

# Life Cycle Assessment of Greenhouse Gases for the Product: Amended Silicates

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## Executive Summary

Mercury emissions from coal-fired power plants are regulated by the United States Environmental Protection Agency Mercury and Air Toxics Standards. Novinda has developed Amended Silicates HgX (AS), a silicate-based sorbent for the removal of mercury at coal-fired power plants. While AS provides a number of important environmental benefits over the use of powdered activated carbon (PAC), in light of current concerns over global climate change Novinda commissioned CH2M HILL to compare the greenhouse gas (GHG) impacts for production of AS compared to PAC. This report presents this comparative analysis.

Life-cycle, or “Cradle-to-Grave”, GHG emissions for the Amended Silicates product were estimated using process specific data and the GaBi4 life-cycle assessment software. These results were compared with existing literature values for production and use of the PAC product. The life-cycle assessment included mining, manufacturing, use in a power plant, disposal, and transportation of materials between each step in the process. The life-cycle assessment concluded that:

- Per pound of material produced and used, GHG emissions associated with Amended Silicates are only 11 percent of the average literature values for GHG emissions of PAC.
- In order for PAC to have equivalent life-cycle GHG emissions per unit of mercury removed from exhaust streams, it would need to be about 10 times more efficient than Amended Silicates. (Comparison of GHG impacts based on mass of mercury removed will depend on removal efficiencies, which will vary from plant to plant for both products.)
- This GHG performance delivers a potential reduction in carbon dioxide equivalent (CO<sub>2</sub>e) emissions of 174,000 metric tons per year if just 10 percent of the market substitutes Novinda’s AS for PAC, based on Novinda estimates of a total mercury sorbent market of 500 million pounds per year<sup>1</sup>.
- A co-benefit of AS is the potential to sell fly ash from the power plants to replace Portland cement in concrete, whereas PAC-containing fly ash must be landfilled. This ability to reuse the fly ash results in avoided GHG emissions of an estimated 91 lbs. of CO<sub>2</sub>e for each pound of AS used, or 1.03 million metric tons per year of avoided CO<sub>2</sub>e emissions, based on the assumption that only 50 percent of fly ash is reused and the same AS 10 percent market usage with an average AS content of 1 percent in the fly ash.

## Introduction

Novinda has developed Amended Silicates (AS), a silicate-based sorbent for the removal of mercury at coal-fired power plants. The current dominant industry product for mercury removal is powdered activated carbon (PAC) or brominated PAC. The focus of this life cycle assessment (LCA) is to provide life-cycle greenhouse gas (GHG) emissions for the AS product using process specific data and compare the results with existing literature values representative of the PAC product.

## Background

This LCA provides information on the relative size and scale of emission sources within the life cycle stages of the product and is performed according to a consistent framework, therefore providing a quantitative performance metric to set targets for improvement, track progress, and communicate successes to stakeholders. The

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<sup>1</sup> Novinda market estimates are based on data from KeyBanc Capital Markets (KeyBanc, 2012)

attributional approach to LCA accounting, as used in this analysis, links the GHG emissions of the unit of analysis to the processes along the product life cycle.

This LCA was done using the concepts and procedures in the World Resources Institute Product Life Cycle Accounting and Reporting Standard (Product Standard) (WRI, 2011), the International Organization of Standardization (ISO) 14040: *Environmental Management – Life Cycle Assessment – Principles and Frame work* (ISO, 2006a) and ISO 14044: *Environmental Management – Life Cycle Assessment – Requirements and Guidelines* (ISO, 2006b) standards.

The Product Standard notes that additional considerations should be taken when performing a direct comparison between products, such as an assurance evaluation or critical review and the development of a product rule, which is a document created by stakeholders that builds a consensus of what additional specifications are required to enable comparisons or declarations regarding the product. Although these items were not developed within the scope of this evaluation to provide a valid comparison the following considerations were taken such that the evaluation would be of similar systems, have the same temporal boundaries, and provide a valid comparison of products:

- The functional unit is the same for both processes: Mass of mercury removed
- The system and temporal boundaries are the same: The same life cycle stages and life cycle duration are included for both evaluations
- Allocation is not used for either evaluation
- The data types, quality, and limitations are discussed for each evaluation to provide transparency

An assurance evaluation or critical review performed by either the reporting company (first party assurance) or an external organization (third party assurance), may be completed at a later point in time. Due to the similar nature of the products, the similar systems, temporal boundaries, and functional unit equivalencies this evaluation provides a valid comparison between the two products PAC and AS, given the study limitations discussed in the subsequent sections.

