculated average prices for neutral and coloured transparent film waste and commercial mixed film waste
Waste/feedstock price	Input-waste to: PR-PE/PA-FW	240.00	EUR/t	Plasticker (2022). Average price of "commercial mixed film (80/20)" waste
Waste/feedstock price	Input-waste to: PR-EPS-CDW	288.54	EUR/t	Plasticker (2022). Average of calculated average prices for PET, HDPE, LDPE, and transparent/commercial film waste
Waste/feedstock price	Input-waste to: CR-TYR	230.00	EUR/t	Farzad et al. (2021)
Waste/feedstock price	Input to: MR-MSP-WEEE-SA MR-MSP-WEEE-CFA	100.00	EUR/t	Plant operators
Recycled/Recovered price	PET regranulate (food-grade)	1275.00	EUR/t	Plant operators
Recycled/Recovered price	PET regranulate (non-food grade)	250.00	EUR/t	Plant operators
Recycled/Recovered price	PET granulate (from CR)	1275.00	EUR/t	Plant operators
Recycled/Recovered price	rPET (IV=0.8)	1500-2000	EUR/t	Survey

Price/cost category	Affected process/ input-waste/ recycled/recovered product	Price/Cost	Unit	Source
Recycled/Recovered price	rPET (IV=0.65)	1000-1500	EUR/t	Survey
Recycled/Recovered price	PP regranulate (non-food grade)	525.00	EUR/t	Plasticker (2019-2021)[1]
Recycled/Recovered price	HDPE regranulate (non-food grade)	845.00	EUR/t	Plasticker (2019-2021)[1]
Recycled/Recovered price	PS (re)-granulate (non-food grade)	909.17	EUR/t	Plasticker (2019-2021)[1]
Recycled/Recovered price	MPO regranulate (non-food grade)	500.00	EUR/t	Plant operators
Recycled/Recovered price	MPO agglomerate	180.00	EUR/t	Plant operators
Recycled/Recovered price	LDPE (re)-granulate (non-food grade)	700.00	EUR/t	Plasticker (2019-2021)[1]
Recycled/Recovered price	PA granulate (non-food grade)	1500-2000	EUR/t	Survey
Recycled/Recovered price	ABS regranulate	850.00	EUR/t	Plasticker (2019-2021)[1]
Recycled/Recovered price	PS (high-impact) regranulate	967.50	EUR/t	Plasticker (2019-2021)[1]
Recycled/Recovered price	Steel billet (secondary)	270.00	EUR/t	EUROSTAT (2021)
Recycled/Recovered price	Aluminium ingot (secondary)	1713.15	EUR/t	https://tradingeconomics.com/commodity/aluminumm (assuming a conversion factor of 0.94 EUR/USD)
Recycled/Recovered price	Secondary graphic paper	118.70	EUR/t	EUROSTAT (2021)
Recycled/Recovered price	Rubber regranulate	833.00	EUR/t	Farzad et al. (2021)
Recycled/Recovered price	RDF[2]	81.91[3]	EUR/t_{RDF}	Martinez-Sanchez et al. (2015)
Recycled/Recovered price	Ethylene glycol	775.00	EUR/t	https://www.echemi.com/productsInformation/pid_Seven2471-ethylene-glycol-eg.html
Recycled/Recovered price	Dimethyl Terephthalate (DMT) food grade	500-1000	EUR/t	Survey
Recycled/Recovered price	Purified terephthalic acid	725	EUR/t	https://www.chemanalyst.com/Pricing-data/purified-terephthalic-acid-pta-18
Recycled/Recovered price	Sodium sulphate	110.10	EUR/t	https://www.echemi.com/productsInformation/temppid160705011365-sodium-sulfate.html
Recycled/Recovered price	Styrene	1000-1500	EUR/t	Survey
Recycled/Recovered price	Hydrocarbons	1000-1500	EUR/t	Survey
Recycled/Recovered price	Naphtha	603	EUR/t	https://www.finanzen.net/rohstoffe/naphthapreis/chart
Recycled/Recovered price	Pyrolysis gas	4.00	EUR/GJ	Martinez-Sanchez et al. (2015)

Price/cost category	Affected process/ input-waste/ recycled/recovered product	Price/Cost	Unit	Source
Recycled/Recovered price	Heavy fuel oil	535	EUR/t	https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average
Recycled/Recovered price	Carbon black	1-500	EUR/t	Survey
Recycled/Recovered price	Wax	630.00	EUR/t	https://tradingeconomics.com/commodity/bitumen
Recycled/Recovered price	Hydro-treated pyrolysis oil	603	EUR/t	https://www.finanzen.net/rohstoffe/naphthapreis/chart
Recycled/Recovered price	Char	630.00	EUR/t	https://tradingeconomics.com/commodity/bitumen
Recycled/Recovered price	Tar	630.00	EUR/t	https://tradingeconomics.com/commodity/bitumen
Recycled/Recovered price	Pyrolysis oil	285.00	EUR/t	https://www.recyclingpyrolysisplant.com/news/industry_news/tyre_pyrolysis_oil_marker_price_728.html
CAPEX	ER – all scenarios	119.00	EUR/t	Andreasi Bassi et al. (2022)
OPEX	ER – all scenarios	50.00	EUR/t	Andreasi Bassi et al. (2022)
Electricity price (sold)	ER – all scenarios	0.05	EUR/MJ	Martinez-Sanchez et al. (2015)
Heat price (sold)	ER – all scenarios	0.014	EUR/kWh	Martinez-Sanchez et al. (2015)
Net cost	Landfill	69.70	EUR/t	Andreasi Bassi et al. (2022)
Transport cost	Transport by truck	0.077	EUR/(t*km)	Anreasi Bassi et al. (2022)

[1] Monthly "BvSE Market Reports" for the period 2019-2021 available from the website "Plasticker – the home of plastics" (https://plasticker.de/preise/marktbericht_en.php). Monthly prices (or average monthly prices) provided for regranulate in each monthly report were used to calculate the three-year average price considered in the analysis (as reported in this table).

[2] Avoided cost from the replacement of Refuse Derived Fuel (RDF) for conventional and alternative fuels used in cement kilns (i.e. cost associated with the supply of the replaced fuel mix). A price equal to zero was assumed for RDF in itself.

[3] Based on an estimated average supply cost for the replaced fuel mix equal to 4.075 EUR per GJ of fuel mix burned in cement kilns, and a lower heating value of RDF equal to 20.1 MJ/t_{RDF}.

Annex 3. Detailed results for life cycle assessment of recycling and energy recovery scenarios: breakdown of impact contributions for individual impact categories

This annex provides the detailed numerical results of the life cycle assessment with regard to the fourteen impact categories considered in this study, i.e.: Climate Change (CC), Ozone Depletion (ODP), Human toxicity, cancer (Htox_c), Human toxicity, non-cancer (Htox_nc), Particulate Matter (PM), Ionising Radiation (IR), Photochemical Ozone Formation (POF), Acidification (AC), Eutrophication, terrestrial (TEU), Eutrophication, freshwater (FEU), Eutrophication, marine (MEU), Ecotoxicity, freshwater (Ecotox), Resource use, minerals and metals (MRU), Resource use, fossils (FRU). The results are expressed per functional unit, i.e. management of one tonne (t) of plastic waste input to each of the compared scenarios (i.e. mechanical recycling, physical recycling, chemical recycling and energy recovery) including any impurities.

Results for "Sorted PET packaging waste (bottles and **trays)"**

Climate change (kg CO_2 eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-1.93E+03	1.24E+03	-1.71E+03	-5.86E+02	-4.89E+02
Transport	3.79E+00	3.78E+00	2.28E+01	3.78E+00	3.78E+00
Substitution of energy	-6.60E+01	-8.54E+02	-6.17E+01	-6.17E+01	-6.17E+01
Substitution of materials	-2.42E+03	-7.51E+00	-2.24E+03	-1.65E+03	-1.78E+03
Processing - Energy	2.55E+02	0.00E+00	3.73E+02	7.69E+02	5.57E+02
Processing - Non-Energy	1.74E+02	0.00E+00	3.25E+01	1.92E+02	6.27E+02
Treatment of residues	1.23E+02	0.00E+00	1.59E+02	1.59E+02	1.59E+02
Incineration	0.00E+00	2.10E+03	0.00E+00	0.00E+00	0.00E+00

Ozone depletion (kg CFC-11 eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	5.74E-03	3.40E-07	1.44E-06	-1.03E-02	-1.10E-02
Transport	2.23E-12	2.22E-12	8.86E-10	2.22E-12	2.22E-12
Substitution of energy	-9.96E-09	-1.29E-07	-9.93E-09	-9.93E-09	-9.93E-09
Substitution of materials	-9.40E-08	-7.53E-15	-9.67E-08	-1.08E-02	-1.13E-02
Processing - Energy	7.74E-08	0.00E+00	1.28E-07	1.18E-05	1.33E-07
Processing - Non-Energy	5.74E-03	0.00E+00	4.41E-09	4.74E-04	2.86E-04
Treatment of residues	5.52E-08	0.00E+00	1.41E-06	1.41E-06	1.41E-06
Incineration	0.00E+00	4.69E-07	0.00E+00	0.00E+00	0.00E+00

Human toxicity, cancer (CTUh)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-5.77E-07	8.47E-06	-6.20E-07	1.67E-07	2.67E-07
Transport	4.75E-10	4.72E-10	5.59E-09	4.72E-10	4.72E-10
Substitution of energy	-7.85E-09	-1.02E-07	-8.08E-09	-8.08E-09	-8.08E-09
Substitution of materials	-1.68E-06	-9.37E-09	-1.68E-06	-1.09E-06	-1.23E-06

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Processing - Energy	3.70E-08	0.00E+00	5.52E-08	1.55E-08	9.37E-08
Processing - Non-Energy	7.78E-08	0.00E+00	3.24E-09	2.46E-07	4.09E-07
Treatment of residues	1.00E-06	0.00E+00	1.00E-06	1.00E-06	1.00E-06
Incineration	0.00E+00	8.58E-06	0.00E+00	0.00E+00	0.00E+00

Human toxicity, non-cancer (CTUh)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-1.07E-05	-3.91E-06	-1.13E-05	-1.09E-05	9.96E-06
Transport	3.41E-08	3.62E-08	1.82E-07	3.62E-08	3.62E-08
Substitution of energy	-3.77E-07	-4.88E-06	-3.60E-07	-3.60E-07	-3.60E-07
Substitution of materials	-1.44E-05	-7.89E-08	-1.36E-05	-1.33E-05	-1.62E-05
Processing - Energy	1.39E-06	0.00E+00	1.93E-06	8.53E-07	4.59E-06
Processing - Non-Energy	2.43E-06	0.00E+00	1.83E-07	1.50E-06	2.15E-05
Treatment of residues	2.12E-07	0.00E+00	3.47E-07	3.46E-07	3.48E-07
Incineration	0.00E+00	1.02E-06	0.00E+00	0.00E+00	0.00E+00

Particulate matter (Disease incidence)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-5.02E-05	-1.94E-05	-4.37E-05	-5.47E-05	5.10E-06
Transport	1.06E-07	1.41E-07	1.71E-06	1.41E-07	1.41E-07
Substitution of energy	-1.83E-06	-2.37E-05	-1.59E-06	-1.59E-06	-1.59E-06
Substitution of materials	-6.58E-05	-2.70E-07	-6.05E-05	-6.68E-05	-7.21E-05
Processing - Energy	7.87E-06	0.00E+00	1.08E-05	1.17E-06	1.69E-05
Processing - Non-Energy	8.62E-06	0.00E+00	3.39E-06	9.86E-06	5.92E-05
Treatment of residues	7.65E-07	0.00E+00	2.55E-06	2.55E-06	2.55E-06
Incineration	0.00E+00	4.42E-06	0.00E+00	0.00E+00	0.00E+00

