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Research article

Plastics value chain – Abatement of greenhouse gas emissions

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Abstract: This study focuses on the possibilities to abate greenhouse gas emissions in the value chain of plastics with special emphasis on efficiency improvements in the virgin plastics production and to recycle or reuse/regenerate plastics from waste streams. The study is restricted to the plastics and their intermediates produced in annual quantities over 20 million tons (Mt) on global scale. The chemicals and polymers considered include intermediate feedstocks ammonia, methanol, ethene and propene, polyolefins polyethylene and polypropylene, and other included polymers are polyester, polyamide and acrylic fibres, polyvinylchloride, polyethylene terephthalate, polyurethane resin and polystyrene. Improved efficiency in the virgin plastic value chain has the potential to reduce global greenhouse gas (GHG) emissions by 531 Mt CO_2eq /y, provided that all of the current global production is upgraded to meet the European Union's best benchmarked facilities. These improvements would mean a 15.4% reduction of all global chemical sector emissions. The evaluation of probability for all global production facilities to reach the EU benchmarked values is excluded as unclear. Increasing the global recycling rate of plastics from the current 18% to 42% would reduce global greenhouse gas emissions by 142.3 Mt CO_2eq /a, provided that the segregation of recyclable materials is improved, and that incineration is not increased. These downstream improvements would mean a 4% reduction of all global chemical sector emissions and reduce the accumulation of plastics not only on land but also in the oceans.

Keywords: plastics; greenhouse gases; abatement; mitigation; recycling; climate change

1. Introduction

Chemicals are the cornerstones of modern life, and plastics are chemicals produced in bulk quantities. The value chain of plastics can be separated into two different parts; virgin plastics

production from cradle-to-gate and recycling of plastic waste. The recycling side comprises of the consumption of plastics, waste generation, disposal of waste and recycling of plastic waste. The share of the OECD countries production capacity is estimated to decrease from 40% to 20% when low energy prices place about 60% of new basic chemical production capacity in non-OECD regions by 2030. This development would increase the global carbon dioxide (CO_2) emissions of the chemical sector by 50% [1]. The vast majority of feedstock used to make plastics, such as ethylene and propylene, originate from fossil hydrocarbons, and the plastics waste produced is seldom biodegradable accumulating, rather than decomposing, in landfills or in the natural environment. On the recycling side increasing urbanization, especially in the Indian Peninsula, Southeast Asia and Africa, causes waste management problems, resulting in the accumulation of plastics not only on land but also in the oceans. The plastic waste in the oceans increases at the rate of about eight million metric tons every year [2]. The environmental losses of global plastic value chain were estimated by Ryberg et al. [3] to 9.2 Mt in 2015. This illustrates the magnitude of the plastics recycling problem that awaits a solution. The World Bank [4] and the World Wildlife Fund [5] have both recently published reports on plastic waste management including future projections up to 2030 and 2050 with growth rates up to 40% in the production of plastics until 2030. Collection of plastic waste prior to landfilling and preventing the leakage of already landfilled plastic waste would considerably reduce the volume of plastics entering the oceans. The environmental impact of plastics was mapped by Ciel [6]. Several countries already restrict the use of disposable single-use plastic utensils. In addition, concerns regarding human consumption of microplastics are growing [7]. The increasing accumulation of plastics in ecosystems needs innovative solutions since a total ban on plastics is hardly an option to solve the problem. The Global Commitment on plastics has already over 450 signatories, mainly large companies, that are determined to start building a circular economy for plastic with a recent progress report [8]. A recent study mapped material flows of seven major plastics in the United States in 2015 stressing the low end-of-life recycling rate [9].

As for greenhouse gas (GHG) emissions, the chemical sector, producer of plastics, is the third largest industrial emitter of carbon dioxide after steel and cement production with 5.5% of global emissions [10]. In addition, the chemical sector is the largest industrial energy consumer and in all responsible for approximately 7% of global GHG emissions [11]. Much research is being directed to reduce the energy, and to improve the efficiency of chemicals production. Energy intensive pyrolysis is proposed as one option to utilize waste plastics as an intermediate for transport fuels [12,13]. A recent study compared the environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. The climate impact of pyrolysis and mechanical recycling were comparable and the avoided GHG emissions of chemical recycling were significant [14]. The research on chemical recycling of waste plastic is increasing and a variety of technologies are identified [15]. Considerable efforts are directed to recycling, reuse and substituting plastics [16], recycling of hard plastic waste [17] and managing plastics in municipal waste [18,19], and to developing plastics from renewable resources including low carbon bioethylene [20], partly biobased and recycled polyethylene terephthalate (PET) [21], fully bioderived PET [22] and polyesters derived from CO_2 [23]. Recent research highlights life cycle impacts of recycled polyethylene (PE) both bio and fossil based by Tonini et al. [24] and of PET, virgin, recycled and bioderived bottles [25] and fossil and biobased PET [26]. The results of Blank et al. [27] on the future of CO_2 and plastic waste are optimistic on manufacture of multiple products from simple bulk chemicals to pharmaceuticals using biotechnology. Walker and Rothman [28] critically reviewed and compared the

life cycle assessments (LCA) of fossil and biobased plastics to the European Union Product Environmental Footprint (EU PEF) standards. The results recommend wider use of the PEF standard to avoid the different system boundaries of LCA. A recent study estimated the supply chain energy and GHG emissions for annual plastics consumption in the United States for 18 major polymer types providing a benchmark against which to compare new technologies, renewable plastics and recycling of plastic waste [29].

Gaps in global production and materials flow data of plastics exist. The identified research gaps are manifold; the relative advantages and disadvantages of dematerialization, substitution, reuse, material recycling, waste-to-energy and conversion technologies need careful assessment. We need less littering, more recycling, and new routes for recovering and utilizing plastic waste as a raw material. Increasing efficiency in the value chain together with recycling and production of renewable plastics offer win-win opportunities to close the carbon loop and to reduce greenhouse gas emissions. The goal of this study is to assess the GHG saving potential in the global value chain of plastic. This study focuses on the midpoint climate impact of efficiency improvements in the virgin plastic production and improved recycling in the plastics value chain compared to the current GHG emissions identified in this study. The study is restricted to the polymers and their intermediates produced in annual quantities over 20 million tons a year (Mt/y) on global scale. The detailed assessment of different mechanical and chemical recycling technologies is excluded from the scope.

2. Materials and methods

The aim of this study is to identify the possibilities of combining the abatement of GHG emissions with resource efficiency, recycling or reproducing key bulk plastics from waste streams on global scale. The key bulk plastics referred here are polymers or resins produced in quantities over 20 Mt/y. The analysis includes also the high-volume raw materials for plastics production. In this study the value chain of plastics is separated into two different parts; virgin plastics production from cradle-to-gate and recycling of plastic waste. The recycling side comprises of the consumption of plastics, waste generation, disposal of waste and recycling of plastic waste. The methodology includes collection of data on the production and consumption of plastics, followed by the evaluation of options for scenario development. Finally, a robust life cycle analysis to evaluate the most promising scenarios completes the study.

2.1. Collection of data on production and consumption of plastics

Attention was especially placed on polymers from fossil resources that accumulate in landfills or litter the environment and leak to seas and lakes. The aim of the survey was to identify the key chemicals/polymers in the value chain of plastics originating from a fossil resource base. The survey includes data collection, analysis and assumptions. Chemicals/polymers produced in quantities over 20 Mt/y were considered. Bio-based or biodegradable plastics currently having a global production capacity of only 2.1 Mt [30] are excluded from this study. However, as new options for future, the renewable production routes can be included.

2.1.1. Data collection

The production statistics of plastics including key feedstock chemicals were compiled from existing public sources. Attention was especially paid on plastics from fossil resources that accumulate in landfills or litter the environment and leak to seas and lakes. The distribution of global plastics production is from [30]. The fossil raw material flows, intermediate chemicals and proxies for chemicals consumed in quantities less than 20 Mt/y on the upstream side were identified. Key data were retrieved from several sources: ammonia [31–33], methanol [34,35], urea [32], ethylene [36] and propylene [37]. The actual plastic production, waste generation, recycling and incineration data rely mainly on Geyer et al. [38] and WWF [5]. Comprehensive data on global geographical distribution of the plastics production was not readily available from public sources and not included in this study.

2.1.2. Data analysis

The current annual production volume, waste generation, recycling and incineration rate reveals the chemicals beneficial for recycling from waste streams or for regeneration/reuse from waste or renewable resources. For this purpose, the global production in the value chain of plastics in this study is defined as follows:

$$\sum \text{Prod (i)} = \sum \text{Waste (i)} - \sum \text{Recycle (i)} - \sum \text{Incinerate (i)} + \sum \text{Difference (i)} \quad (1)$$

where i is the chemical/polymer, Prod is the amount produced in Mt/y, Waste is total waste generation (including recycled and incinerated amounts) in Mt/y, Recycle is the amount recycled waste in Mt/y, Incinerate is the amount incinerated waste in Mt/y, and Difference is the amount of plastics remaining in long-term use. The maximal additional recycling potential of plastics was estimated from Eq 1 by deducting the current amounts of recycling and incineration from the generated waste amounts.

