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

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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

EU puts emphasis on recycling while energy recovery legislation is not elaborate enough. EU legislation classifies all thermochemical conversion technologies in the same category regardless of what the final products are.

As majority of analysed thermochemical conversion technologies are not widely used in waste recovery systems, their inventories were modelled based on data gathered through extensive literature review.

Sustainable development legislation was reviewed and the most important impact categories from legislation aspect were used in this analysis: GWP, ARD, AP & CED.

Results show that use of pyrolysis and gasification can lead to lower impacts when compared to incineration, and provide levelized results based on which current legislative views on individual thermochemical recovery technologies may be re-examined.
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 bio-waste. 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, decoupling 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 CO₂ 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 decoupling 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. 2019), chemical recycling (Huang et al. 2022), thermochemical recovery (Onge 2016; Kremer et al. 2021; Siwal et al. 2021), to energy recovery via incineration (Tomić et al. 2017; Jadhai 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 (E99) 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, monomomers 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 landfiling 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 (Röhrlich 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 leveled 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
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 NOx, CO2, H2O, SO2, 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 NOx by up to 79%, CO2 by up to 34%, SO2 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.
| Flow | Unit | Value | $\sigma_g$ |
|------|------|-------|-----------|
| **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 |
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 1 (continued)

| Flow                                           | Unit       | Value    | $\sigma_g$ |
|------------------------------------------------|------------|----------|------------|
| 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    | $\sigma_g$ |
|------------------------------------------------|------------|----------|------------|
| 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                                         |            |          |            |
| Synthetic gas                                  | MWh        | 0.065    | 1.000      |
| Pyrolytic oil                                  | kg         | 708.653  | 1.140      |
| Pyrolytic gas                                  | kg         | 142.608  | 1.523      |
| 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      |
### Tables

**Table 3** Gasification with ethanol production—Differential LCI dataset

| Flow                  | Unit        | Value   | $\sigma_g$ |
|-----------------------|-------------|---------|------------|
| **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   | $\sigma_g$ |
|-----------------------|-------------|---------|------------|
| **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   | $\sigma_g$ |
|-----------------------|-------------|---------|------------|
| **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     | \( \sigma_g \) |
|------|------|-----------|-----------------|
| 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 | 8.41 | 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 | m³ | 0.500 | 1.105 |
| Output Products: | Clinker | kg | 1.00 | 1.000 |
| Total output: | Inert waste, for final disposal | kg | 0.00008 | 1.105 |
| Other outputs: | 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-tetrachlorodibenzop-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 |
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 CO₂eq)), abiotic resource depletion (ARD (in kg Sbeq)), and acidification potential (AP (in kg SO₂eq)). 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 CO₂ 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—NOₓ, SOₓ 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.

Table 6 (continued)

| Flow                              | Unit | Value     | σg  |
|-----------------------------------|------|-----------|-----|
| 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                             | m³   | 0.000300629  | 1.105 |
| Zinc                              | kg   | 0.000000006 | 1.251 |
| Emissions in water: Wastewater     | m³   | 0.001666    | 1.221 |
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 CO$_2$eq

Fig. 4 AP results in kg SO$_2$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 gases (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](image)

![Fig. 7 Acidification potential—the main contributors](image)
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 valued 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

| Reference | Units | (RTI, 2012) | (RTI, 2012) | (RTI, 2012) | (RTI, 2012) | (RTI, 2012) |
|-----------|-------|-------------|-------------|-------------|-------------|-------------|
| Vendor / Technology | | Agillyx | Environ | 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 requirements | industry standard, grinding/shredding | feedstock is chipped to 1.5 inches or smaller | chipped and shred | 100% plastics | 100% plastics | 100% plastics | polyefins |
| Type of Feedstock (% compositions, if available) | PET, HDPE, PVC, LDPE, PP, PS, other plastics | PET, HDPE, PVC, LDPE, PP, PS, other plastics | PET, PVC in small amounts |
| Contamination limits | 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 dry tonne per day | 9.0718474 | 26.30835746 | 18.1436948 | 18.1436948 |
| Power consumption / parasitic load | KWh/dry tonne | 529.1094292 | 992.0801798 | 0.330693393 | 0.330693393 | 220.4622622 |
| Other inputs (e.g., water, oxygen, etc.) | Oxygen kg/dry tonne | 826.7334832 |
| Catalysts and chemicals | | | | | | |
| CaO | kg/dry tonne | | | | | trade secret |
| Ammonia | kg/dry tonne | | | | | 0.00005 |
| Sand | kg/dry tonne | | | | | 0 |
| Hydrogen | kg/dry tonne | | | | | 1 |
| E-Gas | kg/dry tonne | | | | | 11 |


| Reference | Units | (RTI, 2012) | (RTI, 2012) | (RTI, 2012) | (RTI, 2012) | (RTI, 2012) |
|-----------|-------|-------------|-------------|-------------|-------------|-------------|
| Nitrogen  | kg/dry tonne | minimal amount | | | | |
| NaOH      | kg/dry tonne | | | | | |
| HCl       | kg/dry tonne | | | | | |
| Water     | l/dry tonne | 417.2702222 | 834.5404443 | 125.1810666 | | 1 |
| Carbon    | | | | | | |
| Air       | kg/dry tonne | | | | | |
| Cooling water | l/dry tonne | | | | | |
| Natural gas | MWh/dry tonne | 0.009699145 | 0.001293219 | | | |
| Off-gass  | MWh/dry tonne | | | | | |
| Naphta    | l/dry tonne | | | | | |
| Steam     | MWh/dry tonne | | | | | |
| Heat input | KWh/dry tonne | | | | | |
| Heat input startup | MWh/dry tonne | | | | | |
| Syngas    | MWh/dry tonne | 0.064660969 | | | | |
| Synthetic crude oil | MWh/dry tonne | 12.60888898 | 11.96227928 | 9.699145366 | | |
| kg/dry tonne | | 1051.52096 | 876.2674945 | | | |
| l/dry tonne | | | | | | |
| Heavy fraction (waxes) | kg/dry tonne | 1051.52096 | 876.2674945 | | | |
| Light fraction (liquid) | kg/dry tonne | 150–200 | | | | |
| Gas fraction | kg/dry tonne | | | | | |
| kg/dry tonne | | 100–250 | | | | |
| kg/dry tonne | | | | | | |
| Nitrogen | kg/dry tonne | | | | | |
| Petcoke  | MWh/dry tonne | | | | | |
| kg/dry tonne | | 11.5 | 10 | | | |
| Gasoline | kg/dry tonne | | | | | |
| Reference                      | 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 “Plasti-
|                               |           |             |                        |                          | c2Oil” Process           |                          |                          |
| Location                      |           |             | Grangemouth            |                          | Portland, OR             |                          |                          |
| Method of Depolymerization/ Feed Process |           |             | thermal pyrolysis      |                          |                          |                          |                          |
| Design capacity               |          |             | tonnes per day         |                          |                          | 43.54486752              | 27.2155422               |
| Feedstock requirements        |           |             | 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 plastics, small amounts 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             | 58.88889936              | 266.6666688              | 29.85426467              |
|                              |           |             | KW/dry tonne           | 60                      |                          |                          |                          |
Table 7 (continued)