Ionising radiation (kBq U^{235} eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-1.18E+01	-1.22E+02	5.44E+01	-4.23E+01	2.27E+02
Transport	1.74E-02	1.73E-02	1.19E+00	1.73E-02	1.73E-02
Substitution of energy	-1.29E+01	-1.68E+02	-1.16E+01	-1.16E+01	-1.16E+01
Substitution of materials	-1.01E+02	-1.08E-01	-9.41E+01	-6.88E+01	-8.01E+01
Processing - Energy	8.88E+01	0.00E+00	1.47E+02	4.40E+00	1.54E+02
Processing - Non-Energy	7.60E+00	0.00E+00	9.09E-01	2.25E+01	1.54E+02
Treatment of residues	5.91E+00	0.00E+00	5.44E+01	1.11E+01	1.11E+01
Incineration	0.00E+00	4.56E+01	1.19E+00	0.00E+00	0.00E+00

Photochemical ozone formation (kg NMVOC eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-3.48E+00	-4.67E-01	-3.72E+00	-3.62E+00	-3.08E+00
Transport	2.14E-02	2.04E-02	7.21E-02	2.04E-02	2.04E-02
Substitution of energy	-9.73E-02	-1.26E+00	-3.55E-02	-3.55E-02	-3.55E-02
Substitution of materials	-4.32E+00	-1.49E-02	-4.02E+00	-4.31E+00	-4.67E+00
Processing - Energy	4.06E-01	0.00E+00	1.10E-01	2.22E-02	4.47E-01
Processing - Non-Energy	4.06E-01	0.00E+00	3.09E-02	5.63E-01	1.04E+00
Treatment of residues	1.04E-01	0.00E+00	1.24E-01	1.24E-01	1.24E-01
Incineration	0.00E+00	7.87E-01	0.00E+00	0.00E+00	0.00E+00

Acidification (mol H^+ eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-3.32E+00	-1.28E+00	-3.36E+00	-4.76E+00	1.03E+00
Transport	2.35E-02	2.29E-02	8.06E-02	2.29E-02	2.29E-02
Substitution of energy	-1.71E-01	-2.22E+00	-1.16E-01	-1.16E-01	-1.16E-01
Substitution of materials	-4.66E+00	-2.14E-02	-4.32E+00	-5.61E+00	-6.32E+00
Processing - Energy	7.34E-01	0.00E+00	7.41E-01	8.35E-02	1.28E+00
Processing - Non-Energy	6.29E-01	0.00E+00	9.37E-02	6.96E-01	5.99E+00
Treatment of residues	1.24E-01	0.00E+00	1.61E-01	1.61E-01	1.61E-01
Incineration	0.00E+00	9.38E-01	0.00E+00	0.00E+00	0.00E+00

Eutrophication, terrestrial (mol N eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-1.03E+01	-1.26E+00	-1.14E+01	-7.75E+00	-6.48E+00
Transport	1.23E-01	1.19E-01	3.59E-01	1.19E-01	1.19E-01
Substitution of energy	-3.43E-01	-4.45E+00	-8.40E-02	-8.40E-02	-8.40E-02
Substitution of materials	-1.33E+01	-4.91E-02	-1.23E+01	-9.47E+00	-1.05E+01
Processing - Energy	1.50E+00	0.00E+00	1.42E-01	8.85E-02	1.23E+00
Processing - Non-Energy	1.31E+00	0.00E+00	5.85E-02	1.16E+00	2.38E+00
Treatment of residues	4.08E-01	0.00E+00	4.27E-01	4.27E-01	4.27E-01
Incineration	0.00E+00	3.12E+00	0.00E+00	0.00E+00	0.00E+00

Eutrophication, freshwater (kg P eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	1.25E-02	-1.75E-03	-3.88E-03	-3.39E-02	-1.01E-02
Transport	2.39E-05	2.38E-05	1.11E-04	2.38E-05	2.38E-05
Substitution of energy	-1.59E-04	-2.06E-03	-2.18E-04	-2.18E-04	-2.18E-04

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Substitution of materials	-5.32E-03	-9.19E-06	-5.22E-03	-3.78E-02	-4.54E-02
Processing - Energy	6.11E-04	0.00E+00	8.11E-04	9.43E-04	3.16E-03
Processing - Non-Energy	1.73E-02	0.00E+00	4.06E-04	2.93E-03	3.21E-02
Treatment of residues	4.47E-05	0.00E+00	2.29E-04	2.17E-04	2.35E-04
Incineration	0.00E+00	3.00E-04	0.00E+00	0.00E+00	0.00E+00

Eutrophication, marine (kg N eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	1.84E-01	-1.36E-01	-1.05E+00	-7.75E-01	-6.28E-01
Transport	1.10E-02	1.07E-02	3.21E-02	1.07E-02	1.07E-02
Substitution of energy	-3.33E-02	-4.31E-01	-9.88E-03	-9.88E-03	-9.88E-03
Substitution of materials	-1.23E+00	-4.50E-03	-1.13E+00	-9.25E-01	-1.02E+00
Processing - Energy	1.42E-01	0.00E+00	1.95E-02	6.66E-03	1.45E-01
Processing - Non-Energy	1.25E+00	0.00E+00	5.26E-03	1.02E-01	2.08E-01
Treatment of residues	3.77E-02	0.00E+00	4.11E-02	3.94E-02	3.98E-02
Incineration	0.00E+00	2.89E-01	0.00E+00	0.00E+00	0.00E+00

Ecotoxicity, freshwater (CTUe)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-1.34E+04	-2.21E+03	-2.05E+04	-1.08E+04	1.50E+04
Transport	3.47E+01	3.46E+01	2.05E+02	3.46E+01	3.46E+01
Substitution of energy	-2.43E+02	-3.14E+03	-2.49E+02	-2.49E+02	-2.49E+02
Substitution of materials	-2.55E+04	-1.45E+01	-2.39E+04	-1.35E+04	-1.64E+04
Processing - Energy	1.56E+03	0.00E+00	2.50E+03	3.71E+02	2.90E+03
Processing - Non-Energy	1.06E+04	0.00E+00	6.16E+02	2.26E+03	2.83E+04
Treatment of residues	1.44E+02	0.00E+00	3.47E+02	3.43E+02	3.51E+02
Incineration	0.00E+00	9.16E+02	0.00E+00	0.00E+00	0.00E+00

Resource use, minerals and metals (kg Sb eq.)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-3.44E-01	-3.97E-05	-3.14E-01	-1.21E-02	-1.31E-02
Transport	1.55E-06	1.54E-06	3.15E-05	1.54E-06	1.54E-06
Substitution of energy	-6.10E-06	-7.90E-05	-8.74E-06	-8.74E-06	-8.74E-06
Substitution of materials	-3.45E-01	-4.04E-07	-3.14E-01	-1.30E-02	-1.72E-02
Processing - Energy	5.54E-05	0.00E+00	8.92E-05	1.95E-04	1.10E-04
Processing - Non-Energy	3.16E-04	0.00E+00	5.76E-05	6.36E-04	3.98E-03
Treatment of residues	7.68E-06	0.00E+00	1.30E-05	1.30E-05	1.31E-05

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Incineration	0.00E+00	3.82E-05	0.00E+00	0.00E+00	0.00E+00

Resource use, fossils (MJ)

Process	MR-PET-PW	ER-PET-PW	CR-PET-PW-I	CR-PET-PW-II	CR-PET-PW-III
Total	-5.95E+04	-1.07E+04	-5.24E+04	-4.34E+04	-2.96E+04
Transport	5.23E+01	5.21E+01	3.50E+02	5.21E+01	5.21E+01
Substitution of energy	-9.99E+02	-1.29E+04	-9.08E+02	-9.08E+02	-9.08E+02
Substitution of materials	-6.43E+04	-6.82E+01	-5.97E+04	-4.75E+04	-5.06E+04
Processing - Energy	4.19E+03	0.00E+00	6.30E+03	2.84E+02	8.70E+03
Processing - Non-Energy	1.31E+03	0.00E+00	9.03E+02	3.92E+03	1.25E+04
Treatment of residues	3.09E+02	0.00E+00	6.67E+02	6.67E+02	6.67E+02
Incineration	0.00E+00	2.21E+03	0.00E+00	0.00E+00	0.00E+00

Results for "Sorted PS packaging waste**"**

Climate change (kg CO_2 eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-4.38E+02	1.11E+03	-6.67E+02
Transport	3.63E+00	3.78E+00	3.35E+00
Substitution of energy	-6.00E+01	-1.19E+03	-4.43E+01
Substitution of materials	-1.05E+03	-5.93E+00	-1.48E+03
Processing - Energy	2.73E+02	0.00E+00	2.46E+02
Processing - Non-Energy	3.45E+00	0.00E+00	1.20E+01
Treatment of residues	3.97E+02	0.00E+00	6.00E+02
Incineration	0.00E+00	2.30E+03	0.00E+00

Ozone depletion (kg CFC-11 eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	1.80E-06	2.89E-07	-8.07E-05
Transport	2.14E-12	2.22E-12	1.98E-12
Substitution of energy	-9.06E-09	-1.79E-07	-7.14E-09
Substitution of materials	-1.43E-08	-5.94E-15	-1.05E-04
Processing - Energy	9.24E-08	0.00E+00	7.77E-08
Processing - Non-Energy	2.38E-09	0.00E+00	1.15E-06
Treatment of residues	1.73E-06	0.00E+00	2.30E-05
Incineration	0.00E+00	4.69E-07	0.00E+00

Human toxicity, cancer (CTUh)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-9.68E-08	8.43E-06	-4.98E-06
Transport	4.54E-10	4.72E-10	4.20E-10
Substitution of energy	-7.14E-09	-1.41E-07	-5.80E-09
Substitution of materials	-7.70E-07	-7.40E-09	-5.60E-06
Processing - Energy	4.08E-08	0.00E+00	3.48E-08
Processing - Non-Energy	2.03E-09	0.00E+00	4.33E-09
Treatment of residues	6.37E-07	0.00E+00	5.85E-07
Incineration	0.00E+00	8.58E-06	0.00E+00

Human toxicity, non-cancer (CTUh)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-7.54E-06	-5.73E-06	-7.36E-06
Transport	3.25E-08	3.62E-08	2.99E-08
Substitution of energy	-3.43E-07	-6.78E-06	-2.58E-07
Substitution of materials	-9.74E-06	-6.23E-08	-1.06E-05
Processing - Energy	1.47E-06	0.00E+00	1.11E-06
Processing - Non-Energy	1.33E-07	0.00E+00	1.26E-07
Treatment of residues	9.03E-07	0.00E+00	2.24E-06
Incineration	0.00E+00	1.08E-06	0.00E+00

Particulate matter (Disease incidence)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-8.78E-06	-2.84E-05	-9.04E-05
Transport	9.96E-08	1.41E-07	8.93E-08
Substitution of energy	-1.66E-06	-3.29E-05	-1.14E-06
Substitution of materials	-1.70E-05	-2.13E-07	-1.02E-04
Processing - Energy	8.63E-06	0.00E+00	6.38E-06
Processing - Non-Energy	-1.79E-07	0.00E+00	3.48E-07

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Treatment of residues	1.28E-06	0.00E+00	5.48E-06
Incineration	0.00E+00	4.56E-06	0.00E+00

Ionising radiation (kBq U^{235} eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	5.98E+01	-1.87E+02	4.34E+01
Transport	1.67E-02	1.73E-02	1.54E-02
Substitution of energy	-1.18E+01	-2.33E+02	-8.31E+00
Substitution of materials	-4.06E+01	-8.52E-02	-5.14E+01
Processing - Energy	1.06E+02	0.00E+00	8.92E+01
Processing - Non-Energy	1.58E-01	0.00E+00	2.23E+00
Treatment of residues	6.16E+00	0.00E+00	1.17E+01
Incineration	0.00E+00	4.55E+01	0.00E+00