## **Methodology and Scope**

To provide a reasonable comparison between the life-cycle GHG emissions of AS compared with PAC, a cradle to grave analysis was done. Therefore, all stages of the life cycle for each sorbent, from the extraction of raw materials through the disposal or re-use of materials, are considered.

The functional unit for the product evaluations was determined on the performance characteristics and services delivered by the sorbents. The most relevant functional unit for this evaluation was determined to be the mass of mercury removed. It is assumed that average removal efficiency is equivalent for AS versus PAC, therefore, the relative comparison would be the same whether based on mass of mercury removed or mass of sorbent produced.

The reference flow, which is the amount of product which the results of the study are based upon, is based on a reasonable annual quantity of mercury removed from a nominal 1,000,000 actual cubic feet per minute (acfm) coal fired power plant exhaust stream (89 kilogram (kg)). The time frame for the use of both sorbents are the same, such that each product is valid for a one time use and the environmental impacts would occur in the same time-frame, (i.e. electricity consumed during use would occur instantaneously and material would degrade at the same rate in a landfill).

In this analysis no allocation was necessary because no co-products are produced simultaneous to the AS and PAC production processes. Biogenic emissions and land use changes are not a relevant element within the inventory boundaries.

## **Analysis Boundaries: Process Descriptions**

As required by the Product Standard all attributable processes, or processes that become the product, were included in this analysis as follows: material acquisition and pre-processing, production, distribution, use, and

end-of life. It was assumed that there were no storage requirements that would result in GHG emissions. Non-attributable processes or processes that do not become the product, make the product, or directly carry the product through its life cycle are not included in the analysis. For example, the production of fly ash is a non-attributable process so has not been included in the total life cycle analysis. However, there is additional discussion about the potential avoided emissions associated with the reuse of fly ash because it is relevant to plant operators in evaluating sorbent use as discussed in the Results section.

Table 1 lists the life cycle stages and processes that were considered and included. The specific components of each life cycle stage are shown in the process diagrams in Figures 1 and 2.

## **Material Acquisition and Pre-Processing and Production**

### **Amended Silicates**

Amended Silicates (AS) is produced from bentonite. For the production process, bentonite is extracted using surface mining techniques at a mining facility co-located with the production facility. It is then dried first by stockpiling in the sun and then using an industrial dryer. Once the bentonite has reached a low moisture content it is dry milled into a powder that is less than a 100 microns. The powder is then conveyed to a co-located facility where the second phase of processing occurs. The second processing phase includes the following steps: the addition of chemicals along with some water for mixing, a proprietary processing step, drying and then milling to meet the final specifications of the product.

### **Powdered Activated Carbon**

Coal-based PAC is typically produced through thermal activation. The general process is as follows: coal (various grades such as: bituminous and lignite) is pulverized then pressed into briquettes, the briquettes are crushed and then heated at moderate temperatures to remove volatiles and destroy the coking properties of the coal. The coal is then activated under high temperatures (approximately 1,000 degrees C) in a direct-fire multi-hearth furnace. After activation, the carbon is ground to the powdered form (Baker, F. S., Miller, C. E., Repik, A. J. and Tolles, E. D. 2003).

### **Distribution and Storage**

The distribution and storage is assumed to be the same for both AS and PAC. After production sorbents are distributed to the power plants for use. There is no storage that results in GHG emissions.

### **Use**

The use stage process and assumptions are the same for both AS and PAC. After production, the sorbent is transported to a power plant where it is injected using blowers into the flue gas at a rate ranging from 0.5 pounds per minute (lb/min) to 10 lb/min (for a nominal application with 1,000,000 acfm flue gas flowrate). Removal efficiencies vary depending on several factors, including inlet mercury concentration and speciation (elemental or oxidized), flue gas composition, sorbent mixing and distribution, emissions control equipment, and available reaction time. Sorbent injection rates are determined by what is required to achieve the 2012 Environmental Protection Agency (EPA) Mercury and Air Toxics Standards (MATS) for electric utility steam generating units (EGUs) emission requirements.

### **End-Of-Life**

After the sorbent is consumed in the flue gas, it is combined with the fly ash from the power plant and either re-used or disposed. The fly ash generated with the use of AS can be re-used as a replacement for Portland cement in concrete, otherwise the sorbent and fly ash are sent to a landfill for disposal. Fly ash contaminated with PAC cannot be used as a Portland cement replacement, due to the adverse impact of PAC on the concrete admixture performance, therefore, all of the PAC and fly ash mixture is sent to landfill for disposal.