2.1.3. Data assumptions

Key raw materials, chemicals, precursors and plastics produced in the virgin plastics value chain were selected using the approach of Levi and Cullen [39] for mapping of chemical flows i.e. based on mass balances, key chemical reactions and existing technological solutions. An average standard deviation between −5 and +5% was assumed for the production and consumption amounts found from public sources. It was assumed that end-of life textiles with synthetic fibres are incinerated or discarded as municipal solid waste. Currently no global statistics is available on the recycling or reuse of synthetic fibres, although this is a growing business. Comprehensive data on geographical distribution of the plastics production is not readily available from public sources. Assumptions on production data of chemicals are given in section 3.1. Assumptions used in the preliminary robust life cycle assessment are given in section 3.3.

2.2. Evaluation of options for scenario analysis

The production routes of selected chemicals are analyzed with emphasis on the GHG emissions. Different production routes for each chemical are assessed using the volumes of production and waste generation from Eq.1 as a base. The criteria for efficiency improvements in the virgin plastics value chain is reduced GHG emissions. Renewable options for plastics production are not excluded. On the

recycling side the target is to identify recycling possibilities reducing the GHG emissions. The evaluation results in scenarios for the robust life cycle analysis.

2.3. Preliminary life cycle assessment

Life cycle assessment (LCA) is a common standardized tool [40,41]. LCA consists of four phases: (1) the goal and scope definition, (2) the life cycle inventory (LCI) analysis, (3) the life cycle impact assessment (LCIA) phase and (4) life cycle interpretation.

2.3.1. The goal and scope definition

The goal of this LCA is to assess the GHG saving potential in the global value chain of plastic, and to determine the midpoint climate impact of selected three scenarios illustrated in Figure 1. The scope covers the current virgin plastics product system (Scenario A), improved efficiency in the virgin plastics product system (Scenario B) and increased recycling of waste plastics (Scenario C) in global scale. The system boundary and approach is on a cradle-to-gate basis for virgin plastics production scenarios. The system boundary condition for recycling Scenario C excludes the use phase of plastics and is on waste-to-cradle or new product gate basis. The functional unit (FU) used is 1t of chemical/polymer produced or recycled plastic waste in the LCI for emission coefficient estimation, and Mt of chemical/polymer or recycled plastic waste for global LCIA, the system boundaries are shown in Figure 1. Each chemical/polymer/plastic included in the value chain of study is listed with a LCI result reflecting the FU and the global summary GHG emissions are calculated by multiplying the production or recycled amounts with the corresponding emissions coefficients. The LCIA results are explained in section 3.4 LCIA - Results of scenario analysis. The change from single chemical/polymer LCI to a summary global LCIA is explained also in the methods section. GHG emission allocation is used for the production emissions of ethane and propane in petroleum refineries. The impact category is restricted to midpoint climate impact. The methodology for impact assessment was global warming potential (GWP) calculated for the identified GHG emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) utilizing emission coefficients from IPCC AR4 (2007) in own calculations i.e. 1 for CO_2, 25 for CH_4 and 298 for N_2O. If the reference data contained other GHG's they were not used for GWP calculation. CO_2 emissions alone were used to define the GHG emissions when data on CH_4 and N_2O emissions were not available. The GHGs are expressed in carbon dioxide equivalents (CO_2eq). The results obtained are calculated to correspond the FU's defined for emission coefficients and global production or recycled amounts. A summary for the scope of scenarios is illustrated in Table 1. The robust LCA includes several assumptions relating to the production data of chemicals, e.g. selection of precursors for chemicals not included in this study (section 3.1). The assumptions for LCI data are specified in section 3.3. The GHG emissions connected to land use and land use change (LULUC) are not considered in this study. Detailed LCAs for each chemical/polymer included in this study, and on recycling of all plastics waste generated on a global scale are beyond the scope of this study. The reason behind this is the fact that the plastic production, waste streams, collection data and landfill specifics would require a geographic information system (GIS) meta-analysis from every spot on the globe. This kind of data were not available. The identification of the chemicals/polymers included in this study, and their use in the value chain of plastics is a part of our results (section 3.1).

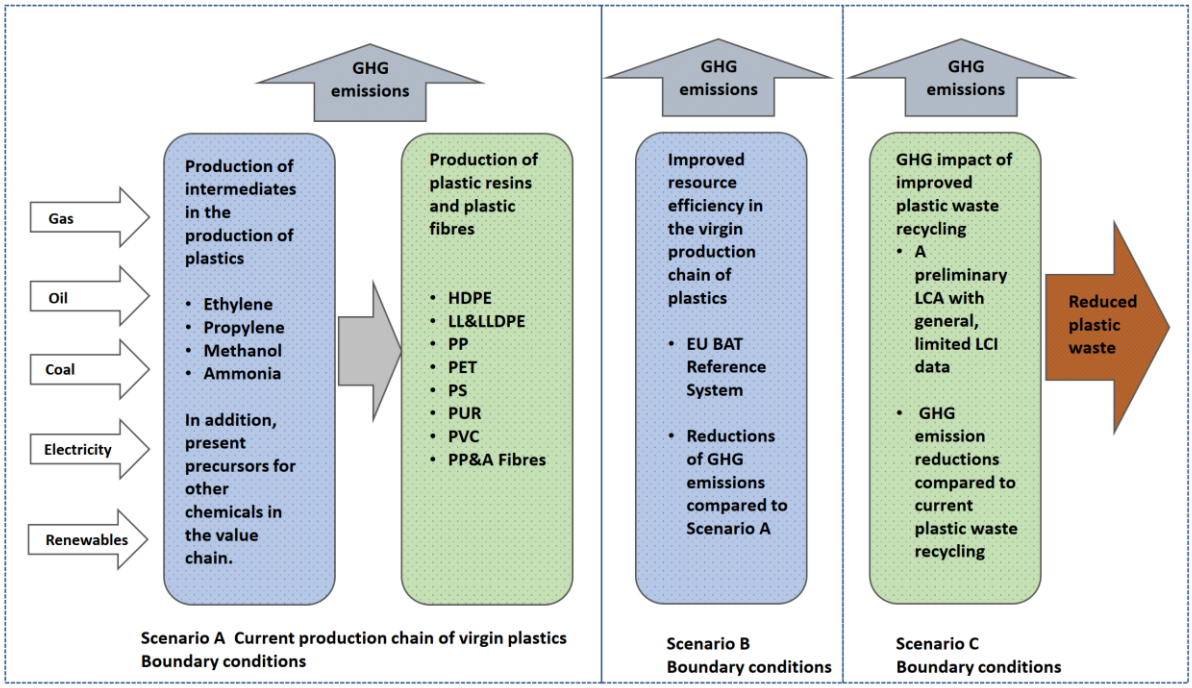

Figure 1. A summary of assessment - LCA scenarios based on production and consumption of plastics. Abbreviations used for plastics are: high-density polyethylene (HDPE) and low-density and linear low-density polyethylene (LD&LLDPE), polypropylene (PP), polyester, polyamide and acrylic (PP&A) fibres, polyvinylchloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR) resin and polystyrene (PS).

2.3.2. The LCI analysis and LCIA

The LCI input/output data are collected from public sources or estimated from the available process and technological data. Only GHG emissions are considered. The LCI results are calculated using the specific emission coefficients, e.g. t CO_2eq/t PUR. Analysis of the robustness and uncertainty of LCI data and assumptions is included. After data collection, the data were validated and related to the reference flow of the functional unit of each chemical/polymer included in the study. The results of LCIA are reported as total global GHG emissions for Scenario A and as total GHG emission reductions identified for Scenarios B and C. Detailed chemical reactions and unit processes in the production chain are not reported.

2.3.3. Life cycle interpretation

The interpretation of LCA results includes evaluation of consistency with the defined goal and scope, identification of the significant issues, evaluation of completeness, sensitivity, limitations of the obtained results and conclusive recommendations. The environmental hot spots are excluded due to the preliminary nature of the LCA and missing geographical data on production locations.

Table 1. Scope of scenarios for LCA.