Photochemical ozone formation (kg NMVOC eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-1.39E+00	-9.47E-01	-1.78E+01
Transport	2.05E-02	2.04E-02	1.90E-02
Substitution of energy	-8.85E-02	-1.75E+00	-2.55E-02
Substitution of materials	-2.02E+00	-1.18E-02	-1.83E+01
Processing - Energy	4.38E-01	0.00E+00	6.38E-02
Processing - Non-Energy	3.44E-03	0.00E+00	1.47E-02
Treatment of residues	2.52E-01	0.00E+00	4.37E-01
Incineration	0.00E+00	7.94E-01	0.00E+00

Acidification (mol H^+ eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-1.09E+00	-2.13E+00	-5.13E+00
Transport	2.25E-02	2.29E-02	2.09E-02
Substitution of energy	-1.56E-01	-3.08E+00	-8.36E-02
Substitution of materials	-2.07E+00	-1.69E-02	-6.12E+00
Processing - Energy	8.04E-01	0.00E+00	4.34E-01
Processing - Non-Energy	2.04E-03	0.00E+00	3.24E-02
Treatment of residues	2.98E-01	0.00E+00	5.84E-01
Incineration	0.00E+00	9.45E-01	0.00E+00

Eutrophication, terrestrial (mol N eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-3.63E+00	-2.95E+00	-9.45E+00
Transport	1.18E-01	1.19E-01	1.09E-01
Substitution of energy	-3.12E-01	-6.17E+00	-6.04E-02
Substitution of materials	-5.78E+00	-3.88E-02	-1.09E+01
Processing - Energy	1.63E+00	0.00E+00	5.73E-02
Processing - Non-Energy	-6.79E-03	0.00E+00	4.17E-02
Treatment of residues	7.22E-01	0.00E+00	1.33E+00
Incineration	0.00E+00	3.14E+00	0.00E+00

Eutrophication, freshwater (kg P eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	3.41E-02	-2.54E-03	-1.22E-02
Transport	2.28E-05	2.38E-05	2.11E-05
Substitution of energy	-1.45E-04	-2.86E-03	-1.57E-04
Substitution of materials	-1.52E-03	-7.26E-06	-5.19E-02

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Processing - Energy	5.95E-04	0.00E+00	4.29E-04
Processing - Non-Energy	2.11E-03	0.00E+00	1.39E-04
Treatment of residues	3.30E-02	0.00E+00	3.93E-02
Incineration	0.00E+00	3.04E-04	0.00E+00

Eutrophication, marine (kg N eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	4.22E+00	-3.00E-01	4.06E+00
Transport	1.06E-02	1.07E-02	9.80E-03
Substitution of energy	-3.02E-02	-5.98E-01	-7.10E-03
Substitution of materials	-5.34E-01	-3.55E-03	-9.78E-01
Processing - Energy	1.53E-01	0.00E+00	8.36E-03
Processing - Non-Energy	6.52E-03	0.00E+00	3.50E-03
Treatment of residues	4.61E+00	0.00E+00	5.02E+00
Incineration	0.00E+00	2.91E-01	0.00E+00

Ecotoxicity, freshwater (CTUe)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-2.17E+04	-3.40E+03	-6.97E+03
Transport	3.32E+01	3.46E+01	3.07E+01
Substitution of energy	-2.21E+02	-4.36E+03	-1.79E+02
Substitution of materials	-3.20E+04	-1.14E+01	-2.19E+04
Processing - Energy	1.80E+03	0.00E+00	1.50E+03
Processing - Non-Energy	3.52E+01	0.00E+00	9.28E+02
Treatment of residues	8.60E+03	0.00E+00	1.27E+04
Incineration	0.00E+00	9.39E+02	0.00E+00

Resource use, minerals and metals (kg Sb eq.)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-6.86E-05	-6.44E-03	-1.21E-02
Transport	1.54E-06	1.38E-06	1.54E-06
Substitution of energy	-1.10E-04	-6.28E-06	-8.74E-06
Substitution of materials	-3.19E-07	-7.02E-03	-1.30E-02
Processing - Energy	0.00E+00	5.46E-05	1.95E-04
Processing - Non-Energy	0.00E+00	4.22E-05	6.36E-04
Treatment of residues	0.00E+00	4.93E-04	1.30E-05
Incineration	3.99E-05	0.00E+00	0.00E+00

Resource use, fossils (MJ)

Process	MR-PS-PW	ER-PS-PW	CR-PS-PW
Total	-3.00E+04	-1.57E+04	-4.27E+04
Transport	5.00E+01	5.21E+01	4.62E+01
Substitution of energy	-9.08E+02	-1.80E+04	-6.53E+02
Substitution of materials	-3.43E+04	-5.38E+01	-4.81E+04
Processing - Energy	4.59E+03	0.00E+00	4.19E+03
Processing - Non-Energy	1.39E+01	0.00E+00	1.59E+02
Treatment of residues	5.52E+02	0.00E+00	1.67E+03
Incineration	0.00E+00	2.22E+03	0.00E+00

Results for "Sorted mixed polyolefins (MPOs) flexible packaging waste**"**

Climate change (kg CO_2 eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-2.09E+02	-5.65E+01	7.70E+02	6.19E+02	5.73E+02	3.05E+02
Transport	5.50E+00	5.46E+00	3.78E+00	3.35E+00	3.35E+00	3.35E+00
Substitution of energy	-5.72E+02	-5.54E+02	-1.21E+03	-2.26E+02	-2.26E+02	-2.26E+02
Substitution of materials	-4.93E+02	-2.26E+02	-1.59E+01	-5.15E+02	-3.52E+02	-3.17E+02
Processing - Energy	2.38E+02	1.27E+02	0.00E+00	8.15E+02	6.43E+02	3.79E+02
Processing - Non-Energy	6.30E+00	0.00E+00	0.00E+00	4.56E+00	3.32E+01	6.18E-01
Treatment of residues	6.07E+02	5.91E+02	0.00E+00	5.37E+02	4.72E+02	4.66E+02
Incineration	0.00E+00	0.00E+00	1.99E+03	0.00E+00	0.00E+00	0.00E+00

Ozone depletion (kg CFC-11 eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-3.93E-05	-3.80E-05	2.86E-07	-5.53E-05	-2.57E-04	-3.97E-04
Transport	3.24E-12	3.21E-12	2.22E-12	1.98E-12	1.98E-12	1.98E-12
Substitution of energy	-3.95E-05	-3.81E-05	-1.83E-07	-3.64E-08	-3.64E-08	-3.64E-08
Substitution of materials	-1.94E-08	-6.05E-09	-1.59E-14	-5.90E-05	-2.85E-04	-3.99E-04
Processing - Energy	7.78E-08	4.67E-08	0.00E+00	1.41E-07	5.52E-08	7.09E-08
Processing - Non-Energy	2.72E-08	0.00E+00	0.00E+00	1.26E-06	2.51E-05	2.16E-07
Treatment of residues	1.13E-07	1.13E-07	0.00E+00	2.31E-06	2.20E-06	1.54E-06
Incineration	0.00E+00	0.00E+00	4.69E-07	0.00E+00	0.00E+00	0.00E+00

Human toxicity, cancer (CTUh)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	1.83E-06	1.92E-06	8.42E-06	2.29E-06	2.26E-06	2.22E-06
Transport	6.88E-10	6.83E-10	4.72E-10	3.43E-10	3.43E-10	3.43E-10
Substitution of energy	-7.12E-08	-6.90E-08	-1.44E-07	-2.96E-08	-2.96E-08	-2.96E-08
Substitution of materials	-2.59E-07	-1.49E-07	-1.77E-08	-1.42E-07	-1.57E-07	-1.67E-07
Processing - Energy	3.52E-08	1.95E-08	0.00E+00	7.99E-08	2.81E-08	2.93E-08
Processing - Non-Energy	1.15E-09	0.00E+00	0.00E+00	9.71E-10	3.13E-08	5.55E-10
Treatment of residues	2.12E-06	2.12E-06	0.00E+00	2.38E-06	2.39E-06	2.38E-06
Incineration	0.00E+00	0.00E+00	8.58E-06	0.00E+00	0.00E+00	0.00E+00

Human toxicity, non-cancer (CTUh)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-5.88E-06	-2.38E-06	-5.85E-06	-1.04E-06	1.31E-06	-3.09E-06
Transport	5.04E-08	5.00E-08	3.62E-08	2.42E-08	2.42E-08	2.42E-08
Substitution of energy	-9.26E-07	-9.07E-07	-6.92E-06	-1.32E-06	-1.32E-06	-1.32E-06
Substitution of materials	-6.92E-06	-2.74E-06	-1.62E-07	-2.47E-06	-3.49E-06	-3.58E-06
Processing - Energy	1.28E-06	6.77E-07	0.00E+00	2.15E-06	8.44E-07	1.07E-06
Processing - Non-Energy	8.11E-08	0.00E+00	0.00E+00	2.94E-08	4.38E-06	1.47E-08
Treatment of residues	5.43E-07	5.41E-07	0.00E+00	5.42E-07	8.65E-07	6.98E-07
Incineration	0.00E+00	0.00E+00	1.19E-06	0.00E+00	0.00E+00	0.00E+00

Particulate matter (Disease incidence)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-1.21E-05	-9.96E-06	-2.93E-05	-1.57E-05	-1.05E-05	-1.12E-05
Transport	1.69E-07	1.68E-07	1.41E-07	8.15E-08	8.15E-08	8.15E-08
Substitution of energy	-7.47E-06	-7.27E-06	-3.35E-05	-5.83E-06	-5.83E-06	-5.83E-06
Substitution of materials	-1.43E-05	-9.12E-06	-7.12E-07	-2.50E-05	-1.54E-05	-1.49E-05
Processing - Energy	7.46E-06	4.11E-06	0.00E+00	1.25E-05	4.76E-06	5.91E-06
Processing - Non-Energy	-8.58E-08	0.00E+00	0.00E+00	1.80E-07	2.19E-06	2.42E-08
Treatment of residues	2.16E-06	2.15E-06	0.00E+00	2.35E-06	3.72E-06	3.54E-06
Incineration	0.00E+00	0.00E+00	4.83E-06	0.00E+00	0.00E+00	0.00E+00

Ionising radiation (kBq U^{235} eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	4.15E+01	2.09E+01	-1.93E+02	9.92E+01	-4.63E+01	-6.61E+01
Transport	2.52E-02	2.50E-02	1.73E-02	1.54E-02	1.54E-02	1.54E-02
Substitution of energy	-2.48E+01	-2.44E+01	-2.38E+02	-4.25E+01	-4.25E+01	-4.25E+01
Substitution of materials	-3.50E+01	-2.01E+01	-7.93E-01	-2.84E+01	-9.09E+01	-1.21E+02
Processing - Energy	8.92E+01	5.34E+01	0.00E+00	1.64E+02	6.38E+01	8.11E+01
Processing - Non-Energy	1.09E-01	0.00E+00	0.00E+00	1.85E+00	6.81E+00	6.13E-02
Treatment of residues	1.19E+01	1.19E+01	0.00E+00	3.86E+00	1.64E+01	1.63E+01
Incineration	0.00E+00	0.00E+00	4.58E+01	0.00E+00	0.00E+00	0.00E+00

Photochemical ozone formation (kg NMVOC eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-1.08E+00	-5.73E-01	-9.91E-01	-1.29E+00	-8.77E-01	-1.33E+00

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Transport	3.06E-02	3.04E-02	2.04E-02	1.79E-02	1.79E-02	1.79E-02
Substitution of energy	-7.16E-01	-6.94E-01	-1.79E+00	-1.30E-01	-1.30E-01	-1.30E-01
Substitution of materials	-1.21E+00	-5.38E-01	-3.28E-02	-1.58E+00	-1.37E+00	-1.67E+00
Processing - Energy	3.81E-01	2.06E-01	0.00E+00	1.64E-01	1.98E-01	2.11E-01
Processing - Non-Energy	4.66E-03	0.00E+00	0.00E+00	6.29E-03	1.68E-01	7.45E-04
Treatment of residues	4.31E-01	4.23E-01	0.00E+00	2.30E-01	2.44E-01	2.39E-01
Incineration	0.00E+00	0.00E+00	8.07E-01	0.00E+00	0.00E+00	0.00E+00