TABLE 1  
**Phases Considered in the LCA**

Life Cycle Stage	Life Cycle Stage: Processes	
	Amended Silicates	PAC
<b>Raw Material Production</b>	Mining of Bentonite, Production of Process Chemicals	Mining of Coal
<b>Transport of Raw Materials to Processing Site</b>	Truck Travel <sup>1</sup>	Truck Travel <sup>1</sup>
<b>Sorbent Production</b>	Energy use for processing	Energy use for processing
<b>Transportation of Sorbent to Facility for Use</b>	Truck Travel <sup>1</sup>	Truck Travel <sup>1</sup>
<b>Sorbent Use</b>	Energy used to power the injection blowers	Energy used to power the injection blowers.
<b>Transport of Sorbent to Landfill</b>	Truck Travel <sup>1</sup>	Truck Travel <sup>1</sup>
<b>Sorbent Disposal</b>	Equipment used to landfill used sorbent	Equipment used to landfill used sorbent
<b>Beneficial Reuse: Generation of Fly Ash</b>	Displacement of Portland Cement and Equipment used to landfill used fly ash: Approximately 50 percent of Fly ash generated during AS use is reused in concrete manufacturing to displace Portland Cement. The remaining fly ash is sent to the landfill.	Equipment used to landfill used fly ash: Fly ash generated during sorbent use is sent to landfill and cannot be reused

<sup>1</sup> Truck travel includes the production and use of transportation fuels.

Figure 1. Amended Silicates Process Diagram

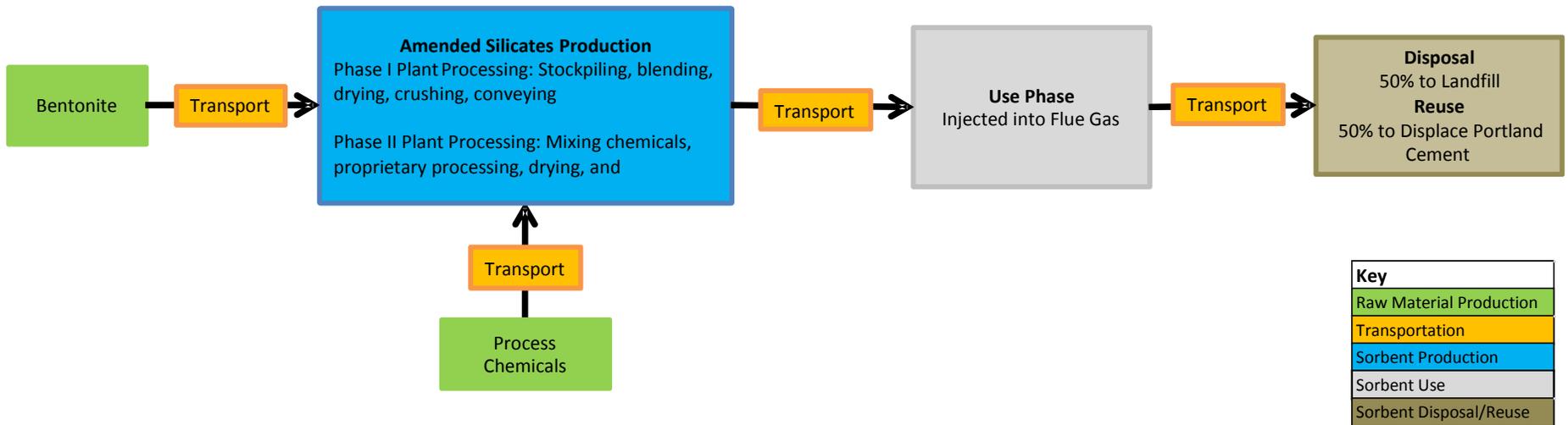
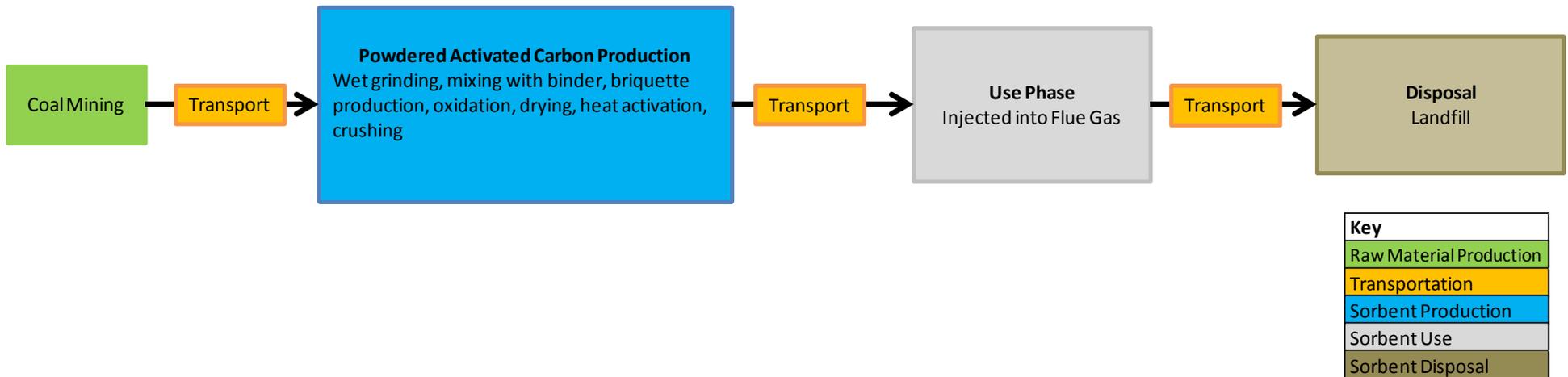


