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ORIGINAL PAPER

Thermochemical recovery from the sustainable economy development point of view—LCA-based reasoning for EU legislation changes

Tihomir Tomić[1] · Iva Slatina[1] · Daniel Rolph Schneider[1]

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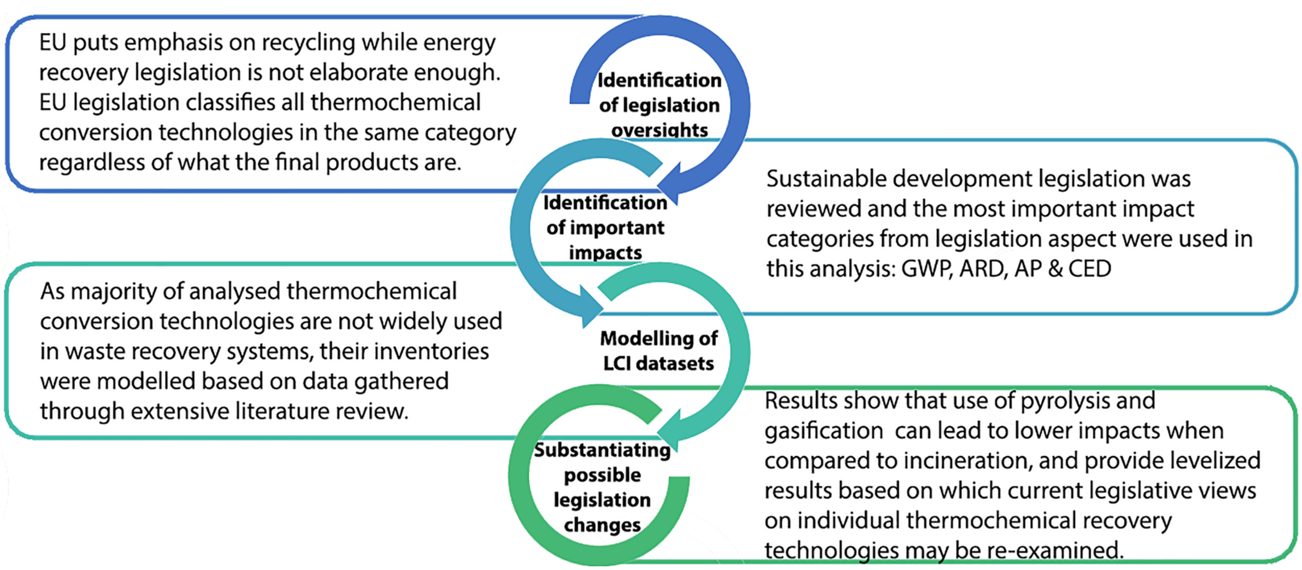
Abstract
The EU legislation put the focus on the material recovery of waste while energy recovery is not elaborate enough and all thermochemical conversion technologies are classified in the same category regardless of the final products, which can hamper overall sustainability. Therefore, this research analyses technologies for recovery of plastic waste to review the existing EU legislation and technology classifications. Most important LCA impact categories from the legislation point of view were identified and used in the analysis. As alternative thermochemical recovery technologies are not widely used, their inventories were modelled based on an extensive literature review. Results show that pyrolysis of plastic waste has 46%, 90%, and 55%, while gasification up to 24%, 8%, and 91%, lower global warming, abiotic depletion, and cumulative energy demand-related impacts, respectively, compared to incineration with CHP generation. Incineration-based scenarios show lower impacts only in the acidification potential category which is dependent on energy mixes of substituted energy vectors which are quickly changing due to the energy transition. Thus, alternative thermochemical recovery technologies can help in reaching sustainable development goals by lowering environmental impacts and import dependence. But, before considering new investments, the substitution of less environmentally sustainable fuels in facilities like cement kilns needs to be looked upon. Results of this analysis provide levelized results for environmental and resource sustainability based on which current legislative views on individual thermochemical recovery technologies may be re-examined.

Graphical abstract



Extended author information available on the last page of the article

Keywords Sustainable development · Legislation changes · Mixed plastic waste · Thermochemical conversion technologies · Environmental and resource sustainability · Life cycle inventory modelling

Introduction

European production of polymers reached 61.8 million tonnes in 2018, which is equivalent to 17% of the world's production (European Plastics 2019). When the distribution of polymer use by industry sectors is looked upon, 40% of overall production is consumed in packaging production, 20% in the construction sector, 10% in automotive, 6% in electrical and electronic, 4% in household leisure and sports, and 3% in agriculture. Where some products can have a life span of less than a day (such as packaging), others need decades to reach waste streams (like automotive or electronic parts). Therefore, the amounts and composition of plastic waste do not correspond to consumption. Thus, in 2018, from a total of 29.1 million tonnes of collected plastic post-consumer waste, over 61% was packaging waste, although packaging production accounts for 40% of polymers consumption (European Plastics 2019).

Even though polymer waste represents a major problem, until recently there was no dedicated legislative framework on the EU level, and this problem has been only indirectly addressed through non-specific waste legislation. Also, during the years EU put emphasis only on material recovery, while energy recovery of waste is neglected. Because of that, energy recovery technologies have been looked upon mainly from the aspect of mixed waste with the exception of biowaste. This led to problems with insufficiently elaborated classifications of waste recovery technologies where legislation does not make difference between different thermochemical recovery technologies. This problem is especially pronounced in the case of plastic waste management (WM), especially nowadays the EU put stricter control on plastic waste exports and completely banned exports to non-OECD countries (EP 2020). When all of this is looked at from the plastic WM aspect, where recycling capacity is capped at 30% of production (on a level of 8.5 million tons per year) (Waste Management World 2021), the importance of energy recovery technologies is much more emphasized.

Due to this, this research provides an important contribution by evaluating the environmental impacts of emerging thermochemical technologies for plastic waste valorization, i.e. pyrolysis and gasification, from the points of view of the most actual legislation defined targets, and comparing them with legislatively recognized technologies, with a goal of the revision of the current technology classification and creation of a more sustainable framework. Results of this study could help in reduction in resource use and imports, decupling prices of petrochemical products and plastic from the oil price, and decrease environmental impacts which leads to increase in sustainability from an environmental, economic, and political point of view.

Waste recovery and wider sustainability agenda

The EU principles for MSW management were defined by the Waste Framework Directive (2008/98/EC) through the waste hierarchy and recovery goals which need to be met by 2020. Further along, the New Waste Package (EP 2018) increased targets for MSW reuse and recycling (55% by 2025, 60% by 2030, and 65% by 2035), MSW disposal (max. 10% by 2035), and packaging waste recycling (70% by 2030), as well ban landfilling of separately collected wastes and recyclable/recoverable wastes (from 2030).

One of the waste categories that had a separate legislative framework for many years now is packaging waste—from 1985 and the Directive on containers of liquids for human consumption (85/339/EEC). Over the years, packaging-related guidelines have been adapted to ensure greater environmental protection and set minimum recovery rates, which included incineration, for overall packaging waste, with specific targets by different materials. Based on a review of waste legislation conducted in 2014, EC revised the Directive on Packaging and Packaging Waste (2015/720) and defined measures for the reduction of the consumption of lightweight plastic bags with a thickness below 50 microns. The latest amendment from 2018 under the Waste Package (EP 2018) raised the packaging recycling target to 70% by 2030, with specific targets per material, whereas for plastics it is set to 55% by 2030 (50% by 2025).

Although the packaging and MSW legislations partially covered the plastic WM, only in recent years, it has been actively addressed. European Strategy for Plastics in a Circular Economy (EC 2018a) from 2018 seeks to change how plastic products are designed, manufactured, used, and recycled. Sorting and recycling capacities are to increase fourfold from 2015 to 2030, exports of poorly sorted plastic waste are to be phased out, all plastic packaging needs to be recyclable by 2030, and the use of single-use plastic and microplastics need to be limited. Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment bans disposable plastic products from the market where alternatives are readily available and affordable and limits the use of other plastic products. Targets of 90% separate collection of plastic bottles by 2029 (77% by 2025), 25% share of recycled plastics in PET bottles by 2025, and 30% in all plastic bottles by 2030 were defined.

WM legislation is a constituent part of wider legislation packages that have a goal of solving the problem of energy and material scarcity in Europe, which at the same time represents economic, political, and security problem of the EU (Tomić and Schneider 2020). Energy scarcity, especially fossil fuels scarcity, and climate change problems are tackled within the same legislation frameworks—the 2020 Climate and Energy Package (EC 2008a) and the 2030 Climate and Energy Framework (EC 2014) whose goals are in line with the Roadmap for moving to a competitive low-carbon economy in 2050 (EC 2011a), the Transport White Paper (EC 2011b), and the Energy Roadmap 2050 (EC 2011c). This path includes GHG emissions reduction of 80% by 2050 (compared to 1990)—transport sector emissions reduction by 60% by 2050 using biofuels and electrification, the power sector should become carbon neutral and heating should be based on renewable electricity or low-emission source. These goals are not specifically connected to EU legislation, as CO_2 emissions mitigation is also part Clean Development Mechanism of the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC) (Alizadeh et al. 2014). Along with this path, Heat Roadmap Europe (Persson et al. 2014) classifies waste as the primary district heating heat source. On the other hand, material scarcity is tackled through the Raw Materials Initiative (EC 2008b) and the Flagship Initiative for a Resource Efficient Europe (EC 2011d) which outlines the transformation of the EU economy into a sustainable one till 2050. It emphasizes the importance of decoupling resource consumption (material and energy) and environmental impact from economic growth. Resource Efficient Europe (EEA 2019) strategy aims for a reduction in raw material consumption, an increase in security of supply, support combat against climate change, and limits the environmental impact associated with the exploitation of resources. On this path, the "transformation within a generation—in energy, industry, agriculture, fisheries, and transport systems" is outlined in the Roadmap to a Resource Efficient Europe (EEA 2019) and Circular Economy (EP 2018) is emphasized as the best concept for this transformation. All these plans and aspirations are concise under the Circular Economy strategy and the European Green Deal with initiatives that cover the entire life cycle of products, aiming to ensure that the used resources are kept within the EU economy for as long as possible, and striving to establish climate-neutral Europe.

As it can be seen, EU waste legislation put emphasis on material recovery (i.e. recycling) while energy recovery is subordinate to it and/or clearly neglected. This is not in line with findings presented in previous publications where it is found that implementation of thermolysis-based energy recovery technologies, besides mechanical recycling, is technically and energetically feasible (Mastellone 2019), and that, next to material recovery, energy recovery also represents an important link in the circular economy (Tomić and Schneider 2022). Thus, material and energy recovery complement each other. Also, EU legislation does not differentiate waste recovery outside of binary classification on material and energy recovery (except anaerobic digestion), and the only well-defined energy recovery technology is waste incineration (Tomić and Schneider 2018). In this context, SUSCHEM (2018) provided an insight into the (thermo)chemical recycling of waste plastics. Post-consumer plastic waste contains impurities and additives (e.g. pigments, paints, and fabric softeners) and other materials (e.g. cellulose, aluminium, and lead), and despite precise selection and separation the polymer materials that enter mechanical recycling are made up of a different mixture of polymers which affects the value and restricts potential use of the recycled material (Ragaert et al. 2020). Also, there is a problem with the quality of the multiple times recycled materials. Other solutions such as thermochemical recycling can be applied to a wide variety of plastic wastes that are not suitable for mechanical recycling and can be the most appropriate recovery technique for mixed plastic waste (MPW). While it can also be sensitive to contaminants of batches with macroscopic contaminants (metal parts, minerals, etc.) and chemicals (chlorine, oxygen, and nitrogen), thus separation of feedstock must be carried out, it is much less sensitive to mixing of different polymers and the majority of contamination-related problems can be solved through the use of catalysts and purification of semi-products/products. Also, mechanical recycling limitations, due to the increase of residues with each new cycle, do not apply to (thermo) chemical recycling (Business Europe 2019). Thus, it represents an option for recycling of mixed and multi-layered, as such, it is complementary to mechanical recycling, and from a life cycle standpoint represents a more viable alternative to incineration and disposal.

Products of alternative thermochemical conversion processes, such as pyrolysis and gasification, can be used as raw materials for fuels, chemicals, and materials production, thereby reducing dependence on petroleum products as well as environmental impact. This helps in decupling prices of petrochemical products and plastic from the oil price, which is in line with EU legislation. However, in the EC document Best Available Techniques (BAT) for waste incineration (EC 2018b), these technologies are listed under alternative technologies for thermal waste treatment and therefore are classified as waste incineration technologies, even though their products can be used as feedstock material in a wide range of production processes. Considering that in EU categorizes anaerobic digestion as recycling, due to the production of compost-like digestate, the classification of alternative thermochemical conversion technologies into the category of recycling should be considered, or it should be otherwise differentiated from waste incineration. Although the EU is very slow when it comes to legislation changes, EU waste legislation already has integrated mechanisms that can circumvent the strict regulatory implementations. Like ones in the Waste Framework Directive, which defines that potential deviations from the waste hierarchy, which underlies overall EU waste legislation, can be justified through considerations that include impacts on the level of the whole life cycle. Therefore, the same approach can be used to differentiate particular technologies. Based on these two premises, the hypothesis of this research is formed and states that by using a legislatively recognized approach and analysing technologies through an approach that includes considerations of impacts on the level of the whole life cycle, comprehensive and legislatively meaningful results can be obtained and used for substantiating possible legislation changes.

Literature review and research objective

Due to importance of "closing the loop", benefits of WM and recovery were analysed from many angles, from separate collection (Schneider et al. 2021) reuse of wastes (Aydin et al. 2017), chemical recycling (Huang et al. 2022), thermochemical recovery (Ongen 2016; Kremer et al. 2021, 2022; Siwal et al. 2021), to energy recovery via incineration (Tomić et al. 2017; Jadhao et al. 2017; Matak et al. 2021). But, when the sustainability of WM is considered, it needs to be analysed at the level of the overall life cycle and is most often conducted through life cycle assessment (LCA), which is a standardized scientific method for assessing life cycle impacts whose framework was adopted through the ISO 14040 and 14,044:2066 standards. Thus, LCA can be used in line with the propositions of the Waste Framework Directive. In addition, the EC emphasized the importance of LCA and classified it as "the best framework for assessing the potential environmental impacts" (Lima et al. 2018). Therefore, over the past two decades, many LCA of MSW WM systems have been conducted (Istrate et al. 2020), but if the search is limited to recent plastic waste-focused ones, the number of publications is much lower.

Aryan et al. (2019) conducted an LCA of landfilling, recycling, and incineration of PE and PET waste in India using the University of Leiden CML method is conducted. The environmental and economic impacts of recycling, incineration, and landfilling as end-of-life management options for HDPE products were compared using the Eco-Indicator 99 (EI99) LCIA method by Simões et al. (2014). Environmental impact analyses of post-consumer and industrial PLA waste mechanical recycling, chemical recycling as well as thermal treatment were conducted by Maga et al. (2019) and reported results of 11 arbitrary selected midpoint ReCiPe impact categories and the Cumulative Energy Demand (CED) method. Zhang et al. (2020) conducted an LCA and life cycle cost (LCC) analysis of recycling of PET and production of blankets using the Shandong University SDU method and reported results for all 15 midpoint impact categories. Nakem et al. (2016) used CML and Eco-indicator 99 methods to assess global warming potential (GWP) and energy use in PVC WM. As can be seen, all these researchers focus on only specific, separate, monopolymers recovery, which is the best possible scenario when polymer waste recovery is analysed.