| Reference | 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 | Oxygen | kg/dry tonne | +                      |                         |                         |                         |
|          | CaO | kg/dry tonne | 0.3                   |                         |                         |                         |                         |
|          | Ammonia | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | Sand | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | Hydrosol | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | E-Gas | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | Nitrogen | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | NaOH | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | HCl | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | Water | l/dry tonne | 1669.080889 | 2000                   |                         |                         |                         |
|          | Carbon | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | Air | kg/dry tonne | 0.000002 | 8.5                   |                         |                         |                         |
|          | Cooling water | l/dry tonne | 40,000 | 86.93129628 |                         |                         |                         |
|          | Natural gas | MWh/dry tonne | 1.283333344 | start up | +                      |                         |                         |
|          | Off-gas | recycled |                         |                         |                         |                         |                         |
|          | Nafta | MWh/dry tonne | 0.036388889 |                         |                         |                         |                         |
|          | Steam | MWh/dry tonne | 0.031111111 |                         |                         |                         |                         |
|          | Heat input | KW/dry tonne | 1.2                   |                         |                         |                         |                         |
|          | Heat input startup | MWh/dry tonne | 1.2                   |                         |                         |                         |                         |
| Reference | Output Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam) | Units | Agillyx | Envion | Climax | JBI | H. Smart | Veba |
|-----------|--------------------------------------------------------------------------|-------|---------|--------|--------|-----|----------|------|
| VT (RTL, 2012) (Tukker et al., 1999) | Syngas MWh/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | L/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.1/25.0/5.3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Synthetic crude oil MWh/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | L/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.8/0.1/7.8/6.4 | 911.31 | 780 | 1/7.8/6.4 | 800 | 911.31 | 891.31 | 800 | 911.31 |
| | Heavy fraction (waxes) kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Light fraction (luicky) kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 5.1/0.0/0.0/5/0.5 | 782 | 780 | 1/7.8/6.4 | 800 | 911.31 | 891.31 | 800 | 911.31 |
| | Gas fraction MWh/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | L/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Nitrogen kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Diesel kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Petcoke kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Gasoline kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | CaO/CaCl2 kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Sand kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Heat kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | CaCl2 kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | Off-gas kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| | HC1 kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| | 7.7/12.5/0.5/3/0.7 | 7.10/4/8.7/2.2 | 82 | 448 | 340 | 147 | 0.07 | 0.0 | 2.6 |
| Vendor / Technology | Units | Agillyx | Environ | Climax | JBI | H. Smart | Veba |
|---------------------|-------|---------|---------|--------|-----|----------|------|
| Residuals (e.g., ash, char, slag, etc.) | kg/dry tonne | 80 | | | 68 | | |
| Char | kg/dry tonne | | | | | | |
| Solid residues | kg/dry tonne | 80 | | | | | |
| Wax | l/dry tonne | | | | | | |
| Spent catalyst and chemicals | kg/dry tonne | | trade secret | 30 | | | |
| Catalyst and sludge | kg/dry tonne | | | | | | |
| Spent SCR catalyst | kg/dry tonne | | 0.1 | | | | |
| Inorganic sludge | kg/dry tonne | 150 | | | | | |
| Residue to incineration | kg/dry tonne | | | | | | |
| 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 | kg/dry tonne | | | | | | |
| PM | mg/mm³ | not regulated | negliable | 10 | 0.019 | | |
| daily average | mg/mm³ | | | | | | |
| half hourly average | mg/mm³ | | | | | | |
| Carbon Dioxide—Fossil (CO₂_fossil) | kg/dry tonne | | | | | | |
| CO₂ | kg/dry tonne | 481 | 3.7–9.25 | 250 | 450 | | |
| Methane (CH₄) | kg/dry tonne | 13–32.5 | | | | | |
| HCl | kg/dry tonne | | | | | | |
| periodic over min 1-h period | mg/mm³ | | | | | | |
| HF | mg/mm³ | | | | | | |