Figure 2. PAC Process Diagram



## Data Sources

In this LCA, a pollutant's 100 year global warming potential (GWP) was used to correlate inventory results such as carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) emissions to carbon dioxide equivalent emissions (CO<sub>2</sub>e). The 100 year GWP values are consistent with other EPA GHG reporting programs (Bare, 2002) and are required by the Product Standard.

The data used for the AS evaluation utilized more primary recent data sources, whereas the data used for the PAC study are from secondary sources based on older studies. The AS process was analyzed using GaBi4 Software (GaBi), a LCA Model produced by PE Americas. Data were evaluated for quality by using quality indicators: technological representativeness, geographical representativeness, temporal representativeness, completeness, and reliability. Tools that were used to fill primary or secondary data gaps are discussed for each component.

## Amended Silicates

The individual life cycle stages identified in Table 1 were evaluated for AS. This section discusses the source of data for each component, the review procedure used to validate the accuracy of the data, and some of the limitations associated with the data used.

**Raw Material Production:** Mining of Bentonite. Process specific emission factors for the mining of bentonite were provided by a third party international bentonite manufacturing company. This value was compared to readily available literature values. The provided emission factor is on the lower end of literature values but this was determined to be reasonable because bentonite used for AS production would be from surface mining rather than mining of bentonite located further underground and consequently would require less energy for extraction. The data is limited to the specific manufacturer's bentonite mining process; the use of other suppliers may result in different inventory results.

**Raw Material Production:** Chemical Manufacturing. Several chemicals are used in the production of AS. Literature values from GaBi representing the average emissions associated with the cradle to gate production of chemicals were used. Literature values for the production of each chemical used in the AS production process were not available, therefore an emission factor for production of representative chemicals was used. The representative emission factor was then compared to emission factors for general classifications of chemicals, such as inorganics, to confirm the validity of the chosen emission factor. This data is limited because it is not specific to the AS production process and is more consistent with the expected range of impacts associated with raw chemical production. The chemical literature data are also based on the production processes located in the European Union, where more data are available.

**Transportation:** All Transportation Phases. Literature values from GaBi were used based on the type of transport: short-range or long range and used average fuel consumption and fuel production data based in the United States. Limitations of this data are associated with the use of average truck data, which assume a standard truck capacity, which may or may not be representative of the actual trucks used for transport.

**Sorbent Production:** Amended Silicates. Process specific emission factors for the phase 1 and phase 2 processing of AS were provided by the bentonite manufacturing company. Data for the phase 1 processing are based on the existing facility production, fuel use, and electricity data. The 2011 annual facility production report and utility bills were reviewed to confirm the validity of the data and it was determined that the resulting emission factors are representative of the plant wide average for phase 1 processing. The phase 1 emission factor is limited since it is not specific to the AS product but represents an average of the emissions associated with drying and milling of bentonite products at the facility. The phase 2 process data were based on production drawings and equipment permits for the planned plant. The maximum rated horsepower and corresponding electrical demand were revised based on process flow diagrams and equipment sizing. The total fuel consumption was validated by reviewing the maximum heat input requirements for fuel burning equipment. The phase 2 process data is limited because it is based on design specification and not on past operation.

