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Life-Cycle Analysis (LCA) for Plastic Recycling

Freepoint Eco-Systems LLC

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Executive Summary

This life-cycle analysis (LCA) report, prepared for Freepoint Eco-Systems LLC (Freepoint), is a carbon intensity (CI) analysis of the recycled low-density polyethylene (LDPE) granulate produced from raw pyrolysis oil (here after termed as "EcoOil" per Freepoint) made by Freepoint's waste plastic recycling process. EcoOil is a recycled crude oil stream produced from the pyrolysis process. Freepoint's recycling process is a pyrolysis of industrial plastic waste to produce syngas and EcoOil. EcoOil produced from Freepoint's facilities can be further processed into prime resin by Freepoint's customers.

All the data used for calculating the CI of EcoOil were supplied by Freepoint. EcoEngineers extended the boundaries of its analysis beyond the processes directly conducted by Freepoint, which included the further processing of EcoOil to produce recycled polyethylene granulate (LDPE granulate). As described in this report, data for these extended processes was sourced from available literature. LDPE granulate was selected as the main product in the evaluation, as studies claim that U.S. industry produces a larger amount of LDPE/HDPE than for any other plastic, followed by PP, PVC, and PET.[1] Furthermore, in 2015, the combined production of LDPE and linear LDPE constituted 23% of the total feedstocks used for thermoplastic productions, followed by 20% (HDPE), 18% (polypropylene), 16% (PVC), 10% (PET), and remaining others. The composition of waste plastic thus can also be expected largely from the LDPE plastic products.

The functional unit for the CI analysis was 1 lb. LDPE granulate, and the CI impact was assessed from a "cradle-to-gate" aspect. The "cradle-to-gate" analysis covers the upstream processes in the production chain of a product until the stage at which the product is ready for use. In this project, the upstream processes are the production and supply of the raw materials (fuel, energy, chemicals, water) that are directly consumed in the production process of LDPE granulate, and is also known as "Background system." The "gate" is the point where the final product (LDPE granulate) is produced, ready for further use, and available at the facility gate. This LCA report evaluates three baseline scenarios explaining how the waste plastic would have otherwise been disposed if not used as a feedstock to produce EcoOil.

The net CI of the recycled LDPE granulate is thus calculated as the difference between the CI from producing the recycled LDPE granulate from EcoOil and that of baseline disposal of the waste plastic feedstock. This LCA report further compares the CI of the recycled LDPE granulate produced from EcoOil and from the traditional fuel feedstock.

Recycling plastic waste could also potentially reduce terrestrial and marine plastics pollution and the depletion of fossil resources, as well as yield other environmental benefits. These non-CI environmental benefits were not modeled in our study. Modeling these may demonstrate additional environmental benefits from pyrolysis of plastic waste to produce plastics.

The LCA was conducted using the standards and approach of ISO 14044.[2] The LCA modeling was carried out using the LCA tool SimaPro 9.2.02.[3] and has used the ReCiPe 2016 Method.[4] ReCiPe is one of the most recent and updated impact assessment methods and is widely accepted in LCA society.[5]

1. https://www.osti.gov/pages/biblio/1761525
2. ISO. Environmental management — Life cycle assessment — Requirements and guidelines. 54 (2006). https://www.iso.org/standard/38498.html
3. https://simapro.com/2021/simapro-9-2/
4. Huijbregts et al. "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level." The International Journal of Life Cycle Assessment 22.2 (2017): 138-147.
5. https://ec.europa.eu/environment/biodiversity/business/assets/pdf/tool-descriptions/RECiPe%20and%20BioScope%20summary%20description.pdf

The following sections provide background, procedures, analysis results, and conclusions for Freepoint.

Key Findings:

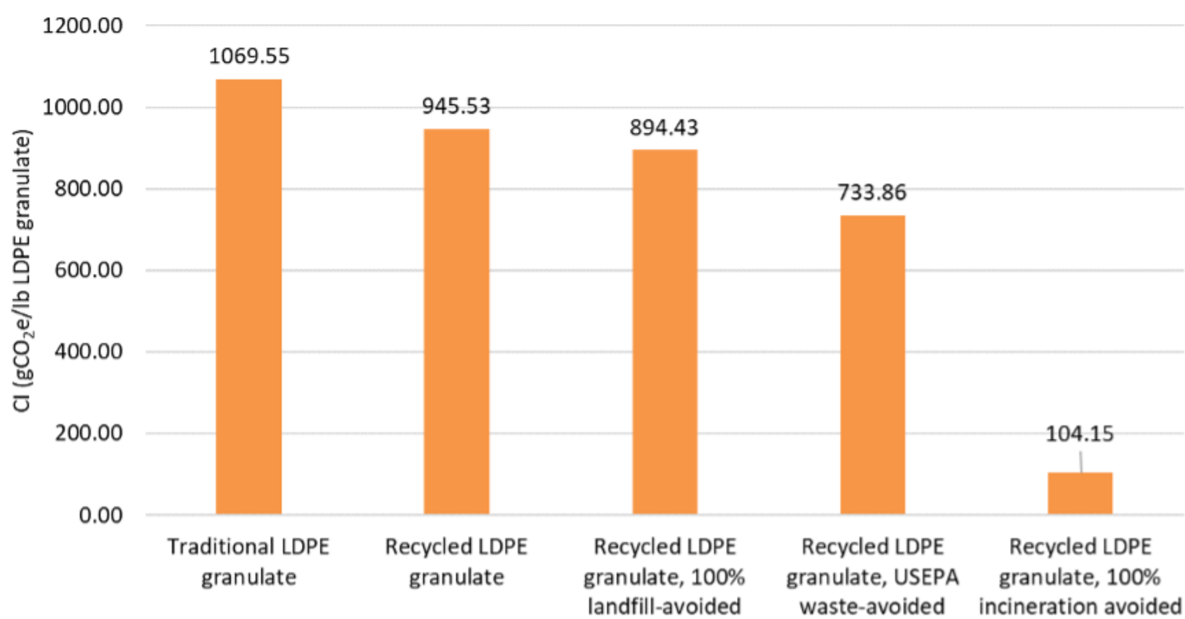
Freepoint's pyrolysis process to produce recycled LDPE granulate from waste plastics has a lower CI than traditionally produced LDPE granulate, even when the credits from avoided baseline emissions are excluded. The CI is even lower when such avoided emission credits are included (Figure 1).