Cascone et al. (2020) analysed plastic granule production from greenhouse covering films through footprint and CED analyses. Ahamed et al. (2020) conducted an LCA of pyrolysis of flexible plastic packaging with pyrolytic oil and nanotubes production and reported on 8 selected ReCiPe midpoint categories. Hou et al. (2018) presented complete BEES method results and compared the environmental impacts of incineration and landfilling as end-of-life treatments for plastic films. Horodytska et al. (2020) used the IMPACT 2002 + method for printed plastic films recycling environmental assessment (upcycling and downcycling) and compared it to incineration. Lin et al. (2022) analysed the environmental impacts of treatment and recycling of express delivery packaging waste via C-footprint assessment. Beigbeder et al. (2019) analysed end-of-life scenarios (mechanical recycling, incineration, and industrial composting) of polymer (PP and PLA) biocomposites using arbitrary selected 6 midpoint ReCiPe categories. La Rosa et al. (2021) used ReCiPe endpoint and CED results for environmental assessment reporting on chemical recycling of carbon fibre thermosets for the production of thermoplastic composites and compared open and closed-loop scenario results. These researchers analysed the treatment of specific polymer wastes, and obtained results were compared with results for only a minority of available alternative recovery technologies.

Less specific plastics waste streams analyses are even less represented, especially when treatments in different technologies are compared. Thus, Khoo (2019) used the ReCiPe method for reporting climate change, terrestrial acidification, and particulate matter formation results and compared MPW recovery systems consisting of a mix of technologies for energy recovery (thermal treatment with electricity generation, gasification with ethanol production, and pyrolysis with diesel production), but only specific scenarios are analysed without analyses of the influence of alternative products production. Gear et al. (2018) used the CML method for designing MPW thermal cracking process, and compared different system configurations results with incineration and landfilling results, but this is a more specific application of LCA. Cossu et al. (2017) analysed different technologies for the treatment of residual waste from plastic waste separation using the EASYWASTE model. In that case, analysed the waste stream consisted of 57% of plastic (where the rest are metals (27%), textiles (3%), and bio-waste (13%)), while analysed technologies are incineration in different plants (including the substitution of coal in cement kiln), gasification, and landfilling. While reviewed research analysed substitution of primary fuel in cement kiln as a treatment option, related changes in emissions were neglected. Also, Benavides et al. (2017) analysed fuel production via gasification of non-recycled plastic waste using the GREET model. In this research, the consumption of fossil energy and water is tracked as well as greenhouse gasses production, but only from one technology. Jeswani et al. (2021) compared environmental impacts of households' MPW chemical recycling and energy recovery via pyrolysis using arbitrarily selected midpoint indicators from two different impact assessment methods (Environmental Footprint and ReCiPe). As it can be seen, these publications analyse the treatment/recovery of MPW or (in majority) plastic containing waste streams, but compare them with only arbitrary selected technologies/scenarios or ignore some of the problems connected with modelling of analysed solutions, as well as possible alternative products.

In many cases, simpler and more practical forms of life cycle-based analyses should be used instead of complete, comparative, LCA of systems and technologies (Petrov 2007), which also represent an important mean to overcome prejudice about the complexity of LCA as well as the difficulty in understanding the obtained results by a broader group of people as well as decision-makers. In this context, energy indicators are used in a wide range of activities (Huijbregts et al. 2010; Arvidsson et al. 2012; Scipioni et al. 2013) to identify possible areas for improving production performance or to compare different scenarios during decision-making. Also, Bueno et al. (2015) concluded that "comparisons of alternative systems in terms of direct energy recovery or direct material recovery should be avoided in favour of other indicators already proposed in the LCA framework, such as the CED category from Ecoinvent, or the global warming potential and the Abiotic Resources Depletion categories from the CML 2001 method". This is based on the properties of those methods, which allow comparison of life cycles of very different systems that encompass energy as well as material flows of a very different nature that are not directly comparable nor can be directly substituted with each other.

CED is an energy-based LCA indicator (Rohrlich et al. 2000) that is quantitative and captures all energy flows which affect the overall life cycle (Huijbregts et al. 2006). It is also an intermediary for environmental impact assessment, correlates with more complex single score impact assessment methods (Mert et al. 2017), gives convergent results with other indicators (such as Ecological Footprint, Cumulative Exergy Extraction in the Natural Environment, Climate Footprint, Ecological Scarcity, and Eco-Indicator), and provides a comparable ranking of impacts (Huijbregts et al. 2010). For this reason, CED is used for selecting a more environmentally friendly alternative (Penny et al. 2013), evaluating the results of overall LCA (Röhrlich et al. 2000), constructing economy-sustainability connection of WM systems (Tomić et al. 2022), and represents an appropriate decision-making tool (Giugliano et al. 2011). Thus, in WM analyses CED was used for sustainability analysis of energy recovery of waste through energy return indicator (Tomić and Schnieder 2017), comparison of municipal WM systems in two towns (Kaufman et al. 2010), and was reported next to CML 2001 results for comparison of different WM practices (Giugliano et al. 2011). Very few publications used CED as an indicator in plastic waste recovery sustainability assessments (Antelava et al. 2019), and only three more recent publications in this field are found—CED results were reported next to Carbon and Water Footprints for energy and environmental assessment of material recovery of greenhouse covering films (Cascone et al. 2020), as well as next to ReCiPe results for the analysis of recycling and incineration of waste PLA (Maga et al. 2019) and for environmental assessment of chemical recycling of carbon fibre thermosets for production of carbon fibre thermoplastic composites (La Rosa et al. 2021). Thus, it can be seen that there is a lack of publications that use CED, as a proven decision-making tool, in MPW management/recovery assessments. This research gap has also been addressed through the presented research.

As it can be seen, while many studies analysed energy recovery of plastic waste from the life cycle perspective, there is a lack of recent studies which are not focused on the specific type of polymers and analyse MPW, especially from an energy recovery perspective. This is even more pronounced from decision-making point of view where a clear lack of comparisons of all applicable technologies can be seen. Also, no previous study has been found to take into account legislative goals in the analysis of the sustainability of the plastic waste recovery, and the majority of reviewed studies report results on all impact category indicators within selected impact assessment method, or on only arbitrary selected ones, without any importance assessments or applicable reasoning. It is important to emphasize these research gaps as EC recognized LCA as a tool that could be used for the elaboration of non-compliance with legislative determinants and thus could be also used as a tool for guiding the changes within the EU legislation. Thus, this research makes a step forward in closing the identified research gaps by conducting LCA-based comparison of alternative thermochemical recovery technologies, taking into account different marketable products that can be produced, and other commonly used technologies for recovery and disposal of MPW through impact indicators which results can be directly connected with specific EU goals in the field of sustainable development. This is done to re-examine the actual industry's views, plastics strategy, and existing stances towards the alternative technologies for thermochemical recovery of plastic waste, thereby substantiating possible changes in the classification of particular technologies within the WM hierarchy, best available techniques reference document for waste incineration, and broader EU waste legislation. Results of this analysis can provide a levelized assessment of environmental and resource sustainability for dedicated and not-dedicated technologies for MPW recovery in the areas which are emphasized as the most important by EU legislation and previously published research, and can give an answer to the following research question: can alternative thermochemical conversion technologies be better option regarding MPW recovery in the overall sustainable and circular economy oriented development. Based on provided answers, current views on individual thermochemical recovery technologies may be re-examined.

Methods

This research is comparing the environmental impacts of the two most recognized alternative technologies for thermochemical conversion of mixed polymer waste, i.e. gasification and pyrolysis, with the most commonly used energy recovery and disposal technologies. The results of this research do not include a comparison with material recovery/recycling technologies because this research puts focus on mixed polymer wastes treatment and does not want to question the position of recycling in the waste hierarchy.

Goal and scope definition

The goal of this research is to use LCA as a legislatively recognized tool to assess the environmental sustainability of differentiation of waste recovery technologies which are by EU legislation classified in the same category, i.e. thermal treatment technologies. Even though the results of this analysis are used to question a part of the EU legislative framework, to reduce the level of aggregation and number of assumptions due to geographical variability, case studies are developed on the basis of the capital city of the newest EU member state (City of Zagreb, Croatia). Croatia became an EU member in 2013, and, since then, implemented many changes in its legislature as well in the WM system to meet EU goals (Luttenberger 2020). Today, the majority of municipal plastic waste is collected as a part of separate packaging waste collection system (Fig. 1). Packaging waste composition is analysed based on 12 samples collected during one day in October of 2019 from different trucks which have collected packaging waste from different parts of the town. Around 120 kg of sampled waste was then homogenized and quartered until the final sample of 7.4 kg was obtained for separation and composition analysis. Separation and composition analysis is done by manual separation using Resin Identification Code (RIC) system labels, through examination of material properties (physical properties, melting range, flame tests, and gravity tests).

LCI datasets, that describe analysed WM technologies, are modelled to represent average technology data for corresponding plants for the treatment of one tonne of collected mixed packaging waste of similar properties as one collected in the City of Zagreb, while background processes are modelled through local market activities as described in Ecoinvent database.

LCA is designed per ISO 14044 standard as cradle-to-grave analysis, and ecomaps all activities needed for treatment of generated plastic waste which is separately collected, starting from its generation through collection/transport, pretreatment (i.e. separation, drying, and shredding), and final treatment, which is important to reassess the classification of particular thermochemical recovery technologies from an environmental sustainability standpoint. Due to emphasis on the comparison of technologies for recovery of MPW fraction, analysed systems are made only of essential components to implement analysed technologies so that their influence on results is minimal, and one tonne of collected waste is used as a functional unit. Thus, only separately collected waste recovery is looked upon and connection to local mixed MSW management system is not modelled.

Analysed systems and boundaries of the systems

Seven different treatment technologies for MPW were analysed and compared—gasification with electricity and ethanol production (a), pyrolysis with emphasis put on oil production (b), incineration with electricity and combined heat and power (CHP) production (c), thermal treatment via co-incineration in the cement kiln (d), and landfilling (e). System boundaries encompass main treatment technologies, collection, and pre-treatment if needed—Fig. 2.

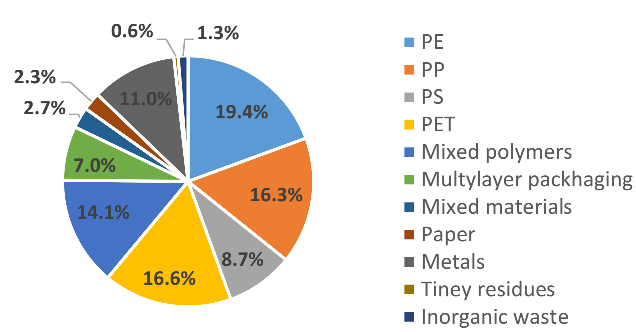


Fig. 1 Composition of separately collected packaging waste in the City of Zagreb

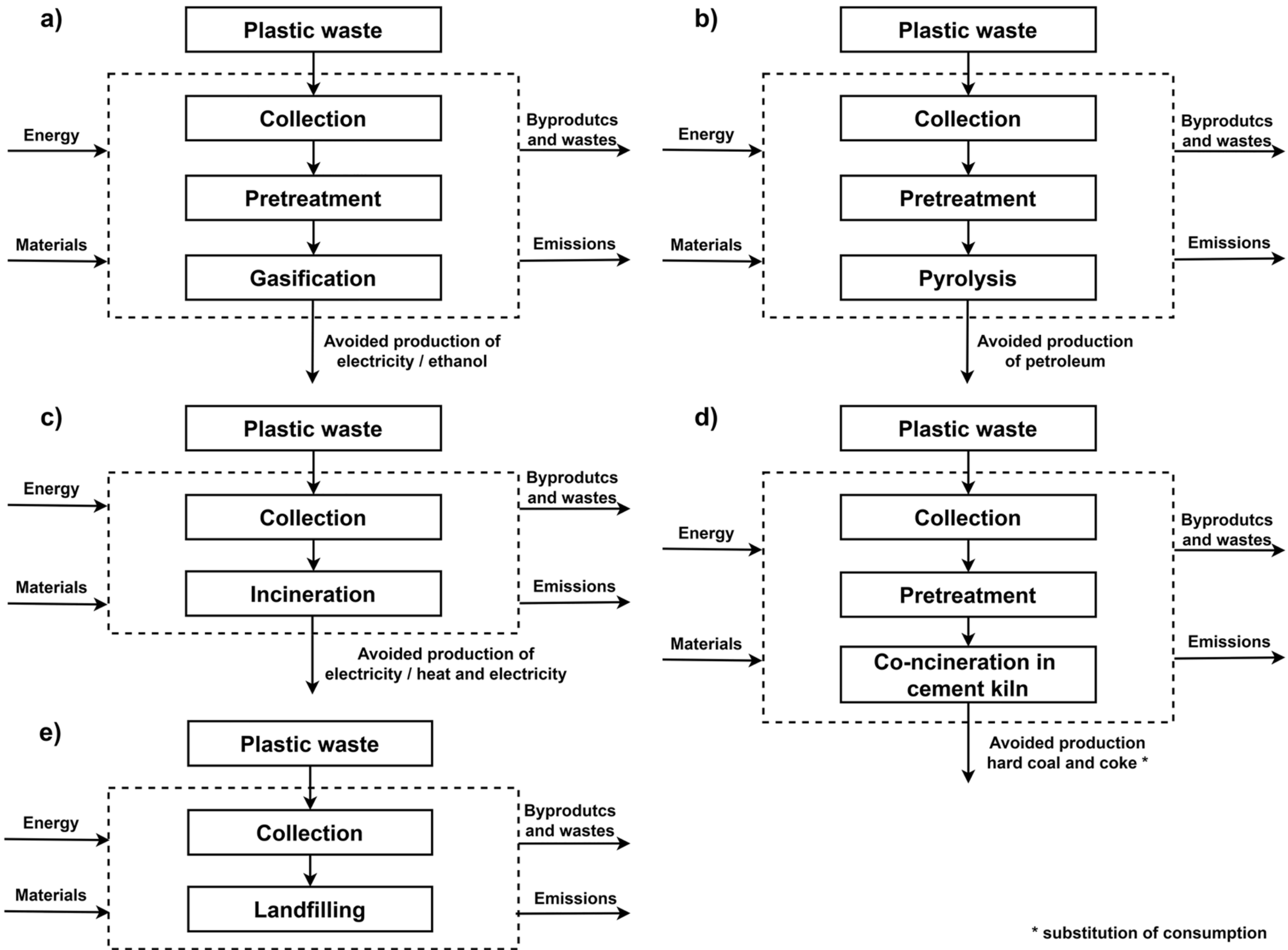


Fig. 2 Boundaries of the analysed systems

Thus, LCA of gasification and pyrolysis encompasses the waste collection, sorting, drying, and shredding of MPW before the main recovery technology. Commonly used technologies such as incineration and disposal usually treat MPW together with other types of wastes (i.e. as it is collected) and pretreatment is not needed, or it is a part of the final treatment plant, as in the case of incineration where separation of metals is done in incineration facility. Regarding co-incineration in cement kiln, because these kinds of plants have strict requirements regarding quality and composition, the collected waste is also sorted, dried, and shredded before use. Gasification can be also used for the treatment of mixed waste, but in this case, this treatment option will not be analysed.

LCA system modelling and uncertainty analysis is done using OpenLCA 1.8.0. software with Ecoinvent 3.5 LCI database where datasets are used for modelling background processes and markets. For final data analysis and presentation of results, Microsoft Excel is used.