**Sorbent Use:** Amended Silicates. The 2012 US EPA MACT requirements were used to determine the mercury removal rate required during the use phase. Average industry data regarding flue gas stream composition and

sorbent injection equipment were used to determine the overall sorbent injection rate and electricity required during the sorbent use phase. Literature emission factors for electricity generation are based on the average US emission factors from coal-fired power plants from GaBi. The injection rate and power requirements data are limited because they are based on an average range of sorbent injection rates using cost competitiveness of sorbent material as the basis, which assumes that injection rates for AS would be the same or similar to injection rates for PAC or BPAC. While this provides a general indication of the potential impacts associated with the use of sorbents they are not process specific and are general estimates. The variability and uncertainty associated with this life cycle stage are the same for both the AS and the PAC evaluations and is discussed in the uncertainty analysis.

**Sorbent Disposal:** Amended Silicates sent to Landfill. Literature values from the USEPA Waste Reduction Model were used to estimate the quantity of fuel used by landfill equipment to place and cap materials. Fuel emissions factors were taken from the US EPA mandatory GHG reporting program. These data are limited to US municipal waste operations.

**Avoided Emissions and Beneficial Use:** Fly Ash displacement of Portland cement. Average industry data were used to determine the mass of fly ash generated per mass of sorbent used. Current market conditions were used to determine the quantity of fly ash that could be used in the production of concrete in-lieu of Portland cement. The emissions associated with the production of Portland cement are based on literature values from the Athena Institute (2006). These data are general in nature and provide an indication of the potential benefits of reusing fly ash and do not represent the actual emissions reduced from one specific plant or process. They also do not include the potential impacts associated with the transport of fly ash. The avoided emissions are outside of the actual life cycle of AS, and are therefore not included in the product LCA; rather the benefits are separately quantified.

### **Powdered Activated Carbon**

The individual life cycle stages of the production of PAC were not evaluated, instead literature values were used for the combined impacts of raw material extraction, transportation to production, and production life cycle stage for PAC as discussed below. The subsequent life cycle stages were evaluated individually using average industry data to provide consistency with the AS system boundaries evaluation.

**Combined Raw Material and Sorbent Production:** Mining of coal and production of PAC. Literature data were not readily available for PAC. However, literature data were readily available for granular activated carbon (GAC). The general difference in production of PAC and GAC is that PAC is ground more finely than GAC (Baker, et al., 2003). It is assumed that this difference in process has a minimal impact on the overall GHG emissions associated with the production of GAC and that the GHG emissions per GAC are effectively the same for PAC on a mass basis. A review of 14 LCA-based documents on the production and use of GAC was completed. Four documents were chosen as representative and included in this analysis based on the following criteria: coal-based, included the mining and production phases, and contained transparent datasets where the impacts could be presented in terms of per kg of GAC (Muños, et al., 2006; Bayer, et al., 2005; Goldblum, 2008; Hernandez, 2004). One article had separate mining and production data that indicated each phase was approximately half of the total impact, the remaining data were aggregated. An Environmental Assessment of a recently constructed PAC plant that included estimated PAC production process CO<sub>2</sub>e emissions was also reviewed (US DOE, 2010). Based on this review, it was determined that the PAC process emissions were within the same range as the representative GAC literature values.

The limitations of this data are that the values are based on average industry studies and not specific to one individual plant. Additionally, while the data were determined to be generally representative of a recent PAC production plant, the studies used in this analysis, which provide an aggregate GHG impact for the raw material and sorbent production, are based on older evaluations for the production of GAC. Finally, since additional grinding is required for PAC, which may cause additional energy use and GHG emissions, the PAC emissions may be under estimated. However, if recent technological advances have been developed in the production of PAC or GAC, which are not captured in the available literature, the GHG impacts may be overestimated. Therefore, given

the uncertainty associated with the PAC GHG emission impacts, the range of representative PAC GHG literature values are included in the results discussion.

**Sorbent Use:** PAC. The same injection rates and power requirement assumptions were used for PAC as for AS, as previously discussed in the AS sorbent use discussion. The average efficiency of PAC and AS in removal of mercury is the same. The uncertainty associated with this assumption is addressed in the uncertainty analysis.

**Sorbent Disposal:** PAC sent to landfill. The same assumptions were used for PAC as for AS, as previously discussed.

## Assumptions

To provide a robust analysis, an effort was made to encompass the entire process for both PAC and AS including stages such as use and disposal which did not differ between the two processes. For the use phase, it is assumed that the mercury removal of AS is the same by weight as PAC or brominated PAC. Detailed assumptions regarding each life cycle stage are provided in Table 2.