Acidification (mol H^+ eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-1.20E+00	-8.43E-01	-2.22E+00	-1.49E+00	-1.80E+00	-2.37E+00
Transport	3.39E-02	3.36E-02	2.29E-02	2.00E-02	2.00E-02	2.00E-02
Substitution of energy	-9.19E-01	-8.93E-01	-3.14E+00	-4.27E-01	-4.27E-01	-4.27E-01
Substitution of materials	-1.47E+00	-8.15E-01	-5.58E-02	-2.18E+00	-2.42E+00	-2.83E+00
Processing - Energy	6.95E-01	3.82E-01	0.00E+00	8.48E-01	4.36E-01	5.61E-01
Processing - Non-Energy	4.36E-03	0.00E+00	0.00E+00	1.83E-02	2.73E-01	2.22E-03
Treatment of residues	4.56E-01	4.49E-01	0.00E+00	2.29E-01	3.19E-01	3.05E-01
Incineration	0.00E+00	0.00E+00	9.59E-01	0.00E+00	0.00E+00	0.00E+00

Eutrophication, terrestrial (mol N eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-2.48E+00	-1.46E+00	-3.10E+00	-2.84E+00	-1.79E+00	-2.75E+00
Transport	1.77E-01	1.75E-01	1.19E-01	1.04E-01	1.04E-01	1.04E-01
Substitution of energy	-2.82E+00	-2.73E+00	-6.30E+00	-3.08E-01	-3.08E-01	-3.08E-01
Substitution of materials	-3.17E+00	-1.56E+00	-1.11E-01	-3.71E+00	-3.51E+00	-4.24E+00
Processing - Energy	1.41E+00	7.69E-01	0.00E+00	1.14E-01	6.45E-01	8.13E-01
Processing - Non-Energy	3.37E-03	0.00E+00	0.00E+00	1.44E-02	3.74E-01	2.85E-03
Treatment of residues	1.92E+00	1.88E+00	0.00E+00	9.48E-01	9.04E-01	8.74E-01
Incineration	0.00E+00	0.00E+00	3.19E+00	0.00E+00	0.00E+00	0.00E+00

Eutrophication, freshwater (kg P eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-4.23E-03	-3.67E-03	-2.60E-03	-2.54E-03	2.59E-04	-1.58E-03
Transport	3.46E-05	3.43E-05	2.38E-05	2.11E-05	2.11E-05	2.11E-05
Substitution of energy	-2.92E-03	-2.82E-03	-2.92E-03	-8.00E-04	-8.00E-04	-8.00E-04

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Substitution of materials	-3.62E-03	-1.23E-03	-1.62E-05	-2.87E-03	-1.80E-03	-1.86E-03
Processing - Energy	5.35E-04	2.56E-04	0.00E+00	7.96E-04	3.08E-04	3.89E-04
Processing - Non-Energy	1.65E-03	0.00E+00	0.00E+00	1.57E-05	5.49E-04	1.65E-05
Treatment of residues	9.21E-05	9.21E-05	0.00E+00	3.00E-04	1.98E-03	6.61E-04
Incineration	0.00E+00	0.00E+00	3.14E-04	0.00E+00	0.00E+00	0.00E+00

Eutrophication, marine (kg N eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-1.58E-01	-1.32E-01	-3.14E-01	-2.66E-01	-1.40E-01	-2.48E-01
Transport	1.59E-02	1.58E-02	1.07E-02	9.36E-03	9.36E-03	9.36E-03
Substitution of energy	-2.40E-01	-2.33E-01	-6.10E-01	-3.63E-02	-3.63E-02	-3.63E-02
Substitution of materials	-3.04E-01	-1.47E-01	-1.01E-02	-3.39E-01	-3.26E-01	-3.88E-01
Processing - Energy	1.33E-01	7.21E-02	0.00E+00	1.56E-02	6.10E-02	6.81E-02
Processing - Non-Energy	7.45E-02	0.00E+00	0.00E+00	1.36E-03	3.41E-02	3.23E-04
Treatment of residues	1.62E-01	1.59E-01	0.00E+00	8.28E-02	1.18E-01	9.78E-02
Incineration	0.00E+00	0.00E+00	2.96E-01	0.00E+00	0.00E+00	0.00E+00

Ecotoxicity, freshwater (CTUe)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-8.34E+03	-3.33E+03	-3.48E+03	-8.91E+02	-6.91E+03	-1.11E+04
Transport	5.04E+01	5.00E+01	3.46E+01	3.07E+01	3.07E+01	3.07E+01
Substitution of energy	-2.20E+03	-2.13E+03	-4.45E+03	-9.12E+02	-9.12E+02	-9.12E+02
Substitution of materials	-8.68E+03	-2.93E+03	-4.01E+01	-3.37E+03	-9.40E+03	-1.26E+04
Processing - Energy	1.53E+03	8.93E+02	0.00E+00	2.80E+03	1.08E+03	1.36E+03
Processing - Non-Energy	1.50E+02	0.00E+00	0.00E+00	1.97E+02	9.77E+02	4.21E+02
Treatment of residues	8.05E+02	7.88E+02	0.00E+00	3.65E+02	1.31E+03	6.72E+02
Incineration	0.00E+00	0.00E+00	9.81E+02	0.00E+00	0.00E+00	0.00E+00

Resource use, minerals and metals (kg Sb eq.)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-1.79E-04	-1.60E-04	-6.87E-05	-2.11E-04	1.86E-05	-1.29E-04
Transport	2.25E-06	2.23E-06	1.54E-06	1.38E-06	1.38E-06	1.38E-06
Substitution of energy	-1.87E-04	-1.81E-04	-1.12E-04	-3.21E-05	-3.21E-05	-3.21E-05
Substitution of materials	-6.64E-05	-2.89E-05	-1.07E-06	-3.25E-04	-1.54E-04	-1.80E-04
Processing - Energy	5.47E-05	3.20E-05	0.00E+00	1.07E-04	4.04E-05	4.87E-05

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Processing - Non-Energy	2.92E-06	0.00E+00	0.00E+00	2.44E-06	1.17E-04	4.60E-06
Treatment of residues	1.51E-05	1.51E-05	0.00E+00	3.56E-05	4.58E-05	2.84E-05
Incineration	0.00E+00	0.00E+00	4.27E-05	0.00E+00	0.00E+00	0.00E+00

Resource use, fossils (MJ)

Process	MR-MPO-FPW-I	MR-MPO-FPW-II	ER-MPO-FPW	CR-MPO-FPW-I	CR-MPO-FPW-II	CR-MPO-FPW-III
Total	-1.74E+04	-8.57E+03	-1.62E+04	-1.36E+04	-1.66E+04	-2.46E+04
Transport	7.59E+01	7.53E+01	5.21E+01	4.62E+01	4.62E+01	4.62E+01
Substitution of energy	-5.84E+03	-5.67E+03	-1.83E+04	-3.33E+03	-3.33E+03	-3.33E+03
Substitution of materials	-1.63E+04	-5.87E+03	-1.59E+02	-2.11E+04	-1.99E+04	-2.58E+04
Processing - Energy	3.97E+03	2.19E+03	0.00E+00	1.07E+04	3.60E+03	3.37E+03
Processing - Non-Energy	1.23E+01	0.00E+00	0.00E+00	1.37E+02	1.92E+03	1.07E+01
Treatment of residues	7.03E+02	7.03E+02	0.00E+00	-1.01E+02	1.09E+03	1.05E+03
Incineration	0.00E+00	0.00E+00	2.27E+03	0.00E+00	0.00E+00	0.00E+00

Results for "Sorted Large-format PE film waste**"**

Climate change (kg CO_2 eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-1.20E+02	6.75E+02	-3.73E+02
Transport	5.09E+00	3.78E+00	4.65E+00
Substitution of energy	-5.91E+02	-1.46E+03	-4.13E+02
Substitution of materials	-5.76E+02	-4.90E+00	-6.99E+02
Processing - Energy	3.45E+02	0.00E+00	2.96E+02
Processing - Non-Energy	1.30E+02	0.00E+00	3.28E+01
Treatment of residues	5.67E+02	0.00E+00	4.06E+02
Incineration	0.00E+00	2.14E+03	0.00E+00

Ozone depletion (kg CFC-11 eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-4.38E-05	2.47E-07	1.05E-03
Transport	3.00E-12	2.22E-12	2.74E-12
Substitution of energy	-4.44E-05	-2.21E-07	-3.04E-05
Substitution of materials	-4.59E-08	-4.88E-15	-5.59E-08
Processing - Energy	1.11E-07	0.00E+00	9.68E-08
Processing - Non-Energy	4.73E-07	0.00E+00	1.08E-03
Treatment of residues	4.28E-08	0.00E+00	4.24E-08
Incineration	0.00E+00	4.68E-07	0.00E+00

Human toxicity, cancer (CTUh)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-5.94E-06	8.40E-06	-7.44E-06
Transport	6.37E-10	4.72E-10	5.82E-10
Substitution of energy	-7.38E-08	-1.74E-07	-5.15E-08
Substitution of materials	-6.79E-06	-5.45E-09	-8.27E-06
Processing - Energy	5.09E-08	0.00E+00	4.38E-08
Processing - Non-Energy	2.58E-08	0.00E+00	2.30E-08
Treatment of residues	8.48E-07	0.00E+00	8.18E-07
Incineration	0.00E+00	8.58E-06	0.00E+00

Human toxicity, non-cancer (CTUh)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-7.92E-06	-7.37E-06	-1.05E-05
Transport	4.65E-08	3.62E-08	4.23E-08
Substitution of energy	-7.42E-07	-8.37E-06	-5.55E-07
Substitution of materials	-1.06E-05	-5.00E-08	-1.29E-05
Processing - Energy	1.87E-06	0.00E+00	1.60E-06
Processing - Non-Energy	1.22E-06	0.00E+00	1.01E-06
Treatment of residues	2.61E-07	0.00E+00	2.33E-07
Incineration	0.00E+00	1.01E-06	0.00E+00

Particulate matter (Disease incidence)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-5.92E-06	-3.63E-05	-8.68E-06
Transport	1.54E-07	1.41E-07	1.38E-07
Substitution of energy	-6.94E-06	-4.06E-05	-4.98E-06
Substitution of materials	-1.30E-05	-2.19E-07	-1.57E-05
Processing - Energy	1.08E-05	0.00E+00	9.28E-06
Processing - Non-Energy	2.08E-06	0.00E+00	1.70E-06

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Treatment of residues	1.01E-06	0.00E+00	9.18E-07
Incineration	0.00E+00	4.42E-06	0.00E+00

Ionising radiation (kBq U^{235} eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	6.28E+01	-2.42E+02	4.27E+01
Transport	2.34E-02	1.73E-02	2.13E-02
Substitution of energy	-1.76E+01	-2.88E+02	-1.37E+01
Substitution of materials	-5.16E+01	-2.44E-01	-6.26E+01
Processing - Energy	1.28E+02	0.00E+00	1.11E+02
Processing - Non-Energy	-1.31E-01	0.00E+00	3.58E+00
Treatment of residues	4.45E+00	0.00E+00	4.45E+00
Incineration	0.00E+00	4.54E+01	0.00E+00

Photochemical ozone formation (kg NMVOC eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-1.68E+00	-1.36E+00	-2.11E+00
Transport	2.84E-02	2.04E-02	2.60E-02
Substitution of energy	-7.28E-01	-2.16E+00	-5.11E-01
Substitution of materials	-1.99E+00	-1.01E-02	-2.42E+00
Processing - Energy	5.52E-01	0.00E+00	4.74E-01
Processing - Non-Energy	1.42E-01	0.00E+00	8.50E-02
Treatment of residues	3.18E-01	0.00E+00	2.44E-01
Incineration	0.00E+00	7.87E-01	0.00E+00