Life cycle inventory (LCI)

Ecoinvent datasets ecomap all known input–output data as data providers allow; thus, it does not incorporate quantitative cut-off criteria (Weidema et al. 2013). To enable consistency, this approach is also applied when using literature data for the creation of inventory datasets; thus, this analysis does not have defined quantitative cut-off criteria. Regarding the possible problems which can arise with using different data sources for technology modelling (Suh et al. 2016), while some of them are avoided by incorporation of all known data in LCI datasets, others are addressed by adaptation to local conditions and matching flows with corresponding local market activities in the Ecoinvent database. Through this, and through averaging of collected datasets, possible problems connected with the use of location-dependent data from different sources, have been also addressed.

Used Ecoinvent database represents one of the biggest commercial LCI databases, and includes average datasets for all common WM technologies like MPW incineration and waste disposal, but it does not recognize not-so-widely implemented thermochemical conversion technologies like gasification or pyrolysis. To model those technologies, input–output data for plastic waste gasification and pyrolysis technologies are sourced from an extensive literature review, and data for 43 different plants are shown in Tables A1, A2, A3, and A4 in Appendix. To model the average technology life cycle inventory (LCI) (input–output) dataset, all available data for analysed technology are gathered and final datasets are modelled using average values of significant flows for the same type of technologies.

While basic pyrolysis processes produce pyrolytic oil, synthetic gas, and char, some of the plants from the technology review have in-house post-processing in a form of fractional distillation for the production of different fuels—Tables A1 and A2. To circumvent these differences, final LCI datasets modelled pyrolysis without any post-processing, and, to simplify modelling and analysis, produced pyrolytic oil has been marketed as petroleum (oil) due to similar properties and use options. As it can be seen from the gasification technology review results (Tables A3 and A4), it is a most common practice to use produced synthetic gas, which is the main product of the plant, to locally generate electricity. The second most common transformation of synthetic gas is its use for ethanol production which is modelled by (Haig et al. 2013).

Based on literature review data and previous elaborations, average technology LCI datasets for thermic gasification of plastic waste in fluidized bed reactor with electricity generation and catalytic pyrolysis with pyrolytic oil production are modelled (Tables 1 and 2), and the differential dataset for ethanol production, which shows the difference between gasification with electricity production LCI dataset and the ethanol producing one, is presented in Table 3.

As presented LCI datasets are based on datasets that cover input–output flows of tens of actual plants, it was possible to calculate confidence intervals for the inventory data. As specific input–output data cannot be negative, for probabilistic design lognormal distribution is assumed and the geometric standard deviation is calculated as a measure of dispersion analogously to the geometric mean of the corresponding technology data reported in the Appendix.

LCI dataset for pre-treatment is also adapted from the literature (Arena et al. 2003) (Table 4), while the waste collection is modelled based on collection and transport service data (Spielmann et al. 2007) and Ecoinvent data for waste collection with a 21-ton lorry (Table 5).

As in most cases, plastic waste is incinerated in grate incinerators together with MSW or as unrecyclable plastic waste or refuse-derived fuel (RDF). Because of that, incineration technology is modelled as incineration of MPW in an average MSW grate incinerator with an electrostatic precipitator based on the existing Ecoinvent LCI unit process (UPR) dataset, and the production of heat and electricity has been adapted through a review of data on existing waste incinerators (ISWA 2017; Tomić et al. 2016). Landfilling of plastic waste is modelled as regulated MSW landfill, as plastic waste is landfilled as a part of the MSW stream, and average (representative) technology is modelled based on data from the used LCI database data.

Cement kilns are also used for the final treatment of many types of burnable wastes that meet certain requirements (Rahman et al. 2013). This makes sense because the replacement of primary fuel enables savings of up to 50 €/t (EcoMondis 2018). In available LCI datasets, a cement kiln is defined as a facility whose main fuels are hard coal and petroleum coke, and its substitution with MPW needs to be modelled. To do this, changes in direct emissions due to co-incineration of MPW are modelled on the basis of stoichiometric calculations and laboratory data (Asamany et al. 2017). These data are obtained from the analysis of changes in emissions of NO_x, CO_2, H_2O, SO_2, volatile organic compounds (VOC), particulate matter (PM) < 2.5 μm, PM > 2.5 μm, and ash production, due to the substitution of coal/coke fuel (1:1 mixture of coal and petroleum coke by mass) with plastic waste materials—plastic containers, films, expanded polystyrene (EPS), Construction and Demolition (C&D) sourced plastics and textiles. It is found that coal/coke substitution with plastic waste, based on the same energy input, can reduce emissions of NO_x by up to 79%, CO_2 by up to 34%, SO_2 by up to 99%, PM < 2.5 μm by up to 14%, PM > 2.5 μm by up to 77%, and increase H2O emissions in air by 194%. Even though VOC emissions are also analysed, because there were no comparative results for the substituted fuel obtained in the same laboratory conditions, these results are not taken into account. Changes in all other emissions and their confidence intervals are also not taken into account. Based on these calculations, the Ecoinvent clinker production dataset is adapted to correspond to 20% of coal/coke fuel mixture substitution by plastic waste mixture, while substitution of emissions is done by supplied energy equivalent. The derived LCI dataset is shown in Table 6.

The inputs and outputs of the respective technologies are connected with the outputs of other activities from the used database and in a majority of cases market activities (i.e. with LCI datasets for local market activities for particular materials, energy vectors, and/or services). Market activities datasets represent a market mix of all activities with the same reference product in a particular area and include the impacts of all the activities that precede the use of an individual product in a specific location (including production, transportation, processing, and transformation), thus representing the average market data for the particular geographic area.

Table 1 LCI dataset for gasification with electricity production

		Flow	Unit	Value	σ_g
Input	Input*	Waste plastic, mixture	t	1.000	1.000
	Energy consumption	Electricity, medium voltage	kWh	524.287	1.620
	Other inputs	Oxygen	kg	1170.461	1.128
		Zeolite, powder	kg	53.500	1.000
		Diesel	l	0.209	1.000
		Sodium hydroxide, without water, in 50% solution state	kg	5.000	1.000
		Activated carbon, granular	kg	0.500	1.011
		Feldspar	l	0.417	1.000
		Heat	kWh	146.377	2.089
		Water, turbine use, unspecified natural origin	l	5591.360	1.969
		Lime, hydrated, loose weight	kg	6.469	1.008
	Additional fuel:	Natural gas, high pressure	kWh	1560.000	1.000
Output	Energy products	Electricity, medium voltage	kWh	1267.587	1.459
		Steam	kg	2210.871	1.876
	Material by-products	Refinery gas	kg	214.000	1.000
		Sulphur	kg	1.500	1.000
		Salt tailing	kg	5.500	1.000
		Ground granulated blast furnace slag	kg	112.000	1.000
	Other:	Char, for disposal	kg	148.660	1.000
		Blast furnace slag	kg	7.942	3.653
		Coal tar	kg	141.500	1.000
		Process-specific burdens, residual material landfill	kg	44.462	2.665
		Waste zeolite	kg	1.695	1.000
		Fly ash and scrubber sludge	kg	92.822	2.131
		Refinery sludge	kg	22.500	1.008
		Process-specific burden, sanitary landfill	kg	6.500	1.000
Output	Emissions in air:	Particulates, > 2.5 um. and < 10um	kg	6.802E-02	3.618
		Particulates, < 2.5 um	kg	3.841E-02	2.425
		Carbon dioxide	kg	1899.1783	2.631
		Methane	kg	0.4725	3.220
		Hydrogen chloride	kg	2.947E-02	2.184
		Sulphur dioxide	kg	1.142E-01	1.657
		Sulphur oxides	kg	1.010E-01	1.028
		Dinitrogen monoxide	kg	9.900E-02	4.052
		Nitrogen oxides	kg	7.154E-02	1.146
		Carbon monoxide	kg	3.975E-01	3.371
		Mercury	kg	9.696E-07	1.738
		Cadmium	kg	4.807E-06	3.557
		Lead	kg	1.607E-03	4.559
		VOC, volatile organic compounds	kg	2.350E-01	4.457
		Hazardous Air Pollutants (HAPs), unspecified	kg	5.000E-02	1.000
		Ammonia	kg	3.350E-05	1.039
		Dioxins and furans, unspecified	kg	5.981E-12	1.299
		Acetaldehyde	kg	0.030	1.000

Table 1 (continued)

	Flow	Unit	Value	σ_g
	NMVOC, Non-methane volatile organic compounds	kg	0.100	1.000
	Antimony	kg	6.562E-04	4.023
	Arsenic	kg	9.594E-07	1.390
	Titanium	kg	2.591E-06	1.270
	Chromium	kg	5.412E-04	2.608
	Iron	kg	2.514E-03	1.876
	Copper	kg	3.322E-03	2.985
	Zinc	kg	6.250E-05	1.000
Emissions in water:	Wastewater	kg	6077.150	2.578

Table 2 LCI dataset for pyrolysis

		Flow	Unit	Value	σ_g
Input	Input*	Waste plastic, mixture	t	1.000	1.000
	Energy consumption:	Electricity, medium voltage	kWh	283.215	3.554
	Other:	Zeolite, powder	kg	21.346	2.258
		Water, turbine use, unspecified natural origin	l	1587.770	3.847
	Additional fuel:	Natural gas, high pressure	MWh	0.431	2.050
Output	Energy products:	Synthetic gas	MWh	0.065	1.000
		Pyrolytic oil	kg	708.653	1.140
		Pyrolytic gas	kg	142.608	1.523
	Other:	Char, for disposal	kg	77.805	1.351
		Process-specific burdens, residual material landfill	kg	128.117	1.602
		Waste zeolite	kg	15.050	2.175
		Process-specific burden, sanitary landfill	kg	15.627	3.544
		Hazardous waste, for incineration	kg	23.000	2.470
		Wastewater, average	l	613.754	4.797
	Emissions in air:	Particulates, > 2.5 um, and < 10um	kg	0.078	3.742
		Carbon dioxide	kg	401.445	1.328
		Hydrogen chloride	kg	1.500E-04	1.000
		Hydrocarbons, unspecified	kg	2.058	1.452
		Sulphur dioxide	kg	0.045	4.129
		Dinitrogen monoxide	kg	0.459	1.563
		Nitrogen oxides	kg	0.583	3.144
		Carbon monoxide	kg	0.482	2.013
		Mercury	kg	1.764E-11	1.000
		Lead	kg	5.050E-03	2.595
		VOC, volatile organic compounds	kg	0.273	4.747
		Ammonia	kg	5.500E-03	1.138

Life cycle impact assessment (LCIA).

However, this research wants to assess the compatibility of analysed technologies with EU legislation goals and challenge the current classification of energy recovery technologies. Because of it, the choice of LCIA indicators is steered by findings of an overview of actual legislation frameworks

Table 3 Gasification with ethanol production—Differential LCI dataset

		Flow	Unit	Value	σ_g
Input	Other inputs	Water, turbine use, unspecified natural origin	kg	+ 5322.000	1.969
	Energy consumption	Heat	kWh	+ 800.000	2.089
Output	Production	Ethanol	kg	584.000	1.667
		Reactor off-gas	kWh	1900.000	1.000
		Electricity medium voltage	kWh	- 1454.760	1.620
	Other	Wastewater, average	kg	+ 5195.000	2.578

Table 4 LCI dataset for waste pre-treatment

		Flow	Unit	Value	σ_g
Input	Input*	Waste plastic mixture, unsorted, from collection service	t	1.730	1.000
	Energy consumption	Diesel	kg	1.4E-3	1.105
		Electricity, medium voltage	kWh	0.284	3.554
Output	Output	Plastic waste mixture, sorted	kg	1.29	1.000
	Residues	Municipal solid waste	kg	0.435	1.000

Table 5 LCI dataset for collection

		Flow	Unit	Value	σ_g
Input	Energy consumption	Diesel	kg	0.336	1.105
	Other inputs	Road	m·a	0.00064	1.000
		Waste collection lorry, 21 metric ton	items	4.520E-7	1.000
Output	Product*	Municipal waste collection service by 21 metric ton lorry	t·km	1	1.000
	Emissions in air	Ammonia	kg	7.95E-6	1.221
		Benzene	kg	6.77E-5	1.221
		Cadmium	kg	4.480E-09	2.253
		Carbon dioxide, fossil	kg	1.060	1.000
		Carbon monoxide, fossil	kg	2.730E-3	2.239
		Chromium	kg	1.690E-08	2.253
		Copper	kg	5.710E-7	2.253
		Dinitrogen monoxide	kg	5.250E-5	1.221
		Lead	kg	4.870E-09	2.253
		Methane, fossil	kg	8.460E-5	1.221
		Nickel	kg	2.350E-08	2.253
		Nitrogen oxides	kg	7.58E-3	1.221
		NMVOC, non-methane volatile organic compounds	kg	3.450E-3	2.253
		Particulates, < 2.5 um	kg	6.150E-4	1.221
		Particulates, > 10 um	kg	1.750E-4	1.221
		Particulates, > 2.5 um, and < 10um	kg	1.050E-4	1.414
		Selenium	kg	3.360E-09	2.253
		Sulphur dioxide	kg	2.020E-4	1.000
		Toluene	kg	2.710E-5	1.221
		Xylene	kg	2.710E-5	1.221
		Zinc	kg	3.330E-6	2.253

Table 6 LCI dataset for clinker production with co-incineration of MPW

		Flow	Unit	Value	σ_g
Input	Input*	Waste plastic, mixture	kg	0.00597015	1.000
	Energy consumption	Hard coal	kg	53.500	1.105
		Heavy fuel oil	kg	0.209	1.105
		Light fuel oil	kg	5.000	1.105
		Petroleum coke	kg	0.417	1.105
	Other inputs	Ammonia, liquid	kg	0.000908	1.105
		Bauxite	kg	0.00012	1.105
		Calcareous marl	kg	0.466	1.105
		Clay	kg	0.331	1.105
		Industrial machine, heavy, unspecified	kg	0.0000376	1.105
		Lime	kg	0.841	1.105
		Lime, hydrated, loose weight	kg	0.00392	1.105
		Lubricating oil	kg	0.0000471	1.105
		Meat and bone meal	kg	0.00961	1.105
		Refractory, basic, packed	kg	0.00019	1.105
		Refractory, fireclay, packed	kg	0.0000821	1.105
		Refractory, high aluminium oxide, packed	kg	0.000137	1.105
		Sand	kg	0.00926	1.105
		Steel, chromium steel 18/8, hot rolled	kg	0.0000586	1.105
		Tap water	kg	0.34	1.105
		Water, unspecified natural origin	m3	0.00162	1.105
	Additional fuel:	Diesel	MJ	524.287	1.105
		Electricity, medium voltage	kWh	1170.461	1.105
		Natural gas, high pressure	m^3	0.500	1.105
Output	Products:	Clinker	kg	1.00	1.000
	Other outputs:	Inert waste, for final disposal	kg	0.00008	1.105
		Municipal solid waste	kg	0.000045	1.105
Output	Emissions in air:	Ammonia	kg	0.0000228	1.105
		Antimony	kg	0.000000002	1.105
		Arsenic	kg	0.000000012	1.251
		Beryllium	kg	0.000000003	1.251
		Cadmium	kg	0.000000007	1.251
		Carbon dioxide, fossil	kg	0.829509391	1.105
		Carbon dioxide, non-fossil	kg	0.014929192	1.105
		Carbon monoxide, fossil	kg	0.000472	1.105
		Chromium	kg	1.45E-09	1.251
		Chromium VI	kg	5.5E-10	1.251
		Cobalt	kg	0.000000004	1.251
		Copper	kg	0.000000014	1.251
		Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	9.6E-13	1.105
		Hydrogen chloride	kg	0.00000631	1.251
		Lead	kg	0.000000085	1.253
		Mercury	kg	0.000000033	1.251
		Methane, fossil	kg	0.00000888	1.105
		Nickel	kg	0.000000005	1.251
		Nitrogen oxides	kg	0.001003442	1.105
		NMVOC, non-methane volatile organic compounds	kg	0.0000564	1.105

Table 6 (continued)

	Flow	Unit	Value	σ_g
	Particulates, < 2.5 um	kg	2.44245E-05	1.105
	Particulates, > 10 um	kg	6.07498E-06	1.251
	Particulates, > 2.5 um, and < 10um	kg	8.50067E-06	1.434
	Selenium	kg	0.000000002	1.253
	Sulphur dioxide	kg	0.000328563	1.105
	Thallium	kg	0.000000013	1.251
	Tin	kg	0.000000009	1.253
	Vanadium	kg	0.000000005	1.251
	Water	m^3	0.000300629	1.105
	Zinc	kg	0.00000006	1.251
Emissions in water:	Wastewater	m^3	0.001666	1.221

regarding WM but also regarding the sustainable development of the entire European economy, as well as findings gathered through literature review in the field of WM and recovery (analyses, comparisons, and decision-making), which are provided as a part of the Introduction section. EC emphasized the importance of assessments on the level of the whole life cycle, especially LCA. Because of this, in this research, the CML baseline 2001 problem-oriented impact assessment characterization method is used for conducting overall LCA, which belongs to a group of problem-oriented approaches (mid-point categories) that are used for environmental and human impact assessments (Aryan et al. 2019).