TABLE 2  
Assumptions for Amended Silicates LCA

Life Cycle Stage	Data Value for Amended Silicates. Values presented per kg of AS produced	Data Source and Assumptions	Corresponding Powder Activated Carbon Component
<b>Raw Material Production</b>	Bentonite extraction: 0.007886 kg CO <sub>2</sub> e / 1 kg Bentonite, 1 kg Bentonite / kg AS	Bentonite mining carbon emissions supplied by manufacturer and include extractions.	Coal extraction.
	Chemicals used in production process	Emission factors (EF) are from literature values for the production of specific chemicals on a mass basis. EFs are for a representative chemicals or representative chemical groups when the specific chemical EF was not available.	No chemicals used.
<b>Transport of Raw Materials to Processing Site</b>	Truck Travel: 60 km	Transport of bentonite was based on literature values assuming a local transportation fleet with an average payload similar to heavy duty medium trucks. Assumed a full payload on delivery but empty on return.	Transport of raw materials to processing plant
	Truck Travel: 805 km	Transport of chemicals was based on literature values using long distance transport, light-heavy duty trucks with an average payload of 3.3 tons. Assume full payload on delivery and empty on return. Travel done on highways.	No chemicals used or transported.
<b>Sorbent Production</b>	Processing of AS: 0.422 kg CO <sub>2</sub> e / kg AS	Emission factors were provided by the manufacturer and include the stockpiling, blending, drying, crushing, conveying, chemical mixing, drying, and milling. These emissions equate to approximately 0.056 kWh/kg AS for the total energy requirement for processing bentonite.	Production of coal into PAC.
<b>Sorbent Use</b>	Injection of AS into flue gas stream: 0.13 kg CO <sub>2</sub> e / kg AS	Emissions factors were calculated by estimating the power requirements for operating one or two blowers with total motor rating of 20 horsepower. Injection rates for sorbents used in mercury removal range from 0.5 to 10 lbs per minute. The average injection rate (5.25 lbs per minute) was assumed as representative for the process. A coal-based power source was used since it was assumed the power would be derived from the operating facility.	Injection of PAC into flue gas stream. Results are the same: 0.13 kg CO <sub>2</sub> e / kg PAC

TABLE 2  
Assumptions for Amended Silicates LCA

Life Cycle Stage	Data Value for Amended Silicates. Values presented per kg of AS produced	Data Source and Assumptions	Corresponding Powder Activated Carbon Component
<b>Sorbent Disposal (including transportation)</b>	Landfilling: 0.02 kg CO <sub>2</sub> e / kg AS	The consumed AS is co-mingled with the fly ash generated. Therefore, since 50-percent of the fly ash is assumed to be reused only 50 percent of spent AS is disposed of in a landfill. Assume that haul distance to the concrete plant is short, so that transportation related emissions are the same for AS hauled for reuse versus AS or PAC hauled to landfill. Emissions were estimated using the diesel fuel requirements for landfill equipment operations based on the USEPA Waste Reduction Model (WARM) Version 12 (USEPA, 2012) and the US EPA mandatory reporting program diesel fuel emission factors. It is assumed that the embedded carbon in the sorbent will not be released into the atmosphere because the material will not degrade in the landfill.	All PAC consumed is sent to the landfill. 0.03 kg CO <sub>2</sub> e / kg PAC
<b>Beneficial Use</b>	Fly Ash Displacement of Portland Cement where fly ash is reused: -91 kg CO <sub>2</sub> e / kg AS	Average usage rates result in approximately 1 percent concentration of AS in fly ash. 50 percent of the fly ash generated is reused as a component in concrete production. 1 kg of fly ash reused in concrete production displaces 1 kg of Portland Cement produced. The GHG emissions associated with the production of Portland Cement are from the Cement Association of Canada (Athena Institute, 2006).	There is no beneficial reuse of fly ash generated with the use of PAC.

## Results

An LCA limited to only GHGs has the benefit of simplifying the analysis, however the limitation is that potential trade-offs or co-benefits between environmental impacts can be missed. Consequently, the results presented here are not representative of the overall environmental performance of a product. These inventory results are expressed in terms of the potential for global warming and do not predict category endpoints (i.e., temperature rise from global warming), the exceeding of thresholds, safety margins, or risks. There are process specific and industry average assumptions associated with the life cycle stages that may impact the LCA results as discussed in the data source section.

The CO<sub>2</sub>e mass emissions are presented in two ways, per mass of sorbent consumed and per the amount of mercury (Hg) removed. Since the function of the sorbent is to remove Hg from the exhaust stream the ‘functional unit’ of the process is considered mass of mercury removed. This analysis assumes that the removal efficiency for AS is the same as PAC. Therefore, the relative difference between the results presented per mass of sorbent consumed and the results presented per mass of mercury removed are the same using this assumption.