Acidification (mol H^+ eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-8.76E-01	-2.86E+00	-1.14E+00
Transport	3.14E-02	2.29E-02	2.87E-02
Substitution of energy	-8.97E-01	-3.80E+00	-6.36E-01
Substitution of materials	-1.49E+00	-1.72E-02	-1.81E+00
Processing - Energy	1.01E+00	0.00E+00	8.65E-01
Processing - Non-Energy	1.64E-01	0.00E+00	1.67E-01
Treatment of residues	3.14E-01	0.00E+00	2.46E-01
Incineration	0.00E+00	9.37E-01	0.00E+00

Eutrophication, terrestrial (mol N eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-2.56E+00	-4.42E+00	-3.26E+00
Transport	1.64E-01	1.19E-01	1.50E-01
Substitution of energy	-2.89E+00	-7.62E+00	-2.03E+00
Substitution of materials	-3.72E+00	-3.40E-02	-4.52E+00
Processing - Energy	2.04E+00	0.00E+00	1.76E+00
Processing - Non-Energy	3.38E-01	0.00E+00	2.40E-01
Treatment of residues	1.50E+00	0.00E+00	1.13E+00
Incineration	0.00E+00	3.12E+00	0.00E+00

Eutrophication, freshwater (kg P eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	1.07E-02	-3.21E-03	-4.35E-04
Transport	3.20E-05	2.38E-05	2.92E-05
Substitution of energy	-3.15E-03	-3.53E-03	-2.18E-03
Substitution of materials	-4.62E-03	-4.98E-06	-5.63E-03

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Processing - Energy	7.85E-04	0.00E+00	6.65E-04
Processing - Non-Energy	1.76E-02	0.00E+00	6.65E-03
Treatment of residues	3.43E-05	0.00E+00	3.43E-05
Incineration	0.00E+00	3.00E-04	0.00E+00

Eutrophication, marine (kg N eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	1.03E+00	-4.42E-01	-2.90E-01
Transport	1.47E-02	1.07E-02	1.35E-02
Substitution of energy	-2.43E-01	-7.38E-01	-1.71E-01
Substitution of materials	-3.56E-01	-3.11E-03	-4.33E-01
Processing - Energy	1.93E-01	0.00E+00	1.66E-01
Processing - Non-Energy	1.30E+00	0.00E+00	4.12E-02
Treatment of residues	1.22E-01	0.00E+00	9.32E-02
Incineration	0.00E+00	2.89E-01	0.00E+00

Ecotoxicity, freshwater (CTUe)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-8.13E+03	-4.45E+03	-1.19E+04
Transport	4.66E+01	3.46E+01	4.26E+01
Substitution of energy	-2.28E+03	-5.39E+03	-1.59E+03
Substitution of materials	-1.19E+04	-1.23E+01	-1.45E+04
Processing - Energy	2.20E+03	0.00E+00	1.91E+03
Processing - Non-Energy	3.16E+03	0.00E+00	1.79E+03
Treatment of residues	6.74E+02	0.00E+00	4.98E+02
Incineration	0.00E+00	9.16E+02	0.00E+00

Resource use, minerals and metals (kg Sb eq.)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-1.14E-04	-9.60E-05	-3.72E-06
Transport	2.08E-06	1.54E-06	1.90E-06
Substitution of energy	-2.06E-04	-1.35E-04	-1.42E-04
Substitution of materials	-8.04E-05	-3.29E-07	-9.78E-05
Processing - Energy	7.85E-05	0.00E+00	6.81E-05
Processing - Non-Energy	8.60E-05	0.00E+00	1.60E-04
Treatment of residues	5.60E-06	0.00E+00	5.62E-06
Incineration	0.00E+00	3.83E-05	0.00E+00

Resource use, fossils (MJ)

Process	MR-PE-FW	ER-PE-FW	PR-PE-FW
Total	-1.92E+04	-2.00E+04	-2.35E+04
Transport	7.02E+01	5.21E+01	6.41E+01
Substitution of energy	-5.77E+03	-2.22E+04	-4.08E+03
Substitution of materials	-2.06E+04	-4.89E+01	-2.50E+04
Processing - Energy	5.74E+03	0.00E+00	4.94E+03
Processing - Non-Energy	1.11E+03	0.00E+00	3.68E+02
Treatment of residues	2.56E+02	0.00E+00	2.61E+02
Incineration	0.00E+00	2.21E+03	0.00E+00

Results for "Post-industrial PE/PA multilayer film waste"

Climate change (kg CO_2 eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	58	826
Transport	3	3
Substitution of energy	0	-1479
Substitution of materials	-2053	0
Processing - Energy	2042	0
Processing - Non-Energy	2	0
Treatment of residues	63	0
Incineration	0	2301

Ozone depletion (kg CFC-11 eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-1.36E-06	2.36E-07
Transport	1.98E-12	1.98E-12
Substitution of energy	0.00E+00	-2.38E-07
Substitution of materials	-1.97E-06	0.00E+00
Processing - Energy	5.74E-07	0.00E+00
Processing - Non-Energy	1.83E-08	0.00E+00
Treatment of residues	1.71E-08	0.00E+00
Incineration	0.00E+00	4.74E-07

Human toxicity, cancer (CTUh)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-8.14E-06	8.38E-06
Transport	3.43E-10	3.43E-10
Substitution of energy	0.00E+00	-1.94E-07
Substitution of materials	-8.41E-06	0.00E+00
Processing - Energy	2.76E-07	0.00E+00
Processing - Non-Energy	1.22E-09	0.00E+00
Treatment of residues	-4.13E-09	0.00E+00
Incineration	0.00E+00	8.58E-06

Human toxicity, non-cancer (CTUh)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-4.58E-06	-7.72E-06
Transport	2.42E-08	2.42E-08
Substitution of energy	0.00E+00	-8.63E-06
Substitution of materials	-1.29E-05	0.00E+00
Processing - Energy	8.33E-06	0.00E+00
Processing - Non-Energy	2.40E-08	0.00E+00
Treatment of residues	-8.83E-08	0.00E+00
Incineration	0.00E+00	8.78E-07

Particulate matter (Disease incidence)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-2.12E-05	-3.41E-05
Transport	8.15E-08	8.15E-08
Substitution of energy	0.00E+00	-3.81E-05
Substitution of materials	-6.84E-05	0.00E+00
Processing - Energy	4.82E-05	0.00E+00
Processing - Non-Energy	7.31E-08	0.00E+00

Process	PR-PE/PA-FW	ER-PE/PA-FW
Treatment of residues	-1.14E-06	0.00E+00
Incineration	0.00E+00	3.90E-06

Ionising radiation (kBq U^{235} eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	5.91E+02	-2.32E+02
Transport	1.54E-02	1.54E-02
Substitution of energy	0.00E+00	-2.77E+02
Substitution of materials	-5.89E+01	0.00E+00
Processing - Energy	6.61E+02	0.00E+00
Processing - Non-Energy	8.70E-01	0.00E+00
Treatment of residues	-1.20E+01	0.00E+00
Incineration	0.00E+00	4.53E+01

Photochemical ozone formation (kg NMVOC eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-4.86E+00	-2.05E-01
Transport	1.79E-02	1.79E-02
Substitution of energy	0.00E+00	-8.52E-01
Substitution of materials	-5.40E+00	0.00E+00
Processing - Energy	5.28E-01	0.00E+00
Processing - Non-Energy	1.38E-03	0.00E+00
Treatment of residues	-9.42E-03	0.00E+00
Incineration	0.00E+00	6.28E-01

Acidification (mol H^+ eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-2.80E+00	-1.95
Transport	2.00E-02	0.02
Substitution of energy	0.00E+00	-2.79
Substitution of materials	-6.03E+00	0.00
Processing - Energy	3.27E+00	0.00
Processing - Non-Energy	5.44E-03	0.00
Treatment of residues	-7.62E-02	0.00
Incineration	0.00E+00	0.82

Eutrophication, terrestrial (mol N eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-1.11E+01	5.54E-01
Transport	1.04E-01	1.04E-01
Substitution of energy	0.00E+00	-2.01E+00
Substitution of materials	-1.18E+01	0.00E+00
Processing - Energy	4.34E-01	0.00E+00
Processing - Non-Energy	3.50E-03	0.00E+00
Treatment of residues	7.63E-02	0.00E+00
Incineration	0.00E+00	2.46E+00

Eutrophication, freshwater (kg P eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-1.71E-02	-4.90E-03
Transport	2.11E-05	2.11E-05
Substitution of energy	0.00E+00	-5.23E-03
Substitution of materials	-2.09E-02	0.00E+00

Process	PR-PE/PA-FW	ER-PE/PA-FW
Processing - Energy	3.19E-03	0.00E+00
Processing - Non-Energy	2.35E-05	0.00E+00
Treatment of residues	5.88E-04	0.00E+00
Incineration	0.00E+00	3.08E-04

Eutrophication, marine (kg N eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-1.12E+00	1.61E-03
Transport	9.36E-03	9.36E-03
Substitution of energy	0.00E+00	-2.37E-01
Substitution of materials	-1.21E+00	0.00E+00
Processing - Energy	6.22E-02	0.00E+00
Processing - Non-Energy	3.46E-04	0.00E+00
Treatment of residues	1.51E-02	0.00E+00
Incineration	0.00E+00	2.29E-01

Ecotoxicity, freshwater (CTUe)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-4.21E+03	-4.99E+03
Transport	3.07E+01	3.07E+01
Substitution of energy	0.00E+00	-5.96E+03
Substitution of materials	-1.54E+04	0.00E+00
Processing - Energy	1.12E+04	0.00E+00
Processing - Non-Energy	1.89E+01	0.00E+00
Treatment of residues	1.83E+01	0.00E+00
Incineration	0.00E+00	9.42E+02

Resource use, minerals and metals (kg Sb eq.)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-8.85E-03	-1.72E-04
Transport	1.38E-06	1.38E-06
Substitution of energy	0.00E+00	-2.09E-04
Substitution of materials	-9.27E-03	0.00E+00
Processing - Energy	4.12E-04	0.00E+00
Processing - Non-Energy	1.96E-06	0.00E+00
Treatment of residues	3.05E-06	0.00E+00
Incineration	0.00E+00	3.61E-05

Resource use, fossils (MJ)

Process	PR-PE/PA-FW	ER-PE/PA-FW
Total	-8.77E+03	-1.95E+04
Transport	4.62E+01	4.62E+01
Substitution of energy	0.00E+00	-2.18E+04
Substitution of materials	-4.22E+04	0.00E+00
Processing - Energy	3.45E+04	0.00E+00
Processing - Non-Energy	3.96E+01	0.00E+00
Treatment of residues	-1.14E+03	0.00E+00
Incineration	0.00E+00	2.20E+03

Results for "EPS from construction and demolition waste**"**

Climate change (kg CO_2 eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	3.40E+02	1.77E+03
Transport	3.55E+00	3.78E+00
Substitution of energy	-4.73E+01	-1.26E+03
Substitution of materials	-1.35E+03	0.00E+00
Processing - Energy	1.62E+03	0.00E+00
Processing - Non-Energy	1.16E-01	0.00E+00
Treatment of residues	1.15E+02	0.00E+00
Incineration	3.40E+02	1.77E+03

Ozone depletion (kg CFC-11 eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	7.78E-07	2.79E-07
Transport	2.09E-12	2.22E-12
Substitution of energy	-8.37E-09	-1.90E-07
Substitution of materials	-1.86E-08	0.00E+00
Processing - Energy	5.94E-07	0.00E+00
Processing - Non-Energy	7.80E-11	0.00E+00
Treatment of residues	2.11E-07	0.00E+00
Incineration	0.00E+00	4.68E-07

Human toxicity, cancer (CTUh)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	-2.84E-07	8.44E-06
Transport	4.44E-10	4.72E-10
Substitution of energy	-6.09E-09	-1.50E-07
Substitution of materials	-9.81E-07	0.00E+00
Processing - Energy	2.48E-07	0.00E+00
Processing - Non-Energy	6.52E-11	0.00E+00
Treatment of residues	4.54E-07	0.00E+00
Incineration	0.00E+00	8.58E-06