Thermochemical recovery from the sustainable economy development point of view—LCA-based...
| Vendor / Technology | Units       | Agillyx | Envion | Climax | JBI      | H. Smart | Veba |
|---------------------|-------------|---------|--------|--------|----------|----------|------|
| Hydrocarbons        | kg/dry tonne |         |        | 4      | 0.00017  | 2        |      |
| Sulphur dioxide (SO₂) | kg/dry tonne | minimum |        |        | 0.007    |          |      |
|                     | ppm         | minimum |        |        |          |          |      |
| Nitrous Oxide (N₂O) | kg/dry tonne | minimum | 0.8    | 18.1–45.25 | minimal  | 1.205    | 0.1  |
| NOx expressed as NO₂ | kg/dry tonne |         |        |        |          |          |      |
|                     | ppm         |         |        |        |          |          |      |
| Carbon monoxide (CO) | kg/dry tonne | 0.5     | 1.8–4.5 | minimal | 0.145    | 0.3      |      |
|                     | ppm         |         |        |        |          |          |      |
| TOC                 | mg/mm³      |         |        |        |          |          |      |
| Mercury (Hg)        | kg/dry tonne |         |        | 1.7637E-11 |          |          |      |
|                     | mg/mm³      |         |        |        |          |          |      |
| Lead (Pb)           | kg/dry tonne |         |        | 0.0001 | 0.01     |          |      |
|                     | mg/mm³      |         |        |        |          |          |      |
| Cadmium (Cd)        | kg/dry tonne |         |        | 0.00017 |          |          |      |
|                     | mg/mm³      |         |        |        |          |          |      |
| VOC                 | kg/dry tonne | 0.8     | negligible | 0.0085 | 0.1      |          |      |
| HAP                 | kg/dry tonne |         |        |        |          | 0.00017  |      |
| Dioxins and furans  | kg/dry tonne |         |        |        |          |          | 0.005|
| NH₃                 | kg/dry tonne |         |        |        |          |          |      |
| Vendor / Technology | Units | BP | BP Chemicals | BP process | Veba process | JBI Inc.’s “Plastio2Oil” Process | Agilyx |
|---------------------|-------|----|--------------|------------|--------------|---------------------------------|-------|
| Output: Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam) | kg/dry tonne |  |  |  |  |  |  |
| Diesel | l/dry tonne | MW/h/dry tonne |  |  |  |  |  |
| CaO/CaCl₂ | kg/dry tonne | 57 |  |  |  |  |  |
| Sand | kg/dry tonne | 76 |  |  |  |  |  |
| Heat | MW/h/dry tonne |  |  |  |  |  |  |
| CaCl₂ | 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 |  |  |  |  |  |
| Solid residues | kg/dry tonne | 200 |  |  |  |  |  |
| Wax | l/dry tonne |  |  |  |  |  |  |
| Spent catalyst and chemicals | kg/dry tonne |  |  |  |  |  |  |
| Catalyst and sludge | kg/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/dry tonne | 0.000015 | 46 |  |  |  |  |
| Heat losses | MW/h/dry tonne |  |  |  |  |  |  |
| Water losses | l/dry tonne |  |  |  |  |  |  |
| Air Emissions Data |  |  |  |  |  |  |  |
| Vendor / Technology            | Units                  | BP          | BP Chemicals | BP process | Veba process | JBI Inc.’s “Plastic2Oil” Process | Agilyx |
|-------------------------------|------------------------|-------------|--------------|------------|--------------|----------------------------------|--------|
| PM                            | kg/dry tonne           | daily average mg/mm³ | half hourly average mg/mm³ |            |              |                                  |        |
| Carbon Dioxide—Fossil (CO₂fossil) | kg/dry tonne               |            |              | 345       |              |                                  |        |
| CO₂                           | kg/dry tonne           |            |              |            |              |                                  |        |
| Methane (CH₄)                 | kg/dry tonne           |            |              |            |              |                                  |        |
| HCl                           | kg/dry tonne           |            |              |            |              |                                  |        |
| HF                            | mg/mm³                 | periodic over min 1-h period mg/mm³ | periodic over min 1-h period mg/mm³ |            |              |                                  |        |
| Hydrocarbons                  | kg/dry tonne           |            |              | 2.23       |              |                                  |        |
| Sulphur dioxide (SO₂)         | kg/dry tonne           | 0.0000005 ppm |              |            |              | 0.02                             |        |
| NOx expressed as NO₂          | kg/dry tonne           | 0.000001 ppm |              |            |              | 0.3                              |        |
| Carbon monoxide (CO)          | kg/dry tonne           | ppm         |              |            |              | 15.1                             |        |
|                               |                        | daily average mg/mm³ | half hourly average mg/mm³ |            |              |                                  | 3.1    |
Table 7 (continued)

| Vendor / Technology | Units | BP | BP Chemicals | BP process | Veba process | JBI Inc.’s “Plaste2Oil” Process | Agilyx |
|---------------------|-------|----|--------------|------------|--------------|--------------------------------|--------|
| daily average       | mg/mm³|    |              |            |              |                                |        |
| half hourly average | mg/mm³|    |              |            |              |                                |        |
| TOC                 |       |    |              |            |              |                                |        |
| daily average       | mg/mm³|    |              |            |              |                                |        |
| half hourly average | mg/mm³|    |              |            |              |                                |        |
| Mercury (Hg)        | periodic over min 1-h period | kg/dry tonne | mg/mm³ | | | | |
| Lead (Pb)           | periodic over min 30 min period | kg/dry tonne | mg/mm³ | | | | |
| Cadmium (Cd)        | periodic over min 30 min period | kg/dry tonne | mg/mm³ | | | | |
| VOC                 |       |    |              |            |              |                                |        |
| HAP                 |       |    |              |            |              |                                |        |
| Dioxins and furans  | periodic over min 1-h period | mg/mm³ | | | | | |
| NH₃                 |       |    |              |            |              | 0.006                          |        |
Table 8  Technology data for the formation of LCI dataset—Pyrolysis of plastic waste

| Reference | 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 | Catalytic Depolymerisation Continuous Feed | Catalytic Depolymerisation Continuous Feed | 
| Design capacity | tonnes per day | 9.0718474 | 76.8 | 76.8 | 18.1436948 | 21.77243376 | 4.5359237 |
| Feedstock requirements | shredding | drying | drying | 
| 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 | dry tonne per day | 72.7296 | 72.7296 | 19.59519038 | 
| Power consumption / parasitic load | KWh/dry tonne | 352.7396195 | 16.49947202 | 16.49947202 | + | + | 211.9829444 |
| 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 | 


