CARBON FOOTPRINT COMPARISON OF GCLs AND COMPACTED CLAY LINERS

CETCO and DAI Environmental performed an analysis comparing the carbon footprint of a conventional compacted clay liner to a GCL for a hypothetical RCRA Subtitle D municipal solid waste landfill. The analysis found that, for a landfill liner site located 1,610 km (1,000 miles) from the GCL manufacturing plant and 16 km (10 miles) from the clay borrow source, a conventional compacted clay liner is expected to produce a 34% larger carbon footprint than a GCL. The largest single component of the overall carbon footprint for both options is transportation. It is estimated that, in order to line a one-hectare area (2.5 acres), over 550 truckloads of clay would be required, compared to only 3.2 truckloads of GCL.

Repeating the analysis over ranges of different haul distances found that in order for the compacted clay liner option to produce a lower carbon footprint than the GCL option, the clay borrow source would need to be within approximately 9 km (5.5 miles) of the job site. This assumes that the GCL manufacturing plant is located 1,610 km (1,000 miles) from the job site. If the GCL plant is located 3,000 km (1,860 miles) from the job site, then the clay borrow source could be within approximately 14 km (8.7 miles) of the job site and still offer a lower carbon footprint. If the GCL plant is located 100 km (62 miles) from the job site, then the clay borrow source would need to be within 2.5 km (1.6 miles) of the job site to produce a lower carbon footprint.

As is the case with evaluations of cost effectiveness, carbon footprint evaluations are site-specific, depending greatly on the relative distances of the project site to the clay borrow source and to the GCL manufacturing plant. Accordingly, project-specific analyses are strongly recommended.

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CARBON FOOTPRINT COMPARISON OF GCLs AND COMPACTED CLAY LINERS

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INTRODUCTION

Geosynthetics are playing an increasingly more important role in environmental and geotechnical applications, as local sources of natural barrier and drainage materials diminish. While much work has already been devoted to comparing the technical effectiveness of geosynthetics to natural soils, there has been little study into the comparative energy efficiencies and sustainability of geosynthetics and soils. Accordingly, the purpose of this study is to compare the carbon footprint (or equivalent greenhouse gas emissions, in kg of CO_2 equivalents per hectare) of a natural compacted clay liner (CCL) with a geosynthetic clay liner (GCL). Specifically, the analysis looked at the following bottom liner options for a hypothetical RCRA Subtitle D municipal solid waste landfill:

- **Option 1.** Prepared subgrade, 0.6-meter thick compacted clay liner with a hydraulic conductivity of 1×10^{-7} cm/sec, 1.5-mm HDPE geomembrane, and sand drainage layer. This is the prescriptive Subtitle D liner system.

- **Option 2.** Prepared subgrade, GCL, 1.5-mm HDPE geomembrane, and sand drainage layer. This is a commonly used alternative to Option 1.

Each of these liner system options is discussed separately below.

COMPACTED CLAY LINERS

Compacted clay liners been historically used as barrier layers in waste containment facilities to either limit the infiltration of surface water into the buried waste (caps) or limit the migration of leachate into the environment (bottom liners). Common regulatory requirements for compacted clay liners are a minimum thickness of 0.6-meters, with a maximum hydraulic conductivity of 1×10^{-7} cm/sec. Off-site borrow sources of clay or silt soils are often required to construct a low-permeability compacted soil liner. Significant upfront investigation is necessary to properly characterize the extent and the quality of the soil at the borrow source. Emissions associated with upfront investigation and characterization of the borrow source are not being included in the carbon footprint analysis.

As discussed by Daniel and Koerner (2007), in some cases, soils from the borrow source are clay-deficient, requiring the addition of bentonite to produce a compacted soil liner that meets the required hydraulic conductivity. For the purposes of this analysis, a "best-case" scenario is assumed, where the soil from the borrow pit has a high enough fines content and plasticity index to meet the hydraulic conductivity requirements without any amendments.

Clay at the borrow source is excavated using standard construction equipment, which also loads the material onto tri-axle dump trucks for transport to the job site. Each truck is assumed to have a capacity of 15 m^3 of loose soil. Using a compaction factor of 1.38, it is estimated that over 550 truckloads of soil would be needed to construct a 0.6-meter thick compacted clay liner over a one-hectare area.

The distance from the borrow source to the job site is, of course, site-specific and can vary greatly. For the purposes of this analysis, a distance of 16 km (10 miles) was assumed. Since transport from the clay borrow source and the job site is such a large component of the overall carbon emissions, the sensitivity of the overall carbon footprint to changes in this site-specific variable is investigated later in this study.

Daniel and Koerner (2007) recommend that the subgrade on which a compacted clay liner is placed should provide adequate support for compaction and be free from mass movements. For this analysis, subgrade preparation is assumed to consist of grading to meet elevations in the grading plan using a bulldozer and a grader. The compacted clay liner itself is constructed by first spreading the soil into thin (0.15- to 0.2-meter) lifts using a bulldozer. Each lift is subjected to numerous passes with a sheepsfoot roller, to knead the soil and break up clods and remold the soil into a homogeneous mass free of voids or large pores. In addition, water is added to produce a moisture content within specification requirements. The surface of the final lift is compacted and smoothed using a smooth-drum roller, to provide an adequate foundation for the geomembrane liner.

A typical compacted clay liner installation rate of 0.25 hectares per day (0.6 acres per day) was assumed. This corresponds to placement of 2,000 m^3 of compacted soil per day, a reasonable expectation during periods of good weather. Once the compacted clay liner is completed, it is also covered with a 1.5-mm (60-mil) thick HDPE geomembrane, which is in turn covered by a 0.3-m (1 foot) drainage sand layer.

GEOSYNTHETIC CLAY LINERS

GCLs are factory-manufactured mats consisting of sodium bentonite clay between two geotextile layers, with a laboratory hydraulic conductivity of 5×10^{-9} cm/sec. Due to their low hydraulic conductivity, GCLs are frequently used as a substitute for compacted clay liners in many containment applications. Bonaparte et al (2002) provide field data from numerous landfill sites demonstrating that GCLs provide equivalent or superior hydraulic performance when compared to 0.6 meters of compacted clay as the lower component of composite liner systems.

Sodium bentonite is a rare clay mineral formed through the aqueous deposition and weathering of volcanic ash. Much of the worldwide sodium bentonite supply lies within the United States, in Wyoming and South Dakota. Trauger (1994) provides a detailed description of the bentonite exploration and mining process. As with the compacted clay liner option, for the purposes of this analysis, emissions associated with upfront exploration and characterization of the bentonite deposits are not being included in the analysis, as they are not expected to be a significant contributor to the overall carbon footprint. Other excluded emissions are identified later in this paper. The analysis will begin with the mining of the bentonite. The typical mining sequence involves excavation of a series of pits. Each pit is approximately one to two acres in area and 5 to 10 meter deep. The bentonite itself occurs in beds that are one to two meters thick. To extract the bentonite, topsoil and overburden are first removed using standard earthmoving equipment. The bentonite, typically gray in color, is easily distinguishable from the overburden and subsoils. As bentonite is removed from one pit, an adjacent pit is excavated. The overburden and topsoil from the adjacent pit are used to backfill the first pit, as part of a continuous reclamation process intended to minimize the disturbed area. The reclaimed pit is graded and seeded, and the mining and reclamation process continues in this fashion until the claim has been fully utilized.