- The CI of Freepoint's process to make LDPE granulate (excluding credits from the baseline disposal scenarios) is 945.53 gCO_2e/lb LDPE granulate
- The CI of traditionally produced LDPE granulate from fossil fuel feedstock is 1069.55 gCO_2e/lb LDPE granulate.
- The CI of freepoint's process producing recycled LDPE granulate is 12% lower than the traditionally produced LDPE granulate.

The net CI (including credits from the baseline disposal scenarios when the waste plastics are diverted to produce recycled LDPE granulate) of the LDPE granulate produced from EcoOil is even lower:

- If 100% plastic waste is landfilled: 894.43 gCO_2e/lb LDPE granulate. This is 16% lower than the CI of the traditional LDPE granulate.
- If 100% plastic waste is incinerated: 104.15 gCO_2e/lb LDPE granulate. This is 90% lower than the CI of the traditional LDPE granulate.
- If of the total waste plastic, 17% is incinerated and 83% are landfilled: 733.86 gCO_2e/lb LDPE granulate. This is 31% lower than the CI of the traditional LDPE granulate.

FIGURE 1: COMPARATIVE CI OF RECYCLED LDPE GRANULATE, WITH VARIOUS AVOIDED BASELINE SCENARIOS AND THE CI OF TRADITIONAL LDPE GRANULATE



1.0 Purpose of Analysis

This report is provided at the request of Freepoint to evaluate the carbon intensity (CI) of its advanced plastic recycling process – a pyrolysis process that converts waste plastics to raw pyrolysis oil (EcoOil), which is then further processed into plastic resin and finally LDPE granulate.

2.0 Production Facilities Background

Freepoint uses a pyrolysis process to convert industrial plastic waste to produce syngas and raw pyrolysis oil (EcoOil), which can be further processed into prime resin by Freepoint's customers.

The baseline end-of-life disposal of the feedstock can be landfilling or incineration depending on the location and local regulations. Freepoint's first waste plastics recycling facility will be located near Columbus, Ohio, with future sites being considered in North America, the European Union, and Asia.

Freepoint can leverage the logistics and trading strength of its affiliate, Freepoint Commodities LLC to acquire feedstock and distribute the end-product. Below, we discuss the process steps for producing LDPE granulate from waste plastic feedstock. The first part of the step, which includes the production of EcoOil, is at the Freepoint's facility.

2.1 Pyrolysis of waste plastics

Pyrolysis is the heating of organic compounds, in the absence of oxygen. Pyrolysis is one of the technologies used to convert carbon-rich feedstocks, such as waste plastics, to an intermediate liquid product. The intermediate liquid product can be further refined to produce plastic and other petrochemical replacements.

At the current level, the evaluation for pyrolysis is carried out for Freepoint's planned facilities that will utilize pyrolysis technology to recycle waste plastic into a gaseous product. The gaseous product is condensed and fractionated to produce EcoOil. The feedstocks and inputs into Freepoint's production processes are waste plastics and limited amounts of natural gas used to start the pyrolysis process. Additionally, natural gas is used as process fuel during the conversion of waste plastic to EcoOil. EcoOil from the pyrolysis process is an intermediate feedstock that plastic producers can use to produce recycled LDPE granulate and then various recycled plastic consumer products. Fuel gas produced was used internally as process fuel, and emissions from the fuel gas combustion are also taken into account. These are further discussed in the following sections.

2.2 Conversion of EcoOil to LDPE granulate

The LDPE production steps that come after the production of EcoOil do not occur within Freepoint facilities. Data on the inputs and outputs after the EcoOil leaves Freepoint facilities are from available literature.[6,7]

[6] SPHERA 2022. Life Cycle Assessment of Chemical Recycling for Food Grade Film.
[7] BASF 2020. Evaluation of pyrolysis with LCA – 3 case studies

The EcoOil produced in the Freepoint's facility is processed by the customer in a hydrotreater where it is purified and hydrogenated. This hydrogenated EcoOil is then used as feedstock to produce ethylene in a steam cracker. The ethylene is then polymerized to produce LDPE granulate.

2.3 Management of waste

Calculation of the CI for the management of waste, including unwanted plastic residues and hazardous materials were handled using the suitable waste handling models, adopted from Ecoinvent v3.[8] Since the recovered energy is utilized internally in the incineration system (Ecoinvent v3), it is not shown separately, and no further expansion of system boundary was necessary. This applies to the management of residual waste produced during the steam cracking and polymerization processes. The LCA database for the baseline waste management scenarios are adopted from Ecoinvent v3 (further discussed in section 4).