| Reference | 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 |                      |                     |                     |             |             |             |
| Natural gas | MWh/dry tonne |                      |                     |                     |             |             |             |
| Off-gass  |                      |                       |                     |                     |             |             |             |
| Naphta    | MWh/dry tonne |                      |                     |                     |             |             |             |
| Steam     | MWh/dry tonne |                      |                     |                     |             |             |             |
| Heat input| KWh/dry tonne | 127.7719113           |                     |                     |             |             |             |
| Heat input startup | MWh/dry tonne | 1.583949314 | 0.844772967 | | | |
| Syngas    | MWh/dry tonne |                      |                     |                     |             |             |             |
| Synthetic crude oil | MWh/dry tonne | 9.926082365 | 7.814149947 | | | |
| Steam     | MWh/dry tonne |                      |                     |                     |             |             |             |
| Heavy fraction (waxes) | kg/dry tonne |                      |                     |                     | 1043.175555 | 792.8134221 | 1043.175555 |
| Light fraction (liquid) | kg/dry tonne |                      |                     |                     |             |             |             |
| Gas fraction | kg/dry tonne | 150                   |                     |                     | 102.4287223 | 60          | 150         |
| Nitrogen  | MWh/dry tonne | 1.939829073           |                     |                     | 0.844772967 |             |             |
| Pet coke  | kg/dry tonne |                      |                     |                     |             |             |             |
| Gasoline  | kg/dry tonne |                      |                     |                     |             |             |             |
| Reference | Units | (ORC, 2015) | (S.C.Inc, 2018) | (Fiega et al. 2018) | (Yu et al., 2018) | (Rodriguez et al., 2018) | (ACC, 2017) |
|-----------|-------|-------------|----------------|-----------------|-----------------|------------------------|-----------|
| Vendor / Technology | Vadex | Sustane Technologies | Pyrolysis system | R-ONETM (Re-generated 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 requirements | cleaning, shredding |
| Type of Feedstock (% compositions, if available) | HDPE, LDPE, PP, PS, other plastics, Tires, EPDM rubber | PE, PP, PS | 85% (PP+PE+PS) | 15% (ABS+PET+PVC, other) |
| Contamination limits | Inorganic matter of feedstock | < % |
| Moisture content of feedstock | < % |
| Energy recovery efficiency | % |
| Heat for drying | kWh/wet tonne |
| Input Tonage of feedstock | dry tonne per day | 54.4310844 | 10 |
| Power consumption / parasitic load | KW/dry tonne | 967.2781753 |
| Other inputs (e.g., water, oxygen, etc.) | Oxygen kg/dry tonne | 39.35 |
| | Catalysts and chemicals | kg/dry tonne | 39.35 |
| | CaO kg/dry tonne | 39.35 |
| | Ammonia kg/dry tonne | 39.35 |
| | Sand kg/dry tonne | 39.35 |
| | Hydrogen kg/dry tonne | 39.35 |
| | E-Gas kg/dry tonne | 39.35 |
| | Nitrogen kg/dry tonne | 39.35 |
| | NaOH kg/dry tonne | 39.35 |
| | HCl kg/dry tonne | 39.35 |
| | Water l/dry tonne | 39.35 |
| | Carbon kg/dry tonne | 39.35 |
| | Air kg/dry tonne | 39.35 |
| | Cooling water l/dry tonne | 39.35 |
| Reference | Units | (ORC, 2015) | (S.C. Inc, 2018) | (Fivga et al. 2018) | (Yu et al., 2018) | (Rodriguez et al., 2018) | (ACC, 2017) |
|-----------|-------|-------------|------------------|--------------------|------------------|--------------------------|-------------|
| Natural gas MWh/dry tonne | start up | | | | | | |
| Off-gass  | MWh/dry tonne | | | | | | |
| Naphtha MWh/dry tonne | 16.07 | | | | | | |
| Steam MWh/dry tonne | | | | | | | |
| Heat input KWh/dry tonne | 411.6 | | | | | | |
| Heat input startup MWh/dry tonne | | | | | | | |
| Output Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam) MWh/dry tonne | | | | | | | |
| Syngas kg/dry tonne | 876.2674665 | | | | | | |
| Synthetic crude oil kg/dry tonne | 953.73 | | | | | | |
| Heavy fraction (waxes) kg/dry tonne | | | | | | | |
| Light fraction (liquid) kg/dry tonne | | | | | | | |
| Gas fraction kg/dry tonne | 175 | | | | | | |
| Nitrogen kg/dry tonne | 794.11 | | | | | | |
| Petcoke MWh/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 | 718.05 | 70222 | | | | |
| l/dry tonne | 297.9309481 | | | | | |
| MWh/dry tonne | 8.975712777 | | | | | |
| CaO/CaCl2 kg/dry tonne | | | | | | | |
| Sand kg/dry tonne | | | | | | | |
| Heat kg/dry tonne | | | | | | | |
| CaCl2 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 | 578.3365464 | | | | | |
| Wax               | l/dry tonne | | | | | | |
| Spent catalyst and chemicals | kg/dry tonne | | | | | | |
| Catalys and sludge | kg/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 | | | | | | 0.950369588 |
| Water losses | l/dry tonne | | | | | | |
| Air Emissions Data | | | | | | | |
| PM | daily average | mg/mm$^3$ | | | | | 15 |
| | half hourly average | mg/mm$^3$ | | | | | 45 |
| Carbon Dioxide—Fossil (CO$_2$) | kg/dry tonne | | | | | | |
| CO$_2$ | kg/dry tonne | 279.7378616 | 88.71172122 | | 56.21787686 |
| Methane (CH$_4$) | kg/dry tonne | | | | | | |
| HCl | periodic over min 1-h period | mg/mm$^3$ | | | | | 15 |
| | periodic over min 1-h period | mg/mm$^3$ | | | | | 2 |
| HF | periodic over min 1-h period | mg/mm$^3$ | | | | | 2 |
| Hydrocarbons | kg/dry tonne | | | | | | |
| Sulphur dioxide (SO$_2$) | kg/dry tonne | ppm | | | | | 75 |
| Nitrous Oxide (N$_2$O) | 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 |
|-----------------------------|-------|--------------------------|-----------|---------------------------|-------|------------------|----------|
| Carbon monoxide (CO)        | ppm   | daily average            |           |                           |       |                  |          |
|                            |       | half hourly average      |           |                           |       |                  |          |
| TOC                         | ppm   | daily average            |           |                           |       |                  |          |
|                            |       | half hourly average      |           |                           |       |                  |          |
| Mercury (Hg)                | kg/dry tonne | periodic over min 1-h period | ppm | daily average            |           |                           | 0.05    |
|                            |       | half hourly average      |           |                           |       |                  |          |
| Lead (Pb)                   | kg/dry tonne | periodic over min, 30 min period | mg/mm³ | daily average            |           |                           | 0.05    |
| Cadmium (Cd)                | kg/dry tonne | periodic over min, 30 min period | mg/mm³ | daily average            |           |                           | 0.05    |
| VOC                         | kg/dry tonne |                             |           |                           |       |                  |          |
| HAP                         | kg/dry tonne |                             |           |                           |       |                  |          |
| Dioxins and furans          | kg/dry tonne | periodic over min 1-h period | mg/mm³ | daily average            |           |                           | 0.1     |
| NH₃                         | kg/dry tonne |                             |           |                           |       |                  |          |

| Vendor/Technology           | Units | Vadxx             | Sustane Technologies | Pyrolysis system | R-OHEMT (Regenerated Oil & New Energy) | NRP Pyrolysis Process | Comparison of emissions |
|-----------------------------|-------|------------------|----------------------|-----------------|----------------------------------------|------------------------|------------------------|
| Output                      |       | Diesel kg/dry tonne |                     |                 |                                       |                        |                        |
| Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam) |       |                   |                     |                 |                                       |                        |                        |
| CaO/CaCl₂                   | kg/dry tonne |                             |                     |                 |                                       |                        |                        |
| Sand                        | kg/dry tonne |                             |                     |                 |                                       |                        |                        |
| Heat                        | MWh/dry tonne |                             |                     |                 |                                       |                        |                        |
| CaCl₂                       | kg/dry tonne |                             |                     |                 |                                       |                        |                        |
| Off-gass                    | kg/dry tonne |                             |                     |                 |                                       |                        |                        |
| HCl                         | kg/dry tonne |                             |                     |                 |                                       |                        |                        |
| Residuals (e.g., ash, char, slag, etc.) | Char kg/dry tonne |                             |                     |                 |                                       |                        | 52.61671492 |
|                             | MWh/dry tonne |                             |                     |                 |                                       |                        | 0.345936185 |