Once excavated from the pit, the "crude" bentonite is placed in haul trucks and transported a short distance to the processing plant. The bentonite mines are located a short distance from the processing plant in Lovell, Wyoming (varying from as close as 1 km up to several km). For the purposes of this analysis, a distance of 30 km was conservatively assumed.

When the bentonite arrives at the bentonite plant, it is segregated into different stockpiles based on grade. The stockpiled material is plowed to facilitate air drying, and depending on the intended end use, may also be blended with other grades of bentonite. The field-dried and blended bentonite is carried into the plant, where it is dried further in an oven. The material then is passed through a crusher to reduce the clay particle size.

The dried and crushed clay is stored in a holding tank until all bentonite quality tests (e.g., fluid loss and free swell) are completed. From there, the clay is transferred by a belt conveyor to the GCL manufacturing line. The GCL manufacturing process, shown in Figure 1, begins by applying bentonite at a typical loading rate of 4.3 kg/m^2 between two geotextiles (in this example, a cover nonwoven geotextile and a base woven geotextile). The woven and nonwoven geotextile components of the GCL are purchased from an outside manufacturer, located in northern Georgia, approximately 2,760 km (1,700 miles) away. The three layers are then passed through a needlepunching loom, where fibers from the nonwoven cover geotextile are driven through the bentonite layer and into the woven base geotextile.

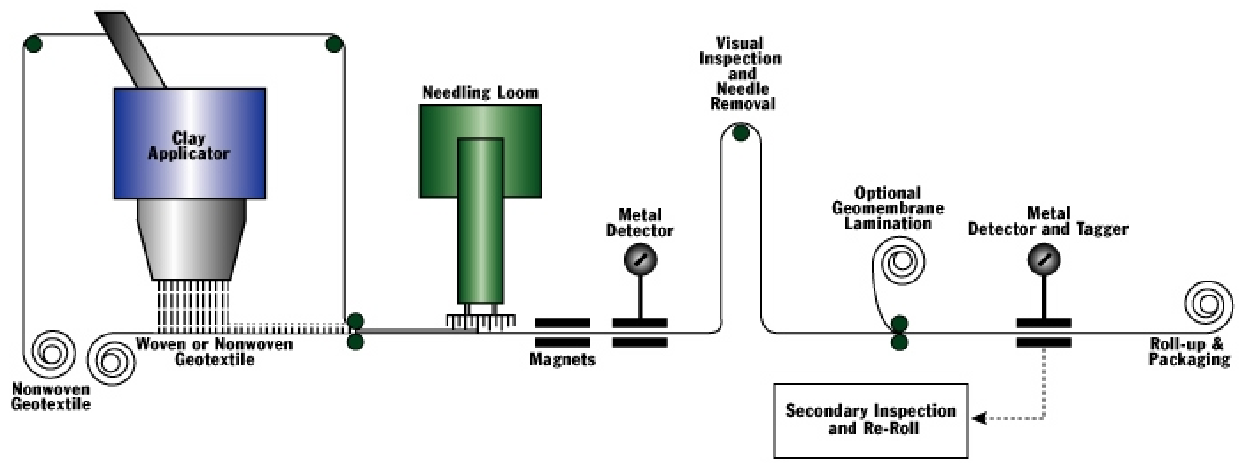

Figure 1. GCL Manufacturing Process

The finished reinforced GCL is packaged in rolls, each containing 209 m^2 of material. GCL rolls are transported to the job site using either flatbed trucks or closed vans. This study assumes that the distance from the GCL production plant in Lovell, Wyoming, to the job site is 1,610 km (1,000 miles). Each truck can hold up to 17 rolls, or 3,555 m^2 of GCL. Using a waste factor of 1.15 (for overlap and scrap), it is estimated that 3.24 truckloads of GCL would be needed to line a one-hectare area.

As the trucks arrive at the job site, the GCL rolls are unloaded using an extendible boom fork lift equipped with a stinger bar. Prior to deploying the GCL, the subgrade soil is prepared to meet project specifications. Subgrade preparation before placing a GCL is typically more involved than the preparation needed prior to constructing a compacted clay liner. As with the compacted clay option, the existing soil surface is graded to meet the elevations in the grading plan using a bulldozer and a grader. In the case of the GCL, an additional step is necessary; a smooth-drum roller is driven over the subgrade to ensure that the finished surface is firm, smooth, and free of large stones that could puncture the liner.

Once the subgrade has been prepared, the GCL rolls are deployed using a spreader bar and core pipe, which can be suspended from common construction equipment, either a front end loader, backhoe, or excavator. A typical GCL installation rate of 0.4 hectares per day (1 acre per day) was assumed. Once deployed, the GCL is covered with a 1.5-mm (60-mil) thick HDPE geomembrane, which is in turn covered by a 0.3-m (1 foot) layer of drainage sand.

METHODOLOGY

Protocol and Boundaries of Analysis

To complete a Carbon Footprint calculation, one must set the boundaries of the calculation. The boundary establishes what is included in the calculation and what is excluded from the calculation. The *de facto* standard in GHG reporting is the World Resources Institute (WRI) "GHG Protocol-A Corporate Accounting and Reporting Standard, Revised Edition" (WRI, 2004) ("Protocol"). This Protocol was developed to assist organizations in calculating a corporate-wide or organization-wide GHG footprint and breaks out the boundary analysis under the categories of "organizational boundaries" and "operational boundaries". However, this paper did not focus on an "organizational" calculation, but instead, provides a comparison of the GHG emissions attributable to two different liner systems (GCL versus CCL). Because the production and installation of each of these systems involves emissions attributable to multiple organizations and processes, certain aspects of the WRI Protocol are not directly applicable or relevant. That said, some of the terminology and methodology used in this paper is consistent with and taken from the WRI Protocol.

In terms of "operational boundaries", our calculation attempted to include all the Scope 1 (direct) emissions, the Scope 2 indirect emissions (purchased electricity), and as many of the other indirect Scope 3 emissions we could practically calculate or estimate. A more specific discussion of the emission sources included (or excluded) and the calculations are provided later in this paper.

GHG Identification and CO_2 Equivalents

The GHGs included in the calculation were the three (3) primary GHGs, namely carbon dioxide, methane, and nitrous oxide. Each of these gases has a different Global Warming Potential (GWP), which is a measure of how much a given mass of a greenhouse gas contributes to global warming or climate change. Carbon dioxide is by definition issued a GWP of 1.0. To quantitatively include the contributions of methane and nitrous oxide to the overall impact, the mass of the methane and nitrous oxide emissions are multiplied by their respective GWP factors and then added to the mass emissions of carbon dioxide to calculate a "carbon dioxide equivalent" mass emission. For purposes of this paper, the GWPs were taken from the values listed in the USEPA regulations "Mandatory Reporting of Greenhouse Gas Emissions" (USEPA, 2010). The GWPs for the GHGs considered in this analysis are:

- Carbon Dioxide = 1.0
- Methane = 21.0

- Nitrous Oxide = 310.0

Using the relative GWPs of the GHGs, the mass of carbon dioxide equivalents (CO_2eq) was calculated as follows:

$$kg\ CO_2 + (21.0 \times kg\ CH_4) + (310.0 \times kg\ N_2O) = kg\ CO_2eq \quad (1)$$

GHG Estimates using Emission Factors and Higher Heating Values

The details and supporting references regarding the individual calculations are provided in more detail in Appendix A and Appendix B, but in general, the GHG emissions were calculated using Emission Factors (EF). In some cases where necessary, Higher Heating Values (HHVs) were also used to convert fuel-use quantities to energy, in cases where the EFs were based on energy units (and not fuel volume or mass). A GHG Emission Factor (EF) is simply a ratio of GHG emitted per unit quantity of energy consumed or material produced (depending on the specific factor).