3.0 Procedures and Methodology Used to Evaluate Carbon Intensity

EcoEngineers performed the following tasks to calculate the CI of the LDPE granulate in the proposed project:

- Data requests were sent to Freepoint. The received data were for the conversion processes from the entry of waste plastics into the Freepoint system until the production of EcoOil (raw pyrolysis oil) through the pyrolysis process.
- Data that covers the remaining steps to convert the raw pyrolysis oil to LDPE granulate was obtained from literature review.
- Periodic meetings via conference calls were conducted to understand the essence of the project and the supplied data.
- Life-cycle assessment models were constructed in SimaPro 9.2.02.
- A preliminary facility-specific CI score, CI breakdown, and a comparison to its traditional counterparts were calculated and presented.
- A sensitivity analysis was conducted on the project by varying key project parameters and reviewing the impacts to the CI score.

8. Wernet G., et al. "The ecoinvent database version 3 (part I): overview and methodology." The International Journal of Life Cycle Assessment 21.9 (2016): 1218-1230.

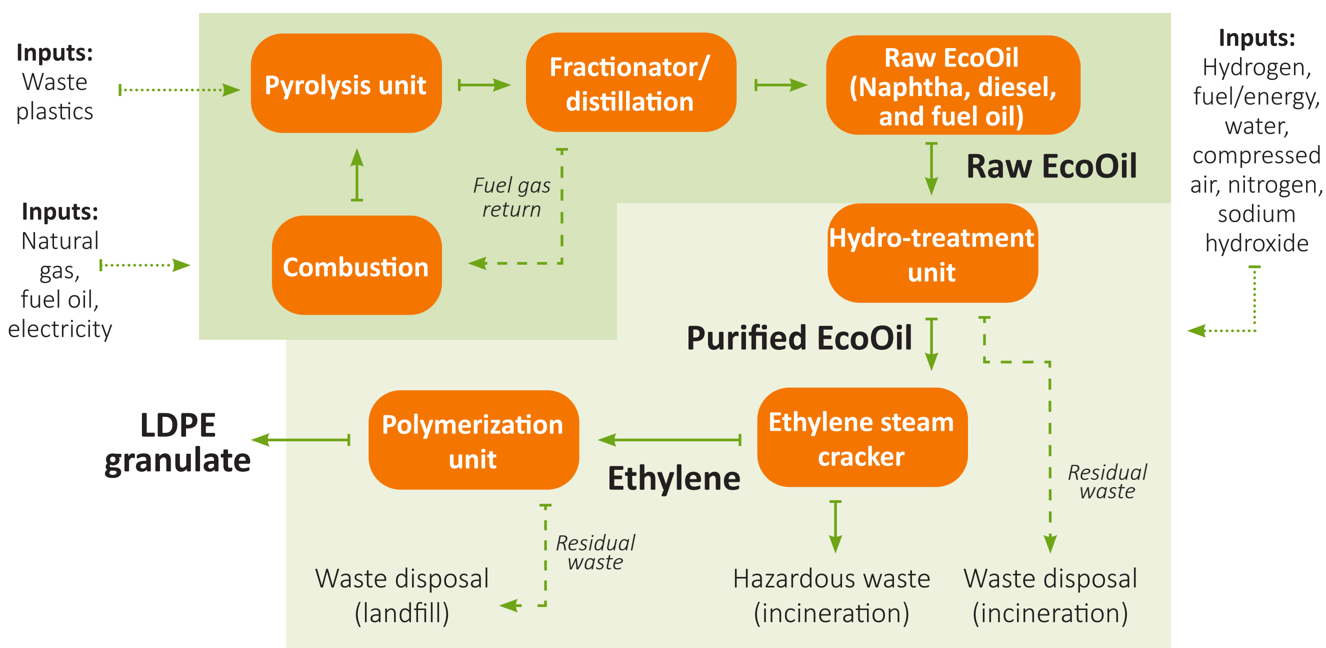
LCA databases are used to calculate the environmental impact accounting both the background and the foreground systems. In LCAs, background systems are the system components that are not directly part of the main product systems but are necessary for the production, use, and disposal of the waste.

4.0 Data, Assumptions, and Scenarios

The system boundary for the evaluation is shown in Figure 2. The functional unit (FU) for the life-cycle impact assessment (LCIA) is 1 lb. LDPE granulate produced from EcoOil, which is equivalent to 1 lb. traditional LDPE granulate. The LCIA was performed using SimaPro 9.2.02, and the Ecoinvent v3 consequential LCA database. LCA databases are used to calculate the environmental impact accounting both the background and the foreground systems. In LCAs, background systems are the system components that are not directly part of the main product systems but are necessary for the production, use, and disposal of the waste. In this project, the contributions of the background system are from the use of inputs (e.g. fuel/energy, water, hydrogen) that are consumed during the production of LDPE granulate. Hence, related emissions during the production of such raw material inputs are also taken into account. Likewise, the foreground system is the actual system that is investigated for LCA; here, the production of EcoOil and then the production of LDPE granulate are covered in the foreground system. All the raw materials coming from the background system are thus eventually used in the foreground system.

All life cycle inventory data considered in the CI analysis are shown in Tables 1-4 on the next pages. The data shown are based on the raw data available from Freepoint and related literature. U.S. grid electricity is assumed as the source of electricity. As discussed in section 2.2, the system boundary covered (i) production of EcoOil, (ii) purification of EcoOil through hydro-treating (iii) production of ethylene undergoing steam cracking, and (iv) polymerization of ethylene to finally produce recycled LDPE granulate (see Figure 2). In the case of traditional LDPE, the CI is calculated considering the crude oil required to produce 1 lb. LDPE granulate. It is assumed that 35.83 MJ crude oil is required to produce 1 lb. LDPE granulate.[9] The LCA database to produce crude oil is adopted from Ecoinvent v3.[10] In the case of traditional LDPE granulate, all the processes and CI, starting from the hydro-treatment process until production of LDPE granulate are assumed to be the same, as calculated for the recycled LDPE granulate. It means only the impact related to production and processing of crude oil required to produce LDPE granulate is accounted for and added to the CI of the subsequent stages (Table 5).