As can be seen from the legislative review, one of the main EU problems is resource scarcity (material and energy), which also encompasses waste recovery, and impact on climate change. Due to this, this research takes into account three CML mid-point category indicators—global warming potential (GWP (expressed in kg CO_{2eq})), abiotic resource depletion (ARD (in kg Sbeq)), and acidification potential (AP (in kg SO_{2eq})). The first two indicators are chosen as they cover emissions of greenhouse gasses and depletion of a wide range of earth resources which is directly connected to EU legislation frameworks. While the World Health Organisation (WHO) emphasizes the positive impacts of the circular economy on GHG emissions, it also comments on the positive influence on air pollution (WHO 2018). Also, in previous publications, the importance of reduction of air pollution in the context of not only EU legislation aiming at improving environmental sustainability and at carbon neutrality, but also international agreements such as the Sustainable Development Goals, Kyoto Protocol, and Paris Climate Agreement is clearly identified (Torkayesh et al. 2021). Thus, the last tracked indicator covers the emission of air pollutants.

GWP accounts for GHG emissions with a time horizon of 100 years, to account for different release times. It tracks emissions of CO_2 from fossil sources only and does not account for biogenic emissions. ARD assesses the extraction of metals, minerals, and fossil fuels considering their depletion rate and reserves. AP covers emissions of compounds with acidification potential—NO_x, SO_x, and ammonia which are considered the main air pollutants by the National Emissions Ceilings (NEC) Directive (2016/2284/EU).

Previous research identified that comparisons of alternative systems in terms of direct energy or material recovery should be avoided in favour of indicators such as CED from Ecoinvent or GWP and ARD from the CML 2001 method (Bueno et al. 2015). Also, CED has been identified as a suitable sustainability indicator for decision-making in WM systems (Röhrlich et al. 2000). Because of that, next to CML 2001 category indicators, this analysis also tracks energy flows (consumption and production) and reports on associated impacts through CED results.

To assess the combined influence of all input uncertainties and a degree of possible deviations of results, especially for modelled pyrolysis and gasification technology results, uncertainty propagations and quantifications, using reported confidence intervals, are reported. For this Monte Carlo approach is used, as the most popular approach for obtaining uncertainty analysis results as a part of LCA (Lloyd and Ries 2007). Normalization and weighting are per ISO standards defined as optional elements of LCA and were not performed as a part of this analysis due to the uncertainties which are associated with the normalization factors calculations (Heijungs et al. 2007; Hung and Ma 2009) as well as because the associated loss of transparency (Reap et al. 2008).

Results and discussion

Based on described methods, environmental impact results are calculated using OpenLCA 1.8.0. program—Figs. 3, 4 and 5. The allocation of impacts and benefits of production of secondary material and energy flows (multifunctionality consideration) was performed using the system expansion method and production was valued through the avoided consumption of primary products/resources. In interpreting the results, a negative value indicates the positive effect, and a higher positive value represents the greater adverse impact.

The worst GWP results can be seen for incineration-based scenarios and pyrolysis shows the best results, a similar situation is in the case of ARD with a difference of gasification with electricity production which here show worse results than incineration, and on the other hand, incineration with electricity production shows the best results regarding AP while all other dedicated waste treatment technologies lag at least 20% behind it, and pyrolysis shows the lowest positive impact regarding AP. Co-combustion of MPW in cement kiln shows overall the best results, being second only to pyrolysis regarding ARD. The last scenario used for comparison, landfilling, shows a relatively small negative impact across all impact analyses which is due to landfilling of inert material and the majority of the impacts come from energy and material consumption which are not offset by any production.

To validate results and compare uncertainties within newly modelled LCI datasets the Monte Carlo Analysis is performed which is a sampling-based uncertainty quantifying method, where, to estimate the uncertainty (i.e. probability distribution of the specific result) the calculation needs to be repeated a number of times (Helton et al. 2006). An obtained probability distribution can be then used for informing decision-makers on characteristics/probability of obtaining reported results through statistical data. There is no clear argument on a number of Monte Carlo runs needed for effective uncertainty analysis, and literature data suggest from 100 iterations (BIPM 2008) over 2000 (Hongxiang and Wei 2013) to over 10,000 (Xin 2006). Thus, in this analysis, Monte Carlo analysis of 10,000 runs is done and statistical analysis is performed on obtained distributions.

Fig. 3 GWP results in kg $CO2_{eq}$

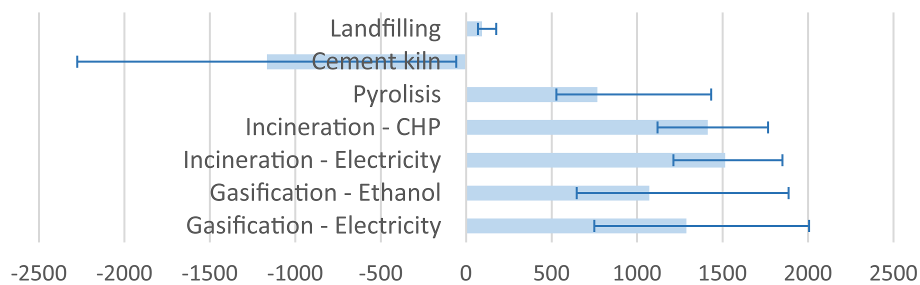


Fig. 4 AP results in kg $SO2_{eq}$

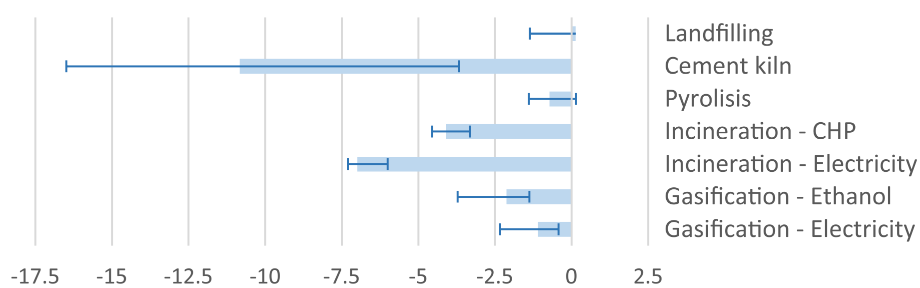
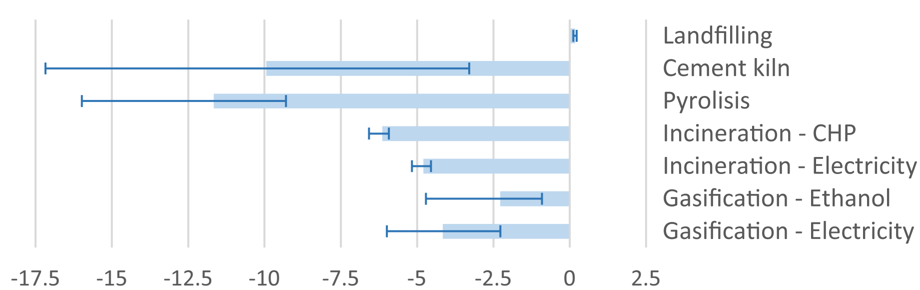


Fig. 5 ARD results in kg Sb_{eq}



Following obtained statistical analysis results, 5% Percentile and 95% Percentile results are denoted by corresponding error lines (Figs. 3, 4 and 5) to depict the quality of assessment and compare uncertainties. It can be seen that the smallest deviations are obtained for landfill and incineration-based technologies, which can be expected as these LCI datasets are based on Ecoinvent data. Possible errors in results for pyrolysis and gasification-based scenarios are double on average when compared to incineration-based scenarios, and the biggest possible errors can be expected with waste treatment in cement kiln due to the biggest dataset needed to model this technology. Overall, even though some scenarios show much bigger dissipation of results, there is a small chance that it can affect previously drown conclusions and rankings.

To analyse the main drivers of these results, the contribution of dedicated technologies and markets are shown in Figs. 6, 7 and 8. To make diagrams more readable, only the six most significant impacts are shown. Here, the greatest overall greenhouse gasses (GHG) emissions are associated with the incineration of MPW with electricity production, followed by incineration with CHP production. This is expected due to direct GHG emissions, which represent the biggest impact, and are only partially offset by energy production. Indirect emissions impacts are at least two orders of magnitude smaller. Gasification-based technologies show better results than incineration-based ones mainly due almost 40% smaller direct emissions. Other significant emissions come from catalyst use and heat consumption. These emissions are partially offset through electricity, steam, and ethanol productions. Pyrolysis has the best results among

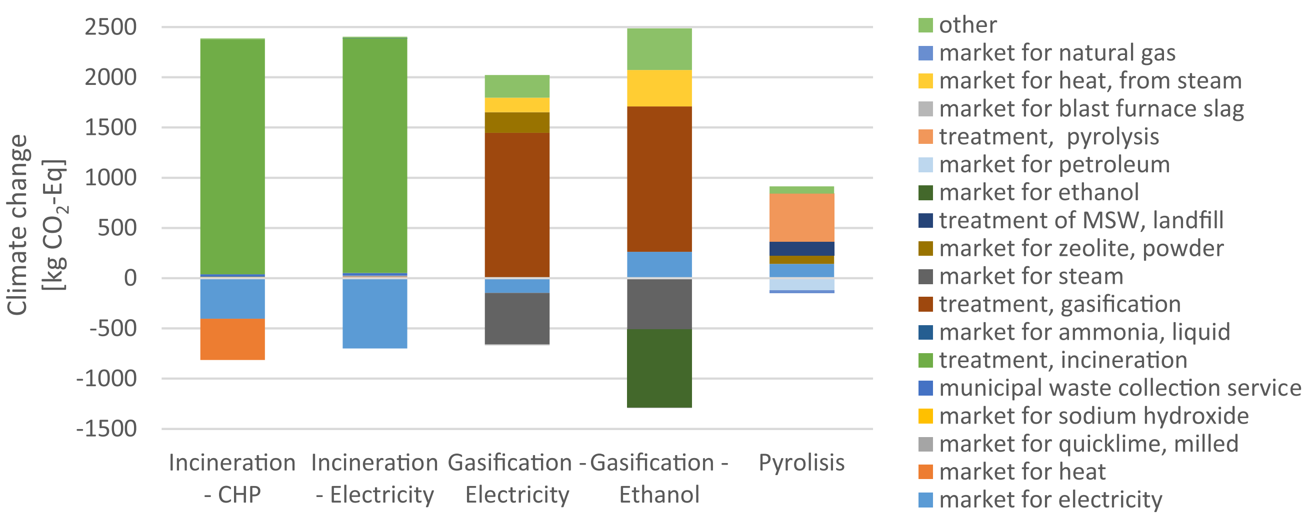


Fig. 6 Climate change—the main contributors

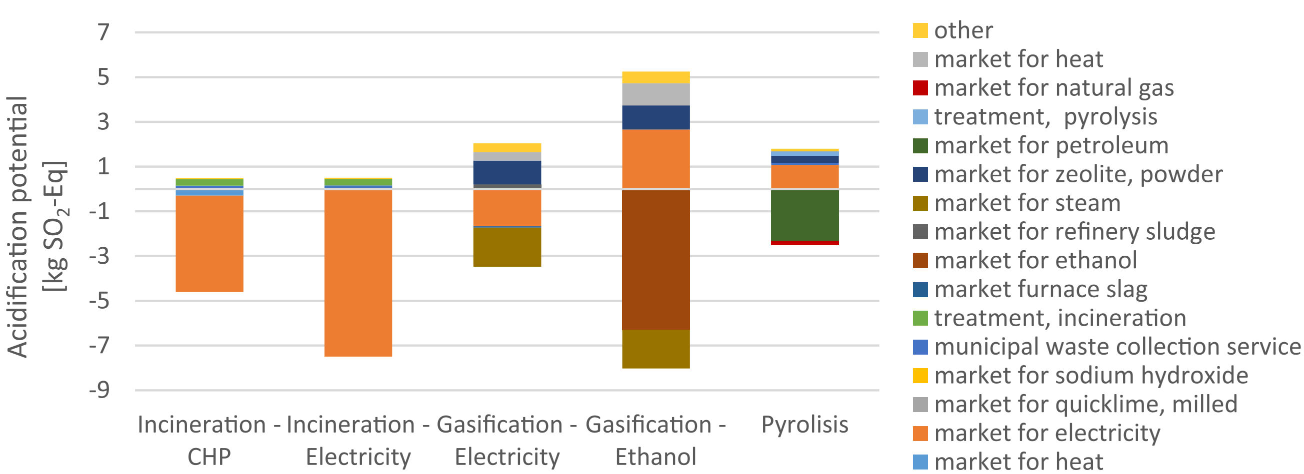


Fig. 7 Acidification potential—the main contributors

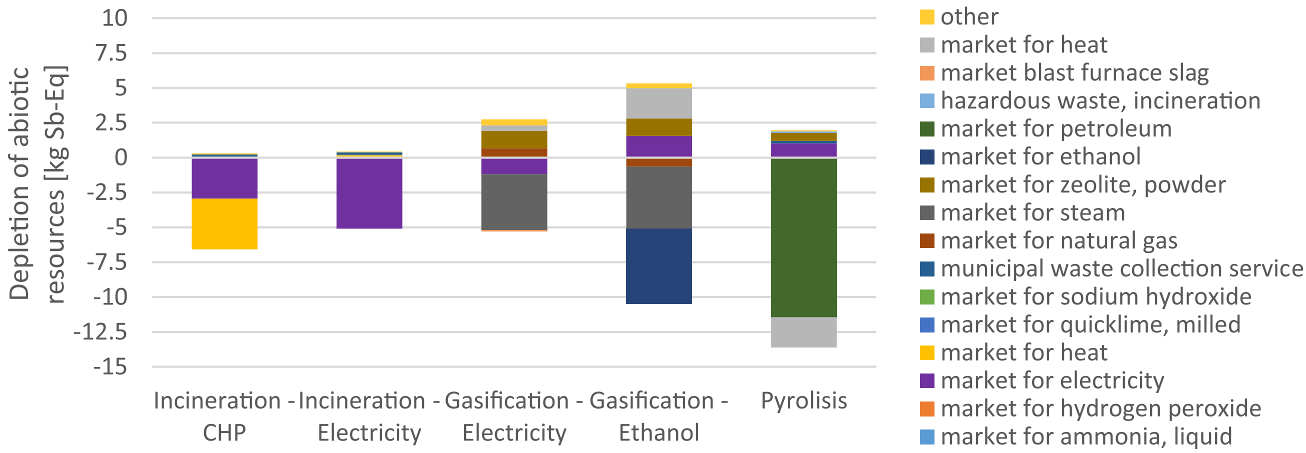


Fig. 8 Abiotic depletion—the main contributors

all recovery technologies due to the smallest direct emissions which are then partially offset with production, mainly pyrolysis oil (which can replace petroleum in refineries). On the other hand, in the case of co-combustion in cement kiln which results are not presented in diagrams because values of influences by each contributor (technology/market) are not in the same order of magnitude as in other scenarios, the majority of GHG emissions are direct emissions, and the majority of emission savings comes from coal and coke substitution. Other impacts are just a few percent and come from the consumption of other inputs needed for clinker production.