Emissions Not Considered

As mentioned previously, this paper did not focus on a comprehensive "organizational" calculation, but instead, provides a comparison of the GHG emissions attributable to two different liner systems (GCL versus CCL). While an attempt was made to reasonably include as many emission sources as possible, selected emission sources were excluded from the study boundaries, since they represent a very small percentage of the overall total carbon footprint and are difficult to estimate. Excluded sources include:

- Emissions associated with the exploration/extraction/production and transport of the fuels themselves.

- Emissions associated with the exploration/characterization of the clay borrow source (option 1) and bentonite pits (option 2).

- Emissions associated with disposal of any wastes at the Lovell, Wyoming GCL manufacturing plant, as well as wastes generated by raw materials suppliers (e.g., geotextiles, resin).

- Emissions associated with commuting/business travel of employees of the material suppliers, engineers, and contractors working on the project.

- Additionally, the carbon footprint values for the layers placed over the low-permeability soil layer (the HDPE geomembrane and the 0.3-meter thick drainage sand layer) were estimated using solely the emission factors in the Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2008), and do not include transport, installation, etc. This approach was considered to be reasonable, since these layers are identical for both of the liner options under consideration, and their footprints simply cancel each other out in the overall comparison.

Even if these various sources were somehow included in the analysis, they would have little impact on the GCL:CCL carbon footprint comparison, and therefore would not change the findings or conclusions of this paper.

CARBON FOOTPRINT ANALYSIS RESULTS

Using the assumptions listed above, carbon footprint analyses (in terms of CO_2 equivalents per hectare of lined area) were performed for both the compacted clay liner and GCL options. The analyses are summarized in Tables 1 and 2, with backup calculations presented in Appendix A. CO_2 emission factors for the various transportation and construction components of each process were obtained from USEPA (2005a, 2005b, 2008a, 2008b, 2008c) and University of Bath (2008). Fuel consumption rates for the various construction equipment used by both options was obtained from Caterpillar (2010). Information on the greenhouse gas emissions associated with the mining and processing of bentonite clay was provided by DAI Environmental (2010), and further described in Appendix B.

A comparison of Tables 1 and 2 shows that, for a scenario where the clay borrow source is located 16 km from the job site and the GCL manufacturing plant is located 1,610 km from the job site, the compacted clay liner option would result in significantly higher (36%) emissions of CO_2 equivalents per hectare of lined area. The disparity is simply due to the greater number of trucks necessary to haul soil from the borrow source to the job site (552, compared to only 3.24 truckloads of GCL per hectare). The largest single component of the overall carbon footprint for both options is transportation: 34% for the GCL and 57% for the compacted clay liner.

Table 1 – Summary of Compacted Clay Liner Carbon Footprint

Process Step		kg CO_2eq / ha	Assumptions
1	Excavate Soil at Borrow Source	2,656	CAT 329 Excavator, operating 40 hours/ha. Assume 24.5 Liters/hr fuel consumption, based on medium work application and medium engine load factor (CAT performance handbook).
2	Haul Clay to Job Site	93,527	Assume site is 16 km from borrow source, and 552 truckloads (each carrying 15 m^3 of clay) are needed to cover 1 hectare.
3	Subgrade preparation		
	Rough grading	1,741	CAT D6 dozer, operating 25 hours/ha. Assume 25.7 Liters/hr diesel fuel consumption.
	Fine grading	1,565	CAT 160 Grader, operating 25 hours/ha. Assume 23.1 Liters/hr diesel fuel consumption.
4	Construct Clay Liner		
	CAT D6 Bulldozer	2,786	Operating 40 hours/ha. Assume 25.7 Liters/hr diesel fuel consumption.
	CAT 815 sheepsfoot compactor	4,553	Operating 40 hours/ha. Assume 42 Liters/hr diesel fuel consumption.
	CAT 815 smooth drum compactor	4,553	Operating 40 hours/ha. Assume 42 Liters/hr diesel fuel consumption.
	10,000-gallon water truck	1,518	Operating 40 hours/ha. Assume 14 Liters/hr diesel fuel consumption.
5	Geomembrane	25,944	from ICE 1.6a (polyethylene) = 1.6 tonnes CO_2/tonne PE
6	Cover Soil	26,004	from ICE 1.6a (sand) = 0.005 tonnes CO_2/tonne sand
	Totals	**164,847**	**kg CO_2eq / hectare lined area**

Since material transport is such a large component of the overall carbon footprint, a sensitivity analysis for this variable was also performed, as shown in Figure 2. The figure shows the linear relationship between the distance from the clay borrow source to the job site and the overall carbon footprint associated with the compacted clay liner. Curves associated with the expected GCL carbon footprint assuming distances of 100, 1610, and 3000 km from the GCL plant to the job site, are also overlaid onto Figure 2. A review of this figure shows that in order for the compacted clay liner option to produce a lower carbon footprint than the GCL option (assuming the GCL manufacturing plant is located 1,610 km from the job site), the clay borrow source would need to be within approximately 9 km (5.5 miles) of the job site. If the GCL plant is located 3,000 km (1,860 miles) from the job site (since there are two plants in the United States, this is realistically the longest GCL transport distance encountered), then the clay borrow source could be within approximately 14 km (8.7 miles) of the job site and still offer a lower carbon footprint. Looking at the other extreme, if the GCL plant is located very close to the job site, say 100 km (62 miles), then the clay borrow source would need to be within 2.5 km (1.6 miles) of the job site in order to produce a lower carbon footprint.

Table 2 – Summary of GCL Carbon Footprint

Process Step	kg CO_2eq / ha	Assumptions
1 Mine Bentonite	391	Emission factor (2.71 kg CO_2e / liter diesel), from EPA420-F-05-001. Assumes 49.45 metric tons of bentonite per hectare lined area.
2 Haul to Processing Plant	280	Emission factor (2.71 kg CO_2e / liter diesel), from EPA420-F-05-001.
3 In-Plant Processing	2,126	Provided by DAI (2010). Includes bentonite processing (stockpiling, blending, drying, crushing, conveying), and GCL needlepunching. Includes all plant fuel sources (electric, gas. diesel, coal, natural gas/propane) for Jan. through Nov. 2010.
4 Geotextiles		
woven		
manufacture	3,416	From ICE 1.6a (polypropylene) = 2.7 tonnes CO_2/tonne PP. Woven geotextile weight = 0.11 kg PP/m^2.
transport to GCL	1,454	Distance from Georgia to Lovell, WY = 2,760 km, with 160-km origination and return trips. 150,580 m^2/truck
nonwoven		
manufacture	6,210	From ICE 1.6a (polypropylene) = 2.7 tonnes CO_2/tonne PP. Nonwoven geotextile weight = 0.2 kg PP/m^2.
transport to GCL	5,269	Distance from Georgia to Lovell, WY = 2,760 km, with 160-km origination and return trips. 28,100 m^2/truck
5 Transport GCL to Job Site	41,894	Assume site is 1,610 km away, with 160-km origination and return trips.
6 Unload GCL	949	CAT TL355 Telehandler, operating 25 hours/ha. Assume 14 Liters/hr diesel fuel consumption, based on medium work application and medium engine load factor (CAT performance handbook).
7 Subgrade preparation		
Rough grading	1,741	CAT D6 dozer, operating 25 hours/ha. Assume 25.7 Liters/hr diesel fuel consumption.
Fine grading	1,565	CAT 160 Grader, operating 25 hours/ha. Assume 23.1 Liters/hr diesel fuel consumption.
Rolling	2,846	CAT 815 Compactor (smooth drum), operating 25 hours/ha. Assume 42 Liters/hr diesel fuel consumption.
8 Deploy GCL	1,660	CAT 329 Excavator, operating 25 hours/ha. Assume 24.5 Liters/hr diesel fuel consumption.
9 Geomembrane	25,944	from ICE 1.6a (polyethylene) = 1.6 tonnes CO_2/tonne PE
10 Cover Soil	26,004	from ICE 1.6a (sand) = 0.005 tonnes CO_2/tonne sand
Totals	**121,749**	**kg CO_2eq / hectare lined area**

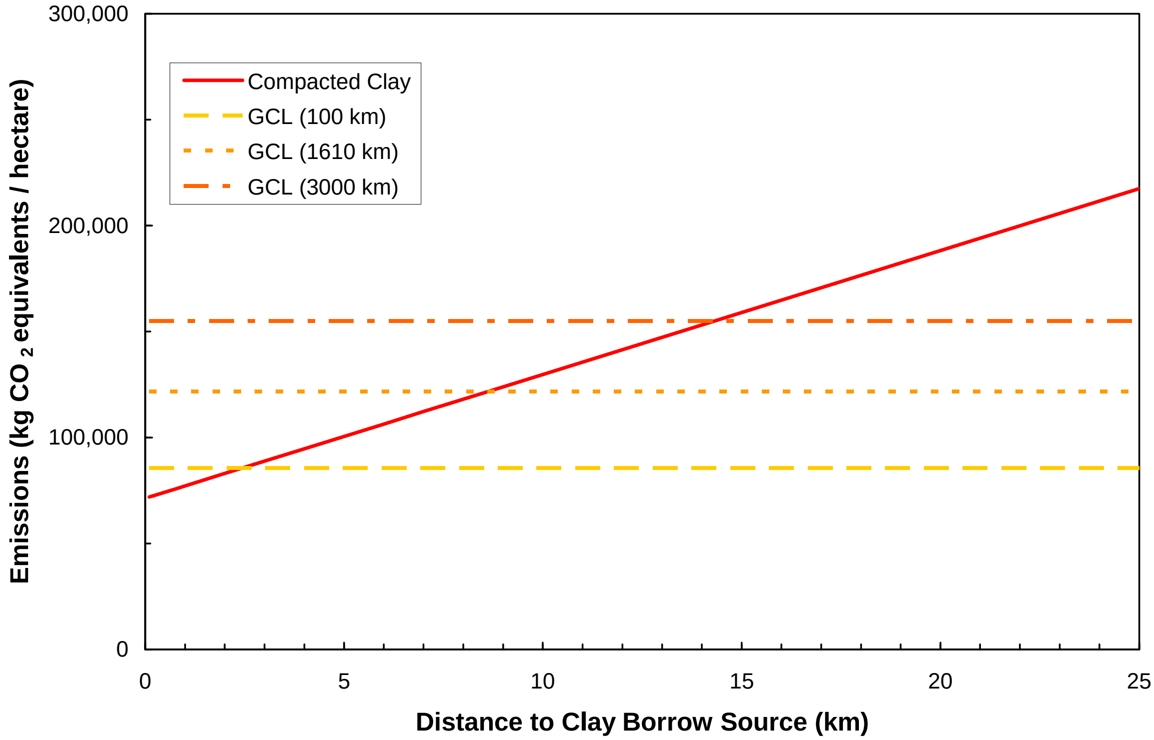

Figure 2. CO_2 Equivalent Emissions as a Function of Distance to Job Site

Not surprisingly, these relationships mimic past analyses comparing the cost effectiveness of these types of low-permeability liners. In general, the overall cost of a compacted clay liner has proven to be less than a GCL if a good quality clay source is available on-site. If soil must be brought from an off-site borrow source, the economics often tip in favor of the geosynthetic option.

SUMMARY AND CONCLUSIONS

CETCO and DAI Environmental performed an analysis comparing the carbon footprint of a conventional compacted clay liner to a GCL for a hypothetical RCRA Subtitle D municipal solid waste landfill. The analysis found that, for a landfill liner site located 1,610 km from the GCL manufacturing plant and 16 km from the clay borrow source, a conventional compacted clay liner is expected to produce a 34% larger carbon footprint than a GCL. The largest single component of the overall carbon footprint for both options is transportation. Repeating the analysis over ranges of different haul distances found that in order for the compacted clay liner option to produce a lower carbon footprint than the GCL option, the clay borrow source would need to be within approximately 9 km (5.5 miles) of the job site. This assumes that the GCL manufacturing plant is located 1,610 km from the job site. If the GCL plant is located 3,000 km (1,860 miles) from the job site, then the clay borrow source could be within approximately 14 km (8.7 miles) of the job site and still offer a lower carbon footprint. If the GCL plant is located 100 km (62 miles) from the job site, then the clay borrow source would need to be within 2.5 km (1.6 miles) of the job site to produce a lower carbon footprint.

As is the case with evaluations of cost effectiveness, carbon footprint evaluations are site-specific, depending greatly on the relative distances of the project site to the clay borrow source and to the GCL manufacturing plant. Accordingly, the conclusions of this study should not be applied to every site; project-specific analyses are strongly recommended.

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APPENDIX A
CALCULATION OF CO_2 EQUIVALENTS FOR CCL AND GCL OPTIONS

A. COMPACTED CLAY LINER

Given:

- 0.6-meter thick compacted soil liner
- Clay density = 1400 kg/m^3 (loose)
- Compaction factor = 1.38
- Compacted soil liner can be placed at a rate of 1500 m^3/day. 4 days to line a one-hectare area (10 hours/day).
- Fuel consumption rates based on medium work application and medium engine load factor
- Emission Factors, from EPA 430-K-08-004 and EPA 430-R-08-006:

$$\frac{10.15\ kg\ CO_2}{gal\ diesel} \times \frac{gal}{3.785\ L} = \frac{2.68\ kg\ CO_2}{L\ diesel}$$

$$\frac{0.26\ g\ N_2O}{gal\ diesel} \times \frac{gal}{3.785\ L} \times \frac{0.31\ kg\ CO_2\ eq}{g\ N_2O} = \frac{0.021\ kg\ CO_2\ eq}{L\ diesel}$$

$$\frac{1.44\ g\ CH_4}{gal\ diesel} \times \frac{gal}{3.785\ L} \times \frac{0.021\ kg\ CO_2\ eq}{g\ CH_4} = \frac{0.008\ kg\ CO_2\ eq}{L\ diesel}$$

$$\therefore 1\ Liter\ diesel = 2.68 + 0.021 + 0.008 = 2.71\ kg\ CO_2eq$$

- Emission Factor for HDPE geomembrane, from ICE (2008): $\frac{1.6\ tonnes\ CO_2}{tonne\ HDPE}$
- Emission Factor for sand, from ICE (2008): $\frac{0.005\ tonnes\ CO_2}{tonne\ sand}$
- On-Road Truck Product Transport Emissions:

$$E = TMT \times \left(EF_{CO_2} + 0.021 \cdot EF_{CH_4} + 0.310 \cdot EF_{N_2O}\right)$$

$$E = TMT \times \left(0.297 + (0.021 \cdot 0.0035) + (0.310 \cdot 0.0027)\right) = TMT \times \frac{0.298\ kg\ CO_2eq}{ton - mile}$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
TMT = Ton Miles Traveled
EF_{CO2} = CO_2 emission factor (0.297 *kg* CO_2*/ton-mile*)
EF_{CH4} = CH_4 emission factor (0.0035 *g* CH_4*/ton-mile*)
EF_{N2O} = N_2O emission factor (0.0027 *g* N_2O*/ton-mile*)
Converting to Metric Units:

$$\frac{0.298\ kg\ CO_2}{ton - mile} \times \frac{1.102\ tons}{tonne} \times \frac{mile}{1.61\ km} = \frac{0.204\ kg\ CO_2}{tonne - km}$$

$$E = TKT \times \frac{0.204\ kg\ CO_2eq}{tonne - km}$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
TKT = Tonne-kilometers Traveled

A1. Excavation at Borrow Source

Assumptions:

- A CAT 329 Excavator is used, operating 40 hours/hectare. The diesel fuel consumption rate is 24.5 Liters/hr (CAT).

$$\frac{40\ hours}{hectare} \times \frac{24.5\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{2656\ kg\ CO_2eq}{hectare}$$

A2. Transport to Project Site

Assumptions:

- Distance from Borrow source to Job Site (Hypothetical) = 16 *km*
- Empty (Tare) Truck Weight = $\frac{15455\ kg}{truck}$
- Typical Load of Soil = $\frac{15\ m^3}{truck} \times \frac{1400\ kg}{m^3} = \frac{21000\ kg}{truck}$
- Typical Loaded Truck Weight (Soil) = $\frac{21000\ kg}{truck} + \frac{15455\ kg}{truck} = \frac{36455\ kg}{truck}$

Loaded Trucks (16-km trip from Borrow Source to Job Site):

$$0.6\ m \times \frac{10000\ m^2}{hectare} \times 1.38\ (compaction\ factor) = \frac{8280\ m^3\ loose\ clay}{hectare}$$

$$\frac{8280\ m^3\ loose\ clay}{hectare} \times \frac{truck}{15\ m^3} = \frac{552\ trucks}{hectare}$$

$$E = \left(16\ km \times \frac{36455\ kg}{truck} \times \frac{tonne}{1000\ kg} \times \frac{552\ trucks}{hectare}\right) \times \frac{0.204\ kg\ CO_2eq}{tonne - km} = \frac{65682\ kg\ CO_2eq}{hectare}$$

Empty Trucks (16-km return trip to Borrow Source):

$$E = \left(16\ km \times \frac{15455\ kg}{truck} \times \frac{tonne}{1000\ kg} \times \frac{552\ trucks}{hectare}\right) \times \frac{0.204\ kg\ CO_2eq}{tonne - km} = \frac{27846\ kg\ CO_2eq}{hectare}$$

Total:

$$E_{CCL} = \frac{65682\ kg\ CO_2eq}{hectare} + \frac{27846\ kg\ CO_2eq}{hectare} = \frac{93528\ kg\ CO_2eq}{hectare}$$

A3. Subgrade Preparation

Assumptions:

- All fill volumes needed to meet grading plan are available on-site.
- A CAT D6 Bulldozer is used for rough grading, operating 25 hours/hectare. The diesel fuel consumption rate is 25.7 Liters/hr (CAT).

$$\frac{25\ hours}{hectare} \times \frac{25.7\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{1741\ kg\ CO_2eq}{hectare}$$

- A CAT 160 Motor Grader is used for fine grading, operating 25 hours/hectare. The diesel fuel consumption rate is 23.1 Liters/hr (CAT).

$$\frac{25\ hours}{hectare} \times \frac{23.1\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{1565\ kg\ CO_2eq}{hectare}$$

A4. Compacted Clay Liner Construction

- A CAT D6 Bulldozer is used for spreading soil, operating 40 hours/hectare. The diesel fuel consumption rate is 25.7 Liters/hr (CAT).

$$\frac{40\ hours}{hectare} \times \frac{25.7\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{2786\ kg\ CO_2eq}{hectare}$$

- A CAT 815 Compactor (sheepsfoot roller) is used during construction of each lift, operating 40 hours/hectare. The diesel fuel consumption rate is 42 Liters/hr (CAT).

$$\frac{40\ hours}{hectare} \times \frac{42\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{4553\ kg\ CO_2eq}{hectare}$$

- A CAT 815 Compactor (smooth drum roller) is used for compaction of final surface prior to geomembrane installation, operating 40 hours/hectare. The diesel fuel consumption rate is 42 Liters/hr (CAT).

$$\frac{40\ hours}{hectare} \times \frac{42\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{4553\ kg\ CO_2eq}{hectare}$$

- A 10,000-gal water truck is used for clay moisture conditioning, operating 40 hours/hectare. The diesel fuel consumption rate is 14 Liters/hr.

$$\frac{40\ hours}{hectare} \times \frac{14\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{1518\ kg\ CO_2eq}{hectare}$$

A5. Geomembrane

Assumptions:

- 1.5-mm thick HDPE geomembrane, with density = 940 kg/m^3.
- HDPE carbon footprint is 1.6 kg CO_2 / kg polyethylene (ICE, 2008).

$$\frac{940\ kg}{m^3} \times 0.0015\ m \times \frac{10000\ m^2}{hectare} \times 1.15\,(scrap) = \frac{16215\ kg\ HDPE}{hectare}$$

$$\frac{16215\ kg\ HDPE}{hectare} \times \frac{1.6\ kg\ CO_2}{kg\ HDPE} = \frac{25944\ kg\ CO_2eq}{hectare}$$

A6. Sand Cover Soil

Assumptions:

- 0.3-meter thick drainage sand layer, with in-place density = 1733 kg/m^3.
- Sand carbon footprint is 0.005 kg CO_2 / kg sand (ICE, 2008).

$$\frac{1733\ kg}{m^3} \times 0.3\ m \times \frac{10000\ m^2}{hectare} = \frac{5.2 \times 10^6\ kg\ sand}{hectare}$$

$$\frac{5.2 \times 10^6\ kg\ sand}{hectare} \times \frac{0.005\ kg\ CO_2}{kg\ sand} = \frac{26000\ kg\ CO_2eq}{hectare}$$

B. GEOSYNTHETIC CLAY LINER

Given:

- The GCL is manufactured with 4.3 kg/m^2 (typical) bentonite placed between a 200 g/m^2 nonwoven cover geotextile and a 105 g/m^2 woven base geotextile.
- 2.5 days to line a one-hectare area (10 hours/day)
- Emission Factor for polypropylene geotextiles, from ICE (2008): $\frac{2.7\ tonnes\ CO_2}{tonne\ polypropylene}$
- Emission Factor for bentonite processing at Lovell, Wyoming plant (DAI, 2010):

$$\frac{43\ kg\ CO_2eq}{tonne\ bentonite}$$

B1. Bentonite Mining

$$\frac{4.3\ kg\ bentonite}{m^2}\times\frac{10000\ m^2}{hectare}\times\frac{tonne}{1000\ kg}\times 1.15\,(scrap)=\frac{49.45\ tonnes\ bentonite}{hectare}$$

$$\frac{0.7\ gal}{ton}\times\frac{3.785\ L}{gal}\times\frac{ton}{2000\ lbs}\times\frac{2.2\ lbs}{kg}\times\frac{1000\ kg}{tonne}=\frac{2.91\ L\ diesel}{tonne\ bentonite}$$

$$\frac{49.45\ tonnes\ bentonite}{hectare}\times\frac{2.91\ L\ diesel}{tonne\ bentonite}\times\frac{2.71\ kg\ CO_2eq}{L\ diesel}=\frac{391\ kg\ CO_2eq}{hectare}$$

B2. Bentonite Transport to Plant

$$\frac{0.5\ gal}{ton}\times\frac{3.785\ L}{gal}\times\frac{ton}{2000\ lbs}\times\frac{2.2\ lbs}{kg}\times\frac{1000\ kg}{tonne}=\frac{2.08\ L\ diesel}{tonne\ bentonite}$$

$$\frac{49.45\ tonnes\ bentonite}{hectare}\times\frac{2.08\ L\ diesel}{tonne\ bentonite}\times\frac{2.71\ kg\ CO_2eq}{L\ diesel}=\frac{280\ kg\ CO_2eq}{hectare}$$

B3. Bentonite Processing/Needlepunching at Lovell, Wyoming plant

$$\frac{43\ kg\ CO_2eq}{tonne\ bentonite}\times\frac{49.45\ tonnes}{hectare}=\frac{2126\ kg\ CO_2eq}{hectare}$$

B4. Geotextiles

Manufacturing (Nonwoven)

$$\frac{0.2\ kg}{m^2}\times\frac{10000\ m^2}{hectare}\times\frac{tonne}{1000\ kg}\times 1.15\,(scrap)=\frac{2.3\ tonnes\ PP}{hectare}$$

$$\frac{2.3\ tonnes\ PP}{hectare}\times\frac{2.7\ tonnes\ CO_2}{tonne\ PP}\times\frac{1000\ kg}{tonne}=\frac{6210\ kg\ CO_2}{hectare}$$

Transport to GCL Plant (Nonwoven)

Assumptions:

- Distance from Geotextile Plant (Ringgold, GA) to GCL Plant (Lovell, Wyoming) = 2760 *km*
- Nonwoven Geotextile Load = $\frac{28100\ m^2}{truck}\times\frac{0.2\ kg}{m^2}=\frac{5620\ kg}{truck}$
- Loaded Truck Weight (Nonwoven Geotextile) = $\frac{5620\ kg}{truck}+\frac{15455\ kg}{truck}=\frac{21075\ kg}{truck}$

Loaded Truck (from Geotextile Plant to GCL Plant):

$$\frac{truck}{28100\ m^2\ NW\ geotextile}\times\frac{10000\ m^2}{hectare}\times 1.15\,(scrap)=\frac{0.409\ truckloads\ NW}{hectare}$$

$$E=\left(2760\ km\times\frac{21075\ kg}{truck}\times\frac{tonne}{1000\ kg}\times\frac{0.409\ trucks}{hectare}\right)\times\frac{0.204\ kg\ CO_2eq}{tonne-km}=\frac{4853\ kg\ CO_2eq}{hectare}$$

Empty Truck (Originates 160 km from Geotextile Plant, and Continues to next destination within 160 km of GCL Plant):

$$E=\left(160\ km\times\frac{15455\ kg}{truck}\times\frac{tonne}{1000\ kg}\times\frac{0.409\ trucks}{hectare}\right)\times\frac{0.204\ kg\ CO_2eq}{tonne-km}=\frac{206\ kg\ CO_2eq}{hectare}$$

Total:

$$E_{Nonwoven}=\frac{4853\ kg\ CO_2eq}{hectare}+2\cdot\left(\frac{206\ kg\ CO_2eq}{hectare}\right)=\frac{5265\ kg\ CO_2eq}{hectare}$$

Manufacturing (Woven)

$$\frac{0.11\ kg}{m^2}\times\frac{10000\ m^2}{hectare}\times\frac{tonne}{1000\ kg}\times 1.15\,(scrap)=\frac{1.265\ tonnes\ PP}{hectare}$$

$$\frac{1.265\ tonnes\ PP}{hectare}\times\frac{2.7\ tonnes\ CO_2}{tonne\ PP}\times\frac{1000\ kg}{tonne}=\frac{3416\ kg\ CO_2}{hectare}$$

Transport to GCL Plant (Woven)

Assumptions:

- Distance from Geotextile Plant (Ringgold, GA) to GCL Plant (Lovell, Wyoming) = 2760 *km*
- Woven Geotextile Load = $\frac{150580\ m^2}{truck}\times\frac{0.11\ kg}{m^2}=\frac{16564\ kg}{truck}$
- Loaded Truck Weight (Woven Geotextile) = $\frac{16564\ kg}{truck}+\frac{15455\ kg}{truck}=\frac{32019\ kg}{truck}$

$$\frac{truck}{150580\ m^2\ W\ geotextile}\times\frac{10000\ m^2}{hectare}\times 1.15\,(scrap)=\frac{0.076\ truckloads\ W}{hectare}$$

Loaded Truck (from Geotextile Plant to GCL Plant):

$$E = \left(2760\ km \times \frac{32019\ kg}{truck} \times \frac{tonne}{1000\ kg} \times \frac{0.076\ trucks}{hectare}\right) \times \frac{0.204\ kg\ CO_2eq}{tonne-km} = \frac{1370\ kg\ CO_2eq}{hectare}$$

Empty Truck (Originates 160 km from geotextile plant, and continues to next destination within 160 km of GCL Plant):

$$E = \left(160\ km \times \frac{15455\ kg}{truck} \times \frac{tonne}{1000\ kg} \times \frac{0.076\ trucks}{hectare}\right) \times \frac{0.204\ kg\ CO_2eq}{tonne-km} = \frac{38\ kg\ CO_2eq}{hectare}$$

Total:

$$E_{Woven} = \frac{1370\ kg\ CO_2eq}{hectare} + 2 \cdot \left(\frac{38\ kg\ CO_2eq}{hectare}\right) = \frac{1446\ kg\ CO_2eq}{hectare}$$

B5. GCL Transport to Job Site

Assumptions:

- Distance from GCL Plant (Lovell, Wyoming) to Job Site (Hypothetical) = 1610 *km*
- Empty (Tare) Truck Weight = $\frac{15455\ kg}{truck}$
- Typical GCL Load = $\frac{20910\ kg}{truck}$
  - Typical Loaded Truck Weight (GCL) = $\frac{20910\ kg}{truck} + \frac{15455\ kg}{truck} = \frac{36365\ kg}{truck}$

Loaded Truck (from GCL Plant to Job Site):

$$\frac{10000\ m^2}{hectare} \times \frac{GCL\ roll}{209\ m^2} \times \frac{truck}{17\ rolls\ GCL} \times 1.15\ (scrap) = \frac{3.24\ truckloads\ GCL}{hectare}$$

$$E = \left(1610\ km \times \frac{36364\ kg}{truck} \times \frac{tonne}{1000\ kg} \times \frac{3.24\ trucks}{hectare}\right) \times \frac{0.204\ kg\ CO_2eq}{tonne-km} = \frac{38697\ kg\ CO_2eq}{hectare}$$

Empty Truck (Originates 160 km from GCL plant, and continues to next destination within 160 km of Job Site):

$$E = \left(160\ km \times \frac{15455\ kg}{truck} \times \frac{tonne}{1000\ kg} \times \frac{3.24\ trucks}{hectare}\right) \times \frac{0.204\ kg\ CO_2eq}{tonne-km} = \frac{1634\ kg\ CO_2eq}{hectare}$$

Total:

$$E_{GCL} = \frac{38697\ kg\ CO_2eq}{hectare} + 2 \cdot \left(\frac{1634\ kg\ CO_2eq}{hectare}\right) = \frac{41966\ kg\ CO_2eq}{hectare}$$

B6. Unloading GCL Rolls

Assumptions:

- A CAT TL355 Telehandler is used, operating 25 hours/hectare. The diesel fuel consumption rate is 14 Liters/hr (CAT).

$$\frac{25\ hours}{hectare} \times \frac{14\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{949\ kg\ CO_2eq}{hectare}$$

B7. Subgrade Preparation

Assumptions:

- All fill volumes needed to meet grading plan is available on-site. Subgrade rough grading estimates same as with compacted clay liner option (see A3 above).
- A CAT 815 Compactor (smooth drum roller) is used for final subgrade rolling prior to placement of the GCL, operating 25 hours/hectare. The diesel fuel consumption rate is 42 Liters/hr (CAT).

$$\frac{25\ hours}{hectare} \times \frac{42\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{2846\ kg\ CO_2eq}{hectare}$$

B8. Deploying GCL Rolls

Assumptions:

- A CAT 329 Excavator is used, operating 25 hours/hectare. The diesel fuel consumption rate is 24.5 Liters/hr (CAT).

$$\frac{25\ hours}{hectare} \times \frac{24.5\ L\ diesel}{hour} \times \frac{2.71\ kg\ CO_2eq}{L\ diesel} = \frac{1660\ kg\ CO_2eq}{hectare}$$

APPENDIX B
EMISSIONS FROM BENTONITE PROCESSING

As part of AMCOL's corporate GHG strategy, each facility measures and reports all of the major components of their energy use at each facility. This information was used to calculate the GHG emissions for the Lovell plant. The processes at the plant assumed to be incorporated into the energy use reported by the plant included stockpiling, blending, drying, crushing, conveying, and GCL (needlepunching) processes. The plant fuel and energy use included in the analysis were purchased electricity, gasoline and diesel fuel consumed at the plant, and coal, natural gas, and propane burned at the plant. The data provided and incorporated in the analysis covered the time period from January 1, 2010 to November 30, 2010. Over this time period, AMCOL also reported the total tons of bentonite processed at plant. The GHG emissions in units of kg CO_2-equivalents (CO_2eq) were calculated, and this value, along with the reported weight of bentonite processed at the plant over this same time period, was used to calculate a "in-plant processing" CO_2eq emission factor in units of kg CO_2eq/tonne bentonite processed.

<u>Scope 1-Direct Emissions</u>
Using the WRI Protocol definitions, Scope 1 Direct Emissions at the plant included emissions from the on-site and/or in-plant burning of natural gas, propane, coal, diesel fuel, and gasoline.

<u>Natural Gas</u>: The plant natural gas consumption data was given in energy units of mmBTU, and then for purposes of this paper, converted into S.I. units (gigajoules, or GJ). The GHG emissions in terms of CO_2eq associated with natural gas were calculated using emission factors for "pipeline natural gas" and Global Warming Potentials (GWPs) from USEPA 40 CFR 98 (2009).

$$E = GJ \times \left(GWP_{CO_2} \cdot EF_{CO_2} + GWP_{CH_4} \cdot EF_{CH_4} + GWP_{N_2O} \cdot EF_{N_2O} \right)$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
GJ = Energy Value of Natural Gas Burned from 1/1/10 – 11/30/10 (*GJ)*
$GWP_{CO2} = 1\ kg\ CO_2eq/kg\ CO_2$
$GWP_{CH4} = 21\ kg\ CO_2eq/kg\ CH_4$
$GWP_{N2O} = 310\ kg\ CO_2eq/kg\ N_2O$
EF_{CO2} = CO_2 emission factor (50.26 *kg* CO_2*/GJ*), (53.02 *kg* CO_2*/mmBTU*)
EF_{CH4} = CH_4 emission factor (0.0009479 *g* CH_4*/GJ*), (0.001 *kg* CH_4*/mmBTU*)
EF_{N2O} = N_2O emission factor (0.00009479 *g* N_2O*/GJ*), (0.0001 *kg* N_2O*/mmBTU*)

<u>Propane</u>: The plant propane gas consumption data was given in units of gallons, and then, for purposes of this paper, converted into SI units (liters). To determine the GHG emissions in terms of CO_2eq associated with the propane combustion, the Higher Heating Value (HHV), emission factors, and Global Warming Potentials (GWPs) from USEPA 40 CFR 98 (2009) were used.

$$E = V \times HHV \times \left(GWP_{CO_2} \cdot EF_{CO_2} + GWP_{CH_4} \cdot EF_{CH_4} + GWP_{N_2O} \cdot EF_{N_2O} \right)$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
V = Volume of Propane burned from 1/1/10 – 11/30/10 (*liters)*
HHV = Higher Heating Value of Propane (0.0254 *GJ/liter)*
$GWP_{CO2} = 1\ kg\ CO_2eq/kg\ CO_2$
$GWP_{CH4} = 21\ kg\ CO_2eq/kg\ CH_4$
$GWP_{N2O} = 310\ kg\ CO_2eq/kg\ N_2O$
EF_{CO2} = CO_2 emission factor (61.10 *kg* CO_2*/GJ*), (61.46 *kg* CO_2*/mmBTU*)
EF_{CH4} = CH_4 emission factor (0.00284 *kg* CH_4*/GJ*), (0.003 *kg* CH_4*/mmBTU*)
EF_{N2O} = N_2O emission factor (0.000569 *kg* N_2O*/GJ*), (0.0006 *kg* N_2O*/mmBTU*)

<u>Coal</u>: The plant coal combustion data was given in units of U.S. (short) Tons, and then, for purposes of this paper, converted into SI units (tonnes). The plant also reported that the coal combusted at the plant was sub-bituminous

coal. To determine the GHG emissions from plant coal combustion, the Higher Heating Value (HHV) and emission factors for sub-bituminous coal from USEPA 40 CFR 98 (2010) were used. To convert the individual GHG emissions into CO_2eq, Global Warming Potentials from USEPA 40 CFR 98 (2010) were used.

$$E = W \times HHV \times \left(GWP_{CO_2} \cdot EF_{CO_2} + GWP_{CH_4} \cdot EF_{CH_4} + GWP_{N_2O} \cdot EF_{N_2O} \right)$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
W = Weight of Coal burned from 1/1/10 – 11/30/10 (*tonnes*)
HHV = Higher Heating Value of Coal (20.06 *GJ/tonne)*
$GWP_{CO2} = 1\ kg\ CO_2eq/kg\ CO_2$
$GWP_{CH4} = 21\ kg\ CO_2eq/kg\ CH_4$
$GWP_{N2O} = 310\ kg\ CO_2eq/kg\ N_2O$
EF_{CO2} = CO_2 emission factor (91.96 $kg\ CO_2/GJ$), (97.02 $kg\ CO_2/mmBTU$)
EF_{CH4} = CH_4 emission factor (0.0104 $kg\ CH_4/GJ$), (0.011 $kg\ CH_4/mmBTU$)
EF_{N2O} = N_2O emission factor (0.00152 $kg\ N_2O/GJ$), (0.0016 $kg\ N_2O/mmBTU$)

<u>Diesel Fuel</u>: The plant diesel fuel consumption data was given in units of gallons, then for purposes of this paper, converted into liters. To determine the GHG emissions from diesel fuel combustion, emission factors taken from the USEPA "Mobile Source" guide (EPA430-K-08-004) (2008) and Global Warming Potentials from USEPA 40 CFR 98 (2010) were used. Because the plant did not provide a detailed breakout as to the volume of diesel fuel used for each type of piece of equipment or vehicle, a reasonable assumption of "construction equipment" for the vehicle/equipment type was made.

$$E = V \times \left(GWP_{CO_2} \cdot EF_{CO_2} + GWP_{CH_4} \cdot EF_{CH_4} + GWP_{N_2O} \cdot EF_{N_2O} \right)$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
V = Volume of Diesel fuel burned from 1/1/10 – 11/30/10 (*liters)*
$GWP_{CO2} = 1\ kg\ CO_2eq/kg\ CO_2$
$GWP_{CH4} = 21\ kg\ CO_2eq/kg\ CH_4$
$GWP_{N2O} = 310\ kg\ CO_2eq/kg\ N_2O$
EF_{CO2} = CO_2 emission factor (2.68 $kg\ CO_2/liter$), (10.15 $kg\ CO_2/gallon$)
EF_{CH4} = CH_4 emission factor (0.000153 $kg\ CH_4/liter$), (0.00058 $kg\ CH_4/gallon$)
EF_{N2O} = N_2O emission factor (0.0000687 $kg\ N_2O/liter$), (0.00026 $kg\ N_2O/gallon$)

<u>Gasoline</u>: The plant gasoline fuel consumption data was given in units of gallons, then for purposes of this paper, converted into liters. To determine the GHG emissions from gasoline fuel combustion, emission factors taken from the USEPA "Mobile Source" guide (EPA430-K-08-004) (2008) and Global Warming Potentials from USEPA 40 CFR 98 (2010) were used. Because the plant did not provide a detailed breakout as to the volume of gasoline fuel used for each type of piece of equipment or vehicle, a reasonable assumption of "construction equipment" for the vehicle/equipment type was made. The gasoline fuel carbon dioxide and nitrous oxide emission factors listed in the guidance are independent of vehicle type. However, the methane emission factors vary by vehicle type, and as such, an assumption on "vehicle type" had to be made.

$$E = V \times \left(GWP_{CO_2} \cdot EF_{CO_2} + GWP_{CH_4} \cdot EF_{CH_4} + GWP_{N_2O} \cdot EF_{N_2O} \right)$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
V = Volume of Gasoline fuel burned from 1/1/10 – 11/30/10 (*liters)*
$GWP_{CO2} = 1\ kg\ CO_2eq/kg\ CO_2$
$GWP_{CH4} = 21\ kg\ CO_2eq/kg\ CH_4$
$GWP_{N2O} = 310\ kg\ CO_2eq/kg\ N_2O$
EF_{CO2} = CO_2 emission factor (2.33 $kg\ CO_2/liter$), (8.81 $kg\ CO_2/gallon$)
EF_{CH4} = CH_4 emission factor (0.000132 $kg\ CH_4/liter$), (0.00050 $kg\ CH_4/gallon$)

EF_{N2O} = N_2O emission factor (0.0000581 *kg* N_2O*/liter*), (0.00022 *kg* N_2O*/gallon*)

Scope 2-Indirect Emissions from Purchased Electricity

The facility provided their purchased electricity quantity in units of kilowatt-hours, which, for purposes of the calculations were converted into megawatt-hours (MWH). To estimate the associated GHG emissions for this purchased electricity, emissions factors for the region that facility is located in were obtained from the USEPA "eGRID 2007-version 1.0" (2008). To convert the individual GHG emissions into CO_2eq, Global Warming Potentials from USEPA 40 CFR 98 (2010) were used. The facility is located in eGRID Region "WECC Northwest", which carries the Region Code "NWPP".

$$E = MWH \times \left(GWP_{CO_2} \cdot EF_{CO_2} + GWP_{CH_4} \cdot EF_{CH_4} + GWP_{N_2O} \cdot EF_{N_2O} \right)$$

Where:
E = Total CO_2 equivalent emissions (*kg*)
MWH = Energy value (Megawatt-Hours) of Electricity purchased from 1/1/10 – 11/30/10 (*MWH)*
$GWP_{CO2} = 1\ kg\ CO_2eq/kg\ CO_2$
$GWP_{CH4} = 21\ kg\ CO_2eq/kg\ CH_4$
$GWP_{N2O} = 310\ kg\ CO_2eq/kg\ N_2O$
EF_{CO2} = CO_2 emission factor (409.26 *kg* CO_2*/MWH*), (902.24 *lbs* CO_2*/MWH*)
EF_{CH4} = CH_4 emission factor (0.0088 *kg* CH_4*/MWH*), (0.0193 *lbs* CH_4*/MWH*)
EF_{N2O} = N_2O emission factor (0.0068 *kg* N_2O*/MWH*), (0.0149 *lbs* N_2O*/MWH*)

Summary of Plant Processing Emissions and Factor Calculation

Figure B-1 summarizes the calculated plant processing emissions by providing the relative percentages of the total plant emissions by GHG source.

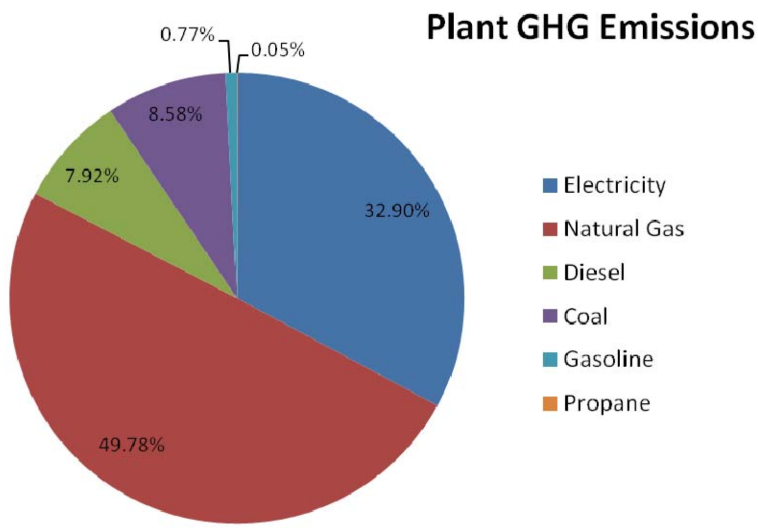

Figure B-1. Relative Plant CO_2 Equivalent Emissions Broken Out by GHG Emission Source

The total CO_2eq value for the plant was used to calculate an "in-plant processing" emission factor, scaled to the tonnes of bentonite processed in the plant:

$$\frac{E\ kg\ CO_2\ eq}{T\ tonnes\ bentonite} = \frac{43.00\ kg\ CO_2\ eq}{tonne\ bentonite}$$

Where:
E = Total CO_2 equivalent emissions from 1/1/10 – 11/30/10 (*kg*)
T = Total bentonite processed by the plant from 1/1/10 – 11/30/10 (*tonnes*)