Thermochemical recovery from the sustainable economy development point of view—LCA based...
| 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               | kg/dry tonne |                           |                                                 |                      |                        |
| Spent catalyst and chemicals | kg/dry tonne |                           |                                                 |                      |                        |
| Catalyst and sludge | kg/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/mm³      |                            |                                                 |                      |                        |
| Half hourly average | mg/mm³      |                            |                                                 |                      |                        |
| Carbon Dioxide—Fossil (CO₂) | kg/dry tonne | 0.5867399                 |                                                    |                      |                        |
| CO₂               | kg/dry tonne |                           |                                                 |                      |                        |
| Methane (CH₄)     | kg/dry tonne |                           |                                                 |                      |                        |
| HCl               | kg/dry tonne |                           |                                                 |                      |                        |
| Periodic over min | mg/mm³      |                            |                                                 |                      |                        |
| 1-h period        | mg/mm³      |                            |                                                 |                      |                        |
| HF                | mg/mm³      |                            |                                                 |                      |                        |
| Periodic over min | mg/mm³      |                            |                                                 |                      |                        |
| 1-h period        | mg/mm³      |                            |                                                 |                      |                        |
| Hydrocarbons      | kg/dry tonne |                           |                                                 |                      |                        |
| Sulphur dioxide (SO₂) | kg/dry tonne | 0.011428571                | 0.0402                                           | 0.166666667          |
| Periodic over min | ppm         |                            |                                                 |                      |                        |
| 1-h period        | mg/mm³      |                            |                                                 |                      |                        |
| Nitrous Oxide (N₂O) | kg/dry tonne |                          |                                                 | 0.766666667          |
| NOx expressed as NO₂ | kg/dry tonne | 1.659428571                |                                                  | 0.01824              |
| Vendor/Technology         | Units                  | Vadxx       | Sustane Technologies | Pyrolysis system | R-ONETM (Regenerated Oil & New Energy) | NRP Pyrolysis Process | Comparison of emissions |
|---------------------------|------------------------|-------------|----------------------|------------------|---------------------------------------|-----------------------|------------------------|
| Carbon monoxide (CO)      | ppm daily average      | mg/mm³     |                      |                  |                                       |                       | 0.930285714             | 0.533333333            |
|                           | half hourly average    | mg/mm³     |                      |                  |                                       |                       |                        |                        |
| TOC                       | ppm daily average      | mg/mm³     |                      |                  |                                       |                       |                        |                        |
|                           | half hourly average    | mg/mm³     |                      |                  |                                       |                       |                        |                        |
| Mercury (Hg)              | kg/dry tonne periodic over min 1-h period | mg/mm³     |                      |                  |                                       |                       |                        |                        |
| Lead (Pb)                 | kg/dry tonne periodic over min 30 min period | mg/mm³     |                      |                  |                                       |                       |                        |                        |
| Cadmium (Cd)              | kg/dry tonne periodic over min 30 min period | mg/mm³     |                      |                  |                                       |                       |                        |                        |
| VOC                       | kg/dry tonne           |             |                      |                  |                                       |                       | 0.121142857             | 0.333333333            |
| HAP                       | kg/dry tonne           |             |                      |                  |                                       |                       |                        |                        |
| Dioxins and furans        | kg/dry tonne periodic over min 1-h period | mg/mm³     |                      |                  |                                       |                       |                        |                        |
| NH₃                       | kg/dry tonne           |             |                      |                  |                                       |                       |                        |                        |
| Reference | Vendor/Technology | Design capacity | Feedstock requirements | Type of Feedstock (% compositions, if available) | Inorganic matter content of feedstock | Moisture content of feedstock | Efficiency of the electricity generating unit (ICE) | Energy recovery efficiency | Heat for drying |
|-----------|------------------|-----------------|------------------------|------------------------------------------------|--------------------------------------|-------------------------------|---------------------------------------------|-------------------------|----------------|
| (RTI, 2012) | (RTI, 2012) | (RTI, 2012) | (Caroline et al., 2010) | (Haig et al., 2013) | (Haig et al., 2013) | (Haig et al., 2013) | (Tukker et al., 1999) | | |
| 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 | | |
| Pontotoc, MS | Narragansett Bay, MS | Ottawa, Ontario, Canada | 710 | 76.8 | 76.8 | 76.8 | 76.8 | | |
| tonnes per day | | | | | | | | | |
| Sorting, drying, shredding | Sorting, drying, shredding | elimination of metals, shredding | 10 inches size | MSW | dried waste plastics | dried waste plastics | dried waste plastics | dried waste plastics | |
| 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 (10%), Yard Trimmings (7.3%), Miscellaneous Inorganic Waste (2.2%), Other (2%) | Shredded or chipped | | | | | | | |
| < % | 15 | 5 | 10 | |
| < % | 20 | 5 | 5 | 5 | 5 | 5 | |
| % | 85 | | | | | | | |
| % | > 72 | 48 | 98 | 126 | 126 | 126 | 126 | | |
| Reference | Units | (RTL, 2012) | (RTI, 2012) | (Caroline et al., 2010) | (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 | 7.10 | 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 |  |  |
|           |          |          |          |          |          |          |          |          |
|           | Heat input kWh/dry tonne |  | 115.2 | 22.17529039 | 22.17529039 | 22.17529039 | 22.17529039 | 1055966209 + |
|           | Steam  | kWh/dry tonne |  |  |  |  |  | 473.0728617 |
|           | Coke   | kg/dry tonne |  |  |  | 38.9 |  |  |
|           | Lignite | kg/dry tonne |  |  |  |  |  |  |
|           | Water  | l/dry tonne | 6768.123003 | 2253.2992 |  |  |  |  |
| Reference | Units | (RTL, 2012) | (RTL, 2012) | (RTI, 2012) | (Haig et al., 2013) | (Haig et al., 2013) | (Haig et al., 2013) | (Tukker et al., 1999) |
|-----------|-------|-------------|-------------|-------------|---------------------|---------------------|---------------------|-----------------------|
| **Hydrated lime** | kg/dry | 5630.411827 |
| **Supplemental fuel use** | | | | | | | | |
| **Syngas** | kWh/dry | | | | | | | |
| **Natural gas** | kg/dry | 7.86 | 1000 | 43.5 | 439.9458333 | | | |
| | MWh/dry | | | | 439.9458333 | | | |
| | m³/dry | | | | | | | |
| **Fuel oil** | kg/dry | | | | | | | |
| **Output** | Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam) | | | | | | | |
| **Electricity** | KWh/dry | 925–1302/0.907 | | | | | | |
| | MWh/dry | | | | 2333.333333 | | | |
| | kg/dry | | | | | | | |
| | MWh/dry | | | | | | | |
| | m³/dry | | | | | | | |
| **Steam** | MWh/dry | 3.233048455 | | | | | | |
| | kg/dry | 954.593453 | 2864.836325 | 2813.093981 | | | | |
| **Hydrogen** | kg/dry | 2.80–307.5 | | | | | | |
| **Ethanol** | kg/dry | | | | | | | |
| | MWh/dry | | | | 616.6842661 | | | |
| **Methanol** | kg/dry | | | | | | | |
| **Purge gas** | MWh/dry | | | | | | | |
| | kg/dry | | | | | | | |
| **F-T Liquids** | MWh/dry | | | | | | | |
| | kg/dry | | | | 2.111932418 | | | |
| **F-T Waxes** | MWh/dry | | | | | | | |
| | kg/dry | | | | 2.111932418 | | | |
Table 9 (continued)