Regarding AP, the smallest positive impact of dedicated recovery technologies is recorded for pyrolysis, as negative impacts associated mainly with electricity consumption and catalyst use are marginally smaller than petroleum substitution-connected impacts. For gasification with electricity production, the biggest negative AP impact is from catalyst consumption, followed by energy consumption and disposal of waste products. Gasification direct emissions contribute only to 10% of emissions compared to catalyst consumption. Regarding positive influence, the situation is similar to the case of GWP where ethanol production has a bigger influence than electricity production. Incineration with electricity production shows the best results due to the local electricity mix which has a bigger AP than heat from district heating. On the other hand, due to modern flue gas filtration, direct emissions of waste incinerators are only 2.4 times bigger than those of waste collection services. In the treatment of MPW in cement kiln, there are similar results on the positive side, where clinker produced with alternative fuel in mix offset all acidification-related emissions, but on the negative side, acidification contribution is more dispersed. Thus, around 60% of emissions are direct emissions, while the rest are distributed evenly across heavy fuel oil, electricity, hard coal, and lime consumptions.

Pyrolysis shows the best ARD results that are directly connected to the production of pyrolysis oil which is valuated as petroleum substitution and more than makes up for abiotic depletion due to electricity and catalyst consumption. In the case of gasification with ethanol production, ethanol and steam market substitution are two main positive contributors, while negative contributors are catalyst use, electricity, and heat consumption. In the case of electricity production, results are worse due to four times lower positive influence than ethanol substitution on market, regardless of smaller energy requirements on the input side. Regarding incineration, the only significant overall impact on ARD result is due to energy substitution on respective markets, while all other impacts are at least one order of magnitude smaller. The cement kiln shows similar results as before on the impact reducing side, while the main contributors to resource consumption are fuel and energy consumption (coal, fuel oil, and electricity).

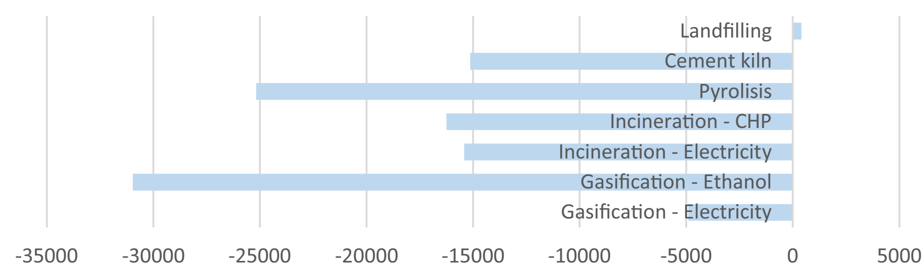
As can be seen, AP shows different results compared to the other two impact categories. This is mainly due substitution of electricity with the average local energy mix which leads to bigger acidification impact reduction but also increases burdens associated with non-electricity producing technologies. Also, a relatively big acidification impact is associated with catalyst consumption. Direct impacts have a minor impact here, which cannot be said for the GWP category where direct emissions generally have the biggest impact. On the other hand, the ARD impact category only accounts for material and energy consumption. ARD factor is based on the state of resources, their reserves, and exploitation rate, and is expressed in the form of equivalent of reference resource depletion—antimony depletion. In this form, this characterization factor accounts for material depletion and does not include consumption of resources which overall reserves cannot be estimated, thus neither is renewable energy accounted for.

Overall results show that incineration, when compared to technologies that produce semi-products (ethanol or petroleum), shows substantially worse overall results when all impact categories are looked upon. Deviation of this conclusion can be seen in the case of AP where incineration with electricity production shows the best results. Climate change results are the most influenced by direct emissions, because cracking of hydrocarbons leads to GHG emissions, and avoided emissions cannot compensate because there are more efficient ways for the production of these products. The worse situation is with incineration because complete combustion leads to the biggest emissions on the one side and avoided emissions from electricity or heat production are low because these energy vectors can be produced from many energy sources including renewable ones. Pyrolysis shows one of the best results, mainly because it has the smallest direct emissions due to the production of the heavier main product. At the same time, the only technology with a negative climate change impact is the cement kiln, mainly due to the type of fuel it substitutes, and reduced CO2 emissions with its substitution. AP results show opposite results regarding incineration mainly due to efficient flue gas filtration/scrubbing, while avoided impacts are energy mix dependent. Other thermochemical transformation technologies have significant negative impacts due to catalyst use and electricity consumption which pushes even the technology with the largest avoided impacts (gasification with ethanol production) to a third place. Similar results regarding negative impacts can be also seen in the case of ARD but final results differ due to avoided production associated impacts, where the biggest ones are due to ethanol and pyrolysis oil/petroleum production. The market placement of other gasification and pyrolysis products also leads to substantial positive environmental impacts.

Another used LCA-based approach is CED assessment which accounts for the overall consumption of each analysed chain and displays its contributions in a form of consumed primary energy (PE) equivalent—Fig. 9. Thus, the CED result accounts for the consumption of all materials from nature through the energy used for their extraction. Not only that it looks upon energy use through extraction, but also through reprocessing, transformation, production, recovery, and disposal, thus covering the entire life cycle of products and materials, taking into account renewable, fossil, and nuclear energy consumption. Even though it does not account for direct contributions it is used for the overall environmental sustainability assessment of WM and recovery systems.

Regarding PE, gasification with ethanol production gives the best results, followed by pyrolysis while incineration is lagging. As can be seen, even though the CED approach looks into energy and material consumption, its results differ from ARD results. Why that is can be seen in Fig. 10 which shows the contribution per type of energy source.

Fig. 9 CED results in MJ



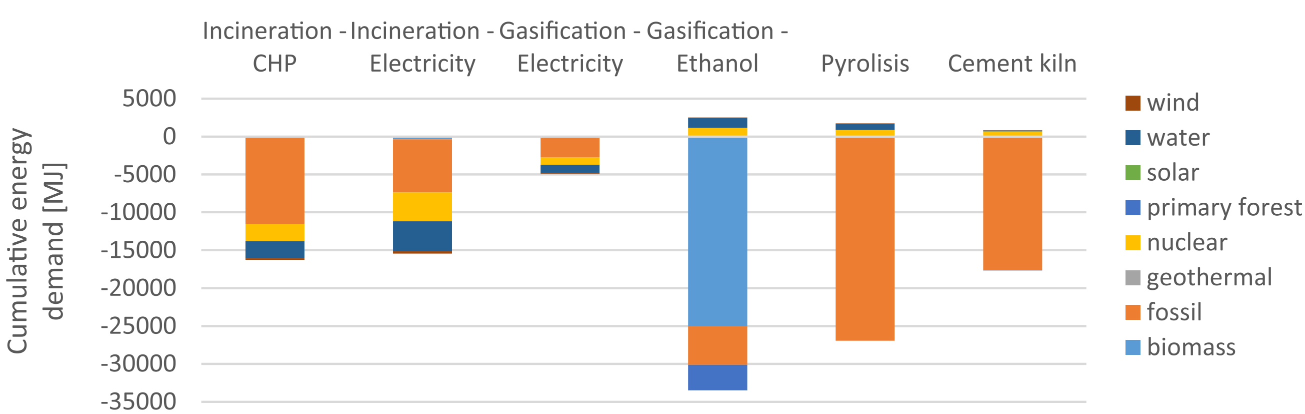


Fig. 10 Cumulative energy demand results per energy source

As it can be seen, 16% of overall PE consumption is covered by renewable energy sources (RES) in the case of incineration with CHP production, 30% in the case of incineration with electricity production, 9% in the case of gasification with electricity production, 3% in the case of pyrolysis production, and 55% in the case of gasification with ethanol production. As ARD, per its definition, take into account resources reserves and exploitation rate, it neglects renewable resources, and thus, does not represent overall resource consumption.

Energy sustainability results calculated through the CED indicator show that gasification with ethanol production has the biggest PE return (avoided impacts) of all analysed recovery technologies, while pyrolysis shows the second-best result. Worst results are achieved by electricity-generating technologies, incineration with electricity production, and gasification with electricity production, due to smaller energy conversion efficiency. The biggest PE return of gasification with ethanol production comes from RES, especially biomass, with over 50% of the overall contribution. In electricity-generating technologies, the majority of renewable energy impacts/benefits are directly dependent on RES share in the electricity mix.

Conclusion

The plastic waste problem is one of the last identified problems by the EU. Even though the EU is tackling this problem through general WM legislation, and in the last years directly through the legislative framework with a goal of reducing plastic waste generation, problems of plastic are also alleviated through the circular economy and other legislative frameworks which tend to increase the efficiency of resource use and increase the sustainability of overall EU economy. In all of this, the main focus was put on material recovery and the legislative framework for energy recovery is not elaborate enough because of which it classifies all thermochemical conversion technologies in the same category as incineration regardless of sustainability results and what the final products are. This is contrary to other waste recovery legislation which classifies anaerobic digestion of bio-waste as material recovery due to one of the products being a compost-like substance, i.e. not having energy only production. Because of this, this research analysed the environmental, resource, and energy intensity of technologies for energy recovery of plastic waste with a goal of reviewing the existing EU legislation technology classification of thermochemical waste recovery technologies. To give appropriate results, EU legislation on sustainable development was reviewed and the most important impact categories from the legislation aspect were used in this analysis, as well as those identified by previous research as the most suitable for WM and recovery system analysis and comparison.

From overall results, it can be concluded that pyrolysis of plastic waste and gasification of plastic waste with ethanol production show better results when climate change potential, abiotic depletion potential, and CED impacts are taken into account. Thus, pyrolysis shows a 49/46% decrease in GHG emissions compared to incineration with electricity/CHP production, and gasification with ethanol production GHG emission results is 29/24% lower, respectively. Differences in abiotic depletion results are also substantial in the case of pyrolysis which shows a 143/90% bigger decrease in abiotic depletion, respectively, while in the case of gasification with ethanol production there is an 8% bigger reduction in comparison with incineration with electricity production, while in comparison with CHP production, a 16% smaller reduction is recorded. Large differences can be also seen in the CED category with a 63/55% bigger increase in primary energy return in the case of pyrolysis and 101/91% in the case of gasification with ethanol production, respectively. The only impact indicator that shows better results in the case of incineration-based scenarios when compared to pyrolysis and gasification is AP. Here, results of gasification with ethanol production are 60/32% worse than from incineration with electricity production/CHP production, respectively, while pyrolysis results are the overall worst. Also, regarding direct emissions, all alternative technologies show better results from incineration, and the difference is generated through indirect emissions/savings.

If gasification with electricity production results is looked upon, they are worse than in the case of ethanol generation, and while it shows around 9 to 15% better results than incineration in GHG emissions, results for abiotic depletion are 14 to 33% worse, and in the case of CED 19 to 20% worse than in the case of incineration. On the other hand, cement kiln CED results show less than half of primary energy recovery than gasification with ethanol production and its result is a little better when compared to pyrolysis, its energy recovery is almost on par with other incineration-based scenarios. In the ARD category, it shows second best results, with the only pyrolysis ahead of it and other technologies' results lagging around 40% and more behind its results. On the other hand, the AP category shows that cement kilns can lead to the largest decrease in acidification-related emissions, and in the case of climate change results, it is the only analysed solution that shows a decrease in GHG emissions. But, when taking into account these results, it should be noted that cement kiln results have the widest spread between 5% Percentile and 95% Percentile results.

Presented results show that the environmental impact of a specific technology is largely dependent on the final products which are placed on the market and thus the sustainability of products it replaces. Thus pyrolysis can be considered largely superior to incineration regarding a large number of EU directives and can help in meeting the goals regarding the establishment of the circular economy, sustainable development, decrease resource use, imports, and climate impacts, as well increase in the security of supply. All of this can also be concluded for gasification with ethanol production, even if ARD results are only, on average, on par with incineration-based technologies. It is because the ARD impact category does not take into account, not depletable resources, such as RES, which are important when conducting sustainability analysis from the legislation point of view. Here, CED impact category proved to be important as it takes into account the consumption of all resources, including RES, and thus complements the results of the ARD impact category. Because of this, it can be concluded that CED is not only the go-to single score impact assessment indicator for benchmarking WM systems, as is concluded in previous research but also an important indicator for sustainability analysis and comparison from the legislation point of view.

The only area where these two technologies are not superior is the air pollution in a form of AP. Even though the reduction of AP-related emissions is larger for incineration-based technologies at this point, these results are strongly linked to the electricity and heat market energy mix and with increased RES share it can be expected that these results will also shift towards pyrolysis and gasification technologies. This is most pronounced in electricity-producing technologies as its market mix quickly is changing towards greater use of RES and is less pronounced in heat generation as district and industrial heating systems transition to other sources of heat (such as electricity or waste heat) much slower. Other recovery technologies are connected to the substitution of final products which production routes are not expected to drastically change in the next decades.

Even though incineration is a less sustainable solution, co-incineration in a cement kiln can be a preferred solution. Here, plastic waste substitutes for coal and petroleum coke which are the most environmentally unsustainable fuels. By doing this, co-incineration of plastic waste becomes the most sustainable and preferred option from the EU legislation standpoint when compared to all other analysed plastic WM solutions.

This analysis provides levelized results for environmental and resource sustainability for MPW recovery technologies in legislatively most important areas. Based on the presented results, it can be concluded pyrolysis and gasification technologies for the treatment of MPW can lead to lower environmental impacts when compared with plastic waste incineration and can help the EU to reach sustainable development goals. This conclusion also answers the research question. These conclusions are viable now, but also in the foreseeable future as the sustainability of electricity and heat generating technologies is expected to decrease with the meeting of EU RES targets. But before building new treatment facilities dedicated to waste treatment, possibilities for (partial) substitution of less environmentally sustainable fuels in other facilities need to be looked upon, which could lead to even better results from the legislation and sustainability standpoints. By looking upon all these findings which are obtained through legislative recognized approach, it can be also concluded that current views on dedicated, but also not dedicated, thermochemical recovery technologies need to be re-examined and EU institutions need to be encouraged to put the effort in revising EU legislation regarding classifying and ranking of different thermochemical process based recovery technologies taking into consideration type of final products and the final impacts of such production, which also represents a confirmation of the established hypothesis. This conclusion is backed up by the fact that the majority of alternative thermochemical conversion technologies products can be used as inputs in other industries, like pyrolysis oil (which can be used for petroleum substitution) and ethanol, and do not need to be strictly used as fuels (i.e. energy vectors). Thus, the same rezoning for legislation changes can be used as the ones used for classifying anaerobic digestion of bio-waste in the recycling category.

In the future work, this analysis will be expanded with sensitivity analysis which analyse the impact of changes in energy mixes on the results as well as broaden to include economic assessment which also makes one of the important pillars in decision-making.