FIGURE 2: SYSTEM BOUNDARY DIAGRAM FOR THE LIFE-CYCLE ASSESSMENT



9. http://cpmdatabase.cpm.chalmers.se/Scripts/sheet.asp?ActId=ABBCR000115611
10. Base oil {RoW}| base oil production, petroleum refinery operation | Conseq, U

TABLE 1: LCI DATA FOR FREEPOINT'S PYROLYSIS UNIT

All inputs are calculated as per FU (i.e., 1 lb. LDPE granulate). Data based on Appendix A on page 18.

ITEM	UNIT	AMOUNT
Resource inputs[a]		
Input Plastics	lb.	1.130
Natural Gas	MMBtu	0.00022
Electricity Demand	kW	0.191
Transport-feedstocks[b]	miles	0.0097
Intermediate Outputs		
EcoOil (raw)[c]	lb.	0.861
Char	lb.	0.0062

a. Data based on the conversion of waste plastic feedstock (used at 22,046 lb/hr) producing EcoOil,c which constitute a mix of 85.4, 173.6 and 94.73 MMBTU/hr of diesel, naphtha and fuel oil respectively. About 24% of the feedstock accounted for fuel gas, as per mass flow data received from Freepoint.

b. Transport of plastics from collection centers to pyrolysis gate assumed to be 12.5 km (one-way distance).

c. EcoOil is unrefined pyrolysis oil which undergo purification process in the next stage (Table 2).

TABLE 2: LCI FOR HYDRO-TREATMENT UNIT PRODUCING PURIFIED ECOOIL

All inputs are calculated as per FU (i.e., 1 lb. LDPE granulate). Data based on Appendix B on page 18.

ITEM	UNIT	AMOUNT
Resource inputs[a]		
EcoOil (raw)	lb.	0.861
Hydrogen	lb.	0.009
Thermal energy (natural gas)	MJ	0.225
Intermediate Outputs[a]		
EcoOil (refined)	lb.	0.810
Residues for internal combustion	lb.	0.052

a. Inputs and outputs are calculated for the conversion of raw EcoOil produced from pyrolysis process to produce a refined pyrolysis oil.

TABLE 3: LCI FOR STEAM CRACKER UNIT PRODUCING ETHYLENE

All inputs are calculated as per FU (i.e., 1 lb. LDPE granulate). Data based on Appendix C on page 19.

ITEM	UNIT	AMOUNT
Resource inputs		
EcoOil (refined)	lb.	0.810
Natural gas	lb.	0.276
Nitrogen	lb.	0.015
Sodium hydroxide (50% solution state)	lb.	0.002
Methanol	lb.	0.001
Water	lb.	7.084
Steam	lb.	0.798
Electricity	MJ	0.083
Heat (natural gas)	MJ	3.976
Intermediate Outputs		
Ethylene	lb.	1.020
Waste		
Water	lb.	0.756
Residual plastic waste	lb.	$3.97*10^{-5}$
Hazardous waste (not specified)	lb.	$1.98*10^{-5}$

TABLE 4: LCI FOR POLYMERIZATION UNIT

All inputs are calculated as per FU (i.e., 1 lb. LDPE granulate). Data based on Appendix D on page 19.

ITEM	UNIT	AMOUNT
Resource inputs		
Ethylene	lb.	1.020
Nitrogen	lb.	0.002
Electricity	MJ	1.47
Water	lb.	1.3
Steam	lb.	0.09
Compressed air (700 kPa)	Nm3	0.014
Outputs		
LDPE granulate	lb.	1.00
Waste		
Water	lb.	0.830
Residual plastic waste	lb.	0.015

5.0 Results and Discussion

Table 5 shows the results along with the contribution from the different inputs on the final CI score. All the impacts are shown as per functional unit (FU), which is 1 lb. LDPE granulate.

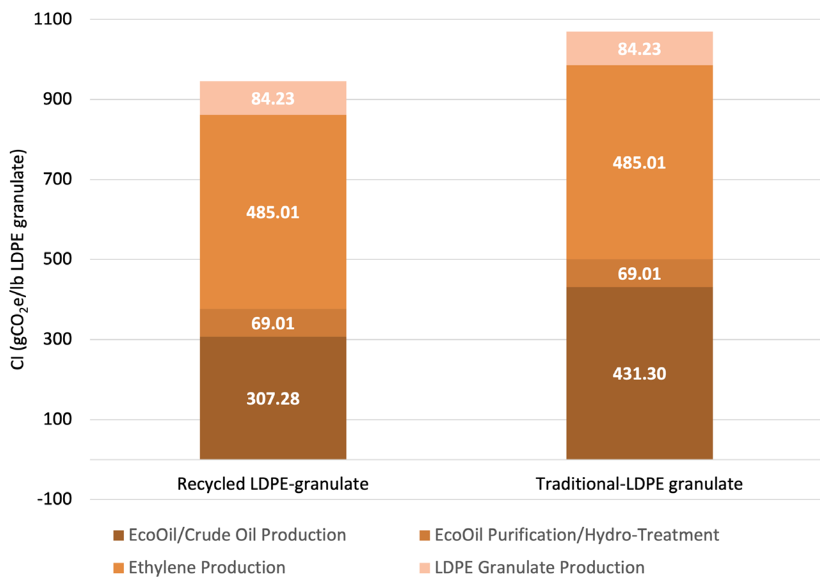
TABLE 5: CI ANALYSIS AND CONTRIBUTIONS DUE TO USE OF DIFFERENT INPUTS IN THE PRODUCTION PROCESS
All scores are calculated with respect to Functional unit (FU), i.e., 1 lb. LDPE granulate production.