| Vendor / Technology | Reference / Units | Units | Enerkem (Pontoctoc) | Ze-gen | Plasco | Alter NRG—integrated gasification combined cycle | Gasification | Gasification and F-T synthesis | Gasification and methanol-to-gasoline synthesis | Gasification and biocconversion to ethanol | Texaco process |
|---------------------|-------------------|------|---------------------|--------|--------|-----------------------------------------------|--------------|--------------------------------------|-----------------------------------------------|--------------------------------------------|----------------|
| Output Material Byproducts | Reactor off-gas | kG/dry tonne | MWh/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne | kg/dry tonne |
| Residuals (e.g., ash, char, slag, etc.) | | | | | | | | | | | | | |
| 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 | 148.66 | | | | | | | | | | | |
| Residuals (e.g., ash, char, slag, etc.) | | | | | | | | | | | | | |
| Slag | kg/dry tonne | 15 | | | | | | | | | | | |
| Tar | kg/dry tonne | | | | | | | | | | | | |
| Gasifier solid residues | kg/dry tonne | 60 | | | | | | | | | | | |
| Spent catalysts and chemicals | kg/dry tonne | 1.695 | | | | | | | | | | | |
| Ash | kg/dry tonne | | | | | | | | | | | | |
| Air Pollution Control System residues | | | | | | | | | | | | | |
| Inorganic sludge | kg/dry tonne | 22.5 | | | | | | | | | | | |
| Gypsum | kg/dry tonne | | | | | | | | | | | | |
| Non-hazardous solid waste | kg/dry tonne | 6.5 | | | | | | | | | | | |

Reference: (RTL, 2012), (RTL, 2012), (RTL, 2012), (Caroline et al., 2010), (Haig et al., 2013), (Haig et al., 2013), (Haig et al., 2013), (Tukker et al., 1999)

154.1710665
4.751847941
354.8046463
20.06335797
14.999472
14.999472
14.999472
20.06335797
### Table 9 (continued)

| Vendor / Technology | Units | Enerkem (Ponatoc) | Ze-gen | Plasco | Alter NRG—integrated gasification combined cycle | 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 | 2086.5491 | 3125.192944 | 1.267159451 | 1.267159451 | 1.478352693 | 1.478352693 | 1.900739176 | 1.267159451 |
| Heat losses         | MWh/dry tonne | 4172.702222 | 2086.351111 | 233.52 | 301.1615628 | 1050.686378 | 1285.216473 |
| Water losses        | kg/dry tonne | 0.1765 | 0.005 | 0.021–0.022 | 0.021–0.022 | 0.0021–0.022 | 0.0021–0.022 | 0.0021–0.022 | 0.0021–0.022 |
| Air Emissions Data | PM        | kg/dry tonne | 0.45 | 0.02 | 0.0000017 | 0.0000003 | 0.0000004 | 0.0000005 |
| PM10                | kg/dry tonne | 0.093 | 0.19 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 |
| PM2.5               | kg/dry tonne | 0.1975 | 0.004 | 0.000025 | 0.000025 | 0.000025 | 0.000025 | 0.000025 | 0.000025 |
| Carbon Dioxide—Biogenic (CO2bio) | kg/dry tonne | 201.94 | 172.5 | 523.78 |
| Carbon Dioxide—Fossil (CO2fossil) | kg/dry tonne | 220–354 | 301.1615628 | 1050.686378 | 1285.216473 |
| Methane (CH4)       | kg/dry tonne | 0.945 | 0.0001 | 0.0012–0.01298 | 0.0012–0.01298 | 0.0012–0.01298 | 0.0012–0.01298 | 0.0012–0.01298 | 0.0012–0.01298 |
| HCl                 | kg/dry tonne | 0.093 | 0.19 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 | 0.058–0.086 |
| Hydrocarbons        | kg/dry tonne | 0.1975 | 0.004 | 0.000025 | 0.000025 | 0.000025 | 0.000025 | 0.000025 | 0.000025 |
| Sulphur dioxide (SO2) | kg/dry tonne | 0.73 | 0.065 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 |
| Sulphur oxide (SO)  | kg/dry tonne | 0.555 | 0.095 | 0.084–0.086 | 0.084–0.086 | 0.084–0.086 | 0.084–0.086 | 0.084–0.086 | 0.084–0.086 |
| Ninous Oxide (N2O)  | kg/dry tonne | 0.73 | 0.065 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 | 0.205–0.22 |
| NOx expressed as NO2 | kg/dry tonne | 0.004 | 0.0005 | 0.000025 | 0.000025 | 0.000025 | 0.000025 | 0.000025 | 0.000025 |
| Mercury (Hg)        | kg/dry tonne | 0.0000017 | 0.000003 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 |
| Cadmium (Cd)        | kg/dry tonne | 0.000000255 | 0.0000005 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 |
| Lead (Pb)           | kg/dry tonne | 0.000003595 | 0.000005 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 | 0.0000004 |
| VOC                 | kg/dry tonne | 0.45 | 0.02 | 0.0000017 | 0.000003 | 0.0000004 | 0.0000005 | 0.0000005 |
| HAP                 | kg/dry tonne | 0.05 | 0.02 | 0.0000017 | 0.000003 | 0.0000004 | 0.0000005 | 0.0000005 |
Table 9 (continued)

| Vendor / Technology | Units | Enerkem (Pon- totoct) | 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   |                                             | 0.1         |                                      |                                        |                                          |                |
| TNMOC               | kg/dry tonne |                         |        |        |                                             |             |                                      |                                        |                                          |                |
| Antimony (Sb)       | kg/dry tonne |                         |        |        |                                             |             |                                      |                                        |                                          |                |
| Arsenic (As)        | kg/dry tonne |                         |        |        |                                             |             |                                      |                                        |                                          |                |
| Titanium (Ti)       | kg/dry tonne |                         |        |        |                                             |             |                                      |                                        |                                          |                |
| Chromium (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 |                        2504—5842 |        |        |                                             |             |                                      |                                        |                                          |                |
| Water Effluent      | kg/dry tonne |                        1453.05—3594.85 |        |        |                                             |             |                                      |                                        |                                          |                |
| Vendor                  | SYZ process Akzo Nobel Stream Gasification Process | POWER HOUSE ENERGY GROUP, DMG | POWER HOUSE ENERGY GROUP, DMG | I    | II   | III  | IV   | V    | VI   |
|------------------------|----------------------------------------------------|-------------------------------|-------------------------------|------|------|------|------|------|------|
| Location               |                                                    |                               |                               | 25   | 25   |      |      |      |      |
| Design capacity        | tons per day                                       |                               |                               |      |      |      |      |      |      |
| Feedstock requirements | 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/tonne                                          |                               |                               |      |      |      |      |      |      |
| Input                   | Tonnage of feedstock dry tonne per day              | 25                            | 25                            | 1    | 1    | 1    |      |      |      |
| Power consumption / parasitic load | kWh/dry tonne | 115,200 |                               |      |      |      |      |      |      |
| Other inputs (e.g., oxygen, water, etc.) | Oxygen kg/dry tonne | 1442, 590775 |                               |      |      |      |      |      |      |
|                         | Air kg/dry tonne                                   | 2300                          |                               |      |      |      |      |      |      |
|                         | Catalysts and chemicals kg/dry tonne               |                               |                               |      |      |      |      |      |      |
|                         | Diesel for preprocessing Udry tonne                 |                               |                               |      |      |      |      |      |      |
Table 10 (continued)

| Reference | Units | (Tukker et al., 1999) | (Tukker et al., 2019) | (PowerHouse, 2019) | (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 | | | | | | | | |
| Feldspar for gas cleaning and cooling | kg/dry tonne | | | | | | | | |
| Heat input | kWh/dry tonne | | | | | | | | |
| Steam | kWh/dry tonne | | | | | | | | |
| Coke | kg/dry tonne | | | | | | | | |
| Lignite | kg/dry tonne | | | | | | | | |
| Water | l/dry tonne | | | | | | | | |
| Hydrated lime | kg/dry tonne | | | | | | | | |
| Supplemental fuel use | l/dry tonne | | | | | | | | |
| Syngas | kWh/dry tonne | | | | | | | | |
| Natural gas | kg/dry tonne | | | | | | | | |
| Fuel oil | kWh/dry tonne | | | | | | | | |
| Output | Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam) | kW/h dry tonne | | | | | | | | |
| Electricity | kW/dry tonne | 2288 | 1120 | 1639.344262 | 1694.955254 | 1136.363636 | 962.5 | 862.0689655 | 862.0689655 |
| Syngas | kWh/dry tonne | | | | | | | | |
| Natural gas | kWh/dry tonne | | | | | | | | |
| Fuel oil | kWh/dry tonne | | | | | | | | |
| Output | Purge gas | kWh/dry tonne | | | | | | | |

| Reference | Units | (Tukker et al., 1999) | (Tukker et al., 2019) | (PowerHouse, 2019) | (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 | | | | | | | | |
| Feldspar for gas cleaning and cooling | kg/dry tonne | | | | | | | | |
| Heat input | kWh/dry tonne | | | | | | | | |
| Steam | kWh/dry tonne | | | | | | | | |
| Coke | kg/dry tonne | | | | | | | | |
| Lignite | kg/dry tonne | | | | | | | | |
| Water | l/dry tonne | | | | | | | | |
| Hydrated lime | kg/dry tonne | | | | | | | | |
| Supplemental fuel use | l/dry tonne | | | | | | | | |
| Syngas | kWh/dry tonne | | | | | | | | |
| Natural gas | kg/dry tonne | | | | | | | | |
| Fuel oil | kWh/dry tonne | | | | | | | | |
| Output | Energy product (e.g., syngas, ethanol, hydrogen, electricity, steam) | kW/h dry tonne | | | | | | | | |
| Electricity | kW/dry tonne | 2288 | 1120 | 1639.344262 | 1694.955254 | 1136.363636 | 962.5 | 862.0689655 | 862.0689655 |
| Syngas | kWh/dry tonne | | | | | | | | |
| Natural gas | kWh/dry tonne | | | | | | | | |
| Fuel oil | kWh/dry tonne | | | | | | | | |
| Output | Purge gas | kWh/dry tonne | | | | | | | |
Table 10 (continued)