Appendix

Gathered data for modelling of LCI datasets for pyrolysis and gasification

As there were no LCI data representing gasification and pyrolysis technologies in available LCI databases, LCI sets had to be modelled from the beginning. As for legislation making, average data for the specific sector/industry and activity/product should be used and not specific cases which could represent extremes instead of average situation, an extensive literature review of used pyrolysis and gasification technologies for the treatment of plastic waste is conducted and all available technology (technical, input/output and emissions) data on these plants/technologies are gathered and presented in Tables 7, 8, 9 and 10. In these tables, all available data from the cited literature are summarized and encompasses data for 42 individual plants for thermochemical conversion of plastic waste, plastic waste mixtures, and wastes that contain plastic in a significant proportion. The presented data are only adapted from the literature data in

Table 7 Technology data for the formation of LCI dataset—Pyrolysis of plastic waste 1

Refrence			Units	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)
Vendor / Technology				Agillyx	Envion	Climax	JBI	H. Smart	Veba
Location				Tigard, OR	Derwood, MD	Fairfax, SC	Niagara Falls, NY		Bottrop, Germany
Method of Depolymerization/ Feed Process									
Design capacity			tonnes per day	9.0718474	26.30835746	18.1436948	18.1436948	48.08079122	581.5054183
Feedstock requirments				industry standard, grinding/ shredding	feedstock is chipped to 1.5 inches or smaller	chipped and shred	shreding or pre-melting		polyeffins
Type of Feedstock (% compositions, if available)				PET, HDPE, PVC, LDPE, PP, PS, other plastics	PET, HDPE, PVC, LDPE, PP, PS, other plastics	100% plastics	HDPE, LDPE, PP		
Contamination limits					PET, PVC in small amounts				
Inorganic matter of feedstock			< %	100	100		5		4.5
Moisture content of feedstock			< %		2	0–5	10		
Energy recovery efficiency			%	82–85	30–80 (62)	75	92		
Heat for drying			kWh/wet tone						
Input	Tonnage of feedstock		dry tonne per day	9.0718474	26.30835746	18.1436948	18.1436948		
	Power consumption / parasitic load		KWh/dry tone		529.1094292	992.0801798	0.330693393		220.4622622
			KW/dry tonne		826.7334832				
	Other inputs (e.g., water, oxygen, etc.)	Oxygen	kg/dry tonne						
		Catalysts and chemicals	kg/dry tonne				trade secret	0.4	
		CaO	kg/dry tonne						0.00005
		Ammonia	kg/dry tonne						
		Sand	kg/dry tonne						
		Hyrdrogen	kg/dry tonne						1
		E-Gas	kg/dry tonne						11

Table 7 (continued)

Refrence			Units	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)	(RTI, 2012)
		Nitrogen	kg/dry tonne			minimal amount			
		NaOH	kg/dry tonne						
		HCl	kg/dry tonne						1
		Water	l/dry tonne		417.2702222	834.5404443	125.1810666		
		Carbon							
		Air	kg/dry tonne						
		Cooling water	l/dry tonne						
	Supplemental fuel use	Natural gas	MWh/dry tonne				0.009699145		0.001293219
		Off-gass							
		Naphta	MWh/dry tonne						
			l/dry tonne						
		Steam	MWh/dry tonne						2.26313E-05
			tonne/tonne						
		Heat input	KWh/dry tonne						
		Heat input startup	MWh/dry tonne						
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Syngas	MWh/dry tone				0.064660969		
		Synthetic crude oil	MWh/dry tonne	12.60888898	11.96227928	9.699145366			64.6609691
			kg/dry tonne						
			l/dry tonne	1051.52096		876.2674945			
		Heavy fraction (waxes)	kg/dry tonne						
		Light fraction (liquid)	kg/dry tonne			150–200			0.015
		Gas fraction	kg/dry tonne		100–250				
			MWh/dry tonne						
		Nitrogen	kg/dry tonne						
		Petcoke	MWh/dry tonne						
			kg/dry tonne						
		Gasoline	kg/dry tonne				11.5	10	

Table 7 (continued)

Refrence		Units	(RTI, 2012)	(Tukker et al., 1999)	(Perugini et al., 2005)	(Perugini et al., 2005)	(Tsiamis et al., 2013)	(Tsiamis et al., 2013)
Vendor / Technology			BP	BP Chemicals	BP process	Veba process	JBI Inc.'s "Plastic2Oil" Process	Agilyx
Location				Grangemouth				Portland, OR
Method of Depolymerization/ Feed Process								thermal pyrolysis
Design capacity		tonnes per day					43.54486752	27.2155422
Feedstock requirments				size reduction and removal of most non-plastic materials				shredded, granulated, and pelletized
Type of Feedstock (% compositions, if available)				Polyolefins: 80 (min. 70) wt% PS: 15 (max. 30) wt%	Polyolefines	Polyolefines	HDPE, LDPE, PP, other plastisc, small amouns of PET	PET, HDPE, PVC, LDPE, PP, PS, other plastics
Contamination limits				PET: 3 (max. 5) % PVC: 2 (max. 4) wt%	max 4% contaminants, 4.5% ash, 2.5% chlorine, and 1% moisture			
Inorganic matter of feedstock		< %						
Moisture content of feedstock		< %		0,5–1	1			
Energy recovery efficiency		%	80	85				
Heat for drying		kWh/wet tone						
Input	Tonnage of feedstock	dry tonne per day			1		43.54486752	27.2155422
	Power consumption / parasitic load	KWh/dry tone	0.033069339		58.88888936	266.6666688	29.85426467	35.82511761
		KW/dry tonne		60				

Table 7 (continued)

Refrence			Units	(RTI, 2012)	(Tukker et al., 1999)	(Perugini et al., 2005)	(Perugini et al., 2005)	(Tsiamis et al., 2013)	(Tsiamis et al., 2013)
	Other inputs (e.g., water, oxygen, etc.)	Oxygen	kg/dry tonne						
		Catalysts and chemicals	kg/dry tonne					+	
		CaO	kg/dry tonne			46	1		
		Ammonia	kg/dry tonne	0.3					
		Sand	kg/dry tonne	0.000002		8.5			
		Hyrdrogen	kg/dry tonne				11		
		E-Gas	kg/dry tonne						
		Nitrogen	kg/dry tonne					+	
		NaOH	kg/dry tonne						
		HCl	kg/dry tonne						
		Water	l/dry tonne	1669.080889		2000			+
		Carbon							
		Air	kg/dry tonne						+
		Cooling water	l/dry tonne		40,000			86.93129628	
	Supplemental fuel use	Natural gas	MWh/dry tonne				1.283333344	start up	+
		Off-gass						recycled	
		Naphta	MWh/dry tonne			0.036388889			
			l/dry tonne						
		Steam	MWh/dry tonne				0.031111111		
			tonne/tonne		1.2				
		Heat input	KWh/dry tonne						
		Heat input startup	MWh/dry tonne						

Table 7 (continued)

Refrence			Units	(RTI, 2012)	(Tukker et al., 1999)	(Perugini et al., 2005)	(Perugini et al., 2005)	(Tsiamis et al., 2013)	(Tsiamis et al., 2013)
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Syngas	MWh/ dry tonne						
		Synthetic crude oil	MWh/ dry tone					7.712505307	7.104148722
			kg/dry tonne				822	780.1788764	800
			l/dry tonne						911.3181943
		Heavy fraction (waxes)	kg/dry tonne		510	448			
		Light fraction (liquid)	kg/dry tonne	0.00005	340	265			
		Gas fraction	kg/dry tonne	0.000035	150	147	90	99.7903214	100
			MWh/ dry tonne					1.265958317	2.644223686
		Nitrogen	kg/dry tonne						
		Petcoke	MWh/ dry tonne					0.07407205	
			kg/dry tonne					27.2155422	
		Gasoline	kg/dry tonne						

Vendor / Technology			Units	Agillyx	Envion	Climax	JBI	H. Smart	Veba
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Diesel	kg/dry tonne				850	750	
			l/dry tonne						
			MWh/dry tonne						
		$CaO/CaCl_2$	kg/dry tonne						
		Sand	kg/dry tonne						
		Heat	MWh/dry tonne						
		$CaCl_2$	kg/dry tonne						1
		Off-gass	kg/dry tonne						
		HCl	kg/dry tonne						

Table 7 (continued)

Vendor / Technology			Units	Agillyx	Envion	Climax	JBI	H. Smart	Veba
	Residuals (e.g., ash, char, slag,etc.)	Char	kg/dry tonne	80			68		
			MWh/dry tonne						
		Solid residues	kg/dry tonne		80				
		Wax	l/dry tonne						
		Spent catalyst and chemicals	kg/dry tonne				trade secret	30	
		Catalys and sludge	kg/dry tonne						
			MWh/dry tonne						
		Spent SCR catalyst	kg/dry tonne					0.1	
		Inorganic sludge	kg/dry tonne		150				
		Residue to incineration	kg/dry tonne						1
		Non-hazardous solid waste	kg/dry tonne				2.5	0.005	10
		Waxy filter to incineration	kg/dry tonne						
	Heat losses		MWh/dry tonne						
	Water losses		l/dry tonne				125.1810666	1669.080889	
	Air Emissions Data								
	PM		kg/dry tonne	not regulated	negliable	10	0.019		
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Carbon Dioxide—Fossil ($CO_{2fossil}$)		kg/dry tonne						
	CO_2		kg/dry tonne	481	3,7–9,25	250		450	
	Methane (CH_4)		kg/dry tonne		13–32,5				
	HCl		kg/dry tonne				0.00015		
		periodic over min 1-h period	mg/mm^3						
	HF	periodic over min 1-h period	mg/mm^3						

Table 7 (continued)

Vendor / Technology			Units	Agillyx	Envion	Climax	JBI	H. Smart	Veba
	Hydrocarbons		kg/dry tonne			4	0.00017		2
	Sulphur dioxide (SO_2)		kg/dry tonne	minimum			0.007		
			ppm						
		periodic over min 1-h period	mg/mm^3						
	Nitrous Oxide (N_2O)		kg/dry tonne	minimum		minimal	0.15		
	NOx expressed as NO_2		kg/dry tonne	0.8	18.1–45.25	minimal	1.205	0.1	
			ppm						
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Carbon monoxide (CO)		kg/dry tonne	0.5	1.8–4.5	minimal	0.145	0.3	
			ppm						
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	TOC	daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Mercury (Hg)		kg/dry tonne		1.7637E-11				
		periodic over min 1-h period	mg/mm3						
	Lead (Pb)		kg/dry tonne		0.0001		0.01		
	Cadmium (Cd)	periodc over min. 30 min period	mg/mm^3						
	VOC		kg/dry tonne	0.8	negliable		0.0085	0.1	
	HAP		kg/dry tonne				0.00017		
	Dioxins and furans	periodic over min 1-h period	mg/mm^3						
	NH_3		kg/dry tonne						0.005

Table 7 (continued)

Vendor / Technology			Units	BP	BP Chemicals	BP process	Veba process	JBI Inc.'s "Plastic2Oil" Process	Agilyx
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Diesel	kg/dry tonne						
			l/dry tonne						
			MWh/dry tonne						
		$CaO/CaCl_2$	kg/dry tonne			57			
		Sand	kg/dry tonne			76			
		Heat	MWh/dry tonne						
		$CaCl_2$	kg/dry tonne				4.1		
		Off-gass	kg/dry tonne						
		HCl	kg/dry tonne				5		
	Residuals (e.g., ash, char, slag,etc.)	Char	kg/dry tonne						100
			MWh/dry tonne						1.654268128
		Solid residues	kg/dry tonne		200				
		Wax	l/dry tonne						
		Spent catalyst and chemicals	kg/dry tonne						
		Catalys and sludge	kg/dry tonne						
			MWh/dry tonne						
		Spent SCR catalyst	kg/dry tonne						
		Inorganic sludge	kg/dry tonne						
		Residue to incineration	kg/dry tonne				66		
		Non-hazardous solid waste	kg/dry tonne				50		
		Waxy filter to incineration	kg/drytonne	0.000015		46			
	Heat losses		MWh/dry tonne						
	Water losses		l/dry tonne						
	Air Emissions Data								

Table 7 (continued)

Vendor / Technology			Units	BP	BP Chemicals	BP process	Veba process	JBI Inc.'s "Plastic2Oil" Process	Agilyx
	PM		kg/dry tonne						
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Carbon Dioxide—Fossil ($CO_{2fossil}$)		kg/dry tonne						
	CO_2		kg/dry tonne			345			
	Methane (CH_4)		kg/dry tonne						
	HCl		kg/dry tonne						
		periodic over min 1-h period	mg/mm^3						
	HF	periodic over min 1-h period	mg/mm^3						
	Hydrocarbons		kg/dry tonne				2.23		
	Sulphur dioxide (SO_2)		kg/dry tonne	0.0000005		2			
			ppm					0.02	
		periodic over min 1-h period	mg/mm^3						
	Nitrous Oxide (N_2O)		kg/drytonne						
	NOx expressed as NO_2		kg/dry tonne	0.0000001		0.3			
			ppm					15.1	
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Carbon monoxide (CO)		kg/dry tonne						
			ppm					3.1	

Table 7 (continued)

Vendor / Technology			Units	BP	BP Chemicals	BP process	Veba process	JBI Inc.'s "Plastic2Oil" Process	Agilyx
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	TOC	daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Mercury (Hg)		kg/dry tonne						
		periodic over min 1-h period	mg/mm3						
	Lead (Pb)		kg/dry tonne						
	Cadmium (Cd)	periodc over min. 30 min period	mg/mm^3						
	VOC		kg/dry tonne						
	HAP		kg/dry tonne						
	Dioxins and furans	periodic over min 1-h period	mg/mm^3						
	NH_3		kg/dry tonne				0.006		

Table 8 Technology data for the formation of LCI dataset—Pyrolysis of plastic waste 2

Refrence			Units	(Tsiamis et al. 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(ORC, 2015)	(ORC, 2015)	(ORC, 2015)
Vendor / Technology				Climax Global Energy Inc	Pyrolysis	Catalytic depolymerisation	Cynar	Golden Renewables	PK Clean
Location				Barnwell County, SC			Bristol, UK	Yonkers, NY, USA	Salt Lake City, UT, USA
Method of Depolymerization/ Feed Process							Thermal Depolymerization Continuous Feed	Thermal Depolymerization Continuous Feed	Catalytic Depolymerization Continuous Feed
Design capacity			tonnes per day	9.0718474	76.8	76.8	18.1436948	21.77243376	4.5359237
Feedstock requirments				shredding	drying	drying		cleaning, drying, shredding	cleaning, shredding
Type of Feedstock (% compositions, if available)				MPW	MWP	MPW	HDPE, LDPE, PP, PS	PVC, LDPE,PP, PS, other plastics	PET, HDPE, PVC, LDPE, PP, PS, other plastics
Contamination limits							PVC: 0% PET: 2%		< 40% PET + PVC
Inorganic matter of feedstock			< %						
Moisture content of feedstock			< %						
Energy recovery efficiency			%				96		
Heat for drying			kWh/wet tonne		126	126			
Input	Tonnage of feedstock		dry tonne per day		72.7296	72.7296		19.59519038	
	Power consumption / parasitic load		KWh/dry tone	352.7396195	16.49947202	16.49947202	+	+	211.9829444
			KW/dry tonne						
	Other inputs (e.g., water, oxygen, etc.)	Oxygen	kg/dry tonne						
		Catalysts and chemicals	kg/dry tonne			24.28722281			+ optional
		CaO	kg/dry tonne						
		Ammonia	kg/dry tonne						
		Sand	kg/dry tonne						
		Hyrdrogen	kg/dry tonne						
		E-Gas	kg/dry tonne						

Table 8 (continued)