Human toxicity, non-cancer (CTUh)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	-3.47E-06	-5.40E-06
Transport	3.18E-08	3.62E-08
Substitution of energy	-2.72E-07	-7.19E-06
Substitution of materials	-1.25E-05	0.00E+00
Processing - Energy	8.62E-06	0.00E+00
Processing - Non-Energy	4.21E-09	0.00E+00
Treatment of residues	6.20E-07	0.00E+00
Incineration	0.00E+00	1.75E-06

Particulate matter (Disease incidence)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	3.01E-05	-3.03E-05
Transport	9.67E-08	1.41E-07
Substitution of energy	-1.33E-06	-3.48E-05
Substitution of materials	-2.15E-05	0.00E+00
Processing - Energy	5.23E-05	0.00E+00
Processing - Non-Energy	-5.32E-09	0.00E+00

Process	PR-EPS-CDW	ER-EPS-CDW
Treatment of residues	5.09E-07	0.00E+00
Incineration	0.00E+00	4.40E-06

Ionising radiation (kBq U^{235} eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	6.20E+02	-2.01E+02
Transport	1.63E-02	1.73E-02
Substitution of energy	-9.77E+00	-2.47E+02
Substitution of materials	-5.26E+01	0.00E+00
Processing - Energy	6.80E+02	0.00E+00
Processing - Non-Energy	8.41E-03	0.00E+00
Treatment of residues	2.44E+00	0.00E+00
Incineration	0.00E+00	4.53E+01

Photochemical ozone formation (kg NMVOC eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	4.46E-02	-1.05E+00
Transport	2.01E-02	2.04E-02
Substitution of energy	-7.32E-02	-1.85E+00
Substitution of materials	-2.59E+00	0.00E+00
Processing - Energy	2.62E+00	0.00E+00
Processing - Non-Energy	1.22E-04	0.00E+00
Treatment of residues	6.87E-02	0.00E+00
Incineration	0.00E+00	7.86E-01

Acidification (mol H^+ eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	2.20E+00	-2.31E+00
Transport	2.21E-02	2.29E-02
Substitution of energy	-1.24E-01	-3.26E+00
Substitution of materials	-2.64E+00	0.00E+00
Processing - Energy	4.87E+00	0.00E+00
Processing - Non-Energy	8.94E-05	0.00E+00
Treatment of residues	2.20E+00	-2.31E+00
Incineration	2.21E-02	2.29E-02

Eutrophication, terrestrial (mol N eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	2.51E+00	-3.31E+00
Transport	1.15E-01	1.19E-01
Substitution of energy	-2.63E-01	-6.54E+00
Substitution of materials	-7.40E+00	0.00E+00
Processing - Energy	9.79E+00	0.00E+00
Processing - Non-Energy	-1.59E-04	0.00E+00
Treatment of residues	2.74E-01	0.00E+00
Incineration	0.00E+00	3.12E+00

Eutrophication, freshwater (kg P eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	1.30E-03	-2.71E-03
Transport	2.23E-05	2.38E-05
Substitution of energy	-1.49E-04	-3.03E-03
Substitution of materials	-1.95E-03	0.00E+00

Process	PR-EPS-CDW	ER-EPS-CDW
Processing - Energy	3.26E-03	0.00E+00
Processing - Non-Energy	6.60E-05	0.00E+00
Treatment of residues	4.92E-05	0.00E+00
Incineration	0.00E+00	2.99E-04

Eutrophication, marine (kg N eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	2.44E-01	-3.34E-01
Transport	1.04E-02	1.07E-02
Substitution of energy	-2.55E-02	-6.34E-01
Substitution of materials	-6.85E-01	0.00E+00
Processing - Energy	9.18E-01	0.00E+00
Processing - Non-Energy	2.09E-04	0.00E+00
Treatment of residues	2.52E-02	0.00E+00
Incineration	0.00E+00	2.89E-01

Ecotoxicity, freshwater (CTUe)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	-2.45E+04	-3.68E+03
Transport	3.25E+01	3.46E+01
Substitution of energy	-2.01E+02	-4.62E+03
Substitution of materials	-4.15E+04	0.00E+00
Processing - Energy	1.14E+04	0.00E+00
Processing - Non-Energy	1.16E+00	0.00E+00
Treatment of residues	5.80E+03	0.00E+00
Incineration	0.00E+00	9.14E+02

Resource use, minerals and metals (kg Sb eq.)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	1.30E-04	-7.65E-05
Transport	1.46E-06	1.54E-06
Substitution of energy	-6.96E-06	-1.16E-04
Substitution of materials	-2.84E-04	0.00E+00
Processing - Energy	4.08E-04	0.00E+00
Processing - Non-Energy	5.56E-08	0.00E+00
Treatment of residues	1.22E-05	0.00E+00
Incineration	0.00E+00	3.83E-05

Resource use, fossils (MJ)

Process	PR-EPS-CDW	ER-EPS-CDW
Total	-1.70E+04	-1.68E+04
Transport	4.90E+01	5.21E+01
Substitution of energy	-7.07E+02	-1.90E+04
Substitution of materials	-4.44E+04	0.00E+00
Processing - Energy	2.78E+04	0.00E+00
Processing - Non-Energy	5.79E-01	0.00E+00
Treatment of residues	1.54E+02	0.00E+00
Incineration	0.00E+00	2.20E+03

Results for "Used tyre waste**"**

Climate change (kg CO_2 eq.)

Process	CR-TYR	ER-TYR
Total	-1050.1	226.0
Transport	3.4	3.4
Substitution of energy	0.0	-884.2
Substitution of materials	-1335.9	-90.0
Processing - Energy	114.8	0.0
Processing - Non-Energy	11.9	0.0
Treatment of residues	155.8	0.0
Incineration	0.0	1196.9

Ozone depletion (kg CFC-11 eq.)

Process	CR-TYR	ER-TYR
Total	-2.62E-04	3.49E-07
Transport	1.98E-12	1.98E-12
Substitution of energy	0.00E+00	-1.42E-07
Substitution of materials	-2.65E-04	-9.03E-14
Processing - Energy	1.18E-09	0.00E+00
Processing - Non-Energy	1.63E-06	0.00E+00
Treatment of residues	1.84E-06	0.00E+00
Incineration	0.00E+00	4.92E-07

Human toxicity, cancer (CTUh)

Process	CR-TYR	ER-TYR
Total	-3.13E-07	8.38E-06
Transport	3.43E-10	3.43E-10
Substitution of energy	0.00E+00	-1.16E-07
Substitution of materials	-6.44E-07	-1.15E-07
Processing - Energy	5.36E-10	0.00E+00
Processing - Non-Energy	3.35E-07	0.00E+00
Treatment of residues	-5.14E-09	0.00E+00
Incineration	0.00E+00	8.61E-06

Human toxicity, non-cancer (CTUh)

Process	CR-TYR	ER-TYR
Total	-8.99E-06	-4.64E-06
Transport	2.42E-08	2.42E-08
Substitution of energy	0.00E+00	-5.16E-06
Substitution of materials	-1.05E-05	-9.38E-07
Processing - Energy	1.69E-08	0.00E+00
Processing - Non-Energy	1.67E-06	0.00E+00
Treatment of residues	-2.40E-07	0.00E+00
Incineration	0.00E+00	1.43E-06

Particulate matter (Disease incidence)

Process	CR-TYR	ER-TYR
Total	-1.02E-04	-1.78E-05
Transport	8.15E-08	8.15E-08
Substitution of energy	0.00E+00	-2.28E-05
Substitution of materials	-1.02E-04	-2.21E-06
Processing - Energy	2.67E-07	0.00E+00
Processing - Non-Energy	1.51E-06	0.00E+00

Process	CR-TYR	ER-TYR
Treatment of residues	-2.45E-06	0.00E+00
Incineration	0.00E+00	7.07E-06

Ionising radiation (kBq U^{235} eq.)

Process	CR-TYR	ER-TYR
Total	-9.80E+01	-1.01E+02
Transport	1.54E-02	1.54E-02
Substitution of energy	0.00E+00	-1.66E+02
Substitution of materials	-7.67E+01	-4.47E-01
Processing - Energy	1.36E+00	0.00E+00
Processing - Non-Energy	4.01E+00	0.00E+00
Treatment of residues	-2.67E+01	0.00E+00
Incineration	0.00E+00	6.58E+01

Photochemical ozone formation (kg NMVOC eq.)

Process	CR-TYR	ER-TYR
Total	-1.65E+00	1.51E-01
Transport	1.79E-02	1.79E-02
Substitution of energy	0.00E+00	-5.09E-01
Substitution of materials	-1.80E+00	-4.18E-02
Processing - Energy	9.76E-02	0.00E+00
Processing - Non-Energy	4.24E-02	0.00E+00
Treatment of residues	-9.32E-03	0.00E+00
Incineration	0.00E+00	6.84E-01

Acidification (mol H^+ eq.)

Process	CR-TYR	ER-TYR
Total	-4.0	-0.8
Transport	0.0	0.0
Substitution of energy	0.0	-1.7
Substitution of materials	-4.3	-0.1
Processing - Energy	0.3	0.0
Processing - Non-Energy	0.2	0.0
Treatment of residues	-0.2	0.0
Incineration	0.0	1.0

Eutrophication, terrestrial (mol N eq.)

Process	CR-TYR	ER-TYR
Total	-2.81E+00	1.44E+00
Transport	1.04E-01	1.04E-01
Substitution of energy	0.00E+00	-1.20E+00
Substitution of materials	-3.60E+00	-4.91E-03
Processing - Energy	3.60E-01	0.00E+00
Processing - Non-Energy	1.23E-01	0.00E+00
Treatment of residues	2.03E-01	0.00E+00
Incineration	0.00E+00	2.54E+00

Eutrophication, freshwater (kg P eq.)

Process	CR-TYR	ER-TYR
Total	-1.04E-02	-2.78E-03
Transport	2.11E-05	2.11E-05
Substitution of energy	0.00E+00	-3.13E-03
Substitution of materials	-1.13E-02	-1.15E-04

Process	CR-TYR	ER-TYR
Processing - Energy	6.53E-06	0.00E+00
Processing - Non-Energy	6.23E-04	0.00E+00
Treatment of residues	2.18E-04	0.00E+00
Incineration	0.00E+00	4.44E-04

Eutrophication, marine (kg N eq.)

Process	CR-TYR	ER-TYR
Total	-2.62E-01	1.04E-01
Transport	9.36E-03	9.36E-03
Substitution of energy	0.00E+00	-1.42E-01
Substitution of materials	-3.28E-01	-6.12E-04
Processing - Energy	3.29E-02	0.00E+00
Processing - Non-Energy	1.68E-02	0.00E+00
Treatment of residues	7.50E-03	0.00E+00
Incineration	0.00E+00	2.37E-01

Ecotoxicity, freshwater (CTUe)

Process	CR-TYR	ER-TYR
Total	-2.46E+04	-2.32E+03
Transport	3.07E+01	3.07E+01
Substitution of energy	0.00E+00	-3.56E+03
Substitution of materials	-2.49E+04	-1.59E+02
Processing - Energy	2.28E+01	0.00E+00
Processing - Non-Energy	5.37E+02	0.00E+00
Treatment of residues	-2.71E+02	0.00E+00
Incineration	0.00E+00	1.37E+03

Resource use, minerals and metals (kg Sb eq.)