INPUT	RECYCLED LDPE GRANULATE CI (gCO_2e/FU)	TRADITIONAL LDPE GRANULATE CI (gCO_2e/FU)
EcoOil/Crude oil production	**307.28**	**431.30**
Natural gas (as process fuel)	18.01	-
Electricity	27.50	-
Transport	0.64	-
Disposal of char, landfill	0.86	-
Fuel gas combustion	260.27	-
EcoOil purification/hydro-treatment	**69.01**	**69.01**
Hydrogen	7.39	7.39
Heat	17.87	17.87
Waste disposal, incineration	43.75	43.75
Ethylene production	**485.01**	**485.01**
Natural gas	58.76	58.76
Nitrogen	0.03	0.03
Sodium hydro-oxide, 50% solution state	1.35	1.35
Methanol	0.31	0.31
Water	1.56	1.56
Steam	104.11	104.11
Electricity	3.33	3.33
Heat	315.55	315.55
Plastic-residual waste disposal	0.002	0.002
Hazardous waste disposal	0.02	0.02
LDPE granulate production	**84.23**	**84.23**
Nitrogen	0.0037	0.0037
Electricity	58.53	58.53
Water	0.29	0.29
Steam	11.75	11.75
Compressed air (700 kPa)	0.47	0.47
Process waste plastic, residues disposal, incinerated	12.43	12.43
Process waste plastic, residues disposal, landfill	0.76	0.76
Total impact	**945.53**	**1,069.55**

Figure 3 shows the contributions from the different stages considered in the conversion of waste plastics feedstock to LDPE granulate. About 32% of the total CI is due to Freepoint's EcoOil production process, followed by 7% (purification of EcoOil, or hydro-treatment process), 51% (ethylene production process, or steam cracking process), and the remaining 9% is related to the polymerization process (producing LDPE granulate).

During the pyrolysis process producing EcoOil, the major CI contribution is from fuel gas combustion (28%); and electricity contributes 3% of the total CI (Table 5); for the hydro-treatment process the major contribution is from the waste disposal (incineration of residual plastics produced in the process, see Table 5). During the ethylene production (at the steam cracker), the major contribution is from the heat required in the system, contributing about 33%, followed by 11% due to consumed steam, and 6% direct consumption of natural gas. The rest of the score is from other inputs consumed during the conversion of purified EcoOil to ethylene (Table 5). During the LDPE granulate production process (at the polymerization unit), the major contribution is due to electricity (6%) and incineration of residual waste (1.4%). The rest of the score from the other raw materials consumed in the process (Table 5).

FIGURE 3: CONTRIBUTIONS FROM THE DIFFERENT STAGES OF THE RECYCLED AND TRADITIONAL LDPE GRANULATE PRODUCTION PROCESSES



Since the goal of the current project is to evaluate the CI of LDPE granulate produced from the waste plastic feedstock, the analysis looked at potential credits that could be gained by the Freepoint's process when compared to baseline waste disposal scenarios. Then, the net CI is calculated, which is the total CI estimated from the production of LDPE granulate minus the emissions from plastic waste disposal in the baseline scenarios. Three baseline scenarios are considered:

1. if 100% plastic waste is disposed at a landfill site;
2. if 100% of plastic waste is incinerated; and
3. if 17% and 83% of the plastics are incinerated and landfilled respectively (based on the national average of plastic incineration and landfilling scenarios as stated in a USEPA factsheet).[11]

[11] https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

In the first case, where 100% of the plastic waste is landfilled, 51.10 gCO_2e/lb LDPE granulate is credited to the process, and the resulting net CI is 894.43 gCO_2e/lb LDPE granulate. CI impact due to landfill includes the GHG emissions from the degradation of plastics and those due to the energy and material consumptions during the landfill operation. The GHG emissions due to the landfill degradation of 1 lb. of plastic waste over a long term (>100 years) is 49 g CO_2e. The degradation of plastic generally takes place for more than 100 years, and it is assumed that 1% of the waste is degraded in 100 years, based on available literature.[12]

Of the total GHG emissions from 1 lb. plastic waste being landfilled, field-specific emissions — particularly due to the degradation — contributed more than 95% of impact. Furthermore, the main driver is methane (as it is more than 84% of the process-specific burden), CO_2 emissions (16%), and a minor contribution from N_2O emissions. Apart from the degradation emissions, other contributing source is mainly the energy input to operate the landfill site, which covered about 5% after the above-mentioned degradation related emissions.

In the scenario where 100% of the waste is assumed to be incinerated, 841.38 gCO_2e/lb LDPE granulate production is credited to the process, and the resulting net CI score is 104.15 gCO_2e/lb LDPE granulate. Freepoint's process displacing incineration can have a higher carbon offset than displacing landfilling, due to the higher avoided emissions from the combustion of waste in the incineration plant. For each pound of waste plastics combusted, 0.5 kWh electricity and 3.48 MJ heat is exported after partial consumption to meet the internal energy demand. Electricity is assumed to displace U.S. grid electricity, and heat is assumed to displace natural gas. The credit from the substituted energy however depends on the sources of displaced energy options. Also, through incineration the non-biogenic carbon in the plastics is released to the atmosphere; that carbon is mostly sequestered in the landfilling scenario.

For the case of the average management of plastic waste, the net CI is 733.86 gCO_2e/lb LDPE granulate, which is due to an offset of 211.67 gCO_2e/lb LDPE granulate (Tables 6 and 7). The municipal waste treatment models (landfill and incineration) considered for the evaluation is adopted from EcoInvent v3.

TABLE 6: CI FOR LDPE GRANULATE AND OTHER INTERMEDIATE PRODUCTS (ECOOIL AND ETHYLENE), UNDER DIFFERENT BASELINE SCENARIOS

PRODUCTS[a]	PRODUCT CI[a] (gCO_2e/lb)	NET CI (gCO_2e/lb)[b]		
		If landfilled	If incinerated	National Average of Incineration and landfill mix[c]
EcoOil	356.66	305.56	-484.72	144.99
Ethylene	844.55	793.45	3.17	632.88
LDPE granulate	945.53	894.43	104.15	733.86

a. Product CI represent the CI of intermediate products and the final products in the chain of LDPE granulate production system.
b. Net CI = Product CI minus emissions in respective baseline scenarios (see Table 7).
c. The national average scenario is used and the calculated breakdown is 17% of the collected waste are incinerated and 83% are disposed in the landfill.[13]

12. https://db.ecoinvent.org/reports/13-iii_landfills_v2.1.pdf?area=463ee7e58cbf8
13. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

TABLE 7: CI FOR BASELINE SCENARIOS OF WASTE PLASTIC MANAGEMENT

	BASELINE SCENARIO CI (gCO_2e/lb)		
	100% plastic waste landfilled[b]	100% plastic waste incinerated[b]	National Average of Incineration and landfill mix[c]
Credits[a]	51.10	841.38	211.67

a. Credits refers to the avoided impact due to diversion of plastic waste to produce recycled plastics, as discussed in the current study.

b. 100% plastic waste managed at landfill and incinerated represent the cases if the waste was otherwise disposed in the respective ways compared to recycling process in the Freepoint facility.

c. The national average scenario represents the average of how non-recycled plastic waste is otherwise disposed across the U.S.; 17% is incinerated and 83% is disposed in the landfill.

The calculated CI of traditional LDPE is 1069.55 gCO_2e/lb LDPE granulate, which was found close to results reported in other studies.[14,15] Table 8 shows the comparative CI of the recycled LDPE granulate production and its traditional counterparts. The impact for producing recycled ethylene and recycled LDPE granulate was 13% and 12% lower, respectively, excluding the credits from the avoided baseline scenarios. The impact is mainly influenced by the emissions from the fuel gas during the production of EcoOil.

TABLE 8: COMPARATIVE CI FOR FREEPOINT'S ECOOIL-BASED RECYCLED ETHYLENE AND LDPE GRANULATE PRODUCTION AND CORRESPONDING TRADITIONAL PRODUCTS

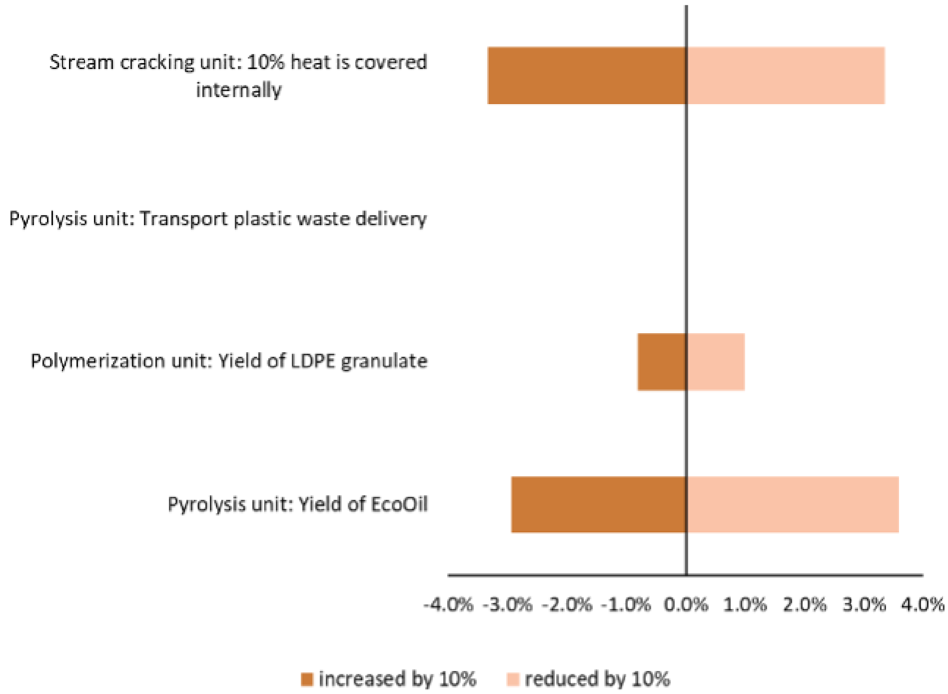
PRODUCT	TOTAL CI (RECYCLED LDPE GRANULATE) gCO_2e/LB	TOTAL CI (TRADITIONAL LDPE GRANULATE) gCO_2e/LB	TOTAL CI (RECYCLED ETHYLENE) gCO_2e/LB	TOTAL CI (TRADITIONAL ETHYLENE) gCO_2e/LB
LDPE granulate (LDPE)	945.53	1,069.55	585.71	671.47
% Reduction compared to respective traditional counterparts	-12%	-	-13%	-

Figure 4 shows the sensitivity of the CI when selected parameters are varied for their input amounts, within a ±10% range compared to the respective amounts shown in Tables 1-4. For instance, consumption of heat in the steam cracking process was one of the major contributing inputs across the production system. So, when 10% of heat consumed (supplied externally and based on natural gas) was assumed to be reduced, mainly through the provision of co-generated heat (within the system), the impact would reduce by 3.3%. Instead, if there is additional demand for heat (increased by 10%) then CI would increase by 3.3%. Similarly, a 10% increase in the yield of the LDPE granulate would reduce the CI by 1%, and a 10% reduction in the yield would increase the CI by 1%. A 10% reduction or increase in the yield of EcoOil would increase the CI by 3% and decrease it by 3.6%, respectively. Varying the transportation distance (for collection and delivery of plastic waste to pyrolysis unit) did not show a significant role in mitigating the impact within the certain limits.

14. Franklin Associate, 2011. https://www.americanchemistry.com/better-policy-regulation/plastics/resources/cradle-to-gate-life-cycle-inventory-of-nine-plastic-resins-and-four-polyurethane-precursors

15. Gervet B., 2007. https://www.ltu.se/cms_fs/1.5035!/plastics%20-%20final.pdf

FIGURE 4: SENSITIVITY ANALYSIS ON THE CI CALCULATED FOR RECYCLED LDPE GRANULATE PRODUCTION PROCESS

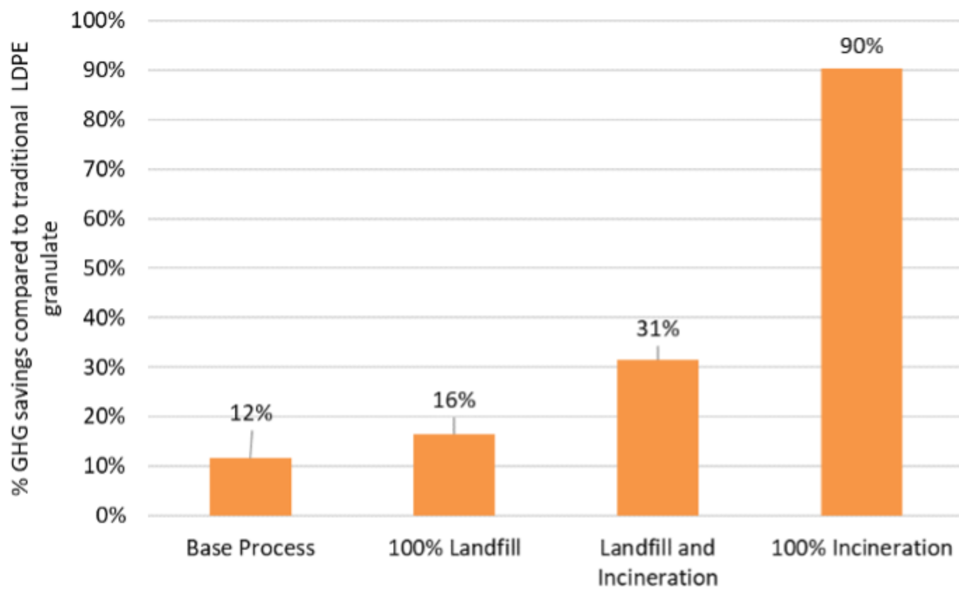


Several key findings from the analysis include:

1. The total CI of recycled LDPE granulate, excluding the credits from the baseline scenarios is 945.53 gCO_2e/lb LDPE granulate. The CI is 12% lower than traditional LDPE granulate available in market.
2. The net CI, if 100% plastic waste was landfilled but is now diverted to produce recycled LDPE granulate, is 894.43 gCO_2e/lb LDPE granulate.
3. The net CI, if 100% plastic waste was incinerated but is now diverted to produce recycled LDPE granulate, is 104.15 gCO_2e/lb LDPE granulate.
4. The net CI, if 17% waste plastic was incinerated and 83% was landfilled but is now diverted to produce recycled LDPE, is 733.86 gCO_2e/lb LDPE granulate.
5. Avoided emission credits are largely dependent on emissions taking place at landfill and incineration systems.
6. Compared to traditional LDPE granulate, excluding credits from baseline, the CI for recycled LDPE granulate is 12% lower. With credits if 100% waste is landfilled, the CI is 16% lower; 31% lower if waste is managed in both landfill and incineration; and 90% less if 100% waste is incinerated (Figure 5).
7. The CI is mainly sensitive to the fuel gas emission during the EcoOil production and heat input (mainly the source of heat) required at steam cracking process, where ethylene is produced.
8. The project CI impacts shown in Tables 5-7 are in the typical range found in the available literature for the similar system boundary.

FIGURE 5: GHG SAVINGS DUE TO FREEPOINT'S ECOOIL-BASED RECYCLED LDPE PRODUCTION COMPARED TO TRADITIONAL LDPE GRANULATE

GHG savings are shown with and without baseline scenarios. Base process represents the CI without baseline credits.



6.0 Conclusions and Perspectives

This report deals with the CI evaluation of producing recycled LDPE granulate from waste plastics. EcoOil produced from the waste plastics at Freepoint's facilities is the intermediate feedstock used to produce ethylene and then LDPE granulate. Without the credits from the baseline scenario, the total CI of recycled LDPE granulate from Freepoint's process is 945.53 gCO_2e/lb LDPE granulate, while traditional LDPE granulate has a CI of 1069.55 gCO_2e/lb LDPE. The direct benefits anticipated from the production of recycled LDPE granulate is the reduction of the consumption of traditional LDPE granulate, which have environmental benefits too. For instance, the CI of recycled LDPE compared to traditional LDPE granulate is 12% lower, even without any credits from the baseline scenarios. With the inclusion of credits from different baseline scenarios, the CI is further reduced: 16%, 31%, and 90% lower when 100% landfill, 83% landfill and 17% incineration, and 100% incineration scenarios are considered as baseline scenarios, respectively.

There may/should be other environmental benefits for waste plastic recycling, including, but not limited to, fine particulate matter formation, water consumption, fossil resource scarcity, marine pollution, etc., which was beyond current scope of work but is recommended as a potential task for next phase of the work in quantifying the full benefits of waste plastic recycling.

This report is based on the information provided by Freepoint. This report is intended solely for Freepoint and is not intended for use by any other parties except with the express permission of Freepoint.

EcoEngineers' client base spans upstream, midstream, and downstream suppliers of fossil and alternate fuel providers and associated industries.

About the Authors

EcoEngineers

EcoEngineers helps organizations create sustainable solutions for a better tomorrow. Our talented team of engineers, scientists, auditors, consultants, researchers, and analysts live and work at the intersection of low-carbon fuel policy, innovative technologies, and the carbon marketplace. Our people are trusted guides who help navigate the ever-changing energy landscape, providing the right tools, guidance, and knowledge to reduce your carbon footprint, and to assess the potential risk to your business from the uncertainties caused by a changing climate and low-carbon policies. Through our systematic approach, we deliver value and proven expertise through the entire clean energy continuum, including education, regulatory engagement, life-cycle analysis, asset development, compliance management, audit, and verification.

EcoEngineers provides California Low Carbon Fuel Standard (LCFS) services to renewable diesel, biodiesel, cellulosic ethanol, renewable natural gas, and other renewable fuel producers and has extensive experience working with the California LCFS program and the CA-GREET models. EcoEngineers has several full-time engineers dedicated to modeling fuel pathways using a variety of LCA tools and has submitted close to 300 pathway applications to California Air Resources Board (CARB) for registration under the LCFS. EcoEngineers has successfully helped producers to obtain more than 100 certified pathways under the newly adopted Low Carbon Fuel Standard (LCFS) regulation effective since January 2019.

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Dr. Zhichao Wang, P.E., is an agricultural engineer and carbon analyst with more than 20 years of research and industry experience focused on renewable energy production, waste treatment and management, and life-cycle analysis. He is a national expert in conducting life-cycle analysis and leads a team of scientists and engineers who provide vital calculations for municipalities, businesses, and low-carbon fuel producers looking to lower their carbon footprint.

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Appendices

APPENDIX A: INPUT & OUTPUT DATA FOR THE WASTE PLASTIC PYROLYSIS PROCESS

ITEM	UNIT	VALUE
Inputs		
Input Plastics	lb./hr	22,046
Natural Gas	MMBtu/hr	5.50
Electricity Demand	kW	4,907
Fuel Gas	MMBtu/hr	47.57
Outputs		
Diesel	MMBtu/hr	85.40
Naphtha	MMBtu/hr	173.60
Fuel Oil	MMBtu/hr	94.73
Char	lb/hr	156.16
Total EcoOil (raw)	**MMBtu/hr**	**353.73**

APPENDIX B: INPUT & OUTPUT DATA FOR HYDRO-TREATMENT PROCESS TO PURIFY ECOOIL

ITEM	UNIT	AMOUNT
Resource inputs[a,b]		
EcoOil (raw)	lb.	957.68
Hydrogen	lb.	9.55
Thermal energy	MJ	250.27
Intermediate Outputs[a,b]		
EcoOil (refined)	lb.	900.15
Residues for internal combustion	lb.	57.42

a. Inputs and outputs calculated for the conversion of unrefined EcoOil produced from pyrolysis process to a purified EcoOil.

b. All the data are calculated for the LDPE-granulate portion only, reported in the literature.17 Inputs and outputs for the LDPE granulate was calculated following the subdivision between LDPE granulate and polypropylene.

16. SPHERA 2022. Life Cycle Assessment of Chemical Recycling for Food Grade Film.

APPENDIX C: INPUT & OUTPUT DATA FOR STEAM CRACKER UNIT PRODUCING ETHYLENE

ITEM	UNIT	AMOUNT
Resource inputs[a]		
EcoOil (refined)	lb.	900.15
Natural gas	lb.	307.10
Nitrogen	lb.	17.20
Sodium hydroxide (50% solution state)	lb.	2.20
Methanol	lb.	0.66
Water	lb.	7874
Steam	lb.	886.92
Electricity	MJ	92.80
Heat	MJ	4,419.50
Intermediate Outputs[a]		
Ethylene	lb.	1,113.62
Waste		
Water	lb.	840.84
Residual plastic waste	lb.	0.04
Hazardous waste (not specified)	lb.	0.022

[a.] Inputs and outputs for the LDPE granulate was calculated following the subdivision between LDPE granulate and polypropylene

APPENDIX D: INPUT & OUTPUT DATA FOR POLYMERIZATION UNIT

ITEM	UNIT	AMOUNT
Resource inputs		
Ethylene	lb.	1,133.84
Nitrogen	lb.	2.20
Electricity	MJ	1633.50
Water	lb.	1,444.91
Steam	lb.	100.09
Compressed air (700 kPa)	Nm3	15.1
Outputs		
LDPE granulate	lb.	1,111.57
Waste		
Water	lb.	922.41
Residual plastic waste	lb.	16.53

The information contained in this report provides general guidance on matters discussed. The interpretation and application of environmental regulations are subject to specific facts involved. Given the changing nature of these regulations and the unique set of facts related to each project, there may be inconsistencies between the information contained in this report and a specific interpretation or application of a rule at a specific site by a federal or state agency. While we have made every attempt to ensure that the information contained in this report is accurate and reliable, EcoEngineers is not responsible for any errors or omissions, or for the results obtained from the use of this information. The information on this report is provided with the understanding that the authors are not herein engaged in rendering legal, accounting, tax, or other professional advice and services. As such, it should not be used as a substitute for consultation with professional accounting, tax, legal or other competent advisers.

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