Refrence			Units	(Tsiamis et al. 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(ORC, 2015)	(ORC, 2015)	(ORC, 2015)
		Nitrogen	kg/dry tonne						
		NaOH	kg/dry tonne						
		HCl	kg/dry tonne						
		Water	l/dry tonne				+		6018.320512
		Carbon							
		Air	kg/dry tonne						
		Cooling water	l/dry tonne						
	Supplemental fuel use	Natural gas	MWh/dry tonne					start up	start up
		Off-gass							
		Naphta	MWh/dry tonne						
			l/dry tonne						
		Steam	MWh/dry tonne						
			tonne/tonne						
		Heat input	KWh/dry tonne		127.7719113				
		Heat input startup	MWh/dry tonne		1.583949314	0.844772967			
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Syngas	MWh/dry tonne						
		Synthetic crude oil	MWh/dry tonne		9.926082365	7.814149947			
			kg/dry tonne			650.4751848			
			l/dry tonne				1043.175555	792.8134221	1043.175555
		Heavy fraction (waxes)	kg/dry tonne						
		Light fraction (liquid)	kg/dry tonne						
		Gas fraction	kg/dry tonne	150		102.4287223	60	150	
			MWh/dry tonne	1.939829073		0.844772967			
		Nitrogen	kg/dry tonne						
		Petcoke	MWh/dry tonne						
			kg/dry tonne						
		Gasoline	kg/dry tonne						

Table 8 (continued)

Refrence			Units	(ORC, 2015)	(S.C.Inc, 2018)	(Fivga et al. 2018)	(Yu et al., 2018)	(Rodriguez et al., 2018)	(ACC, 2017)
Vendor / Technology				Vadxx	Sustane Technologies	Pyrolysis system	R-ONETM (Regenerated Oil & New Energy)	NRP Pyrolysis Process	Comparison of emissions
Location				Akron, OH	Sherwood, Canada		Hukou, Taiwan		
Method of Depolymerization/ Feed Process				Thermal Depolymerization Continuous Feed					
Design capacity			tonnes per day	54.4310844	10	2.4	2	9.0718474	
Feedstock requirments					cleaning, shredding				
Type of Feedstock (% compositions, if available)				HDPE, LDPE, PP, PS, other plastics, Tires, EPDM rubber	HDPE, LDPE, PP, PS	PE, PP, PS	85% (PP + PE + PS) 15% (ABS + PET + PVC, other)	MPW (60% PP, 40% PE)	MPW
Contamination limits									
Inorganic matter of feedstock			< %						
Moisture content of feedstock			< %						
Energy recovery efficiency			%						
Heat for drying			kWh/wet tonne						
Input	Tonnage of feedstock		dry tonne per day	54.4310844	10				
	Power consumption / parasitic load		KWh/dry tonne	967.2781753					
			KW/dry tonne				250		
	Other inputs (e.g., water, oxygen, etc.)	Oxygen	kg/dry tonne						
		Catalysts and chemicals	kg/dry tonne				39.35		
		CaO	kg/dry tonne						
		Ammonia	kg/dry tonne						
		Sand	kg/dry tonne						
		Hyrdrogen	kg/dry tonne						
		E-Gas	kg/dry tonne						
		Nitrogen	kg/dry tonne					45.359237	
		NaOH	kg/dry tonne				0.4		
		HCl	kg/dry tonne						
		Water	l/dry tonne			50			
		Carbon							
		Air	kg/dry tonne			2884.7			
		Cooling water	l/dry tonne						

Table 8 (continued)

Refrence			Units	(ORC, 2015)	(S.C.Inc, 2018)	(Fivga et al. 2018)	(Yu et al., 2018)	(Rodriguez et al., 2018)	(ACC, 2017)
	Supplemental fuel use	Natural gas	MWh/dry tonne	start up					
		Off-gass					+		
		Naphta	MWh/dry tonne						
			l/dry tonne				16.07		
		Steam	MWh/dry tonne						
			tonne/tonnne						
		Heat input	KWh/dry tonne			411.6			
		Heat input startup	MWh/dry tonne						
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Syngas	MWh/dry tonne						
		Synthetic crude oil	MWh/dry tonne			10.55		8.186078689	
			kg/dry tonne				794.11	598	
			l/dry tonne	876.2674665			953.73	738.5682932	
		Heavy fraction (waxes)	kg/dry tonne						
		Light fraction (liquid)	kg/dry tonne						
		Gas fraction	kg/dry tonne	175				312.0715506	
			MWh/dry tonne					2.149977223	
		Nitrogen	kg/dry tonne					45.359237	
		Petcoke	MWh/dry tonne						
			kg/dry tonne						
		Gasoline	kg/dry tonne						

Vendor/Technology			Units	Climax Global Energy Inc	Pyrolysis	Catalytic depolymerisation	Cynar	Golden Renewables	PK Clean
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Diesel	kg/dry tonne		718.0570222				
			l/dry tonne	297.9309481					
			MWh/dry tonne		8.975712777				
		$CaO/CaCl_2$	kg/dry tonne						
		Sand	kg/dry tonne						
		Heat	MWh/dry tonne						
		$CaCl_2$	kg/dry tonne						
		Off-gass	kg/dry tonne						
		HCl	kg/dry tonne						
	Residuals (e.g., ash, char, slag,etc.)	Char	kg/dry tonne	100	102.4287223		50	50	75
			MWh/dry tonne	0.821194308	0.422386484				

Table 8 (continued)

Vendor/Technology			Units	Climax Global Energy Inc	Pyrolysis	Catalytic depolymerisation	Cynar	Golden Renewables	PK Clean
		Solid residues	kg/dry tonne						
		Wax	l/dry tonne	578.3365464					
		Spent catalyst and chemicals	kg/dry tonne						
		Catalys and sludge	kg/dry tonne			199.5776135			
			MWh/dry tonne			1.795142555			
		Spent SCR catalyst	kg/dry tonne						
		Inorganic sludge	kg/dry tonne						
		Residue to incineration	kg/dry tonne						
		Non-hazardous solid waste	kg/dry tonne						
		Waxy filter to incineration	kg/dry tonne						
	Heat losses		MWh/dry tonne		0.950369588				
	Water losses		l/dry tonne						
	Air Emissions Data								
	PM		kg/dry tonne						
		daily average	mg/mm^3				15		
		half hourly avarage	mg/mm^3				45		
	Carbon Dioxide—Fossil ($CO_{2fossil}$)		kg/dry tonne						
	CO_2		kg/dry tonne	279.7378616	58.71172122	56.21787686			
	Methane (CH_4)		kg/dry tonne						
	HCl		kg/dry tonne						
		periodic over min 1-h period	mg/mm^3				15		
	HF	periodic over min 1-h period	mg/mm^3				2		
	Hydrocarbons		kg/dry tonne						
	Sulphur dioxide (SO_2)		kg/dry tonne						
			ppm						
		periodic over min 1-h period	mg/mm^3				75		
	Nitrous Oxide (N_2O)		kg/dry tonne						
	NOx expressed as NO_2		kg/dry tonne						

Table 8 (continued)

Vendor/Technology			Units	Climax Global Energy Inc	Pyrolysis	Catalytic depolymerisation	Cynar	Golden Renewables	PK Clean
			ppm						
		daily average	mg/mm^3				300		
		half hourly avarage	mg/mm^3				600		
	Carbon monoxide (CO)		kg/dry tonne						
			ppm						
		daily average	mg/mm^3				75		
		half hourly avarage	mg/mm^3				150		
	TOC	daily average	mg/mm^3				15		
		half hourly avarage	mg/mm^3				30		
	Mercury (Hg)		kg/dry tonne						
		periodic over min 1-h period	mg/mm3				0.05		
	Lead (Pb)		kg/dry tonne						
	Cadmium (Cd)	periodc over min. 30 min period	mg/mm^3				0.05		
	VOC		kg/dry tonne						
	HAP		kg/dry tonne						
	Dioxins and furans	periodic over min 1-h period	mg/mm^3				0.1		
	NH_3		kg/dry tonne						
Vendor/Technology			**Units**	**Vadxx**	**Sustane Technologies**	**Pyrolysis system**	**R-ONETM (Regenerated Oil & New Energy)**	**NRP Pyrolysis Process**	**Comparison of emissions**
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Diesel	kg/dry tonne		900				
			l/dry tonne						
			MWh/dry tonne						
		$CaO/CaCl_2$	kg/dry tonne						
		Sand	kg/dry tonne						
		Heat	MWh/dry tonne			1.156			
		$CaCl_2$	kg/dry tonne						
		Off-gass	kg/dry tonne			3060	88.7		
		HCl	kg/dry tonne						
	Residuals (e.g., ash, char, slag,etc.)	Char	kg/dry tonne	100				52.61671492	
			MWh/dry tonne					0.345936185	

Table 8 (continued)

Vendor/Technology			Units	Vadxx	Sustane Technologies	Pyrolysis system	R-ONETM (Regenerated Oil & New Energy)	NRP Pyrolysis Process	Comparison of emissions
		Solid residues	kg/dry tonne				104.35		
		Wax	l/dry tonne						
		Spent catalyst and chemicals	kg/dry tonne						
		Catalys and sludge	kg/dry tonne						
			MWh/dry tonne						
		Spent SCR catalyst	kg/dry tonne						
		Inorganic sludge	kg/dry tonne						
		Residue to incineration	kg/dry tonne						
		Non-hazardous solid waste	kg/dry tonne						
		Waxy filter to incineration	kg/dry tonne						
	Heat losses		MWh/dry tonne						
	Water losses		l/dry tonne			47			
	Air Emissions Data								
	PM		kg/dry tonne		0.089142857		0.002667139		0.2
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Carbon Dioxide—Fossil ($CO_{2fossil}$)		kg/dry tonne						
	CO_2		kg/dry tonne	0.5867399					
	Methane (CH_4)		kg/dry tonne						
	HCl		kg/dry tonne						
		periodic over min 1-h period	mg/mm^3						
	HF	periodic over min 1-h period	mg/mm^3						
	Hydrocarbons		kg/dry tonne						
	Sulphur dioxide (SO_2)		kg/dry tonne		0.011428571		0.0402		0.166666667
			ppm						
		periodic over min 1-h period	mg/mm^3						
	Nitrous Oxide (N_2O)		kg/dry tonne						0.766666667
	NOx expressed as NO_2		kg/dry tonne		1.659428571		0.01824		

Table 8 (continued)

Vendor/Technology			Units	Vadxx	Sustane Technologies	Pyrolysis system	R-ONETM (Regenerated Oil & New Energy)	NRP Pyrolysis Process	Comparison of emissions
			ppm						
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Carbon monoxide (CO)		kg/dry tonne		0.930285714				0.533333333
			ppm						
		daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	TOC	daily average	mg/mm^3						
		half hourly avarage	mg/mm^3						
	Mercury (Hg)		kg/dry tonne						
		periodic over min 1-h period	mg/mm^3						
	Lead (Pb)		kg/dry tonne						
	Cadmium (Cd)	periodc over min. 30 min period	mg/mm^3						
	VOC		kg/dry tonne		0.121142857				0.333333333
	HAP		kg/dry tonne						
	Dioxins and furans	periodic over min 1-h period	mg/mm^3						
	NH_3		kg/dry tonne						

Table 9 Technology data for the formation of LCI dataset—Gasification of plastic waste 1

Refrence	Units	(RTI, 2012)	(RTI, 2012)	(RTtI, 2012)	(Caroline et al., 2010)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Tukker et al., 1999)
Vendor/Technology		Enerkem (Pontotoc)	Ze-gen	Plasco	Alter NRG—integrated gasification combined cycle	Gasification	Gasification and F–T synthesis	Gasification and methanol-to-gasoline synthesis	Gasification and bioconversion to ethanol	Texaco process
Location		Pontotoc, MS	Narragansett Bay, MS	Ottawa, Ontario, Canada						Montebello, California
Design capacity	tonnes per day	299.3709642	68–136	84.36818082	710	76.8	76.8	76.8	76.8	10
Feedstock requirments		Sorting, drying, shredding	Sorting, drying, shredding	elemination of metals, shredding	10 inches size					Shredded or chipped
Type of Feedstock (% compositions, if available)		post-MRF-sorted MSW, industrial waste, construction and demolition waste, treated wood, bagasse, corn stover, wheat straw, rice hulls, wood chips, sawdust, bark, thinning, limbs, needles	95% wood based material, consisting of railroad crossties (90%), clean wood waste (5%), nonrecycled source-separated plastics (5%)	Paper and paperboard (24.3%), Plastics (16.2%), Metals (7.2%), Glass (6.1%), Rubber & Leather (3.3%), Textiles (5.9%), Wood (7.4%), Food Scraps (18%), Yard Trimmings (7.3%), Miscellaneous Inorganic Waste (2.2%), Other (2%)	MSW	dried waste plastics	dried waste plastics	dried waste plastics	dried waste plastics	MPW(< 10% PVC)
Inorganic matter content of feedstock	< %	15	5							10
Moisture content of feedstock	< %		20			5	5	5	5	5
Efficiency of the electricity generating unit (ICE)	%		85							
Energy recovery efficiency	%	> 72	48	98						
Heat for drying	kWh/wet tonne					126	126	126	126	

Table 9 (continued)

Refrence			Units	(RTI, 2012)	(RTI, 2012)	(RTtI, 2012)	(Caroline et al., 2010)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Tukker et al., 1999)
Input	Tonnage of feedstock		dry tonne per day	299.3709642	68–136	84.36818082	710	72.7296	72.7296	72.7296	72.7296	
	Power consumption / parasitic load		KWh/dry tonne	540.1325424	220.4622622		200		383.3157339	665.2587117		
	Other inputs (e.g., water, oxygen, etc.)	Oxygen	kg/dry tonne	723			172	1102.428722	1102.428722	1102.428722	1102.428722	+
		Air	kg/dry tonne									
		Catalysts and chemicals	kg/dry tonne									
		Diesel for preprocessing	l/dry tonne			0.208635111						
		Caustic for gas cleaning and cooling	kg/dry tonne			5						
		Chemicals, Catalysts, Guard Bed Materials	kg/ dry tonne	45.45454545								
		Activated Carbon for gas cleaning and cooling	l/dry tonne			0.834540444						
			kg/ drty tonne									
		Feldspar for gas cleaning and cooling	l/dry tonne			0.417270222						
		Heat input	kWh/ dry tonne				115.2	22.17529039	22.17529039	22.17529039	22.17529039	
		Steam	kWh/dry tonne								105.5966209	+
			kg/dry tonne								473.0728617	
		Coke	kg/dry tonne				38.9					
		Lignite	kg/dry tonne									
		Water	l/dry tonne	6768.123003	2253.2592							

Table 9 (continued)

Refrence			Units	(RTI, 2012)	(RTI, 2012)	(RTtI, 2012)	(Caroline et al., 2010)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Tukker et al., 1999)
			kg/dry tonne								5630.411827	
		Hydrated lime	kg/dry tonne									
	Supplemental fuel use	Syngass	kWh/dry tonne									
		Natural gas	kg/ dry tonne	7.86	1000	43.5						
			MWh/dry tonne		439.9458333							
			m^2/dry tonne									
		Fuel oil	kg/ dry tonne									
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Electricity	KWh/dry tonne			925–1302/0,907	929					
		Syngas	MWh/dry tonne		29.0974361			8.342133052				
			kg/dry tonne					1940.865892				
			Nm^3/dry tonne									2333.333333
		Steam	MWh/dry tonne		3.233048455			0.739176346	2.111932418	2.111932418		
			kg/drytonne					954.593453	2864.836325	2813.093981		
		Hydrogen	kg/dry tonne									
		Ethanol	kg/dry tonne	280–307.5							616.6842661	
			MWh/dry tonne								5.068637804	
		Methanol	kg/dry tonne									
		Purge gas	MWh/dry tonne						1.372756072	2.217529039		
			kg/dry tonne						1212.249208	1284.05491		
		F-T Liquids	MWh/dry tonne						3.167898627			
			kg/dry tonne						240.7602957			
		F-T Waxes	MWh/dry tonne						2.006335797			