Process	CR-TYR	ER-TYR
Total	1.26E-03	-7.10E-05
Transport	1.38E-06	1.38E-06
Substitution of energy	0.00E+00	-1.25E-04
Substitution of materials	-1.48E-03	-4.52E-06
Processing - Energy	8.34E-07	0.00E+00
Processing - Non-Energy	2.70E-03	0.00E+00
Treatment of residues	2.79E-05	0.00E+00
Incineration	0.00E+00	5.74E-05

Resource use, fossils (MJ)

Process	CR-TYR	ER-TYR
Total	-4.48E+04	-1.03E+04
Transport	4.62E+01	4.62E+01
Substitution of energy	0.00E+00	-1.30E+04
Substitution of materials	-4.28E+04	-7.95E+02
Processing - Energy	6.50E+01	0.00E+00
Processing - Non-Energy	2.79E+02	0.00E+00
Treatment of residues	-2.47E+03	0.00E+00
Incineration	0.00E+00	3.45E+03

Results for "Mixed shredded plastics from small WEEE (small domestic and ICT **appliances)"**

Climate change (kg CO_2 eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-8.30E+02	9.01E+02
Transport	5.07E+00	3.50E+00
Substitution of energy	-6.44E+02	-1.31E+03
Substitution of materials	-1.32E+03	-2.45E+00
Processing - Energy	3.48E+01	0.00E+00
Processing - Non-Energy	4.43E+00	0.00E+00
Treatment of residues	1.09E+03	8.73E+01
Incineration	0.00E+00	2.12E+03

Ozone depletion (kg CFC-11 eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	3.72E-06	2.16E-05
Transport	2.99E-12	2.06E-12
Substitution of energy	-3.60E-06	-1.97E-07
Substitution of materials	-1.44E-05	-2.43E-15
Processing - Energy	1.22E-08	0.00E+00
Processing - Non-Energy	1.98E-07	0.00E+00
Treatment of residues	2.15E-05	2.13E-05
Incineration	0.00E+00	4.35E-07

Human toxicity, cancer (CTUh)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	3.34E-06	7.89E-06
Transport	6.34E-10	4.37E-10
Substitution of energy	-7.62E-08	-1.56E-07
Substitution of materials	-3.62E-07	-2.53E-09
Processing - Energy	5.25E-09	0.00E+00
Processing - Non-Energy	1.26E-09	0.00E+00
Treatment of residues	3.77E-06	1.02E-07
Incineration	0.00E+00	7.94E-06

Human toxicity, non-cancer (CTUh)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-8.43E-06	-5.61E-06
Transport	4.63E-08	3.35E-08
Substitution of energy	-3.50E-06	-7.47E-06
Substitution of materials	-7.04E-06	-2.46E-08
Processing - Energy	1.86E-07	0.00E+00
Processing - Non-Energy	4.93E-08	0.00E+00
Treatment of residues	1.83E-06	7.58E-07
Incineration	0.00E+00	1.09E-06

Particulate matter (Disease incidence)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-6.29E-05	-3.18E-05
Transport	1.53E-07	1.30E-07
Substitution of energy	-1.68E-05	-3.62E-05
Substitution of materials	-5.24E-05	-1.22E-07
Processing - Energy	1.11E-06	0.00E+00
Processing - Non-Energy	5.46E-07	0.00E+00

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Treatment of residues	4.58E-06	1.81E-07
Incineration	0.00E+00	4.27E-06

Ionising radiation (kBq U^{235} eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-8.93E+01	-2.15E+02
Transport	2.33E-02	1.60E-02
Substitution of energy	-1.05E+02	-2.57E+02
Substitution of materials	-2.11E+01	-1.74E-01
Processing - Energy	1.39E+01	0.00E+00
Processing - Non-Energy	2.97E-02	0.00E+00
Treatment of residues	2.33E+01	-1.53E+00
Incineration	0.00E+00	4.38E+01

Photochemical ozone formation (kg NMVOC eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-3.52E+00	-1.16E+00
Transport	2.83E-02	1.89E-02
Substitution of energy	-9.41E-01	-1.93E+00
Substitution of materials	-3.22E+00	-5.16E-03
Processing - Energy	5.59E-02	0.00E+00
Processing - Non-Energy	3.57E-02	0.00E+00
Treatment of residues	5.20E-01	1.87E-02
Incineration	0.00E+00	7.38E-01

Acidification (mol H^+ eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-4.72E+00	-2.45E+00
Transport	3.13E-02	2.12E-02
Substitution of energy	-1.60E+00	-3.39E+00
Substitution of materials	-3.98E+00	-9.55E-03
Processing - Energy	1.03E-01	0.00E+00
Processing - Non-Energy	2.64E-02	0.00E+00
Treatment of residues	6.95E-01	5.00E-02
Incineration	-4.72E+00	-2.45E+00

Eutrophication, terrestrial (mol N eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-8.08E+00	-3.70E+00
Transport	1.63E-01	1.10E-01
Substitution of energy	-3.34E+00	-6.81E+00
Substitution of materials	-7.28E+00	-1.76E-02
Processing - Energy	2.08E-01	0.00E+00
Processing - Non-Energy	1.30E-01	0.00E+00
Treatment of residues	2.03E+00	9.28E-02
Incineration	0.00E+00	2.92E+00

Eutrophication, freshwater (kg P eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-1.25E-02	6.33E-04
Transport	3.19E-05	2.20E-05
Substitution of energy	-1.84E-03	-3.15E-03
Substitution of materials	-1.48E-02	-2.19E-06

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Processing - Energy	7.33E-05	0.00E+00
Processing - Non-Energy	3.23E-05	0.00E+00
Treatment of residues	3.98E-03	3.48E-03
Incineration	0.00E+00	2.87E-04

Eutrophication, marine (kg N eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-8.18E-01	-3.77E-01
Transport	1.47E-02	9.92E-03
Substitution of energy	-3.22E-01	-6.59E-01
Substitution of materials	-7.28E-01	-1.61E-03
Processing - Energy	1.96E-02	0.00E+00
Processing - Non-Energy	1.18E-02	0.00E+00
Treatment of residues	1.85E-01	3.60E-03
Incineration	0.00E+00	2.71E-01

Ecotoxicity, freshwater (CTUe)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-1.47E+04	-5.87E+02
Transport	4.65E+01	3.20E+01
Substitution of energy	-2.25E+03	-4.81E+03
Substitution of materials	-1.68E+04	-7.04E+00
Processing - Energy	2.35E+02	0.00E+00
Processing - Non-Energy	3.79E+01	0.00E+00
Treatment of residues	3.98E+03	3.31E+03
Incineration	0.00E+00	8.86E+02

Resource use, minerals and metals (kg Sb eq.)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-2.34E-04	2.70E-04
Transport	2.07E-06	1.42E-06
Substitution of energy	-7.00E-05	-1.21E-04
Substitution of materials	-5.62E-04	-1.85E-07
Processing - Energy	8.43E-06	0.00E+00
Processing - Non-Energy	9.56E-06	0.00E+00
Treatment of residues	3.77E-04	3.52E-04
Incineration	0.00E+00	3.72E-05

Resource use, fossils (MJ)

Process	MR-MSP-WEEE-SA	ER-MSP-WEEE-SA
Total	-3.86E+04	-1.80E+04
Transport	7.00E+01	4.82E+01
Substitution of energy	-9.33E+03	-1.98E+04
Substitution of materials	-3.19E+04	-2.58E+01
Processing - Energy	5.89E+02	0.00E+00
Processing - Non-Energy	5.67E+01	0.00E+00
Treatment of residues	1.89E+03	-3.20E+02
Incineration	0.00E+00	2.12E+03

Results for "Mixed shredded plastics from large WEEE (cooling and freezing **appliances)"**

Climate change (kg CO_2 eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-1.52E+03	1.09E+03
Transport	4.00E+00	3.41E+00
Substitution of energy	-3.34E+02	-1.16E+03
Substitution of materials	-1.77E+03	-7.07E+01
Processing - Energy	3.06E+01	0.00E+00
Processing - Non-Energy	3.73E+00	0.00E+00
Treatment of residues	5.45E+02	1.15E+02
Incineration	0.00E+00	2.21E+03

Ozone depletion (kg CFC-11 eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	1.52E-05	2.84E-05
Transport	2.36E-12	2.00E-12
Substitution of energy	-8.97E-06	-1.76E-07
Substitution of materials	-4.21E-06	-7.01E-14
Processing - Energy	1.03E-08	0.00E+00
Processing - Non-Energy	1.69E-07	0.00E+00
Treatment of residues	2.82E-05	2.81E-05
Incineration	0.00E+00	4.25E-07

Human toxicity, cancer (CTUh)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-1.52E-07	7.67E-06
Transport	5.01E-10	4.26E-10
Substitution of energy	-3.96E-08	-1.39E-07
Substitution of materials	-1.13E-06	-7.29E-08
Processing - Energy	4.57E-09	0.00E+00
Processing - Non-Energy	1.07E-09	0.00E+00
Treatment of residues	1.01E-06	1.35E-07
Incineration	0.00E+00	7.74E-06

Human toxicity, non-cancer (CTUh)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-1.42E-05	-5.10E-06
Transport	3.61E-08	3.26E-08
Substitution of energy	-1.42E-06	-6.65E-06
Substitution of materials	-1.51E-05	-7.08E-07
Processing - Energy	1.65E-07	0.00E+00
Processing - Non-Energy	4.14E-08	0.00E+00
Treatment of residues	2.11E-06	1.00E-06
Incineration	0.00E+00	1.23E-06

Particulate matter (Disease incidence)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-7.07E-05	-3.06E-05
Transport	1.14E-07	1.27E-07
Substitution of energy	-7.04E-06	-3.23E-05
Substitution of materials	-7.17E-05	-3.53E-06
Processing - Energy	9.66E-07	0.00E+00

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Processing - Non-Energy	4.51E-07	0.00E+00
Treatment of residues	6.51E-06	2.39E-07
Incineration	0.00E+00	4.86E-06

Ionising radiation (kBq U^{235} eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-1.32E+02	-1.91E+02
Transport	1.84E-02	1.56E-02
Substitution of energy	-2.85E+01	-2.29E+02
Substitution of materials	-1.29E+02	-5.03E+00
Processing - Energy	1.18E+01	0.00E+00
Processing - Non-Energy	2.52E-02	0.00E+00
Treatment of residues	1.30E+01	-2.02E+00
Incineration	0.00E+00	4.44E+01

Photochemical ozone formation (kg NMVOC eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-3.78E+00	-1.07E+00
Transport	2.25E-02	1.84E-02
Substitution of energy	-4.67E-01	-1.72E+00
Substitution of materials	-3.83E+00	-1.49E-01
Processing - Energy	4.91E-02	0.00E+00
Processing - Non-Energy	2.95E-02	0.00E+00
Treatment of residues	4.19E-01	2.46E-02
Incineration	0.00E+00	7.50E-01

Acidification (mol H^+ eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-6.00E+00	-2.31E+00
Transport	2.48E-02	2.06E-02
Substitution of energy	-7.10E-01	-3.02E+00
Substitution of materials	-6.04E+00	-2.75E-01
Processing - Energy	9.00E-02	0.00E+00
Processing - Non-Energy	2.19E-02	0.00E+00
Treatment of residues	6.06E-01	6.60E-02
Incineration	-6.00E+00	-2.31E+00

Eutrophication, terrestrial (mol N eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-1.11E+01	-3.38E+00
Transport	1.29E-01	1.07E-01
Substitution of energy	-1.70E+00	-6.06E+00
Substitution of materials	-1.14E+01	-5.07E-01
Processing - Energy	1.82E-01	0.00E+00
Processing - Non-Energy	1.08E-01	0.00E+00
Treatment of residues	1.61E+00	1.22E-01
Incineration	0.00E+00	2.96E+00

Eutrophication, freshwater (kg P eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-1.86E-03	2.04E-03
Transport	2.52E-05	2.14E-05

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Substitution of energy	-1.35E-03	-2.81E-03
Substitution of materials	-5.78E-03	-6.31E-05
Processing - Energy	6.74E-05	0.00E+00
Processing - Non-Energy	2.73E-05	0.00E+00
Treatment of residues	5.14E-03	4.59E-03
Incineration	0.00E+00	3.02E-04

Eutrophication, marine (kg N eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-1.04E+00	-3.45E-01
Transport	1.16E-02	9.66E-03
Substitution of energy	-1.59E-01	-5.87E-01
Substitution of materials	-1.06E+00	-4.64E-02
Processing - Energy	1.72E-02	0.00E+00
Processing - Non-Energy	9.75E-03	0.00E+00
Treatment of residues	1.43E-01	4.74E-03
Incineration	0.00E+00	2.74E-01