Scenario	A Base case	B Improved efficiency	C Improved recycling
Investigated options	Current value chain of plastics	Production efficiency improved to the EU benchmark	Recycling increased with near term recyclable amounts from Figure 3
Functional unit (FU) for LCI emission coefficients	1 t of chemical/polymer produced	1 t of chemical/polymer produced	1 t recycled waste plastics
Functional unit (FU) for LCIA of the global value chain	Mt of chemical/polymer produced	Mt of chemical/polymer produced	Mt of recycled waste plastics
Time horizon	2015–2021	2015–2030	2015–2030
Geographical boundaries	Global	Global	Global
System boundary	cradle-to-gate	cradle-to-gate or feedstock-to-gate	waste-to-new product gate or cradle
Allocation	Allocation used only if listed in life cycle inventory (LCI) data.		
Impact category	Midpoint Climate change. GHG emissions expressed in carbon dioxide equivalents (CO2eq).		
Limitations	Greenhouse gas emissions connected to land use and land use change (LULUC) are not considered in this study.		

3. Results and discussion

The results start with the identification of the key bulk chemicals in the production chain of plastics on a global scale. Thereafter follows the analysis of the production routes of selected chemicals aimed to identify the precursors of chemicals not included in the study. The results cover the evaluation of options for scenario development, taking into account the specific consumption patterns of each chemical. Finally, a robust LCA of the selected scenarios completes the results.

3.1. Identification of chemicals and polymers in the value chain of plastics

The analysis of available production data revealed 12 bulk chemicals/polymers as the most prevalent for further screening with potential for recycling and reuse/regeneration from waste or renewable resources in the value chain of plastics. In order of magnitude, these chemicals/polymers are as follows: ethylene (C_2H_4), propylene (C_3H_6), high-density polyethylene (HDPE) and low-density and linear low-density polyethylene (LD&LLDPE), methanol (CH_3OH), polypropylene (PP), polyester, polyamide and acrylic (PP&A) fibres, polyvinylchloride (PVC), ammonia (NH_3), polyethylene terephthalate (PET), polyurethane (PUR) resin and polystyrene (PS). The global production of plastic resins and fibres including their additives reached over 400 Mt in 2015. On average, non-fibrous plastics contain 93% polymer resin and 7% additives by mass. In addition to the plastic resins and fibres the production of other polymers and additives accounted for 41 Mt. NH_3, C_2H_4, CH_3OH and C_3H_6 are intermediates in the production of both plastic resins and fibres and are commodity chemicals widely utilized for various applications. The global annual production of the

key feedstock chemicals and their share in the value chain of plastics is shown in Table 2. The estimates for NH_3 and CH_3OH use in the production chain of plastics are also precursors for the use of all other fossil feedstock chemicals not listed here and, therefore, do not represent their actual consumption figures in the production of plastics. The use of NH_3, C_2H_4, CH_3OH and C_3H_6 as precursors for other chemicals is explained in Table 2. The annual global production of plastics is shown in Table 3. The geographical distribution of C_2H_4 and C_3H_6 production is illustrated in Figure 2.

Table 2. Global production of key feedstock chemicals and their use in the value chain of plastics.

Chemical	Global production Mt/y	% of the production in the value chain of plastics	Additional remarks
Ammonia	175	20.57*	For the production of urea for PUR and methyl 2-methylpropenoate, a key monomer for the manufacture of various acrylic polymers.
Urea	173	n.a.	Produced from ammonia and counted as ammonia.
Methanol	95	64.21*	Methanol as precursor is used for the production of ethylene and propylene (methanol-to-olefins or MTO) and formaldehyde.
Ethylene	177	97.74*	In 2016, polyethylene accounted for nearly 62% of total ethylene consumption. In addition, ethylene is used as a precursor for PET, PVC and PS production feedstock since ethylene oxide is primarily for PET production via ethylene glycol, and ethylene dichloride is for PVC production via vinyl chloride.
Propylene	96	100*	Polypropylene accounted for nearly 71% of total propylene consumption in 2015, and the latter is, in addition, used as a precursor for PUR production as feedstock.

Note: *Partly precursors for other chemicals in the plastics production chain.

Table 3. Global production of polymers in Mt/y.

Plastics	HDPE	LD&LLDPE	PP	PS	PVC	PET*	PUR resins	PP&A fibres
Production (Mt/y)	52	64	68	25	38	33	27	59

Note: *PET used for polyester production is included in PP&A fibres amount.

The estimates for the waste generation, recycling and incineration of chemicals/polymers are based on collected data and several assumptions. The assumption was that all NH_3 is utilized without recycling or incineration. Similarly, it was assumed no direct waste generation, recycling or incineration for C_2H_4, CH_3OH and C_3H_6 in the value chain of plastics. Plastic resin and fibre waste generation accounted for 74.2% of total polymer production in 2015. The recycling and incineration of plastics vary considerably depending on the geographical location. Detailed global data on recycling and incineration for different non-fibrous plastics is scattered and scarce. An 18% global recycling and 24% global incineration rates was assumed. PVC is practically not recycled (only 0.5 Mt in Europe),

and no data is available on its incineration. PE, PP and PET are most common in packaging materials and more easily recycled. PS and PUR are seldom recycled and thus the assumption was zero recycling and 24% incineration. PP&A fibre waste practically all landfilled or incinerated, and 11% incineration on the global scale was assumed [4]. Production of recycled fibres exists in small quantities, e.g. recovered from plastic waste in the oceans. The volumes of waste generation, recycling and incineration of chemicals included in this study are illustrated in Table 4.

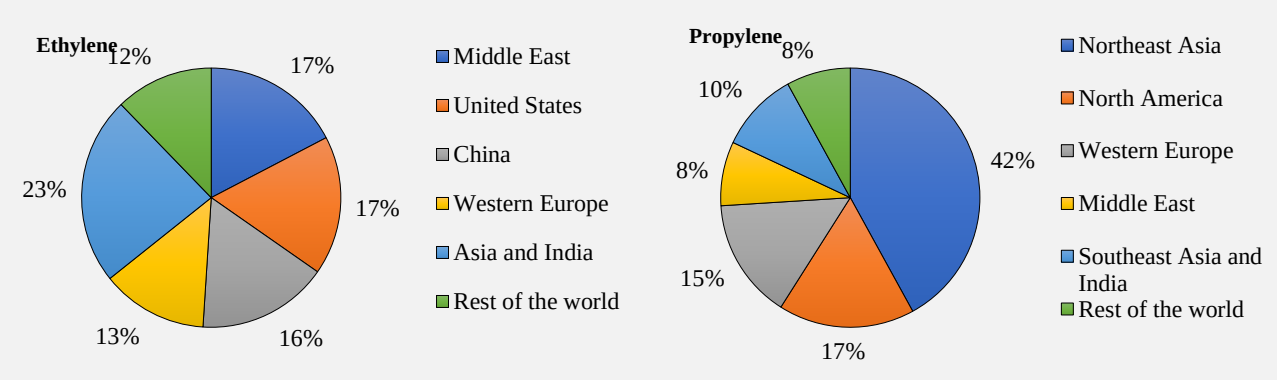

Figure 2. World consumption of ethylene 177 Mt and propylene 96 Mt in 2016. Ethylene and propylene being the key intermediates in the plastics production, these consumption figures also indicate the geographical distribution of plastics production and follow the European Bioplastics statistics [30] without PP&A fibres (Nafta 18%, Europe 17%, CIS 3%, Asia 51%).

Table 4. Global production or consumption, waste generation, recycling and incineration in the value chain of plastics in Mt/y from Eq 1.

Chemical	Consumption or Production	Waste	Recycled waste	Incinerated waste
NH_3**	36	0	0	0
CH_3OH**	61	0	0	0
C_2H_4**	173	0	0	3
C_3H_6**	96	0	0	2
HDPE	52	40	7	11
LD&LLDPE	64	57	13	15
PP	68	55	13	14
PS	25	17	0	4
PVC	38	15	0	n.a.
PET*	33	32	8	8
PUR	27	16	0	4
PP&A fibres	59	42	0	5

Notes: *PET used for polyester production is included in PP&A fibres amount. **Partly precursors for other chemicals in the plastics production chain, explained in Table 2.

Total primary non-fibrous plastic waste generation accounts for 232 Mt in Table 4, nearly 53% of which consists of packaging waste. The overall conversion efficiency of feedstock, including precursors, to plastics listed in Table 1. is 67%, and 74% if all plastics and their additives from fossil resources are included.

3.2. Evaluation of options for scenario analysis

The evaluation started with the analysis of the production routes of selected chemicals. Different options, both in the virgin plastics production and recycling of plastic waste, were evaluated, taking into account the specific consumption patterns of each chemical. In particular, the possibilities for increased direct recycling and resource-efficient technologies were highlighted.

3.2.1. Virgin plastics production

Traditionally, NH_3 is produced from natural gas (CH_4) via Haber-Bosch synthesis and the process is energy-intensive. China produces CH_4 by coal gasification. Similarly, CH_3OH is produced from CH_4 or coal. C_2H_4 is produced in petroleum refinery cracking units using crude oil and natural gas as primary resources. C_3H_6 is produced by the propane dehydrogenation units of petroleum refineries and other on-purpose units. These intermediate chemicals in the value chain of plastics do not generate physical long-life waste (in normal use and excluding accidents) in the environment, only emissions into the atmosphere. Therefore, direct recycling, reuse and waste-to-energy are not realistic options for these chemicals. Changing to renewable resources and utilizing resource-efficient technologies are the best options for achieving better material efficiency and reduction in the use of fossil resources in the value chain of plastics. Development of alternative, substitute materials for plastics is also an option worth considering as a long-term solution. Similarly, chemical recycling of plastic waste, i.e. as a feed stream for petroleum refineries or other chemical treatment facilities, is a realistic option available before 2030.

3.2.2. Plastic waste recycling options

Plastic resins and fibres, i.e. HDPE and LD&LLDPE, PP, PP&A fibres, PVC, PET, PUR and PS, all generate long-life waste in the environment. Therefore, direct recycling, reuse, substitution with renewable materials, material's use reduction and waste-to-energy solutions are the primary options for material efficiency and reduction in the use of fossil resources. The current waste generation of these plastics equals 274 Mt/y and recycled and incinerated waste amounts to 102 Mt/y (Table 4). Consequently, maximal additional recyclable waste amounts to 172 Mt/y. The near-term potential for improving recycling, starting from the consumption pattern of each non-fibrous plastic was evaluated. The polymer-specific end-use data per market sector was combined with the sector-specific waste generation data and the current polymer-specific incineration and recycling amounts were deducted from the obtained values and detailed in the Figure S1. The additional potential for near-term recycling of non-fibrous plastics amounts to 86 Mt/y, and that of fibres to 8 Mt/y. The maximal and near-term potential additional recyclable waste volumes are illustrated in Figure 3.

The estimates indicate that improving near-term recycling (the values shown in brackets are additional volumes eligible for recycling) is easiest for packaging materials, i.e. LD&LLDPE (22 Mt/y), HDPE (14 Mt/y), PP (17 Mt/y) and PET (12 Mt/y). Additional recycling or incineration of PS (8 Mt/y) is also possible. PVC (7 Mt/y) and PUR (6 Mt/y) would need partial or full chemical recycling. The total global recycling rates identified in this study are lower than e.g. those estimated for the EU by Tallentire and Steubing [42]. Better regulation of the global plastic waste export trade would reduce the amount of poorly recyclable, low-quality waste. Increased recycling and reuse of plastics would

allow more time to develop replacement technologies for plastics, with alternative, preferably renewable materials that have positive impacts on the environment.

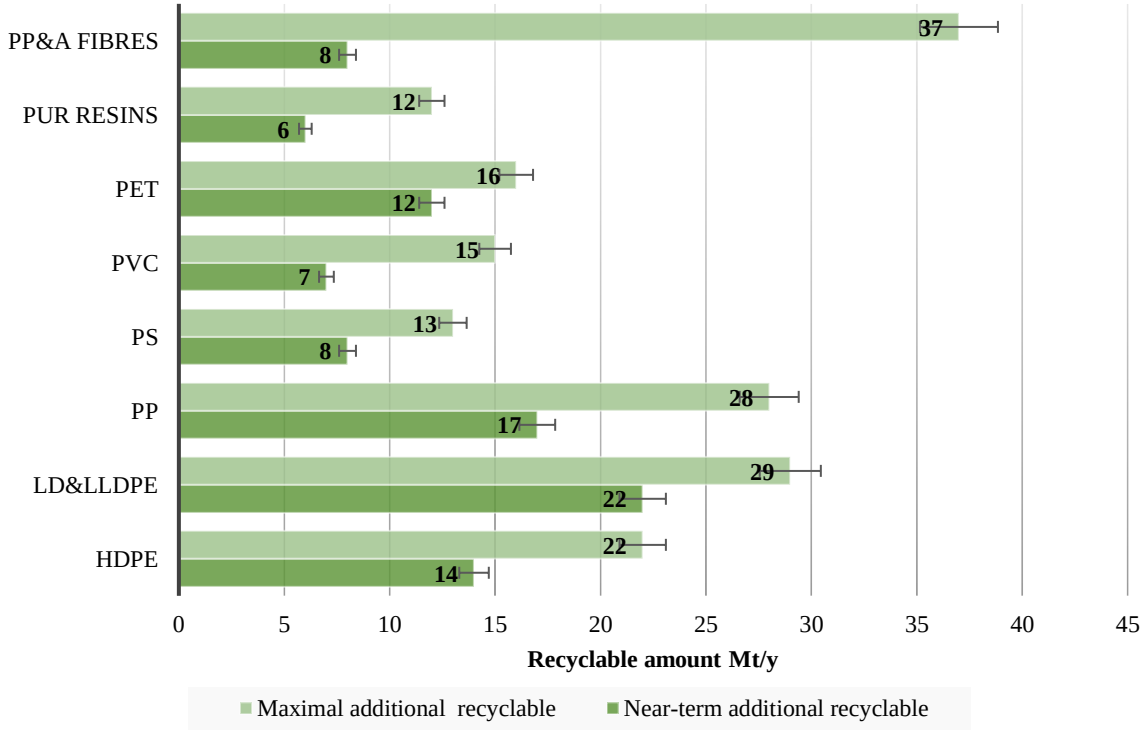

Figure 3. Global additional recycling potential of plastics in Mt/y.

3.3. Preliminary life cycle assessment

A robust life cycle estimation of the GHG emissions of the potentially best options for reducing virgin material consumption and GHG emissions in the global supply chain of each chemical/plastic produced or plastic waste recycled complete this study. Three different scenarios, base case and two based on technological choices from Figure 1 are included and explained in Table 1 section 2.3.

3.3.1. Key inventory data and assumptions for Scenarios A and B

The global GHG and CO2 emissions are taken from UNEP [43]. The corresponding chemical sector emissions were calculated using the percentages of global emissions given by IEA [11]. It was assumed that % not amounts were unchanged between 2013 and 2018 for the chemical industry on the global scale. Key LCI data for scenarios A and B is shown in Table 5. For the selected impact category of midpoint climate change the parameter is GHG emissions expressed in t CO_2eq/t of chemical produced.

3.3.2. LCI data for improved recycling of plastic waste

The embedded emissions of PET amount to 2.04 t CO_2eq /t, and those of PE and PP are 3.14 t CO_2eq /t. The production emissions of PE and PP amount to 2.38 t CO_2eq /t. Accordingly, PET production emissions are 3.26 kg CO_2eq /kg. The GHG emissions from incineration of PET trays is 2.0 t CO_2eq/t, and 1.3 t CO_2eq/t by avoiding the use of fossil energy. The mechanical recycling of PET

trays has GHG emissions of 0.15 t CO_2eq/t and avoided emissions of 2.35 t CO_2eq/t by avoiding the use of virgin material. Similarly, mechanical recycling of mixed plastics emits 0.8 t CO_2eq/t and would have avoided emissions of 0.5 t CO_2eq/t by avoiding the use of virgin material. In general, the recycling losses from incineration would amount to 1.7 t CO_2eq/t of mixed plastics by avoiding the use of fossil energy (incineration and recycling data from Bergsma [44]). The recycling of PVC is challenging; it is assumed that the annual quantity of products that can be considered as substitutes for virgin PVC consists of 90% pre-consumer waste and 10% post-consumer waste. The recycling rate of PVC waste in the EU reached 16% in 2014, and the average GHG emissions of recycled PVC total 1.9 t CO_2eq/t, a saving of 0.9 t CO_2eq/t compared to virgin PVC.

Table 5. Emission coefficients in t CO_2eq/t of chemical/polymer produced for Scenarios A and B.

Product	Scenario A: Base case	Scenario B: Improved efficiency
NH_3	Global 2 [48], India residual oil 2.8**	EU BAT* 1.618.
CH_3OH	Global 2.61 [49], China 5.3 [50], China after 2013 installations 3.0 (assumption).	EU Lowest in Sweden 0.462 [51].
C_2H_4	Global from naphtha 1.73 and from ethane 0.95 *. Assumption 60% from naphtha and 40% from on-purpose refinery units for ethane or olefins.	EU BAT 0.702, 26% efficiency improvement in steam cracking.
C_3H_6	Global from naphtha 1.73 and from propane 1.04**. Assumption 60% from naphtha and 40% from on-purpose refinery units for olefins.	EU BAT 0.702, 26% efficiency improvement in steam cracking.
PE	2.38***. Feedstock-to-product (PE film). Assumed the same in global scale.	Emission 1.664. Own estimation based on EU BAT of C_2H_4. Feedstock-to-product.
PP	2.38***. Feedstock-to-product (plastic tray). Assumed the same in global scale.	Emission 1.624. Own estimation based on EU BAT of C_3H_6. Feedstock-to-product.
PET	3.26***. Feedstock-to-product (plastic tray). Assumed the same in global scale.	Emission 2.544. Own estimation based on EU BAT of C_2H_4. Feedstock-to-product.
PVC	2.8* when 89% PVC bulk and 11% PVC latex. Share of polymerization 0.352. Feedstock-to-product. Assumed the same in global scale.	EU BAT 0.085 for PVC bulk, 0.238 for PVC latex and 0.204 for vinyl chloride. Feedstock-to-product. Excludes electricity emissions.
PUR	4.2 [52]. Feedstock-to-product. Assumed the same in global scale.	Emission reduction 0.36. Own estimation based on the EU BAT of styrene production. Feedstock-to-product.
PS	3.3 [52]. Feedstock-to-product. Assumed the same in global scale. Share of styrene monomer 0.887*.	EU BAT 0.527 for styrene monomer. Emission reduction 0.36. Feedstock-to-product.
PP&A fibres	Global 5.05 [5]. Assumed feedstock-to-fibre.	No emission reductions estimated.

Notes: The emission values in Table 3. for Scenario A were selected from several options prioritizing IPCC coefficients. Own calculations are based on production amounts from Table 4 and emissions coefficients from EU BAT. For example, equally probable would be the selection of gasoil for C_3H_6 production (IPCC coefficient 2.29 t CO_2eq/t of C_3H_6 and C_2H_4). This would result in higher GHG emissions in the production chain of propylene. * Boulamanti and Moya [45], ** IPCC [46], *** Patel et al. [47].

3.4. LCIA - Results of scenario analysis

This section describes the results of the robust LCA for the selected three scenarios, and give an overview on GHG emissions of the current production chain of plastics, estimates the impact of process efficiency improvements and highlights near term GHG benefits of increased recycling of plastic waste.

3.4.1. Scenario A: Base case

The GHG emissions of the current value chain of plastics on a cradle-to-gate basis were evaluated in this Scenario A Base Case. The key LCI results for Scenario A are in Table 6. The global chemical sector GHG emissions amounted to 3444 Mt CO_2eq/y and the summed GHG emissions of NH_3, CH_3OH, C_2H_4 and propylene, used as key feedstock chemicals in the value chain of plastics total 616 Mt CO_2eq/y, corresponding to 18% of chemical sector GHG emissions. The GHG emissions of plastics production amounted to 1146 Mt CO_2eq/y and contributed 33.3% to the chemical sector GHG emissions. Thus, the whole value chain of plastics is responsible for 51% percent of the current chemical sector emissions. The average GHG emission resulted 4.81 t CO_2eq/t of plastics.

Table 6. Key Life Cycle Inventory results for Scenario A: Base case global GHG emissions in Mt CO2eq/y.

Emission data	Amount of GHG	Reference
Global GHG	49 200*	UNEP [43]
Global CO_2	37 000	UNEP [43]
Chemical industry GHG	3 444	IEA et al. [11]**
Chemical industry CO_2	2 350	IEA et al. [11]**
NH_3 GHG	72	CAT [48]
CH_3OH GHG	159	own calculations
C_2H4 GHG	245	own calculations
C_3H_6 GHG	140	own calculations
PE GHG	276	own calculations
PP GHG	162	own calculations
PET GHG	108	own calculations
PVC GHG	106	own calculations
PUR GHG	113	own calculations
PS GHG	83	own calculations
PP&A fibres GHG	298	WWF [5]

Notes: *excluding emissions from land use change (LUC). **only percentage of chemical industry of global emissions. Own calculations are based on production amounts from Table 4 and emissions coefficients from Table 5. The production amounts are multiplied with the corresponding emission coefficient to give the total amount of GHG.

3.4.2. Scenario B: Improved virgin plastic production efficiency

The European Union (EU) has benchmarked chemical sector performance on GHG emissions (Table 5). The benchmark values relate to 10% of the best industry performers in the EU. These values

indicate improvement potential in reducing GHG emissions in the production of chemicals when best available techniques (BAT) are implemented. The first step to improve the GHG balance of NH_3, C_2H_4 and C_3H_6 would be to strive for the EU benchmarked values of GHG emissions on the global scale. For NH_3, this would mean a reduction of 0.382 t CO_2eq/t of ammonia produced. Correspondingly, for C_2H_4 and C_3H_6 the reduction would be 0.716 t CO_2eq/t of C_2H_4 and 0.756 t CO_2eq/t of C_3H_6. These and all other GHG impacts of improved resource efficiency on the global scale are illustrated in Figure 4. CH_3OH production has no EU benchmark. Currently the lowest GHG emissions of CH_3OH production are in Sweden and amount to 0.462 t CO_2eq/t of CH_3OH (Table 5). Consequently, switching the current CH_3OH production to the GHG emission level of CH_3OH in Sweden would reduce GHG emissions by 2.148 t CO_2eq/t of CH_3OH.

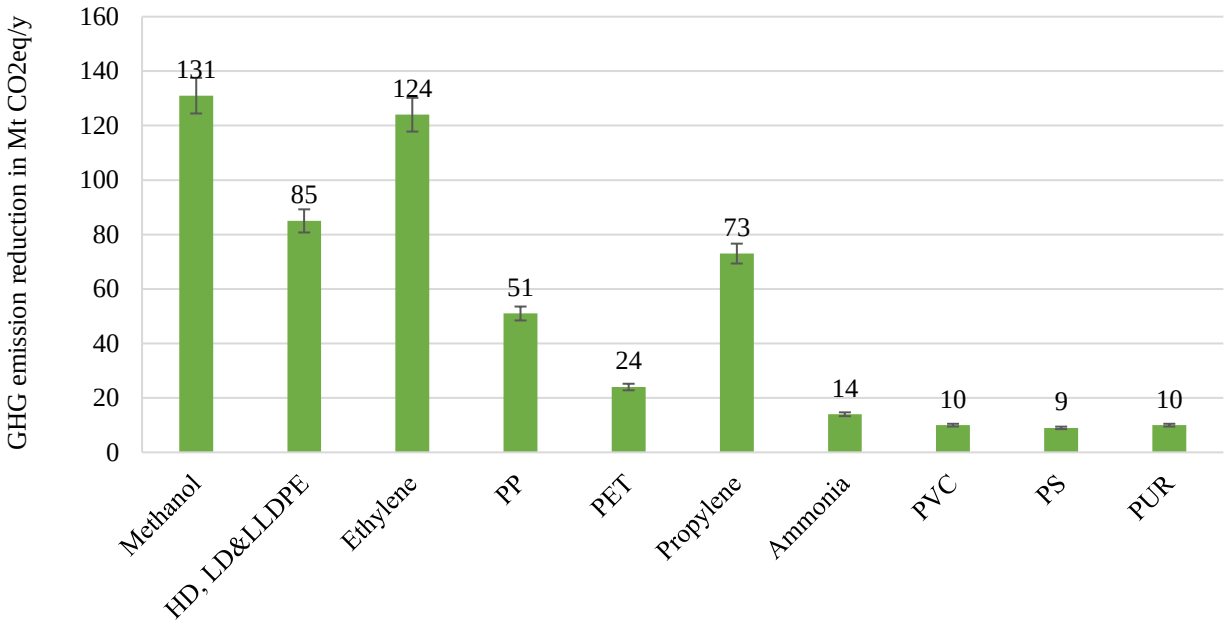

Figure 4. Scenario B: Global GHG impact of improved resource efficiency in Mt CO_2eq/y.

The emission reductions for PE, PET and PP were calculated applying the same C_2H_4 and C_3H_6 emission reduction targets for the feedstock-to-product (plastic tray and PE film). Applying the EU benchmark values, it was possible to reduce the GHG emissions of polymerization with 0.25 t CO_2eq/t of PVC. Similarly, the emissions for PS and PUR were reduced by 0.36 t CO_2eq/t. The global emissions reduction potential of PP&A fibres remained unsolved. The identified near-term possibilities for reducing the GHG impact of the chemicals selected for this study amount to 531 Mt CO_2eq/y. This would mean a 15.4% reduction of all global chemical sector GHG emissions. With these reductions the average GHG emission would drop to 3.36 t CO_2eq/t of plastics. However, the probability for all global production facilities to reach the EU benchmarked values is unclear. To conclude, the option for improved efficiency in the virgin plastics production is readily available for implementation if the financial gains and political will lower the threshold to start GHG reductions in the chemical sector.

3.4.3. Scenario C: Improved recycling

The estimation of GHG emission reductions from improved recycling (Figure 3) would require detailed analysis of the recycling value chain of each polymer, which is beyond the scope of our study. Therefore, only a robust estimate of GHG emission reductions for near-term additional recycling of plastics was performed. Generally, long-life plastics are considered as fossil carbon sinks (embedded CO_2 emissions only), provided that production emissions (cradle-to-gate) are counted as emissions. The incineration of waste plastics also releases the embedded CO_2 emissions. The generation of energy reduces the GHG impact of incinerated plastics. Hence, mechanical and chemical recycling of plastics should be favored. This section includes both LCI data and LCA results for improved recycling of plastic waste.

A robust estimate for the avoided GHG emissions of mixed mechanical recycling of HDPE, LD&LLDPE, PP and PET in the near term (Figure 3) would mean 65 Mt/y of additional recycled plastics with annual avoided GHG emissions of 37.5 Mt CO_2eq. Improved segregation of plastics recycling would considerably increase the amount of avoided GHG emissions: for 12 Mt/y recycled PET the GHG saving alone would be 28 Mt CO_2eq. Assuming the same relation between virgin product emissions and segregated recycled production emissions as for virgin and segregated recycled PET, avoided emissions of 1.716 t CO_2eq/t is possible for recycled HD-PE, LD&LLDPE and PP by avoiding the use of virgin material. This would give avoided GHG emissions of 108 Mt CO_2eq annually on the global scale with an additional recycled volume of 65 Mt/y. The assumption was that it is possible to reach the same PVC recycling rate on the global scale as in the EU. The avoided GHG emissions of additionally recycled PVC would be 6.3 Mt/y. The estimates for the GHG savings from additional recycling of PUR, PS or PP&A fibres remained unsolved. The identified downstream near-term recycling possibilities for segregated plastics would reduce the GHG impact by 142.3 Mt CO_2eq/y. This would mean an additional 4% reduction of all global chemical sector emissions. The downstream GHG impacts of recycling on global scale are illustrated in Figure 5.

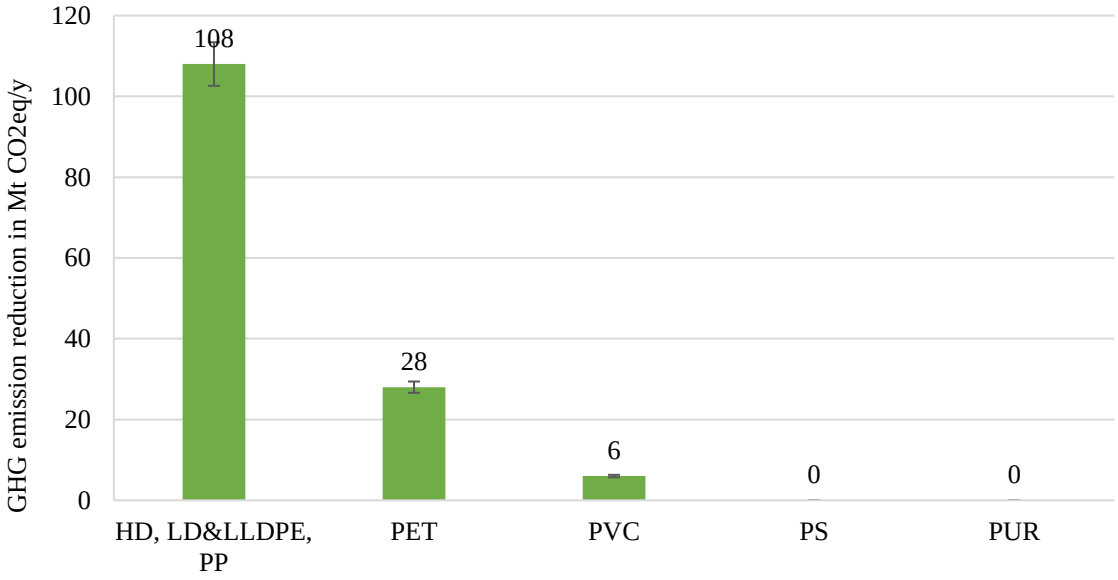

Figure 5. Scenario C: Global GHG impact of improved additional recycling of segregated plastics in Mt CO_2eq/y.

3.4.4. Discussion on green value chain of plastics

We restricted our study on high volume plastics produced from fossil resources. The growing production of renewable plastics and their carbon footprints give mixed results. A LCA study of Tonini et al. [24] found the carbon footprints of biobased production of HDPE from sugarcane, polylactic acid (PLA) from organic waste and polybutylene succinate (BPS) exceeding the recycled fossil HDPE value of 1.7–1.8 t CO_2eq/t. PLA had a carbon footprint of 19–20 t CO_2eq/t. Green C_2H_4 production from corn ethanol reduces GHG emissions only if the energy used in the process is from renewable sources. This is because its production is highly energy-intensive, including H_2 production in the NH_3 fertilizer manufacture and the dehydration of ethanol with consequent water separation. Corn photosynthesis only partly offsets these emissions by CO_2 removal from the atmosphere. Assuming natural gas as the energy resource in green C_2H_4 production, the cradle-to-gate GHG emissions amount to 1.347 t CO_2eq/t of C_2H_4 [53]. The use of natural gas as the energy resource contributes almost 85% of the GHG emissions. Consequently, green C_2H_4 production utilizing only renewable energy resources would reduce the GHG emissions to 0.202 t CO_2eq/t of C_2H_4. Increasing the production of green C_2H_4, and in the future also green C_3H_6, with fully renewable energy would reduce, accordingly, the current GHG emissions by an astounding 1.216 t CO_2eq/t of C_2H_4 and 1.256 t CO2eq/t of C_3H_6. However, we consider this not to be a near-term option. Green NH_3 technology, using air, water and renewable electricity, is under development and expected to be piloted by 2025 [54]. New CH_3OH technologies include production from CO_2 and hydrogen (H_2) [34], and from renewable forest resources [55,56]. The methanol production from captured CO_2 and renewable H_2 delivers a negative emission of −0.752 t CO_2eq/t of CH_3OH. The highest negative emission amounts to −0.914 t CO_2eq/t of CH_3OH produced from forest biomass [46]. Accordingly, captured CO_2 and renewable H_2 technology would reduce current GHG emissions by 3.363 t CO_2eq/t of CH_3OH, and forest biomass technology by 3.525 t CO_2eq/t of CH_3OH. The current production of biobased plastics amounts 2 Mt/y and is no match to the current 400 Mt/y fossil based production of plastic resins, fibres and additives in the value chain of plastics. Increased recycling and reuse of fossil based plastics would allow more time to develop replacement technologies with alternative, preferably renewable materials with positive impacts on the environment.

3.5. Interpretation of results

The interpretation of LCA results includes an assessment of consistency with the defined goal and scope, identification of significant issues and evaluation of completeness of the results. The robustness and sensitivity of the obtained results are addressed, and the limitations of the method used are discussed. Conclusions (section 4) include recommendations for future work. The environmental hot spots are excluded due to the preliminary nature of the LCA and missing geographical data on production locations.

The results are consistent with the defined goal to assess the GHG saving potential in the global value chain of plastic. The implemented scope of the preliminary LCA is consistent with the set target to assess the midpoint climate impact of the current global production of plastics (Scenario A) and to identify the GHG emission reduction potential by improving the efficiency of the virgin plastics production (Scenario B) and by increasing the recycling of waste plastics (Scenario C). Significant issues identified include the found possibilities to improve the global efficiency of the virgin plastics

production and considerable potential to increase the amount of recycled plastic waste. The completeness of the results is adequate for the preliminary and robust level set for the LCA.

3.5.1. Robustness, sensitivity and limitations of the results

We have based our study on references and several assumptions about them. Therefore, our results should be considered with a degree of caution, especially concerning the additional recycling amounts of plastic waste. The preliminary LCA of GHG emissions and their climate impact use published emission values. We have assumed that the LCI values based on references have a maximum confidence interval of between +5 and −5%. Data quality has geographical limitations on production technology used, precision, completeness and representativeness of sources that increase the uncertainty of results. The global data of different plastics produced or consumed differ in various sources e.g. the data set of Rydberg et al. [3] composed from different sources from 2015–2017 differ from the data set of this study. We assume no serious overlapping of GHG emissions in scenarios B and C. Our average emissions for the current plastics production chain are 4.81 t CO_2eq/t compared to a recent average estimate is 5.05 t CO_2eq/t of plastics [5] and even 6 t CO_2eq/t of LDPE or PET are reported [57]. Considerably lower cradle-to-gate emissions in the value chain of plastics, an average of 2.81 t CO_2eq/t for plastics produced in the United States of America (US), are reported using not LCA but the US-focused supply chain modeling tool, Materials Flows through Industry [29]. Efficiency improvement in the virgin plastic production is highly sensitive to the GHG emissions of C_2H_4 and C_3H_6. Mechanical recycling of plastic waste is highly sensitive to the segregation of HDPE, LD&LLDPE, PP and PET. The impact of additional, fully segregated recycling of the plastic waste PE, PP and PET 136 Mt CO_2eq/y drops to 37.5 Mt CO_2eq/y of mixed plastics. Figure 6 illustrates the sensitivity of avoided emissions to the efficiency improvement of C_2H_4 and C_3H_6 production. Figure 7 illustrates the sensitivity of avoided emissions to the segregated recycling of plastics.