Table 9 (continued)

Refrence			Units	(RTI, 2012)	(RTI, 2012)	(RTtI, 2012)	(Caroline et al., 2010)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Haig et al., 2013)	(Tukker et al., 1999)
			kg/dry tonne						154.1710665			
		Gasoline	MWh/dry tonne							4.751847941		
			kg/dry tonne							354.8046463		
Vendor / Technology			Units	Enerkem (Pontotoc)	Ze-gen	Plasco	Alter NRG—integrated gasification combined cycle	Gasification	Gasification and F–T synthesis	Gasification and methanol-to-gasoline synthesis	Gasification and bioconversion to ethanol	Texaco process
Output	Material Byproducts	Reactor off-gas	MWh/dry tonne								2.006335797	
			kg/dry tonne								1469.904963	
		Residual gas	kg/dry tonne	214								
		Sulphur	kg/dry tonne			1.5						
		Salt	kg/dry tonne			4,5–6,5						
		Slag	kg/dry tonne			12–212						
		Filter cake	kWh/tonne									
		NaCl	kWh/tonne									
		HCl	kg/dry tonne									
		Solids	kWh/tonne									
	Residuals (e.g., ash, char, slag,etc.)	Char	kg/dry tonne	148.66								
		Slag	kg/dry tonne		15							
		Tar	kg/dry tonne					141.499472	141.499472	141.499472	141.499472	
		Gasifier solid residues	kg/dry tonne	60	15							
		Spent catalysts and chemicals	kg/dry tonne	1.695								
		Ash	kg/dry tonne					20.06335797	20.06335797	20.06335797	20.06335797	
		Air Pollution Control System residues	kg/dry tonne									
		Inorganic sludge	kg/dry tonne	22.5								
		Gypsium	kg/dry tonne									
		Non-hazardous solid waste	kg/dry tonne	6.5								

Table 9 (continued)

Vendor / Technology			Units	Enerkem (Pontotoc)	Ze-gen	Plasco	Alter NRG—integrated gasification combined cycle	Gasification	Gasification and F–T synthesis	Gasification and methanol-to-gasoline synthesis	Gasification and bioconversion to ethanol	Texaco process
		Water	kg/dry tonne						675.8183738	644.1393875	5485.744456	
		Potable water	kg/dry tonne									
			l/dry tonne			2086.5491–312,519.2944						
	Heat losses		MWh/dry tonne				1.267159451	1.267159451	1.478352693	1.478352693	1.900739176	1.267159451
	Water losses		l/dry tonne	4172.702222	2086.351111							
			kg/dry tonne									
	Air Emissions Data											
	PM		kg/dry tonne	0.1765	0.005	0.021–0.022						
	PM10		kg/dry tonne			0.00035						
	PM2.5		kg/dry tonne									
	Carbon Dixide—Biogenic (CO_{2bio})		kg/dry tonne			233.52						
	Carbon Dioxide—Fossil ($CO_{2fossil}$)		kg/dry tonne	201.94	172.5	523.78						
	CO_{2eq}		kg/dry tonne			220–354			301.1615628	1050.686378	1285.216473	
	Methane (CH_4)		kg/dry tonne	0.945		0.0001						
	HCl		kg/dry tonne			0,012–0,01,298						
	Hydrocarbons		kg/dry tonne		0.004							
	Sulphur dioxide (SO_2)		kg/dry tonne	0.093	0.19	0.058–0.086						
	Sulphur oxide (SO)		kg/dry tonne			0.000025						
	Nitrous Oxide (N_2O)		kg/dry tonne	0.1975		0.0005						
	NOx expressed as NO_2		kg/dry tonne	0.555	0.095	0,084–0,086						
	Carbon monoxide (CO)		kg/dry tonne	0.73	0.065	0.205–0.22						
	Mercury (Hg)		kg/dry tonne		0.0000017	0.0000003						
	Cadmium (Cd)		kg/dry tonne		0.000000255	0.000004						
	Lead (Pb)		kg/dry tonne		0.000003595	0.000005						
	VOC		kg/dry tonne	0.45	0.02							
	HAP		kg/dry tonne	0.05								

Table 9 (continued)

Vendor / Technology		Units	Enerkem (Pontotoc)	Ze-gen	Plasco	Alter NRG—integrated gasification combined cycle	Gasification	Gasification and F–T synthesis	Gasification and methanol-to-gasoline synthesis	Gasification and bioconversion to ethanol	Texaco process
	NH3	kg/dry tonne									
	Dioxins and furans	kg/dry tonne									
	Acetaldehyde	kg/dry tonne	0.03								
	TNMOC	kg/dry tonne			0.1						
	Antimony (Sb)	kg/dry tonne									
	Arsenic (As)	kg/dry tonne									
	Titanium (Ti)	kg/dry tonne									
	Chromimu (Cr)	kg/dry tonne									
	Iron (Fe)	kg/dry tonne									
	Copper (Cu)	kg/dry tonne									
	Zinc (Zn)	kg/dry tonne									
	Water Emissions Data	kg/dry tonne									
	Water Effluent	l/dry tonne	2504—5842								
		kg/dry tonne			1453.05–3594.85						

Table 10 Technology data for the formation of LCI dataset—Gasification of plastic waste 2

Refrence			Units	(Tukker et al., 1999)	(Tukker et al., 1999)	(PowerHouse, 2019)	(PowerHouse, 2019)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)
Vendor				SVZ process	Akzo Nobel Stream Gasification Process	POWER HOUSE ENERGY GROUP, DMG	POWER HOUSE ENERGY GROUP, DMG	I	II	III	IV	V	VI
Location													
Design capacity			tonnes per day			25	25						
Feedstock requirments				particle size: 20-80 mm, chlorine content: 2%		Sorting, Drying, Shredding,	Sorting, Drying, Shredding,						
Type of Feedstock (% compositions, if available)				MPW agglomerate, waste oil	PP, PE, PVC	SRF, plastics, WEE plastics, tyre	SRF, plastics, WEE plastics, tyre	PE—Recycled polyethylene, derived from separate collection of MSW	GS3—Mix of recycled polyolefinic plastics obtained from plastic packaging for food and beverages by means of sorting and washing treatments	Neolite -Mix of plastics obtained from separate collection of plastic post-consumer packaging, but containing also ferrous and non-ferrous metals	Mix of plastics obtained from separate collection	PDF—Mix of different kinds of food packaging, generally consisting of multilayer packaging of plastic, paper and aluminium	PDF—Mix of different kinds of food packaging, generally consisting of multilayer packaging of plastic, paper and aluminium
Inorganic matter content of feedstock			< %										
Moisture content of feedstock			< %										
Efficiency of the electricity generating unit (ICE)			%										
Energy recovery efficiency			%										
Heat for drying			kWh/wet tonne										
Input	Tonnage of feedstock		dry tonne per day			25	25	1	1	1			
	Power consumption / parasitic load		KWh/dry tone		115,200								
	Other inputs (e.g., water, oxygen, etc.)	Oxygen	kg/dry tonne	1442.590775									
		Air	kg/dry tonne		2300								
		Catalysts and chemicals	kg/dry tonne										
		Diesel for preprocessing	l/dry tonne										

Table 10 (continued)

Refrence			Units	(Tukker et al., 1999)	(Tukker et al., 1999)	(PowerHouse, 2019)	(PowerHouse, 2019)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)
		Caustic for gas cleaning and cooling	kg/dry tonne										
		Chemicals, Catalysts, Guard Bed Materials	kg/dry tonne										
		Activated Carbon for gas cleaning and cooling	l/dry tonne										
			kg/dty tonne					0.508196721	0.491525424	0.5	0.5	0.5	0.5
		Feldspar for gas cleaning and cooling	l/dry tone										
		Heat input	kWh/dry tonne										
		Steam	kWh/dry tonne			915.2	915.2						
			kg/dry tonne		300								
		Coke	kg/dry tonne										
		Lignite	kg/dry tonne	1226.692836									
		Water	l/dry tonne	7752.698724	87,000	+							
			kg/dry tonne										
		Hydrated lime	kg/dry tonne					6.557377049	6.440677966	6.477272727	6.40625	6.465517241	6.465517241
	Supplemental fuel use	Syngass	kWh/dry tonne			1560	1560						
		Natural gas	kg/dry tonne										
			MWh/dry tonne										
			m2/dry tonne	98.13542689									
		Fuel oil	kg/dry tonne	39.25417076									
Output	Energy product (e.g., syngas,ethanol, hydrogen, electricity,steam)	Electricity	KWh/dry tonne	621.5243753		2288	1120	1639.344262	1694.915254	1136.363636	1562.5	862.0689655	862.0689655
		Syngas	MWh/dry tonne										
			kg/dry tonne	200.1962709	900								
			Nm3/dry tonne										
		Steam	MWh/dry tonne			1.56	1.152						
			kg/dry tonne										
		Hydrogen	kg/dry tonne				40						
		Ethanol	kg/dry tonne										
			MWh/dry tonne										
		Methanol	kg/dry tonne	698.7242395									
		Purge gas	MWh/dry tonne										
			kg/dry tonne										

Table 10 (continued)

Refrence			Units	(Tukker et al., 1999)	(Tukker et al., 1999)	(PowerHouse, 2019)	(PowerHouse, 2019)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)	(Ardolino et al., 2018)
		F-T Liquids	MWh/dry tonne										
			kg/dry tonne										
		F-T Waxes	MWh/dry tonne										
			kg/dry tonne										
		Gasoline	MWh/dry tonne										
			kg/dry tonne										
Vendor			Units	SVZ process	Akzo Nobel Stream Gasification Process	POWER HOUSE ENERGY GROUP, DMG	POWER HOUSE ENERGY GROUP, DMG	I	II	III	IV	V	VI
Output	Material Byproducts	Reactor off-gas	MWh/dry tonne			4.5968							
			kg/dry tonne										
		Residual gas	kg/dry tonne										
		Sulphur	kg/dry tonne										
		Salt	kg/dry tonne										
		Slag	kg/dry tonne										
		Filter cake	kWh/tonne			0.0104							
		NaCl	kWh/tonne			1.9968							
		HCl	kg/dry tonne		210								
		Solids	kWh/tonne			4.68							
	Residuals (e.g., ash, char, slag,etc.)	Char	kg/dry tonne										
		Slag	kg/dry tonne	0.883218842									
		Tar	kg/dry tonne										
		Gasifier solid residues	kg/dry tonne										
		Spent catalysts and chemicals	kg/dry tonne										
		Ash	kg/dry tonne		220			146.8852459	100.8474576	82.27272727	35.78125	68.36206897	68.36206897
		Air Pollution Control System residues	kg/dry tonne					7.049180328	6.949152542	6.931818182	6.875	6.982758621	6.982758621

Table 10 (continued)

Vendor		Units	SVZ process	Akzo Nobel Stream Gasification Process	POWER HOUSE ENERGY GROUP, DMG	POWER HOUSE ENERGY GROUP, DMG	I	II	III	IV	V	VI
	Inorganic sludge	kg/dry tonne										
	Gypsium	kg/dry tonne	98.13542689									
	Non-hazardous solid waste	kg/dry tonne										
	Water	kg/dry tonne										
	Potable water	kg/dry tonne										
		l/dry tonne										
Heat losses		MWh/dry tonne										
Water losses		l/dry tonne										
		kg/dry tonne	9715.407262									
Air Emissions Data												
PM		kg/dry tonne										
PM10		kg/dry tonne										
PM2.5		kg/dry tonne					0.01	0.012881356	0.066931818	0.01890625	0.061551724	
Carbon Dixide—Biogenic (CO_{2bio})		kg/dry tonne										
Carbon Dioxide—Fossil ($CO_{2fossil}$)		kg/dry tonne	12,177.26397				2622.95082	2762.711864	2409.090909	2828.125	1922.413793	1922.413793
CO_{2eq}		kg/dry tonne										
Methane (CH_4)		kg/dry tonne										
HCl		kg/dry tonne					0.000180328		0.104204545	0.0053125	0.027327586	0.027327586
Hydrocarbons		kg/dry tonne										
Sulphur dioxide (SO_2)		kg/dry tonne										
Sulphur oxide (SO)		kg/dry tonne							0.098863636	0.0984375	0.103448276	0.103448276
Nitrous Oxide (N_2O)		kg/dry tonne										

Table 10 (continued)

Vendor	Units	SVZ process	Akzo Nobel Stream Gasification Process	POWER HOUSE ENERGY GROUP, DMG	POWER HOUSE ENERGY GROUP, DMG	I	II	III	IV	V	VI
NOx expressed as NO_2	kg/dry tonne					0.070327869	0.071355932	0.0625	0.06953125	0.066034483	0.066034483
Carbon monoxide (CO)	kg/dry tonne										
Mercury (Hg)	kg/dry tonne					6.55738E-07	6.77966E-07	1.13636E-06	1.5625E-06	8.62069E-07	8.62069E-07
Cadmium (Cd)	kg/dry tonne					1.63934E-06	1.69492E-06	2.27273E-05	4.6875E-06	1.72414E-06	1.72414E-06
Lead (Pb)	kg/dry tonne					0.000245902	0.002305085	0.008522727	0.000328125	0.000724138	0.000724138
VOC	kg/dry tonne										
HAP	kg/dry tonne										
NH3	kg/dry tonne					3.27869E-05	3.38983E-05	3.40909E-05	0.00003125	3.44828E-05	3.44828E-05
Dioxins and furans	kg/dry tonne					6.55738E-12	6.77966E-12	6.81818E-12	6.25E-12	3.44828E-12	3.44828E-12
Acetaldehyde	kg/dry tonne										
TNMOC	kg/dry tonne										
Antimony (Sb)	kg/dry tonne					3.27869E-06	1.52542E-05	0.000352273	5.3125E-07	1.12069E-05	1.12069E-05
Arsenic (As)	kg/dry tonne					6.55738E-07	6.77966E-07	1.13636E-06	1.5625E-06	8.62069E-07	8.62069E-07
Titanium (Ti)	kg/dry tonne					3.27869E-06	1.69492E-06	2.27273E-06	0.000003125	2.58621E-06	2.58621E-06
Chromimu (Cr)	kg/dry tonne							0.000988636	0.00009375		
Iron (Fe)	kg/dry tonne							0.004659091	0.0028125	0.001293103	0.001293103
Copper (Cu)	kg/dry tonne							0.013068182	0.000171875	2.58621E-05	2.58621E-05
Zinc (Zn)	kg/dry tonne								0.0000625		
Water Emissions Data	kg/dry tonne										
Water Effluent	l/dry tonne										
	kg/dry tonne	9630.350915									

a way that they are converted to the metric system to be comparable.

As can be seen, available data from different data sources vary greatly, both in the amount of data and in the form of their presentation. Thus, for the formation of a representable dataset, many data sources are consulted and collected data adapted and averaged to represent the general dataset for analysed technologies. This way, the lack of data from individual data sources can be compensated, as well as errors and inconsistencies in the gathered data.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors and Affiliations

Tihomir Tomić[1] · Iva Slatina[1] · Daniel Rolph Schneider[1]

✉ Tihomir Tomić
tihomir.tomic@fsb.hr

[1] Department of Energy, Power and Environmental Engineering, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia