Viability of Leveraging Spent Coffee Grounds (SCG)

By: Sondra Halperin, Youssef Machkhas, Jocelyn Marchyok, Alicia Quilici, James Tang

Overview

RECOMMENDATION

RESULTS

- Comparison to Current Practices
- Comparison to Base Case Scenarios

METHODOLOGY

- PHA
- Fertilizer
- Anaerobic Digestion
- Pyrolysis

CONCLUSIONS

Recommendations

- We recommend that Starbucks continues to allocate spent coffee grounds to **composting**.

- Compared to composting, anaerobic digestion saves energy when creating biogas and fertilizer, but emits more carbon dioxide.

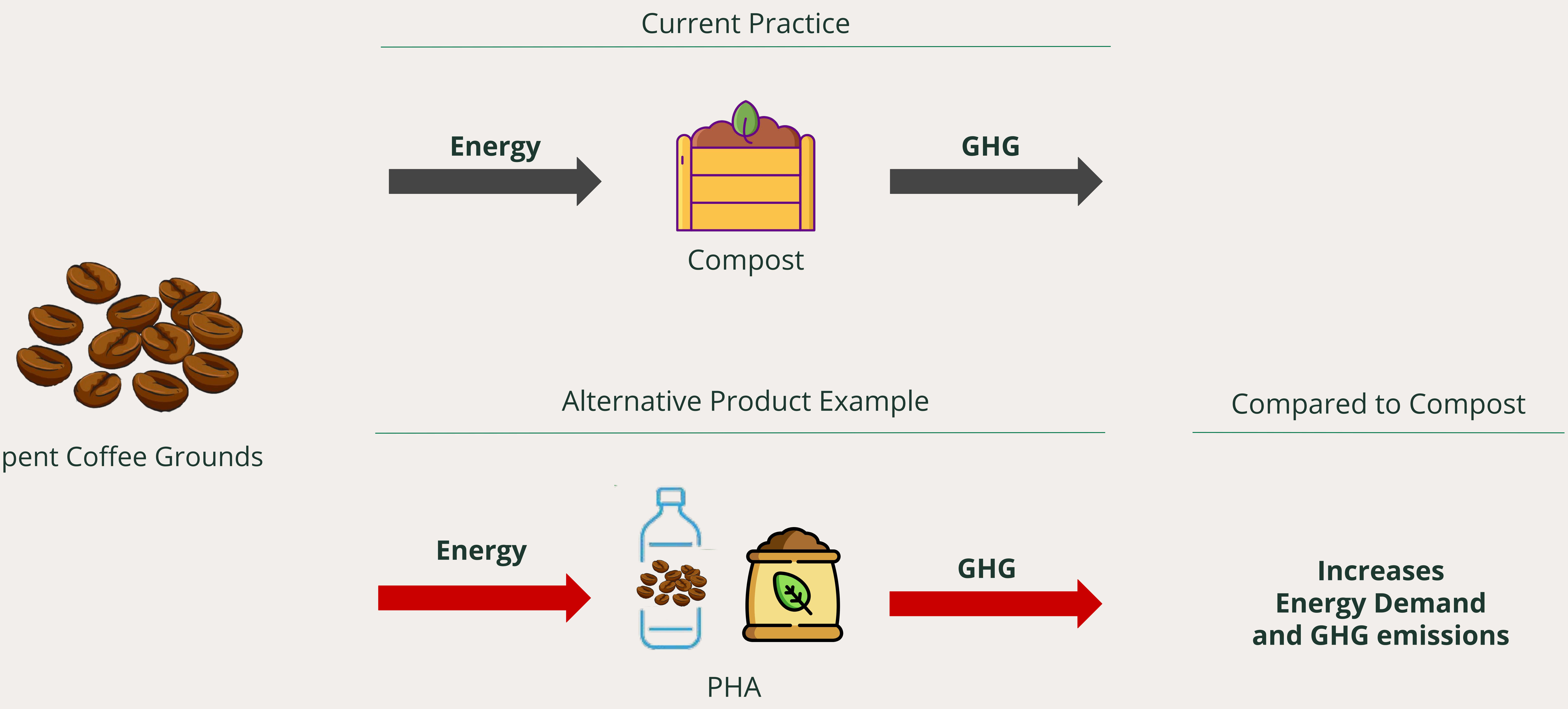
- Anaerobic digestion and using SCG to make PHA is more efficient than market alternatives. However, because these alternatives require more energy and GHG than composting we do not recommend pursuing them at scale.

- Embracing public-private partnerships with schools and communities to 1) divert SCG from landfill, 2) engage public on environmental education, and 3) educate the next generation on composting practices

RESULTS

- Comparison to compost
- Comparison to displaced alternative

Alternatives Compared to Composting



Spent Coffee Grounds

Current Practice

Energy → Compost → **GHG**

Alternative Product Example

Energy → PHA → **GHG**

Compared to Compost

Increases Energy Demand and GHG emissions

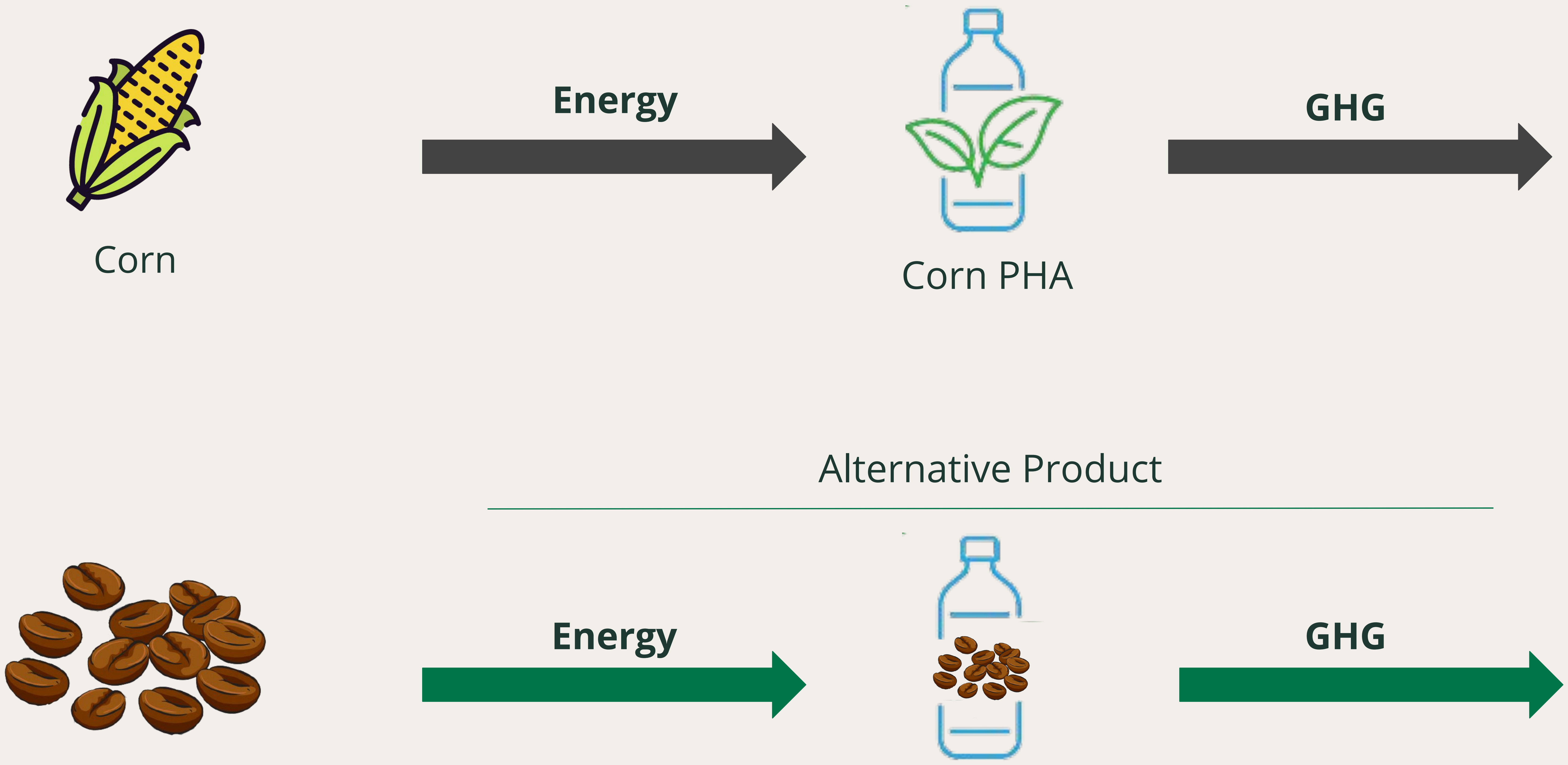
Comparison to Current Practices

ALTERNATIVE VS COMPOST

Alternative Name	**Greenhouse Gas Emissions (Metric Tons)**	**Energy (MJ)**
SCG PHA	1,249	26,440,493
Fertilizer	2,333	25,720,965
Pyrolysis	11,208	21,623,811
Anaerobic Digestion	134	-1,268,629

Alternatives Compared to Baseline Scenarios

A systems perspective



Baseline Scenario

Corn

Energy

Corn PHA

GHG

Alternative Product

Compared to Corn PHA

Spent Coffee Grounds

Energy

SCG PHA

GHG

Decreases
Energy Demand
and GHG emissions

Comparison to Baseline Scenarios

ALTERNATIVE VS COMPLEMENTARY PROCESS

Alternative Name	**Greenhouse Gas Emissions (Metric Tons)**	**Energy (MJ)**
SCG PHA+Fertilizer - Corn PHA+Animal Feed *15,000,000 kg plastic	-1,153	-115,423,610
Fertilizer - Compost *10,925 tons	2,333	25,720,965
Pyrolysis - Fertilizer + Natural Gas *1,660.73 kg/8,892,420 MJ	10,551	-6,828,804
Anaerobic Digestion - Fertilizer + Natural Gas *8,958 tons/7,700,000 MJ	-1,425	-28,285,969

METHODOLOGY

Assumptions are that:

1. Simapro 9.1 version
2. Yearly scale of 10924.3 short ton of spent coffee ground from Oct 2017 to Sep 2018
3. Goal and scope starts with SCG from Augusta Georgia site and ends with end of life of the product (without any customer/ store engagement)
4. Transportation was the same across all processes
5. ERCOT grid composition is similar to that of the Georgia
6. We all included carbon credits for composting excess SCG that was not used in our processes or creating a fertilizer byproduct
7. For processes with a drying step, 49.3% moisture is used
8. Biogenic methane does not add carbon to the air when combusted

Fertilizer | Methodology

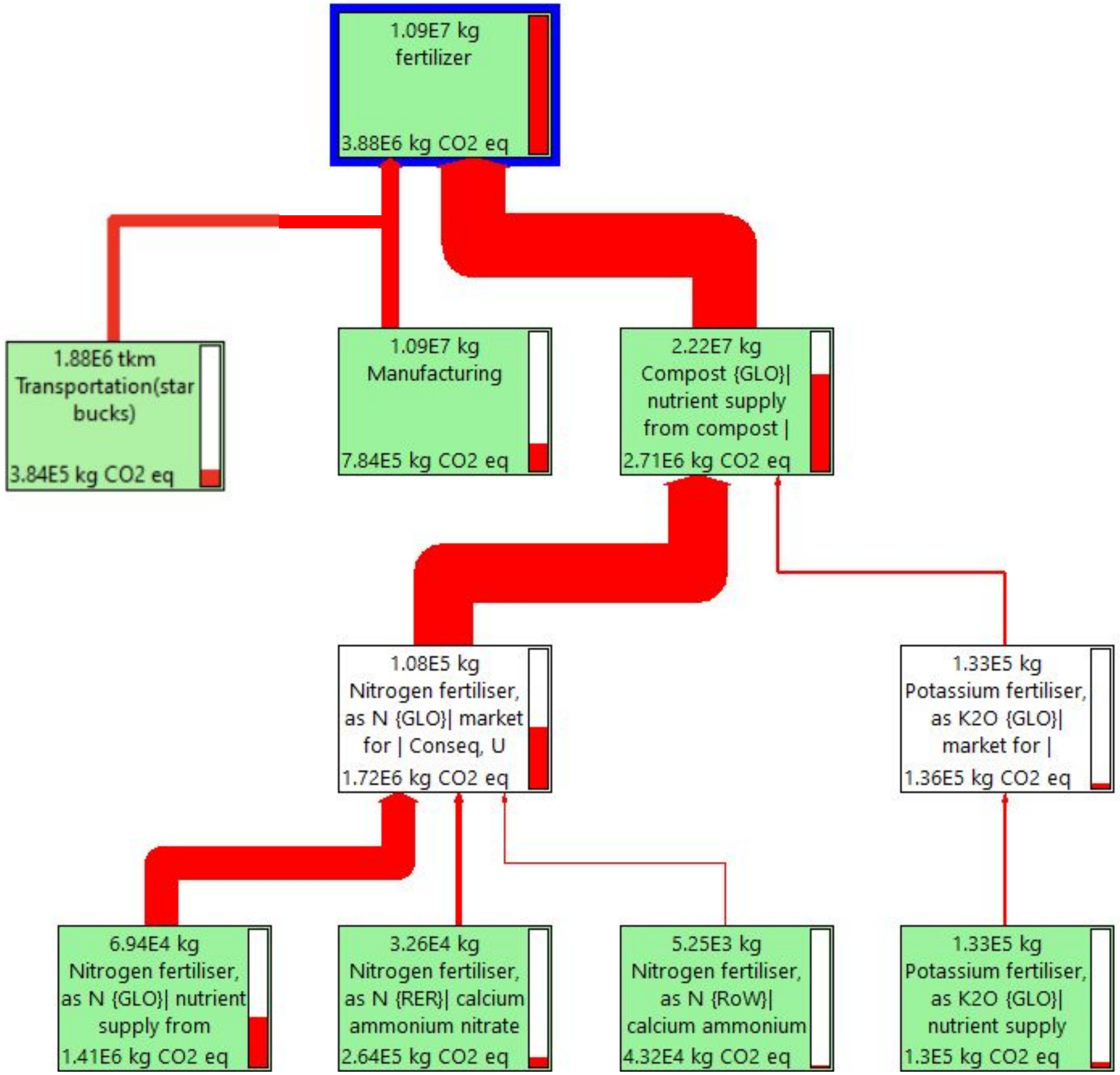
FERTILIZER VS COMPOST

Greenhouse Gas Emissions

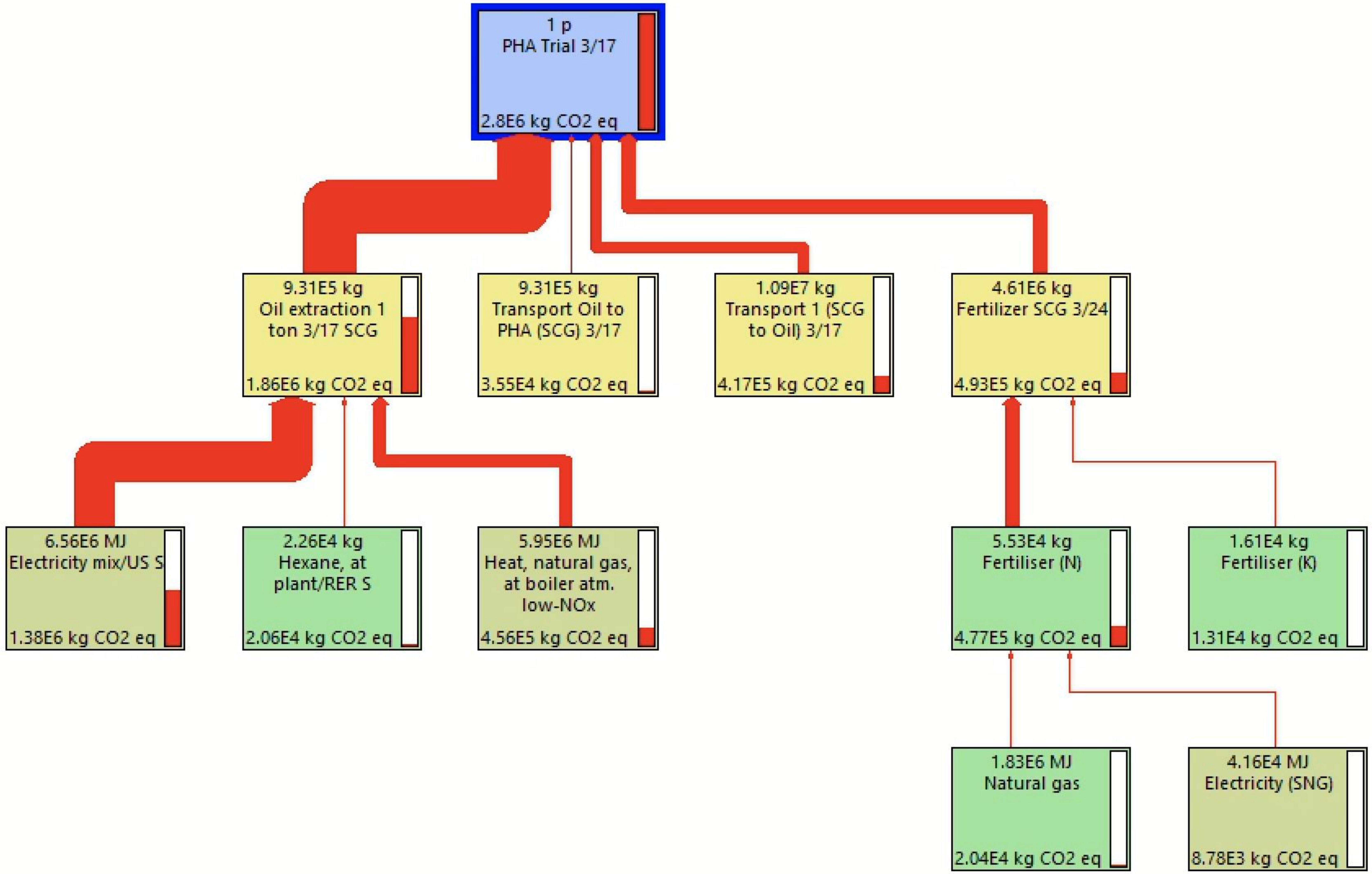
2,333 Metric Tons

Energy

25,720,965 MJ



SCG PHA | Methodology



SCG PHA VS COMPOST

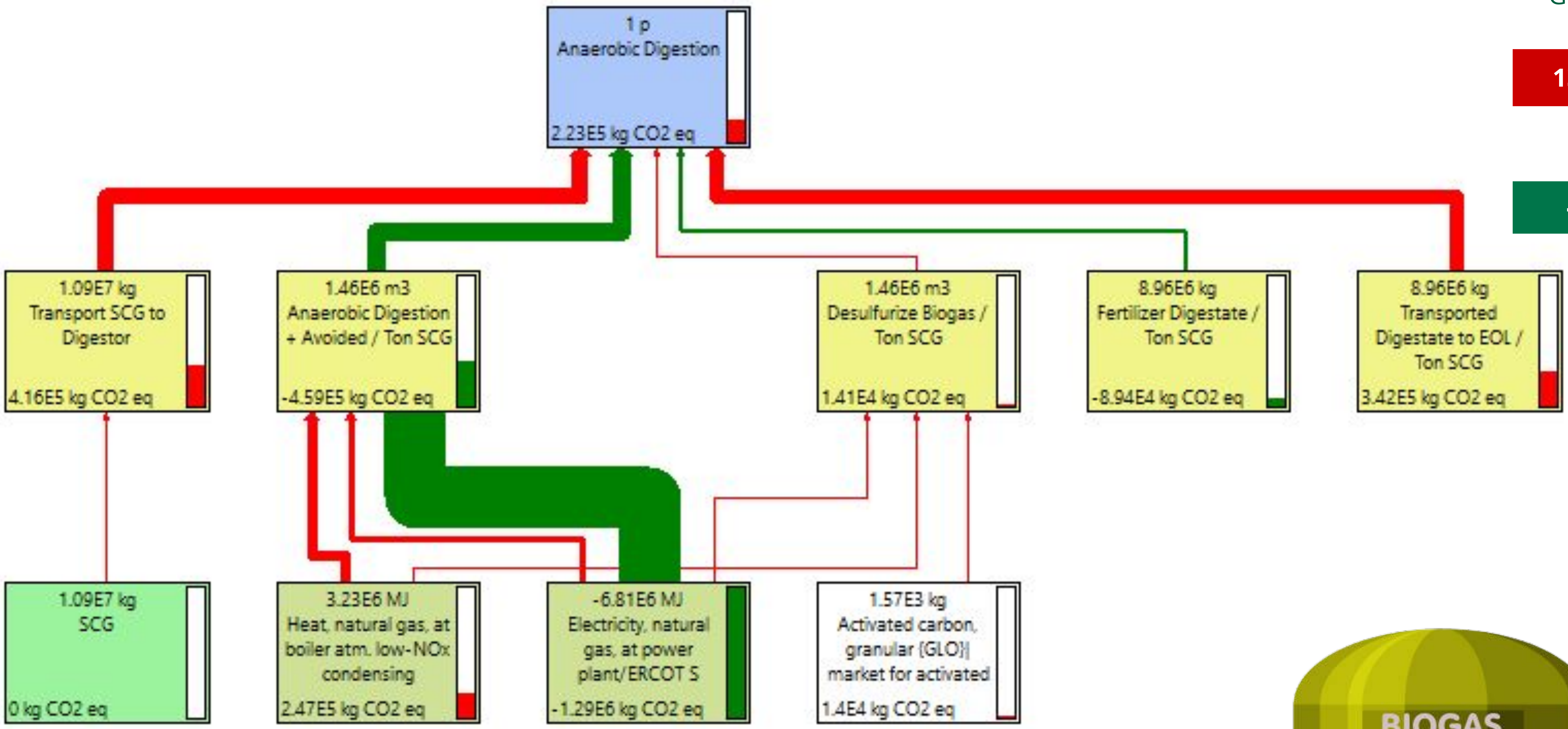
Greenhouse Gas Emissions

1,249 Metric Tons

Energy

26,440,493 MJ

Anaerobic Digestion | Methodology



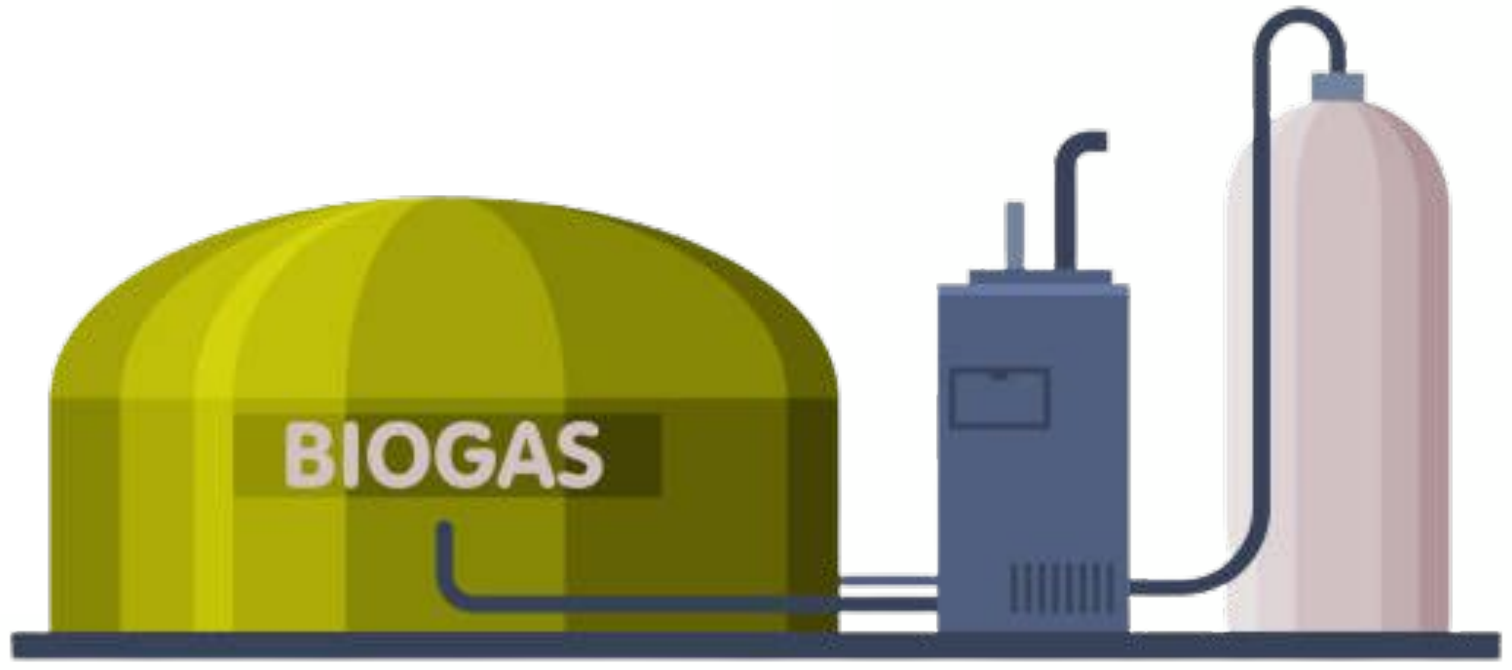
ANAEROBIC DIGESTION VS COMPOST

Greenhouse Gas Emissions

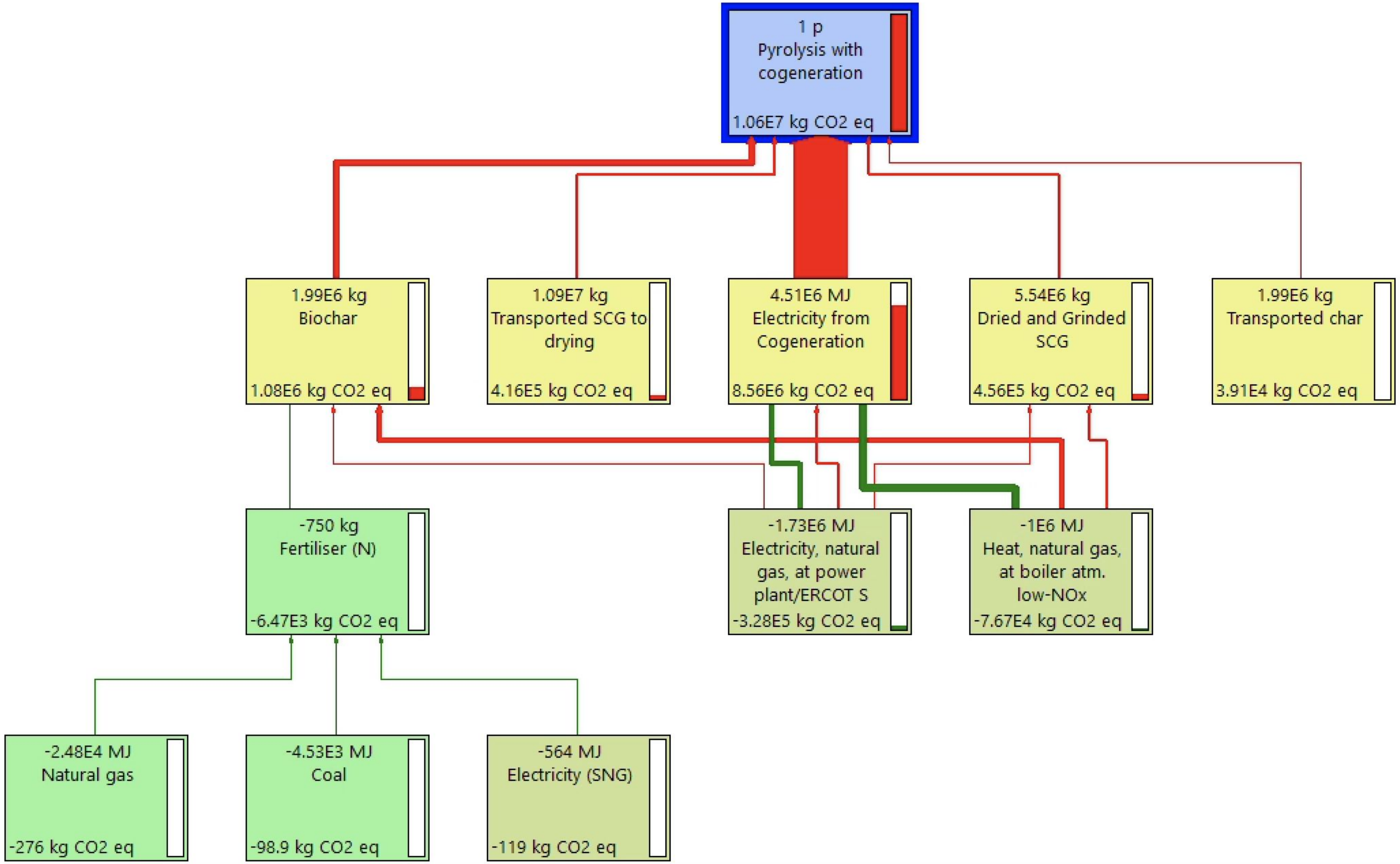
134 Metric Tons

Energy

-1,268,629 MJ



Pyrolysis | Methodology



PYROLYSIS VS COMPOST

Greenhouse Gas Emissions

11,208 Metric Tons

Energy

21,623,811 MJ

Takeaways

- The biggest barrier to reducing carbon intensity of processes are the grid emissions factors.
- Composting remains the best large scale solution.
- We do not recommend pursuing the PHA (coffee oil), pyrolysis or anaerobic digestion at scale.
- Partner with public sectors WSDA on its School, Garden & Farm Based Education Program

THANK YOU
Any Questions?

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PHA

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Anaerobic Digestion / Natural Gas

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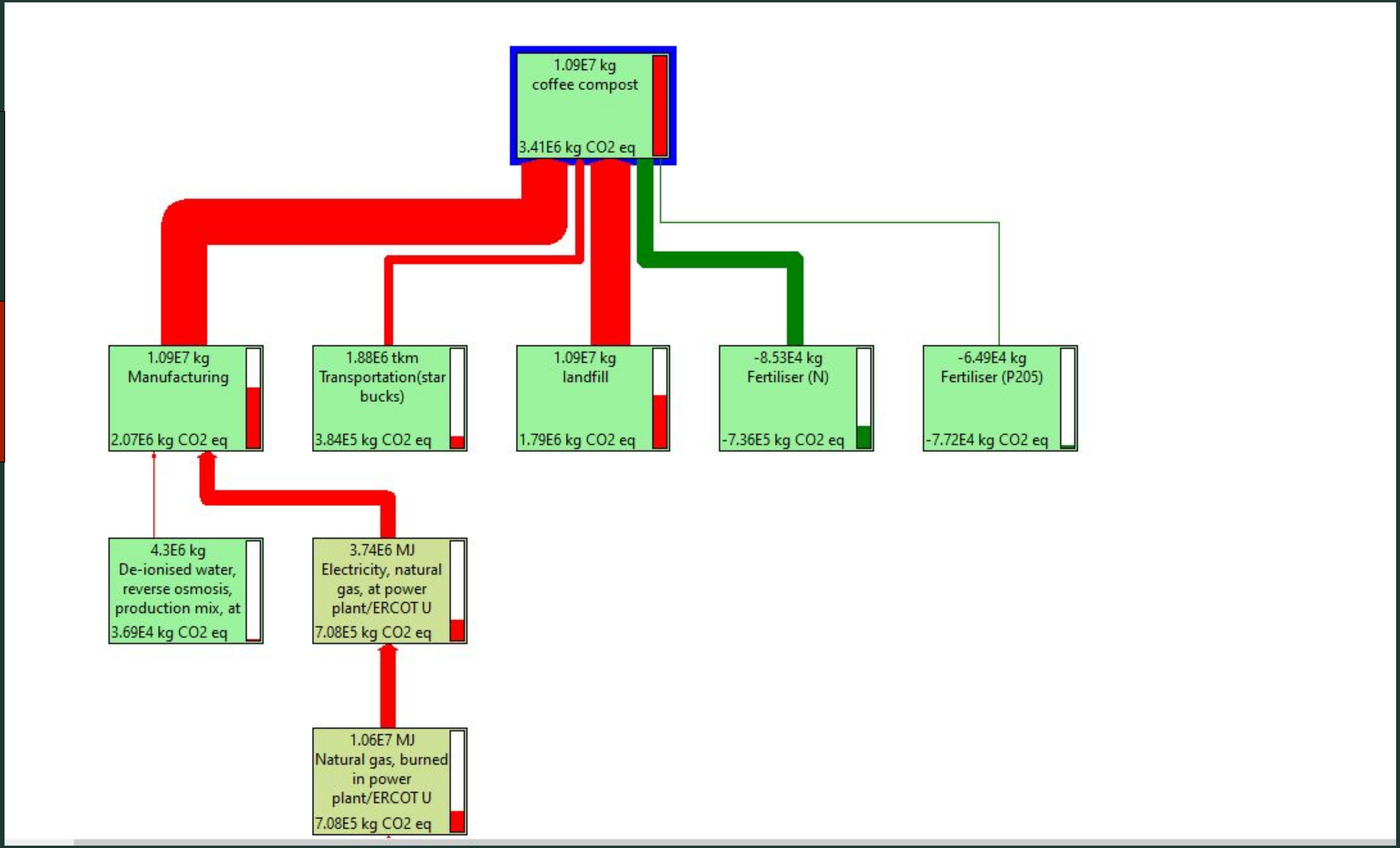
Compost

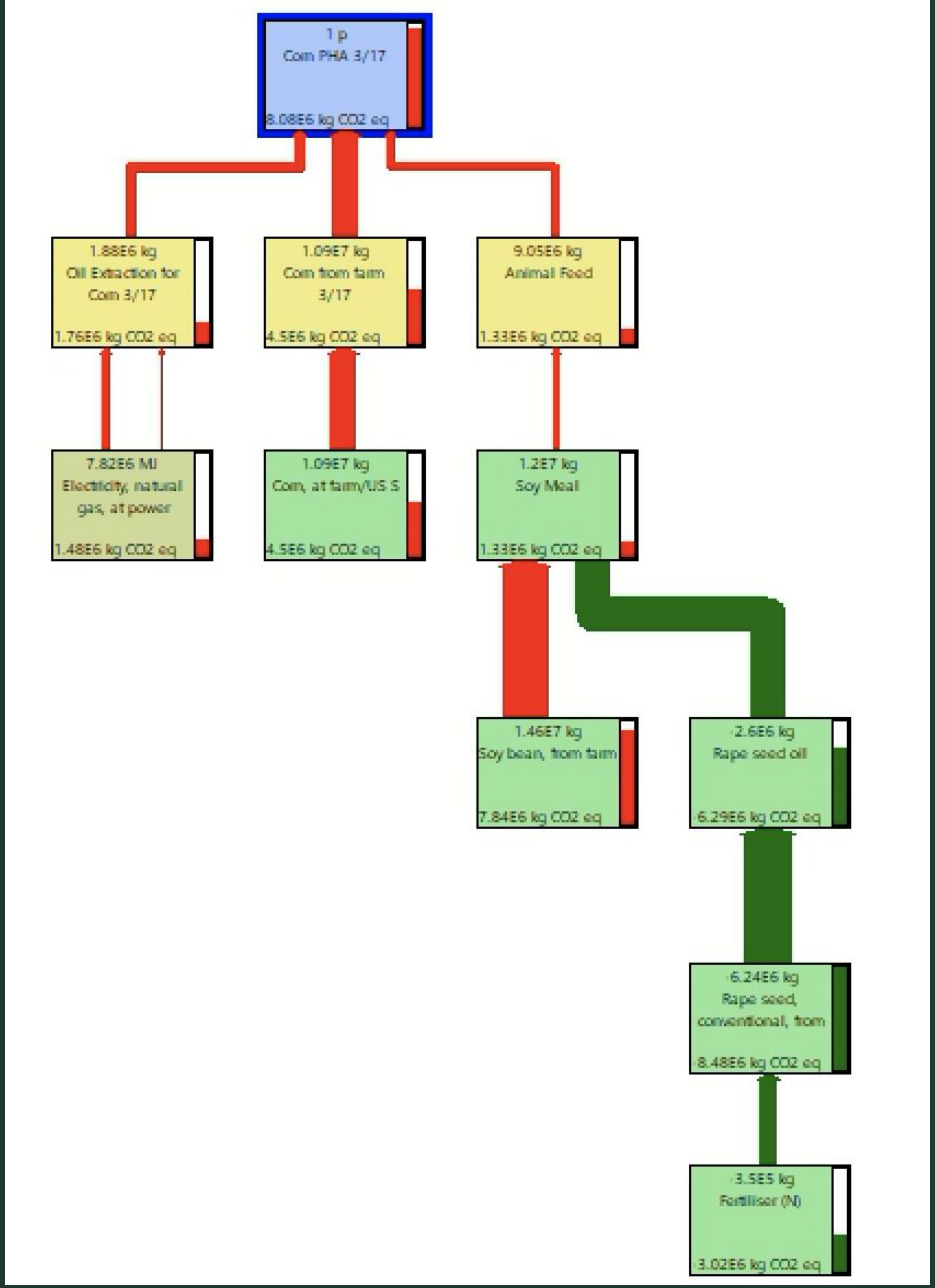
Methodology

Alternative Name	Greenhouse Gas Emissions (Metric Tons)	Energy (MJ)
Fertilizer Compost	**1,480**	**10,391,284**



Corn PHA

Methodology



Compost | Methodology

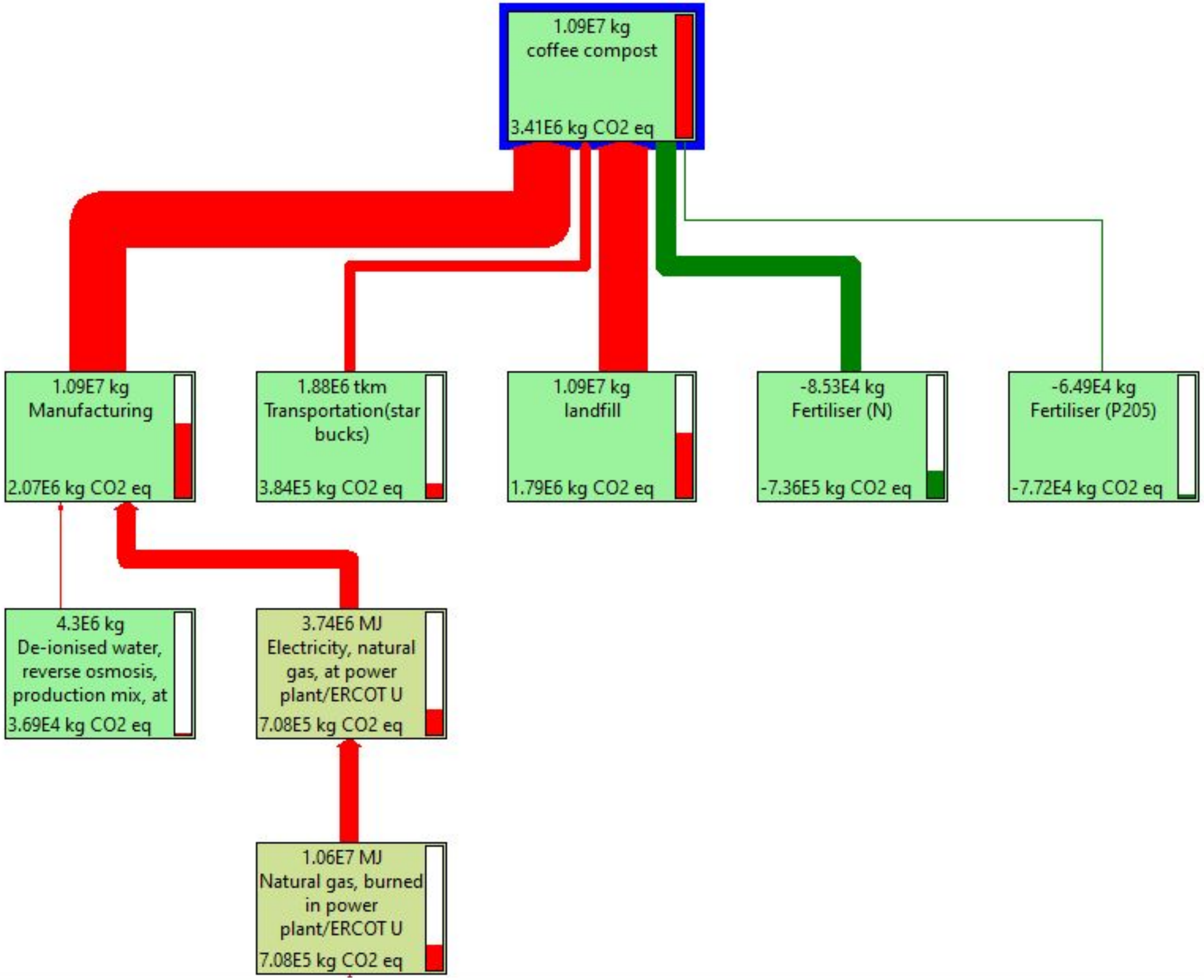
FERTILIZER VS COMPOST

Greenhouse Gas Emissions

1,480 Metric Tons

Energy

10,391,284 MJ



Results Based on Alternatives (Landfill)

Alternative Name	Greenhouse Gas Emissions (Metric Tons)	Energy (MJ)
SCG PHA - Corn PHA	**-1,136**	**-118,054,729**
Fertilizer - Compost	**1,420**	**10,391,284**
Pyrolysis - Fertilizer	**10,551**	**-6,828,804**
Anaerobic Digestion- Natural Gas	**1,634**	**-19,012,942**

Comparison to Base Case (Landfill Annually)

Alternative Name	Greenhouse Gas Emissions (Metric Tons)	Energy (MJ)
SCG PHA Compost	-596	30,847,183
Fertilizer Compost	1,420	10,391,284
Pyrolysis Compost	9,353	21,623,811
Anaerobic Digestion Compost	-402	-1,268,629

Overall Group Assumptions and Methods used in every alternative:

1. Simapro 9.1 version
2. Yearly scale of 10924.3 short ton of spent coffee ground from Oct 2017 to Sep 2018
3. Goal and scope starts with SCG from Augusta Georgia site and ends with end of life of the product (without any customer/ store engagement)
4. Transportation was the same across all processes
5. For electricity and heat in all processes, we used the ERCOT grid composition is similar to that of the Georgia
6. We all included carbon credits for composting excess SCG that was not used in our processes or creating a fertilizer byproduct
7. For processes with a drying step, 49.3% moisture is used
8. Biogenic methane does not add carbon to the air when combusted
9. Results were presented accurate to the ones digit

Transportation to initial processing (for all alternatives):

Our process started with transporting SCG from the Augusta, GA site to a processing facility. We tried to keep transportation the same within all alternatives and therefore assumed that the oil extraction facility would be within 64 miles of the Augusta site. We started with 10925 short tonnes of SCG (based on 2017-2018 yearly supply-Starbuck's data) that was transported using an HGV Vehicle- unknown engine size and the GHG calculation tool *Transport_Tool_v2_6_transport_basecase.xlsx.* 12 round trips were estimated to haul the year supply of SCG which amounted to 1536 miles (12*128 mi). The emissions were calculated for hauling the weight of a single trip 10925/12=910.4167 and then scaled for the total number of trips. Emissions from the GHG calculator for CO2, CH4, and N2O were plugged into a single Simapro Process for 1 ton and scaled to the full amount. Inputs for the process were the following: CO2: 0.038 metric tons, CH4: 4.48×10^{-4} kg, and N2O: 3.456×10^{-4} kg.

Inputs	Amount	Units
Number of trips	12	trips
Distance per round trip	128	miles
Total weight transported	10925	tons
Weight transported per trip	910.4167	tons

Outputs	Amount	Units
CO2	0.038	metric tons
CH4	4.48×10^{-4}	kg
N2O	3.456×10^{-4}	kg

Overall initial transportation emissions

Total Output	Amount	Units
CO_2	415.15	metric tons
CH_4	4.89	kg
N_2O	3.77	kg

Anaerobic Digestion

The life cycle of the anaerobic digestion process to transform spent coffee grounds to biogas and fertilizer included 5 stages: transportation to processing facility, fermentation, gas desulfurization, transportation to end of life, and end of life use.

Step 1: Transportation to Processing Facility
The initial transportation step for all alternatives were assumed to be the same, and the description can be found above.

Step 2: Anaerobic Digestion
Anaerobic digestion requires the following input to ferment the spent coffee grounds[1]:

Inputs	**Amount / Metric Ton SCG**	**Total Amount**
Electricity	91.08 MJ	904,536 MJ
Heat	324.72 MJ	3,224,868 MJ

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[1] Schmidt Rivera, X. C., Gallego-Schmid, A., Najdanovic-Visak, V., & Azapagic, A. (2020). Life cycle environmental sustainability of valorisation routes for spent coffee grounds: From waste to resources. Resources, Conservation and Recycling, 157, 104751.

The outputs of anaerobic digestion are 146.3 m^3 biogas and 0.82 metric tons digestate per metric ton of SCG input. 70% of the biogas is methane[2]. It is assumed that 2% of the biogas that is produced will leak when the coffee grounds are fermented[3]. Processing 9,911 metric tons of SCG will produce approximately 1,455,997 m^3 biogas and 8,126 metric tons of digestate. This process produces 101.2 kg CO_2 and uses 706.2 MJ of energy per metric ton SCG. The biogas can be combusted and used as an alternative to electricity produced from natural gas combustion. Literature suggests that digestate can be immediately applied to land as an alternative to fertilizer[4].

Step 3: Biogas Desulfurization

The biogas composition is approximately 61.9% CH_4, 0.3% H_2S, 37.5 CO_2, and 0.3% N_2. H_2S is a corrosive compound that must be removed to avoid damage in processing equipment[5]. There are multiple ways to accomplish desulfurization. The method chosen for this analysis was passing the biogas through an impregnated activated carbon bed without regeneration. The bed requires the inputs of 0.111 kg activated carbon, 0.00968 MJ electricity, and 0.0706 MJ heat to desulfurize the biogas produced from one ton of SCG. Approximately 0.0777 kg NH_3 and 0.0164 kg H_2S are directly emitted during desulfurization which equates to 1.419 kg CO_2 equivalent that is emitted due to process inputs per ton SCG input. This process uses about 17.6 MJ of energy per metric ton SCG input.

Inputs	**Amount / Ton SCG**	**Total Amount**
Activated Carbon	0.111 kg	1103 kg
Electricity	0.00968 MJ	96 MJ
Heat	0.0777 MJ	771 MJ

Step 4: Transportation to End of Life

The last step to take into account is transportation of the digestate fertilizer to the end user. Assuming a 120 miles round trip, 12 trips per year, and $\frac{8126}{12} = 677.17$metric tons per trip, the transportation tool used for the first step of each of our processes estimated

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[2] Bernstad, A., & La Cour Jansen, J. (2011). A life cycle approach to the management of household food Waste – a SWEDISH Full-scale case study. *Waste Management, 31*(8), 1879-1896.

[3] Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. (2019). Environmental sustainability of anaerobic digestion of household food waste. *Journal of Environmental Management, 236*, 798-814.

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23 metric tons of $CO_{2\text{-eq}}$ per trip. This equates to 0.0341 metric tons $CO_{2\text{-eq}}$ per metric ton SCG.

Step 5: Digestate Application and Biogas Combustion

The digestate is assumed to be applied directly as a fertilizer. The bioavailable nutrients in the digestate are equivalent to the mass percentages 1.94% N and 0.62% P.[4] The literature indicates that the application of the digestate to land without storage saves approximately 9 kg CO_2 per metric ton SCG input when accounting for the GHG emissions from application and GHG savings from avoided fertilizer production.

Combusting the desulfurized biogas produces 776.16 MJ per metric ton of SCG. There are no emissions associated with this process because we are considering the biogas to be biogenic.

Total Anaerobic Digestion Emissions and Energy Consumption

Process	**CO_2 (kg/Metric Ton SCG)**	**Energy Resources (MJ/Metric Ton SCG)**	**CO_2 (Metric Tons)**	**Energy Resources (MJ)**
Initial Transportation	41.8	0	416	0
Anaerobic Digestion	101.2	706.2	1,002	7,010,775
Biogas Desulfurization	1.43	17.6	14	176,103
Fertilizer Application	-9.02	0	-89	0
Final Transportation	35.41	0	342	0
Total	**170.82 kg CO_2/metric ton SCG**	**723.8 MJ/metric ton SCG**	**1,685 metric ton CO_2**	**7,186,878 MJ**

Anaerobic Digestion vs. Natural Gas Electricity and Fertilizer

The lifecycle of anaerobic digestion to produce electricity from biogas and digestate was compared to producing electricity from natural gas and producing fertilizer.

Natural Gas Electricity

The 146.3 m^3 of biogas created from 1 metric ton of SCG can create up to 776.16 MJ of electricity.[3] The CO_2 emissions and energy use from creating the same amount of electricity produced from natural gas combustion was calculated to estimate the life cycle savings. Producing and combusting natural gas as a source of electricity was a premade option in Simapro. This premade process estimated 0.125 metric tons CO_2 were emitted and 2398 MJ energy resources were used per 776.16 MJ electricity created.

Fertilizer

The bioavailable nutrients in the digestate are composed of 1.94% N and 0.62% P. A fertilizer with an equivalent composition was analyzed in Simapro with premade fertilizer options. The production of 0.0159 metric ton N and 0.005 metric ton P fertilizers were analyzed to compare to the digestate produced from 1 metric ton of SCG. This fertilizer composition created approximately 165 kg of CO_2 and used 1100 MJ energy resources.

Anaerobic Digestion Comparison

When compared to the market alternatives, the products from anaerobic digestion saved the following amount of CO_2 and energy resources:

Process	**CO_2 (kg/metric ton SCG)**	**Energy Resources (MJ/ metric ton SCG)**	**CO_2 (Metric Tons)**	**Energy Resources (MJ)**
Anaerobic Digestion	170.82	723.8	1,685	7,186,878
Natural Gas + Fertilizer	303.9	3737.86	3,110	35,472,847
Difference (Savings)	**- 130**	**- 3014**	**- 1,425**	**- 28,285,969**

Pyrolysis

Step 1: Transportation to Processing

The initial transportation step for all alternatives were assumed to be the same, and the description can be found above.

Step 2: Drying

Before the spent coffee grounds undergo pyrolysis, they must be dried and grinded. A moisture content of 49.3% was assumed for these calculations, meaning the input/output values are prone to change if a more accurate value was defined. The following table details the inputs and outputs from this process. The input values were taken from this article and converted from metric tonnes to tons[6].

Inputs	Value (MJ)	Outputs	Value (tonnes)
Heat	544	SCG	0.507
Electricity	0.145	Waste Water	0.493

To dry and grind 1 ton of SCG, 544 MJ of heat and 0.145 MJ of electricity are needed. The water would thus be separated from the rest of the process and will become waste.

Step 3: Pyrolysis

In order to prioritize the production of biochar, slow pyrolysis is preferred. This means lower temperatures but longer residence times, as liquids and gases prefer higher temperatures. Therefore, a heating rate of 50°C/min was chosen. Values of 27, 21, and 27.2 for biochar, gas, and condensate were found through literature[7]. These were converted to percentages and, by averaging out the percentage of condensate that was bio-oil, 12% of condensate was assumed to find the percentage of oil. After multiplying these values by 0.507 to account for the lesser SCG after drying, the following outputs were calculated per ton of SCG, where aqueous phase is condensate minus bio-oil.

Output	Value (tonnes)
Biochar	0.165
Biogas	0.128
Bio-oil	0.0200
Aqueous phase	0.146

The energy and heat needed for this process was calculated by multiplying the values in this article[8] by the 0.507 tons of dried SCG in the process. To convert electricity from MWh to MJ for these results, a capacity factor of 100% was assumed.

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[6] https://www.sciencedirect.com/science/article/pii/S0921344920300732

[7] https://bioresourcesbioprocessing.springeropen.com/articles/10.1186/s40643-019-0281-5/tables/2

[8] https://www.mdpi.com/1996-1073/12/11/2166

Heat	1840
Electricity	91.44

Emissions were found similarly from this article[9], but the 1MJ of bio-oil basis was converted assuming a 18MJ/kg heat capacity and the 0.022 tons found in the previous step.

Emissions	Value (kg)
CO_2	15.4
CO	0.0962
HAP	0.0270
NO_x	0.0428
SO_x	0.0000750
VOC	0.00431
Particulates	0.0329
Water	32.7

The main appeal for biochar is that it can replace fertilizer, which uses a lot of energy and emits a lot during production. They also harm the environment in a variety of ways, whether it is through polluting waterways or the air. The biochar would be used in the area surrounding the Augusta Georgia plant. Displaced fertilizer was found in this article[10], then multiplied by 0.182 (the amount of biochar produced) to account for the difference in functional unit.

Fertilizer type	Value (tonnes)
N	0.000120
K	0.0000182
P	0.0000237

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[9] https://www.osti.gov/servlets/purl/1080273

[10] https://www.mdpi.com/1996-1073/12/11/2166

Step 4: Cogeneration

The bi-products bio-oil and biogas can be cogenerated together to produce energy and heat. While this process does require electricity, the energy and heat produced will displace some from natural gas. Converting the bio-oil (14.1 MJ/kg)[11] and biogas (17.5 MJ/kg)[12] to MJ using their individual heating values. Almond shell was picked as the alternative because it was most similar to SCG's heating value and yield of char. Adding the MJ values and dividing by 6.13 (the basis for the article[13] whose values I used) gave me a coefficient of 411.07 to multiply all values in the article by. This gave me the following inputs and outputs.

Energies	Value (MJ)
Electricity output	411.07
Heat output	1603
Electricity input	205.54
Waste heat	505.6

The emissions from this step are as follows.

GHG	Value (kg)
CO_2	943
CO	0.350
NO_2	0.700
SO_2	0.325
Particulates	0.210
VOC	0.0210

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[11] http://biorefinery.utk.edu/technical_reviews/char%20bio-oil%20HHV.pdf

[12] https://bioresourcesbioprocessing.springeropen.com/articles/10.1186/s40643-019-0281-5/tables/5

[13] https://www.sciencedirect.com/science/article/pii/S1876610212007989#:~:text=This%20work%20concerns%20the%20production,wood%20waste)%20in%20cogeneration%20plants.&text=The%20objective%20is%20to%20compare,LCA%20methodology%20is%20therefore%20presented.

This step is what makes pyrolysis unviable as there is a lot of carbon emissions. However, these are a little overestimated since the article these values were taken from also assumed other steps like grinding that is not happening here. Still, the little fertilizer that the biochar would displace also explains pyrolysis' potential not being met.

Step 5: End of Life

The last step to take into account is transportation of the biochar to where it would be used. Assuming a 60 mile distance per trip, 12 trips per year (so 760 miles total) and $\frac{0.182*10924.349}{12} = 165.686\ tons\ per\ freight$, the transportation tool used for the first step of each of our processes gave CO_2, CH_4, and N_2O emissions. These values were then divided by 10924.349 to convert to the 1 ton SCG functional unit. The final emissions are displayed below.

GHG	Value (kg)
CO_2	3.57
CH_4	0.0000421
N_2O	0.0000325

Once all steps are created as separate processes, they are added to a single product stage. Energy resources were calculated using the Eco-Indicator 95 method while carbon emissions were calculated using IPCC 2013 GWP 100a method. The flow diagrams for each step were found using the network button on Simapro. For the final calculations, the entire 10924.349 tons of SCG were used. The following results were obtained.

Energy resources (MJ)	21,623,811
Carbon emissions (kg)	11,208

Compost:

The goal and scope of the Compost included 3 different stages, Transportation to the composting facility(Longwood, GA), Manufacturing, and End of Life.

Step 1: Transportation to composting facility (Longwood, GA)

Based on the preliminary telephone meeting with Starbucks, we are informed that Starbucks transports its coffee waste towards the Longwood organic composting facility from its Augusta factory. The distance between two places is approximately 80 miles.

Plus 40 miles to the golf course, the total distance reaches 120 miles which is coherent with our initial assumption.

The calculation step can be seen in the above section.

Step 2: Manufacturing process

As for the manufacturing phase, the spent coffee ground is collected and dispersed in the facility to dry out its water. After the drying process, the coffee ground is dumped into the windrow with constant temperature and moisture. This is also the curing phase of the compost. All the energy consumption data are extracted from the relevant literature. The curing phase requires 95 kwh/metric ton of coffee compost for energy[14], 394 litre/ metric ton of water[15], and roughly 4 litre/ metric ton of diesel[16]; and it emits 118kg/ tonne of carbon dioxide[17] and 49g/tonne methane ($CH4$)[18].

Input (Manufacturing)	Value (per ton of SCG)
De-Ionised water at plant	394 kg
Diesel	3.4 kg
Electricity, ERCOT	95 kwh

Step 3: End of Life

The end of life of compost can be dissected into two parts, a) synthetic fertilizer displaced and b) biogenic carbon emission. In particular, the End of Life phase includes the emission that would be generated, had synthetic fertilizers been deployed in the same situation. As for biogenic carbon emission, adamedic perceptions are dichotomous and disputable. IPCC argues that we shall treat the biogenic emission as zero since the compost is going through a natural process of decomposition. But, we contend that there is human involvement, be it intellectual or physical, in displacing the chemical inorganic fertilizers in the golf course. Thus, for the purpose of this project, this process is considered non-biogenic.

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[14] Cadena EColón JArtola A et al, 2009

[15] Armington et al., 2008

[16] D Edwards, C Williams - 2011
Cadena EColón JArtola A et al., 2009

[17] Armington et al., 2008

[18] Armington et al,. 2008

Input (Avoided material)	Value (per ton SCG)
Fertiliser (N)	7.81 kg
Fertiliser (P2O5)	5.94 kg
Fertiliser (K2O)	4.51 kg

In summary, when the numbers are scaled into 10925 tons of SCG, the total environmental impact of compost

	GHG emission (tonne)	Energy consumption(MJ)
Compost	1,550.567	8,455.507

Fertilizer:

The goal and scope of the Fertilizer of SCG include 4 different stages, Transportation, Manufacturing (compost), Refining (transform compost into proper fertilizer) and End of Life. Typically this can be viewed as the compost with an additional refining stage.

Step 1: Transportation
The initial transportation step for all alternatives were assumed to be the same, and the description can be found above.

Step 2: Manufacturing of compost
This is the same as the step 2 in the compost.

Step 3: Refining
Because there is weight loss and water evaporation (49.3% water in SCG) in the process, we are assuming that it takes 2.03 functional units of the refining process in order to produce one ton of SCG. [19]This application provides the nutrients N, P2O5 and K2O contained in the compost. Namely, it contains 0.7% nitrogen, 0.4% P2O5 and 0.6% K2O.

Step 4: End of Life
The end of life phase of the fertilizer is different from others, because the end of life phase is also the use phase (or application phase) of the fertilizer. In this study, we aren't particularly interested in the use phase of every alternative, due to countless

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[19] Simapro 9.1,Material-Fertilizes(organic)-Transformation- Compost(GLO) nutrient supply from compost

different scenarios where it can be adopted. Thus, the end of life phase does contain the inorganic fertilizer displaced, but not contain the biogenic carbon emission.

	GHG emission (tonne)	Energy consumption(MJ)
Compost	3,883.558	34,176,472

SCG PHA

The goal and scope of the SCG PHA process included 5 different stages, Transportation to Oil extraction, Oil extraction, Transportation to PHA facility, PHA production, and End of Life.

Step 1: Transportation to Oil Extraction

Our process started with transporting SCG from the Augusta, GA site to an oil extraction facility. We tried to keep transportation the same within all alternatives and therefore assumed that the oil extraction facility would be within 64 miles of the Augusta site. We started with 10925 short tonnes of SCG (based on 2017-2018 yearly supply-Starbuck's data) that was transported using an HGV Vehicle- unknown engine size and the GHG calculation tool *Transport_Tool_v2_6_transport_basecase.xlsx.* 12 round trips were estimated to haul the year supply of SCG which amounted to 1536 miles (12*128 mi). The emissions were calculated for hauling the weight of a single trip 10925/12=910.417 and then scaled for the total number of trips. Emissions from the GHG calculator for CO2, CH4, and N2O were plugged into a single Simapro Process for 1 ton and scaled to the full amount. Inputs for the process were the following: CO2: 0.038 metric tons, CH4: $4.48x10^{-4}$ kg, and N2O: 3.456^{-4} kg.

Inputs	Amount	Units
Number of trips	12	miles
Distance per trip	64	miles
Total weight transported	9910.993	Metric tons
Weight transported per trip	825.916	Metric tons

Outputs	Amount	Units
CO2	0.038	Metric tons
CH4	$4.48x10^{-4}$	kg
N2O	3.456^{-4}	kg

Step 2: Oil Extraction

Again inputs were plugged into a Simapro model for 1 ton of SCG and scaled for the full year supply of 10925 tons. The oil extraction process requires the following inputs: hexane, drying and heating of SCG, electricity for grinding SCG, dried SCG, and wastewater. The process also produces outputs of fertilizer and oil.

From Shelie Miller's paper, we found there is a ratio of 0.013 kg of hexane/ 5.7 kg of soy.[20] Applied to 1 ton of SCG this is 907.185 kg SCG*0.013 kg of hexane/ 5.7 kg of SCG. This calculation results in 2.069 kg of hexane.

From the Rivera paper, we found that it takes 1140 MJ of energy for the heating and drying of SCG and 0.145 MJ of electricity for grinding.[21]The amount of energy used varied widely based on the literature we read. We do want to note that we used the higher energy end of the spectrum that we saw in the literature, so this is an assumption that could be varied if our study was repeated with a more efficient process. In Simapro, we used the Electricity, Natural Gas, at powerplants ERCOT S for the electricity for grinding and Heat, natural gas, boiler atm, low-NOx condensing non-modulating <100kW/RER S for heating and drying SCG. After a ton of the SCG is dried it leaves 0.507 tons of dry weight and produces 0.493 tons of waste water. Oil extraction only uses 16.8% of the weight of the dried SCG and the rest was converted into a byproduct of fertilizer.[22] For the full year supply this produced 930.548 tons of oil and 4608.27 tons of fertilizer. We made our own fertilizer process within Simapro that required percentage

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[20] Comparison of Life-Cycle Inventory Databases A Case Study Using Soybean Production. Sheltie Miller, Thomas Theis. Journal of Industrial Ecology. Volume 10, Number 1-2, 2006. http://mitpress.mit.edu.proxy.lib.umich.edu/jie

[21] Life cycle environmental sustainability of valorisation routes for spent coffee grounds: From waste to resources.Schmidt Rivera, Ximena C.,Gallego-Schmid, Alejandro,Najdanovic-Visak, Vesna, et. al. Resources, Conservation and Recycling, (2020), 157 https://www.sciencedirect.com/science/article/pii/S0921344920300732

[22] Anabolism of Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) by Cupriavidus necator DSM 545 from Spent Coffee Grounds Oil.Ingram, Haydn Rhys,Winterburn, James Benjamin. New Biotechnology, (2020).

inputs for N,P,K. We found that SCG is composed of 1.2% Nitrogen, 0.35% Potassium, and 0.02% Phosphorus. [23][24]

Inputs	Amount	Units
Hexane	2.069	Kg
Energy for heating and drying	1140	MJ
Electricity for grinding	0.145	MJ
Waste water	118.148	gallons

Outputs	Amount	Units
Oil	0.077	Metric tons
Fertilizer	0.383	Metric tons

Step 3: Transportation to PHA Facility

The methodology for this transportation was the same as the above method but the weight transported changed as we were transporting oil instead of SCG. The imputed weight into the *Transport_Tool_v2_6_transport_basecase.xlsx* was 844.179 tons of oil. The emissions were calculated for hauling the weight of a single trip and then scaled for the total number of trips (12). Emissions from the GHG calculator for CO2, CH4, and N2O were plugged into a single Simapro Process for 1 ton and scaled to the full amount. Inputs for the process were the following: CO2: 0.038 metric tons, CH4: 4.48×10^{-4} kg, and N2O: 3.45^{-4} kg.

Step 4: PHA production

PHA production required an input of oil, electricity, natural gas, and steam mixtures to perform the fermentation processes.[25] Simapro did not have a good input for steam, so

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[23] The Use of Spent Coffee Grounds in Growing Media for the Production of Brassica Seedlings in Nurseries. Chrysargyris, A., Antoniou, O., et. al. Environmental Science and Pollution Research. Springer Nature. 2020. https://doi.org/10.1007/s11356-020-07944-9

[24] Vardon, Derek R., et al. “Complete Utilization of Spent Coffee Grounds To Produce Biodiesel, Bio-Oil, and Biochar.” *ACS Sustainable Chemistry & Engineering*, vol. 1, no. 10, 2013, pp. 1286–1294., doi:10.1021/sc400145w.

[25] Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly-β-hydroxybutyric acid using life cycle analysis. Harding, K. G., Dennis, J. S., von Blottnitz, H., et. al. Journal of Biotechnology, (2007), 57-66, 130(1)

we allocated the energy from steam (0.051816 MJ) equally to electricity and natural gas. The following inputs/outputs are for one ton oil inputted and are scaled up for the total input of 844.179 tons of oil. The total amount of PHA produced 6.75343 metric tons.

Inputs	Amount	Units
Oil	0.077	Metric tons
Electricity	0.041	MJ
Natural Gas	0.034	MJ

Output	Amount	Units
PHA	0.0004	Metric tons

Step 5: End of Life

We calculated the emissions and energy associated with a composting and landfill end of life. For the composting process we used the Simapro model *Compost at Plant/ CH S.* For Landfill we used the EPA tool Landgem-v303.xlsm. The following inputs were taken from the EPA calculator and plugged into our model as a process for disposing 1 ton of PHA. The process was then scaled for the full amount of PHA (6.75343 metric tons).

Input	Amount	Unit
Methane	5.545×10^{-4}	Metric tons
CO2	1.52	Metric tons
NMVOC	3.6×10^{-5}	Metric tons

In order to normalize our comparison with corn we determined the exact amount of emissions to produce 1 g of PHA using both the corn and SCG processes. The corn process produces a total 23.545 metric tons of PHA, SCG produces 6.753 metric tons in comparison. To determine the emissions for 1 g of PHA from corn and SCG we divided these total amounts by the total input of corn and SCG which was the same at 9910.488 metric tons for a year's supply. This gave us the amount of corn (0.0004 metric tons) versus the amount of SCG (0.0014 metric tons) to produce 1 g of PHA. We took the total emissions from our Simapro model for each process and divided it by the total amount of corn/SCG used (9910.488 g). This gave us the emission for 1 g of corn/SCG and then multiplied that number by 0.0004 metric tons for corn and 0.0014 metric tons for SCG to determine the amount of emissions for 1 g PHA. We then multiplied this number by 15,000,000 to determine the overall emissions to produce 15,000,000 g of PHA from both processes.

When SCG was compared to current practices, there was 1249 Metric tons of CO2 and 26,440,493 MJ of energy expelled. When compared to corn, an additional 1,912 metric tons of CO2 would be required but 77,210,374 MJ of energy would be saved. Though the energy required to convert SCG to PHA is lower as it uses the waste product instead of making virgin corn, the efficiency is much less and therefore counteracts the benefits of performing a lower energy process.This is due to the fact that the yield of PHA from SCG is much lower than corn, and therefore requires more SCG to be converted in order to make the same amount of corn.

Corn PHA

The goal and scope of the Corn PHA included 6 different stages. Corn production, transportation to oil extraction, oil extraction, transportation to PHA facility, PHA production, and end of life.

Step 1: Corn Production
This process started with corn grown on the farm. We used a model in Simapro that included the cultivation of corn in the USA which included diesel, machines, fertilizers, and pesticides. We used the equivalent amount of SCG to corn, which is 9910.993 metric tons. After the corn is grown and ready for extraction, it will be transported to the oil extraction facility.

Step 2: Transportation to Oil Extraction
The transportation to oil extraction can be found above.

Step 3: Oil Extraction
For the oil extraction process, we scaled the corn to the full year supply, equivalent to the amount of SCG which was 9910.993 metric tons. For this process, the oil needs to be extracted using electricity, and adding hexane. The oil yield for corn is 17%[26]. We used the equivalent method as the SCG, with the electricity (natural gas, ERCOT S) being 649.242 MJ and hexane being 2.06 kg per ton of corn. The amount of corn that is extruded is 1704.7 metric ton. Instead of composting the meal (8025.6 metric tons), we sent it to animal feed. In simapro, the meal equivalent we used is soy meal.

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[26] Surfactant-Based Oil Extraction of Corn Germ. Sezin Islamoglu Kadioglu • Tri T. Phan • David A. Sabatini.J Am Oil Chem Soc (2011) 88:863–869 DOI 10.1007/s11746-010-1719-2

From Shelie Miller's paper, we found there is a ratio of 0.013 kg of hexane/ 5.7 kg of soy.[27] Applied to 1 ton of SCG this is 907.185 kg SCG*0.013 kg of hexane/ 5.7 kg of SCG. This calculation results in 2.06 kg of hexane.

Inputs	Amount	Units
Hexane	2.06	Kg
Electricity (ERCOT)	1.65	Wh
Electricity (ERCOT)	649.24	MJ
Waste water	309.12	gallons

Outputs	Amount	Units
Oil	1704.7	Metric tons
Animal Feed	8025.6	Metric tons

Step 4: Transportation to PHA facility

To transport the 1704.7 metric tons of oil to the PHA facility, we used the same methodology as the above method.

The methodology for this transportation was the same as the above method but the weight transported changed as we were transporting oil instead of SCG. The input weight into the *Transport_Tool_v2_6_transport_basecase.xlsx* was 1704.7 metric tons of oil. The emissions were calculated for hauling the weight of a single trip and then scaled for the total number of trips (12). Emissions from the GHG calculator for CO2, CH4, and N2O were plugged into a single Simapro Process for 1 ton and scaled to the full amount. Inputs for the process were the following: CO2: 0.038016 metric tons, CH4: 0.000448 kg, and N2O: 0.000345 kg.

Step 5: PHA production

For this step, electricity and heat are being used. The electricity (natural gas, ERCOT) is .041 MJ per ton of PHA produced and the natural gas (burned at power plant ERCOT) is .0344 MJ per ton of PHA. THe PHA produced was 0.0004 metric tons per ton of oil and when scaled up there was 23.545 metric tons of PHA.

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[27] Comparison of Life-Cycle Inventory Databases A Case Study Using Soybean Production. Sheltie Miller, Thomas Theis. Journal of Industrial Ecology. Volume 10, Number 1-2, 2006. http://mitpress.mit.edu.proxy.lib.umich.edu/jie

Inputs	Amount	Units
Oil	0.077	Metric tons
Electricity	0.041	MJ
Natural Gas	0.034	MJ

Output	Amount	Units
PHA	4.09×10^{-4}	Metric tons

Step 6: End of Life

We assumed both composting and landfilling for the end of life. For the composting process we used the Simapro model *Compost at Plant/ CH S.* For Landfill we used the EPA tool Landgem-v303.xlsm.

The following inputs were taken from the EPA calculator and plugged into our model as a process for disposing 1 ton of PHA. The process was then scaled for the full amount of PHA which was 23.55 metric tons.

The normalization part is listed under the SCG PHA.

Input	Amount	Unit
Methane	5.545×10^{-4}	Metric tons
CO2	1.521	Metric tons
NMVOC	3.6×10^{-5}	Metric tons