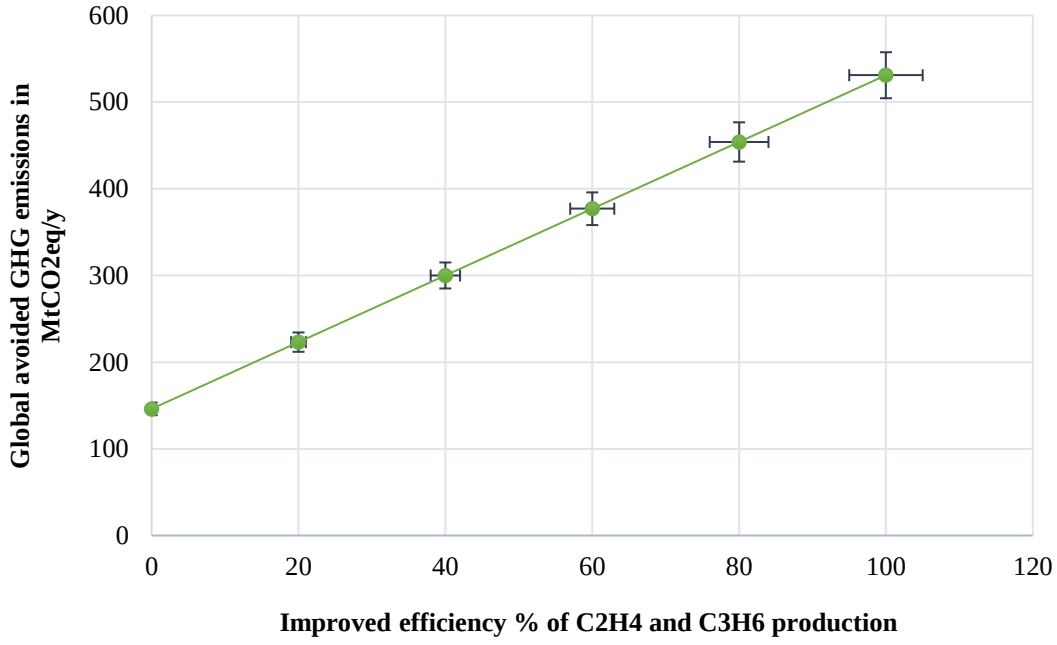

Figure 6. Sensitivity of avoided emissions to improving efficiency of C_2H_4 and C_3H_6 production.

The total impact of resource efficiency is the upper limit of resource efficiency measures without bioplastics or renewable ammonia, methanol, ethylene and propylene, and can be reached incrementally. We estimated the global plastic value chain emission to 1762 t CO_2eq/y in 2016 and corresponding emission reduction to 531 Mt CO_2eq/y. This compares well with the 1781 t CO_2eq/y in 2015 and an emission reduction of 535 Mt CO_2eq/y reported by Zheng and Suh [58] although the approaches differ. We estimated maximum avoided emissions of 1.716 t CO_2eq/t for recycled HDPE, LD&LLDPE and PP. The results of Cascone et al. [59] of avoided emissions of 1.495 t CO_2eq/t for recycled LDPE pellets in Sicily is 13% lower than our maximum estimate. Jeswani et al. [14] estimated that chemical recycling of plastic waste generates 2.3 t CO_2 eq/t less than the virgin plastic. However, the value chain started from nafta and virgin plastics production emission was estimated to 1.89 eq/t. The result is based on high quality plastic packaging waste.

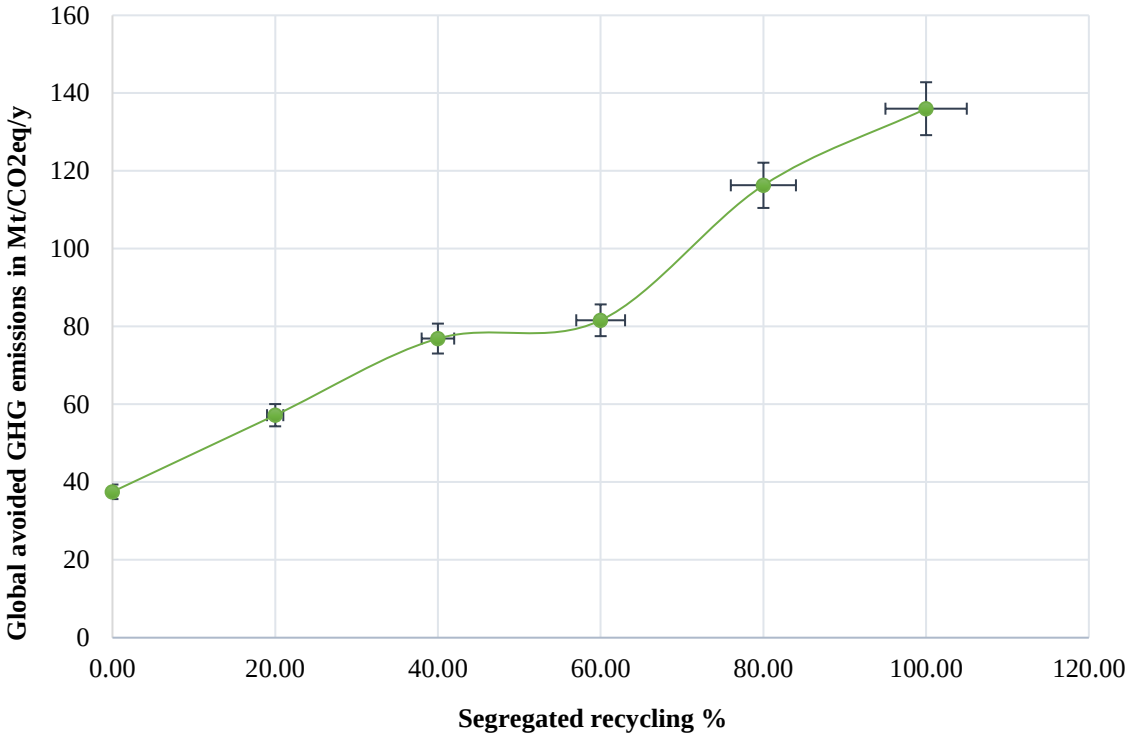

Figure 7. Sensitivity of avoided emissions to segregated recycling of HDPE, LL&LLDPE, PP and PET.

4. Conclusions

This study focuses on the abatement of global GHG emissions of intermediates and polymers in the value chain of plastics produced in annual quantities over 20 Mt. The GHG emissions of the global plastics production are 1762 Mt CO_2eq/y on a cradle-to-gate basis. This makes the sector responsible for 51% percent of the current chemical sector emissions. Focusing on improved efficiency for NH_3, CH_3OH, C_2H_4, C_3H_6, PE, PP, PET, PS and PVC in the value chain of plastics has the potential to reduce global GHG emissions by 531 Mt CO_2eq /y, provided that all of the current global production is upgraded to the level of the EU BAT. These upstream improvements in resource efficiency would mean a 15.4% reduction of all global chemical sector emissions. However, the probability for all global production facilities to reach the EU BAT is unclear. On the recycling side, increasing the recycling

rate of non-fibrous plastic resins from the current 18% to 42% would reduce global GHG emissions by 142.3 Mt CO_2eq/y provided that incineration is not increased and that the segregation of recycling is improved. These downstream improvements in recycling would mean an additional 4% reduction of all global chemical sector emissions. Fastest immediate GHG emission reductions come from the improved recycling (either mechanical or chemical) of plastics. Efficiency improvements in the virgin plastics production chain come next and after that the new renewable replacements of current plastics. Better regulation of the global plastic waste export trade would reduce the amount of poorly recyclable, low-quality waste. Increased recycling and reuse of plastics would allow more time to develop replacement technologies for plastics, with alternative, preferably renewable materials with positive impacts on the environment. This study estimated the near-term possibilities to reduce the global GHG impact of the plastics value chain. The implementation would require both financial resources from the industry and political will from governments. Current caps in the global, plant level production data restricted to obtain more than preliminary and robust LCA results. Future research needs include a detailed LCA assessment of the global supply chain of each chemical and polymer, complemented by investment cost estimates of the best options.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

References

1. Broeren MLM, Saygin D, Patel MK (2014) Forecasting global developments in the basic chemical industry for environmental policy analysis. *Energy Policy* 64: 273–287.
2. Jambeck JR, Geyer R, Wilcox C, et al. (2015) Plastic waste inputs from land into the ocean. *Science* 347: 768–771.
3. Ryberg MW, Hauschild, MZ, Wang F, et al. (2019) Global environmental losses of plastics across their value chains. *J Res Con Rec* 151: 1–10.
4. Kaza S, Yao L, Bhada-Tata P, et al. Washington. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. The World Bank, Washington.
5. WWF (2019) Solving Plastic Pollution Through Accountability. A WWF Report, Gland, Switzerland.
6. Ciel (2019) Plastic & Climate the hidden costs of a plastic planet. available from www.ciel.org/plasticandclimate.
7. Cox KD, Covernton GA, Davies HL, et al. (2019) Human Consumption of Microplastics. *Environ Sci Technol* 53: 7068–7074.
8. EMF (2020) Ellen Macarthur Foundation, The Global Commitment 2020 Progress Report. Available from www.ellenmacarthurfoundation.org.