Ecotoxicity, freshwater (CTUe)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-2.51E+04	8.67E+02
Transport	3.67E+01	3.12E+01
Substitution of energy	-1.08E+03	-4.28E+03
Substitution of materials	-2.93E+04	-2.03E+02
Processing - Energy	2.01E+02	0.00E+00
Processing - Non-Energy	3.18E+01	0.00E+00
Treatment of residues	5.00E+03	4.37E+03
Incineration	0.00E+00	9.55E+02

Resource use, minerals and metals (kg Sb eq.)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	6.36E-05	3.94E-04
Transport	1.64E-06	1.39E-06
Substitution of energy	-5.94E-05	-1.08E-04
Substitution of materials	-3.80E-04	-5.32E-06
Processing - Energy	7.18E-06	0.00E+00
Processing - Non-Energy	8.17E-06	0.00E+00
Treatment of residues	4.86E-04	4.65E-04
Incineration	0.00E+00	4.13E-05

Resource use, fossils (MJ)

Process	MR-MSP-WEEE-CFA	ER-MSP-WEEE-CFA
Total	-4.25E+04	-1.65E+04
Transport	5.52E+01	4.70E+01
Substitution of energy	-4.20E+03	-1.76E+04
Substitution of materials	-4.11E+04	-7.45E+02
Processing - Energy	5.14E+02	0.00E+00
Processing - Non-Energy	4.77E+01	0.00E+00
Treatment of residues	2.21E+03	-4.23E+02
Incineration	0.00E+00	2.22E+03

Annex 4. Summary of life cycle assessment results per plastic waste input and management scenario

This annex reports the LCA results -total potential impacts- of the management scenarios investigated for each plastic waste stream, across the entire set of impact categories considered. Within each category, the scenario with the lowest impact (best performance) is indicated in *dark green*, while the scenario with the highest impact (worst performance) is indicated in *dark red*. For the other scenarios, the following colour scale is used, in ascending order of impact and based on the number of scenarios that need to be differentiated in the specific impact category (i.e. not all the colours listed are necessarily used): *light blue*, *yellow*, *orange* and *light brown*. When three scenarios are compared (or when three groups of scenarios with comparable impacts are identified based on the rule described below), *yellow* is always used to indicate the scenario(s) with intermediate impact/performance (regardless of the colour scale reported above). Scenarios having comparable impacts/performances are indicated with the same colour (possibly with different shades) or pattern. However, to enable differentiation, scenarios that are comparable with the best performing one are indicated in *light green* (instead of dark green), while those comparable with the worst performing one are indicated in *light red* (instead of dark red).

Comparability of scenarios is evaluated considering impact values ranked in ascending order, and calculating relative impact differences between each scenario and the one(s) with lower impacts. A scenario is considered comparable with the scenario(s) having lower impact when the relative impact difference compared to the latter does not exceed 20% (i.e. impact differences between scenarios are considered significant only if larger than 20%).

For instance, following this rule, in Photochemical Ozone Formation (POF) the management scenarios analysed for sorted MPO flexible packaging waste result in the following raking: CR-III (dark green) with the lowest impact/best performance; CR-I (light green) comparable to CR-III (same colour); MR-I (light green with diagonal stripes) comparable to both CR-I and CR-III (same colour); ER (yellow with diagonal stripes) comparable to MR-I (same pattern) but not to CR-I and CR-III (different colour and no pattern); CR-II (yellow with diagonal stripes) comparable to ER (same colour and pattern) and to MR-I (same pattern); MR-II (dark red) with the highest impact/worst performance (and not comparable to any of the former scenarios).

The following acronyms are used for the analysed waste management scenarios: *CR*: *chemical recycling*; *ER*: *energy recovery*; *MR*: *mechanical recycling*; *PR*: *physical recycling*. Acronyms used for the different impact categories are defined in Section 2.1.6.

Sorted PET packaging waste (bottles and trays)	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
MR	-1.9E+03	5.7E-03	-5.8E-07	-1.1E-05	-5.0E-05	-1.2E+01	-3.5E+00	-3.3E+00	-1.0E+01	1.3E-02	1.8E-01	-1.3E+04	-3.4E-01	-5.9E+04
ER	1.2E+03	3.4E-07	8.5E-06	-3.9E-06	-1.9E-05	-1.2E+02	-4.7E-01	-1.3E+00	-1.3E+00	-1.7E-03	-1.4E-01	-2.2E+03	-4.0E-05	-1.1E+04
CR-(I)	-1.7E+03	1.4E-06	-6.2E-07	-1.1E-05	-4.4E-05	5.4E+01	-3.7E+00	-3.4E+00	-1.1E+01	-3.9E-03	-1.0E+00	-2.0E+04	2.1E+02	-7.0E+02
CR-(II)	-5.9E+02	-1.0E-02	1.7E-07	-1.1E-05	-5.5E-05	-4.2E+01	-3.6E+00	-4.8E+00	-7.8E+00	-3.4E-02	-7.8E-01	-1.1E+04	-1.2E-02	-4.3E+04
CR-(III)	-4.9E+02	-1.1E-02	2.7E-07	1.0E-05	5.1E-06	2.3E+02	-3.1E+00	1.0E+00	-6.5E+00	-1.0E-02	-6.3E-01	1.5E+04	-1.3E-02	-3.0E+04

Sorted PS packaging waste	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
MR	-4.4E+02	1.8E-06	-9.7E-08	-7.5E-06	-8.8E-06	6.0E+01	-1.4E+00	-1.1E+00	-3.6E+00	3.4E-02	4.2E+00	-2.2E+04	-1.2E-05	-3.0E+04
ER	1.1E+03	2.9E-07	8.4E-06	-5.7E-06	-2.8E-05	-1.9E+02	-9.5E-01	-2.1E+00	-3.0E+00	-2.5E-03	-3.0E-01	-3.4E+03	-6.9E-05	-1.6E+04
CR	-6.7E+02	-8.1E-05	-5.0E-06	-7.4E-06	-9.0E-05	4.3E+01	-1.8E+01	-5.1E+00	-9.4E+00	-1.2E-02	4.1E+00	-7.0E+03	-6.4E-03	-4.3E+04

Sorted mixed polyolefins (MPOs) flexible packaging waste	**CC**	**ODP**	**Htox_c**	**Htox_nc**	**PM**	**IR**	**POF**	**AC**	**TEU**	**FEU**	**MEU**	**Ecotox**	**MRU**	**FRU**
MR-(I)	-2.1E+02	-3.9E-05	1.8E-06	-5.9E-06	-1.2E-05	4.1E+01	-1.1E+00	-1.2E+00	-2.5E+00	-4.2E-03	-1.6E-01	-8.3E+03	-1.8E-04	-1.7E+04
MR-(II)	-5.6E+01	-3.8E-05	1.9E-06	-2.4E-06	-1.0E-05	2.1E+01	-5.7E-01	-8.4E-01	-1.5E+00	-3.7E-03	-1.3E-01	-3.3E+03	-1.6E-04	-8.6E+03
ER	7.7E+02	2.9E-07	8.4E-06	-5.9E-06	-2.9E-05	-1.9E+02	-9.9E-01	-2.2E+00	-3.1E+00	-2.6E-03	-3.1E-01	-3.5E+03	-6.9E-05	-1.6E+04
CR-(I)	6.2E+02	-5.5E-05	2.3E-06	-1.0E-06	-1.6E-05	9.9E+01	-1.3E+00	-1.5E+00	-2.8E+00	-2.5E-03	-2.7E-01	-8.9E+02	-2.1E-04	-1.4E+04
CR-(II)	5.7E+02	-2.6E-04	2.3E-06	1.3E-06	-1.1E-05	-4.6E+01	-8.8E-01	-1.8E+00	-1.8E+00	2.6E-04	-1.4E-01	-6.9E+03	1.9E-05	-1.7E+04
CR-(III)	3.1E+02	-4.0E-04	2.2E-06	-3.1E-06	-1.1E-05	-6.6E+01	-1.3E+00	-2.4E+00	-2.8E+00	-1.6E-03	-2.5E-01	-1.1E+04	-1.3E-04	-2.5E+04

Sorted large-format PE film waste	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
MR	-1.2E+02	-4.4E-05	-5.9E-06	-7.9E-06	-5.9E-06	6.3E+01	-1.7E+00	-8.8E-01	-2.6E+00	1.1E-02	1.0E+00	-8.1E+03	-1.1E-04	-1.9E+04
ER	6.7E+02	2.5E-07	8.4E-06	-7.4E-06	-3.6E-05	-2.4E+02	-1.4E+00	-2.9E+00	-4.4E+00	-3.2E-03	-4.4E-01	-4.4E+03	-9.6E-05	-2.0E+04
PR	-3.7E+02	1.1E-03	-7.4E-06	-1.1E-05	-8.7E-06	4.3E+01	-2.1E+00	-1.1E+00	-3.3E+00	-4.3E-04	-2.9E-01	-1.2E+04	-3.7E-06	-2.3E+04

Post-industrial PE/PA multilayer film waste	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
PR	5.8E+01	-1.4E-06	-8.1E-06	-4.6E-06	-2.1E-05	5.9E+02	-4.9E+00	-2.8E+00	-1.1E+01	-1.7E-02	-1.1E+00	-4.2E+03	9.1E+03	-4.3E+02
ER	8.3E+02	2.4E-07	8.4E-06	-7.7E-06	-3.4E-05	-2.3E+02	-2.1E-01	-2.0E+00	5.5E-01	-4.9E-03	1.6E-03	-5.0E+03	-1.3E+04	-4.5E+01

EPS construction and demolition waste	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
PR	3.4E+02	7.8E-07	-2.8E-07	-3.5E-06	3.0E-05	6.2E+02	4.5E-02	2.2E+00	2.5E+00	1.3E-03	2.4E-01	-2.4E+04	1.3E-04	-1.7E+04
ER	1.8E+03	2.8E-07	8.4E-06	-5.4E-06	-3.0E-05	-2.0E+02	-1.0E+00	-2.3E+00	-3.3E+00	-2.7E-03	-3.3E-01	-3.7E+03	-7.6E-05	-1.7E+04

Used tyre waste	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
CR	-1.1E+03	-2.6E-04	-3.1E-07	-9.0E-06	-1.0E-04	-9.8E+01	-1.6E+00	-4.0E+00	-2.8E+00	-1.0E-02	-2.6E-01	-2.5E+04	-2.2E+03	1.2E+02
ER	2.3E+02	3.5E-07	8.4E-06	-4.6E-06	-1.8E-05	-1.0E+02	1.5E-01	-7.9E-01	1.4E+00	-2.8E-03	1.0E-01	-2.3E+03	-7.1E+03	-2.3E+01

Mixed shredded plastics from small WEEE (small domestic and ICT appliances)	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
MR	-8.3E+02	3.7E-06	3.3E-06	-8.4E-06	-6.3E-05	-8.9E+01	-3.5E+00	-4.7E+00	-8.1E+00	-1.2E-02	-8.2E-01	-1.5E+04	-2.3E-04	-3.9E+04
ER	9.0E+02	2.2E-05	7.9E-06	-5.6E-06	-3.2E-05	-2.1E+02	-1.2E+00	-2.5E+00	-3.7E+00	6.3E-04	-3.8E-01	-5.9E+02	2.7E-04	-1.8E+04

Mixed shredded plastics from large WEEE (cooling and freezing appliances)	CC	ODP	Htox_c	Htox_nc	PM	IR	POF	AC	TEU	FEU	MEU	Ecotox	MRU	FRU
MR	-1.5E+03	1.5E-05	-1.5E-07	-1.4E-05	-7.1E-05	-1.3E+02	-3.8E+00	-6.0E+00	-1.1E+01	-1.9E-03	-1.0E+00	-2.5E+04	6.4E-05	-4.2E+04
ER	1.1E+03	2.8E-05	7.7E-06	-5.1E-06	-3.1E-05	-1.9E+02	-1.1E+00	-2.3E+00	-3.4E+00	2.0E-03	-3.5E-01	8.7E+02	3.9E-04	-1.7E+04

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