The conversion from mass of sorbent to mass of mercury removed was done by calculating the average mass of mercury removed by mass of sorbent for a representative exhaust stream using the US EPA MACT removal requirement of 90-percent. An average injection rate of 2.4 kg sorbent per minute (~ 5 pounds per minute) was used for both AS and PAC. It was assumed that the representative exhaust stream has an inlet concentration of 10 micrograms per standard cubic meter and an average flow rate of 1,000,000 acfm. Based on these estimates approximately 14,000 kg of sorbent is used per kg of Hg removed.

The results for each sorbent are presented below in Table 3 and Figure 3 for the functional unit of 1 kg of sorbent and 1 kg of Hg removed. The results presented below are based on the average sorbent removal efficiency. The PAC high and low range values are based on the representative literature values and are presented to demonstrate where the process specific AS results are relative to these values.

TABLE 3  
**LCA Results Assuming an Average Sorbent Removal Efficiency**

Life Cycle Stage	Amended Silicates		Powdered Activated Carbon					
	kg CO <sub>2</sub> e/ kg AS	kg CO <sub>2</sub> e/kg Hg Removed	kg CO <sub>2</sub> e/ kg PAC <sup>1,2</sup>	kg CO <sub>2</sub> e/kg Hg Removed	kg CO <sub>2</sub> e/ kg PAC <sup>1,2</sup>	kg CO <sub>2</sub> e/kg Hg Removed	kg CO <sub>2</sub> e/ kg PAC <sup>1,2</sup>	kg CO <sub>2</sub> e/kg Hg Removed
			Literature Values					
			High		Average		Low	
<b>Raw Material Production and Transport</b>			11.1 <sup>3</sup>	155,600	8.5 <sup>4</sup>	119,500	6.5 <sup>5</sup>	90,300
<i>Bentonite (AS)</i> <sup>6</sup>	0.017	240						
<i>Process Chemicals (AS)</i>	0.41	5,800						
<b>Sorbent Production</b> <sup>7</sup>	0.42	5,900						
<b>Sorbent Use and Transportation</b>	0.13	1,500	0.13	1,500	0.13	1,500	0.13	1,500
<b>Sorbent Disposal and Transportation</b>	0.02	300	0.03	400	0.03	400	0.03	400
<b>Total</b> <sup>8</sup>	1.0	13,700	11.3	157,600	8.7	121,500	6.6	92,300

1 Only aggregated data available, however literature data indicates that approximately half of the CO<sub>2</sub>e emissions are from raw material production and transport and the other half are from sorbent production (Hernandez, 2004).