9. Di J, Reck BK, Miatto A, et al. (2021) United States plastics: Large flows, short lifetimes, and negligible recycling. *Resour Conserv Recyc* 167: 105440
10. IEA (2017) Energy Technology Perspectives 2017. Catalysing Energy Technology Transformations. IEA/OECD, Paris.
11. IEA, ICCA, Dechema (2013) Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes. OECD/IEA, Paris.
12. Al-Salem SM, Antelava A, Constantinou A, et al. (2017) A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *J Env Manag* 197: 177–198.
13. Faussone GC (2018) Transportation fuel from plastic: Two cases of study. *Waste Manage* 73: 416–423.
14. Jeswani H, Krüger C, Russ M, et al. (2019) Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Sci Total Environ* 769: 144483.
15. Solis M, Silveira S (2020) Technologies for chemical recycling of household plastics – A technical review and TRL assessment. *Waste Manage* 105: 128–138.
16. BGC (2019) Boston Consulting Group, Rubel H, Jung U, Follette C, et al. Circular Solution To Plastic Waste, July 2019.
17. Faraca G, Martinez-Sanchezb V, Astrup TF (2019) Environmental life cycle cost assessment: Recycling of hard plastic waste collected at Danish recycling centres. *Resour Conserv Recyc* 143: 299–309.
18. Mohammadi M, Jämsä-Jounela SL, Harjunkoski I (2019) Sustainable Supply Chain Network Design for the Optimal Utilization of Municipal Solid Waste. *AIChE J* 65: 1–19.
19. Burnley S, Coleman T (2018) The environmental and financial benefits of recovering plastics from residual municipal waste before energy recovery. *Waste Manag* 79: 79–86.
20. Foster G (2019) Low-Carbon Futures for Bioethylene in the United States. *Energies* 12: 1958.
21. Rorrer NA, Nicholson S, Carpenter A, et al. (2019) Combining Reclaimed PET with Bio-based Monomers Enables Plastics Upcycling. *Joule* 3: 1006–1027.
22. Semba T, Sakai S, Sakanishi T, et al. (2018) Greenhouse gas emissions of 100% bio-derived polyethylene terephthalate on its life cycle compared with petroleum-derived polyethylene terephthalate. *J Clean Prod* 195: 932–938.
23. Valderrama MAM, van Putten RJ, Gruter GJM (2019) The potential of oxalic – and glycolic acid based polyesters (review). Towards CO2 as a feedstock (Carbon Capture and Utilization – CCU). *European Polym J* 119: 445–468.
24. Tonini D, Schrijvers D, Nessi S, et al. (2021) Carbon footprint of plastic from biomass and recycled feedstock: methodological insights. *Int J Life Cyc* Assmt 26: 221–237.
25. Benavides PT, Dunn JB, Han J, et al. (2018) Exploring Comparative Energy and Environmental Benefits of Virgin, Recycled, and Bio-Derived PET Bottles. *ACS Sust Chem Eng* 6: 9725−9733.
26. Chen L, Pelton REO, Smith TM (2016) Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. *J Clean Prod* 137: 667–676.
27. Blank LM, Narancic T, Mampel J, et al. (2020) Biotechnological upcycling of plastic waste and other non-conventional feedstocks in a circular economy. *Curr Opin Biotechnol* 62: 212–219.
28. Walker S, Rothman R (2020) Life cycle assessment of bio-based and fossil-based plastic: A review. *J Clean Prod* 261: 121158.

29. Nicholson SR, Rorrer NA, Carpenter AC, et al. (2021) Manufacturing energy and greenhouse gas emissions associated with plastics consumption. *Joule* 5: 673–686.
30. European Bioplastics (2018) Bioplastics—Facts and Figures. European Bioplastics, Berlin. Plastic – the facts 2019 available from https://plasticseurope.org.
31. USGS (2017) U.S. Mineral Commodity Summaries. U.S. Geological Survey Publication. *Jan* 2017: 119.
32. IHS (2016b) Urea-chemical-economics-handbook. https://ihsmarkit.com/products (accessed 24.6.2019).
33. ECI (2016) http://www.essentialchemicalindustry.org/chemicals/ammonia.html (accessed 16.10.2018).
34. Räuchle K, Plass L, Wernicke HJ, et al. (2016) Methanol for renewable energy storage and utilization. *Energ Technol* 4: 193–200.
35. IHS (2016c) Methanol, Marc Alvarado, February 2016. Available from: http://www.methanol.org/wpcontent/uploads/2016/07/Marc-Alvarado-Global-Methanol-February-2016-IMPCA-for-uploadto-website.pdf.
36. IHS (2017) Ethylene-chemical-economics-handbook. https://ihsmarkit.com/products (accessed 16.10.2018).
37. IHS (2016a) Propylene-chemical-economics-handbook. https://ihsmarkit.com/products (accessed 24.6.2019).
38. Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. *Sci Adv* 3: e1700782.
39. Levi P G, Cullen J M (2018) Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products. *Environ Sci Technol* 52: 1725−1734.
40. ISO (2006a) Environmental Management—Life Cycle Assessment—Principles and Framework. ISO 14040:2006. ISO/IEC.
41. ISO (2006b) Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO 14044:2006. ISO/IEC.
42. Tallentire C W, Steubing B (2020) The environmental benefits of improving pack- aging waste collection in Europe. *Waste Manage* 103: 426–436. https://doi.org/10.1016/j.wasman.2019.12.045.
43. UNEP (2018) The Emissions Gap Report 2018. United Nations Environment Programme, Nairobi.
44. Bergsma G (2019) Chemical recycling and its CO_2 reduction potential. CE Delft. Available from www.ce.nl.
45. Boulamanti A, Moya JA (2017) Energy efficiency and GHG emissions: Prospective scenarios for the chemical and petrochemical industry. *Report 9789279657344, EU Science Hub*
46. IPCC (2006) Intergovernmental Panel on Climate Change (IPCC), 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 3 – Industrial Processes and Product Use, Chapter 3 – Chemical Industry Emissions.
47. Patel MK, Bechu A, Villegas JD, et al. (2018) Second-generation bio-based plastics are becoming a reality –Non-renewable energy and greenhouse gas (GHG) balance of succinic acid based plastic end products made from lignocellulosic biomass Biofuels. *Bioprod Bioref* 12: 426–441.
48. CAT (2018) http://www.catalystgrp.com. PROP-Ammonia-Production-April-2018.pdf (accessed 28.6.2019).

49. Matzen M, Mahdi A, Demirel Y (2015) Chemical storage of wind energy by renewable methanol production: Feasibility analysis using a multi-criteria decision matrix. *Energy* 93: 343–353.
50. Su LW, Li XR, Sun ZY (2013) Flow chart of methanol in China. Renew. *Sust Energ Rev* 28: 541–550.
51. Kajaste R, Hurme M, Oinas P (2018) Methanol – Managing greenhouse gas emissions in the production chain by optimizing the resource base. *AIMS Energy* 6: 1074–1102.
52. Ruuska A (Eds.) (2013) Carbon footprint for building products. VTT Technology 115, Espoo.
53. Ghanta M, Fahey D, Subramaniam B (2014) Environmental impacts of ethylene production from diverse feedstocks and energy sources. Appl. *Petrochem Res* 4: 167–179.
54. AI (2019) https://ammoniaindustry.com (accessed 28.6.2019).
55. Andersson J, Lundgren J, Marklund M (2014) Methanol production via pressurized entrained flow biomass gasification—Techno-economic comparison of integrated vs. stand-alone production. *Biomass Bioenerg* 64: 256–268.
56. Melin K, Kohl T, Koskinen J, et al. (2016) Enhanced biofuel processes utilizing separate lignin and carbohydrate processing of lignocellulose. *Biofuels* 7: 31–54.
57. TFC (2021) http://timeforchange.org/plastic-bags-and-plastic-bottles-co2-emissions-during-their-lifetime/ (accessed 20.2.2021).
58. Zheng J, Suh S (2019) Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change* 9: 374–378.
59. Cascone S, Ingrao C, Valenti F, et al. (2020) Energy and environmental assessment of plastic granule production from recycled greenhouse covering films in a circular economy perspective. *J Env Manag* 254: 109796.

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