| Reference | 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) |
|-----------|-------|-----------------------|-----------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| F-T Liquids | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| F-T Waxes | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| Gasoline | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne | MWh/dry tonne | kg/dry tonne |
| Vendor | Units | SVZ process | Ako Nobel Stream Gasification Process | POWERHOUSE ENERGY GROUP, DMG | POWERHOUSE ENERGY GROUP, DMG |
|-----------|-------|----------------|--------------------------------|---------------------------|---------------------------|
| Output Material | Reactor off-gas | MWh/dry tonne | kg/dry tonne | 4.5968 | 4.5968 | 4.5968 | 4.5968 | 4.5968 | 4.5968 | 4.5968 |
| Residuals | Residual gas | kg/dry tonne | kg/dry tonne | 0.0104 | 0.0104 | 0.0104 | 0.0104 | 0.0104 | 0.0104 | 0.0104 |
| | Sulphur | kg/dry tonne | kg/dry tonne | 1.9968 | 1.9968 | 1.9968 | 1.9968 | 1.9968 | 1.9968 | 1.9968 |
| | Salt | kg/dry tonne | kg/dry tonne | 210 | 210 | 210 | 210 | 210 | 210 | 210 |
| | Slag | kg/dry tonne | kg/dry tonne | 4.68 | 4.68 | 4.68 | 4.68 | 4.68 | 4.68 | 4.68 |
| | Filter cake | kg/dry tonne | kg/dry tonne | | | | | | | |
| | HCl | kg/dry tonne | kg/dry tonne | | | | | | | |
| | NaCl | kWh/tonne | kWh/tonne | | | | | | | |
| | Solids | kWh/tonne | kWh/tonne | | | | | | | |
| | Char | kg/dry tonne | kg/dry tonne |
| | Slag | kg/dry tonne | kg/dry tonne | 0.8832 | 0.8832 | 0.8832 | 0.8832 | 0.8832 | 0.8832 | 0.8832 |
| | Tar | kg/dry tonne | kg/dry tonne |
| | Gasifier solid residues | kg/dry tonne | kg/dry tonne |
| | Spent catalysts and chemicals | kg/dry tonne | kg/dry tonne |
| | Ash | kg/dry tonne | kg/dry tonne | 220 | 220 | 220 | 220 | 220 | 220 | 220 |
| | Air Pollution Control System residues | kg/dry tonne | kg/dry tonne | 146.88 | 146.88 | 146.88 | 146.88 | 146.88 | 146.88 | 146.88 |
| | | | | 100.84 | 100.84 | 100.84 | 100.84 | 100.84 | 100.84 | 100.84 |
| | | | | 82.27 | 82.27 | 82.27 | 82.27 | 82.27 | 82.27 | 82.27 |
| | | | | 35.78 | 35.78 | 35.78 | 35.78 | 35.78 | 35.78 | 35.78 |
| | | | | 68.36 | 68.36 | 68.36 | 68.36 | 68.36 | 68.36 | 68.36 |
| | | | | 68.36 | 68.36 | 68.36 | 68.36 | 68.36 | 68.36 | 68.36 |
| Unit | Inorganic sludge | Gypsum | Non-hazardous solid waste | Water | Potable water | Heat losses | Water losses | Air Emissions Data | CO2eq kg/dry tonne |
|------|------------------|--------|---------------------------|-------|--------------|------------|--------------|------------------|------------------|
| kg/dry tonne | 98.13542689 | 9715.407262 | 9715.407262 | 9715.407262 | 9715.407262 | 9715.407262 | 9715.407262 | 9715.407262 | 9715.407262 |
| kg/dry tonne | 0.01 | 0.012881356 | 0.066931818 | 0.01890625 | 0.061551724 | 0.01 | 0.012881356 | 0.066931818 | 0.01890625 | 0.061551724 |
| kg/dry tonne | 12,177.26397 | 2622.95082 | 2762.711864 | 2409.090909 | 2828.125 | 1922.413793 | 1922.413793 | 1922.413793 | 1922.413793 |
| kg/dry tonne | 0.000180328 | 0.104204545 | 0.0053125 | 0.027327586 | 0.027327586 | 0.000180328 | 0.104204545 | 0.0053125 | 0.027327586 | 0.027327586 |
| kg/dry tonne | 0.098863636 | 0.0984375 | 0.103448276 | 0.103448276 | 0.103448276 | 0.098863636 | 0.0984375 | 0.103448276 | 0.103448276 | 0.103448276 |
| kg/dry tonne | 0.01 | 0.012881356 | 0.066931818 | 0.01890625 | 0.061551724 | 0.01 | 0.012881356 | 0.066931818 | 0.01890625 | 0.061551724 |
| Vendor       | Units               | SVZ process | Akzo Nobel Stream Gasification Process | POWER HOUSE ENERGY GROUP, DMG | I            | II            | III           | IV            | V            | VI           |
|--------------|---------------------|-------------|----------------------------------------|-----------------------------|--------------|--------------|---------------|--------------|--------------|--------------|
| NOx          | kg/dry tonne        |             |                                        |                             | 0.0703227869 | 0.071355932 | 0.0625        | 0.06953125   | 0.066034483 | 0.066034483 |
| Carbon monoxide (CO) | kg/dry tonne |             |                                        |                             |              |              |               |              |              |              |
| Mercury (Hg) | kg/dry tonne        |             |                                        |                             | 6.55738E-07  | 6.77968E-07 | 1.13636E-06  | 1.5625E-06   | 8.62069E-07 | 8.62069E-07 |
| Cadmium (Cd) | kg/dry tonne        |             |                                        |                             | 1.6934E-06   | 1.69492E-06 | 2.27273E-05  | 4.8875E-06   | 1.72144E-06 | 1.72144E-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        |             |                                        |                             |              |              |               |              |              |              |
| NH33         | kg/dry tonne        |             |                                        |                             | 3.27869E-05  | 3.38983E-05 | 3.40099E-05  | 0.00003125   | 3.44828E-05 | 3.44828E-05 |
| Dioxins and furans | kg/dry tonne |             |                                        |                             | 6.55738E-12  | 6.77968E-12 | 8.18818E-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  | 6.77968E-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-05  | 0.00003125   | 2.58621E-06 | 2.58621E-06 |
| Chromium (Cr) | kg/dry tonne |             |                                        |                             | 0.000988636  | 0.0009375   |               |              |              |              |
| Iron (Fe)    | kg/dry tonne        |             |                                        |                             | 0.00659091   | 0.0028125   | 0.001293103   | 2.58621E-05 | 2.58621E-05 | 2.58621E-05 |
| Copper (Cu)  | kg/dry tonne        |             |                                        |                             | 0.01306182   | 0.00171875  | 0.0000625    |              |              |              |
| Zinc (Zn)    | kg/dry tonne        |             |                                        |                             |              |              |               |              |              |              |
| Water Emission Data | kg/dry tonne |             |                                        |                             |              |              |               |              |              |              |
| Water Effluent | l/dry tonne       |             |                                        |                             |              |              |               |              |              |              |

Water Emission Data: 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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Data availability All used data and materials are referenced in the manuscript.

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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