2 Data not available for PAC, granular activated carbon used, results may underestimate total CO<sub>2</sub>e

3 Reference: Bayer, et al., 2005

4 Average of (Bayer, et al., 2005; Goldblum, 2008; Muñoz, 2006; Hernandez, 2004)

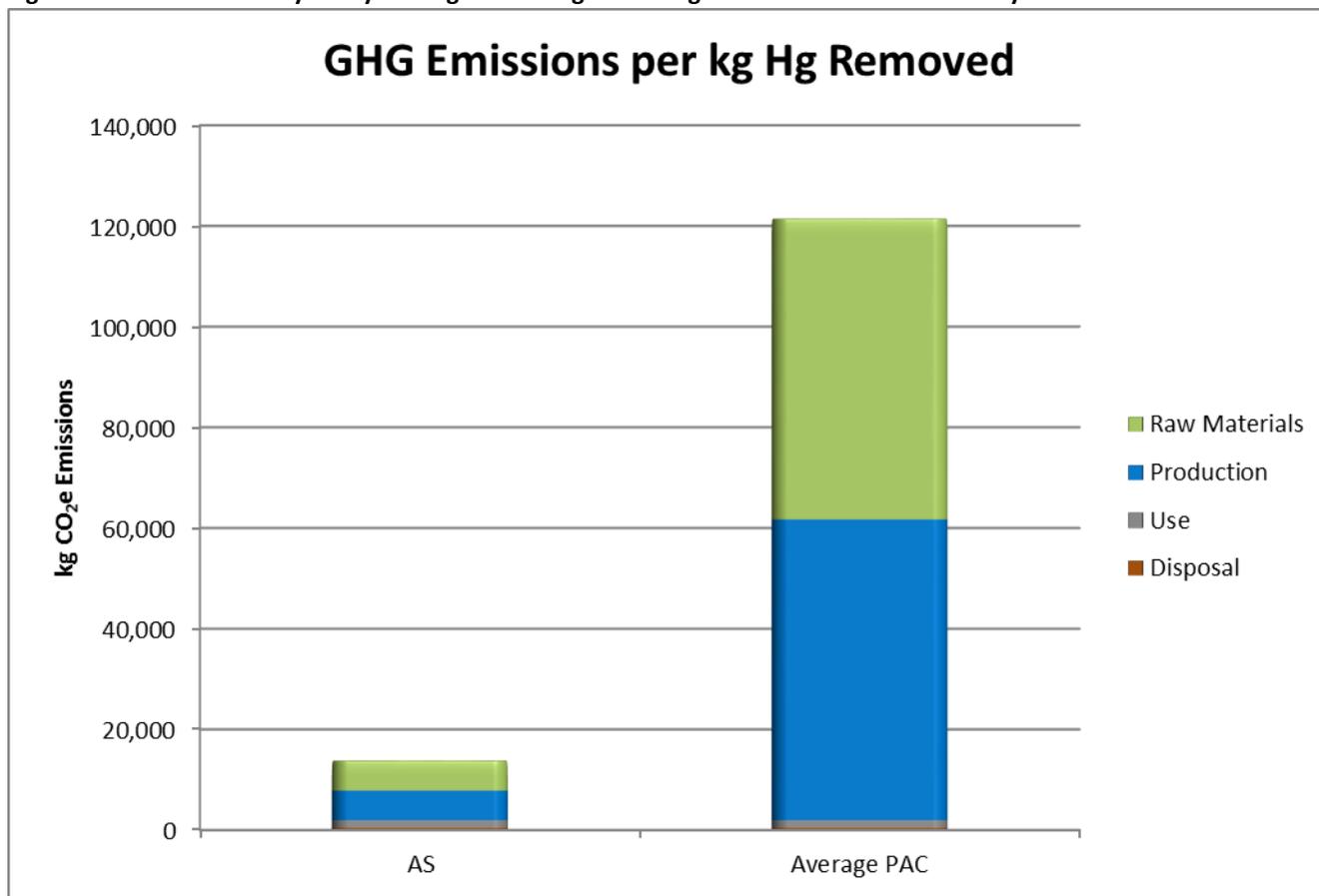
5 Reference: Goldblum, 2008

6 Value supplied by manufacturer.

7 Manufacturer estimates approximately 1/3 of total sorbent production emissions is due to indirect GHG emissions from electrical use in a relatively low GHG emission factor for grid electricity. If AS is produced in locations with significantly higher grid electrical factors, impacts from this stage of production could increase

8 Total may not be exact due to rounding

Figure 3. GHG Emissions by Lifecycle Stage Assuming an Average Sorbent Removal Efficiency



Note: Results based on an average sorbent injection rate of 5.25 lb per minute at a nominal 1,000,000 acfm plant. The distribution of CO<sub>2</sub>e emissions for PAC raw material and production is based on literature values, which provides approximately an even distribution of emissions between coal extraction and PAC processing (Hernandez, 2004). The disposal portion is very small relative to the total emissions.

## Discussion

In general the GHG emissions associated with the life cycle of AS are around 9-15 percent of the GHG emissions associated with the life cycle of PAC, per pound of product used. This is largely because the production of AS has lower GHG emissions by several orders of magnitude compared with PAC production, primarily because the PAC raw material is carbon based and emits carbon dioxide gas when it is heated during activation, whereas AS is silica based.

Based on data provided by Novinda (referencing KeyBanc 2012), total market potential for mercury sorbents is 500 million pounds per year. If AS captures 10 percent of market share, 50 million pounds per year will be produced. Using the average of the PAC life cycle GHG impacts, production of this amount would avoid the emission of 174,000 metric tons per year of CO<sub>2</sub>e.

The highest proportion of GHG emissions for both AS and PAC is attributed to the raw material extraction and sorbent production stages. More than 95-percent of the GHG inventory emissions in the PAC LCA are from these life cycle stages and about 75-percent of the AS GHG emissions are from these stages. The GHG emissions associated with the use of PAC is small relative to the overall PAC GHG inventory (less than 4-percent of the total PAC inventory emissions), but is on the same order of magnitude (25-percent of the total AS inventory emissions) as the AS raw materials production and AS production process (both 37-percent of the total AS inventory emissions). Since during the use phase, it is assumed that the blower is drawing the same power regardless of sorbent load and the total amount of mercury removed from the exhaust stream is constant regardless of the sorbent used, the GHG emissions per mass of mercury removed during the use phase is the same for both AS and PAC. However, variations in the overall efficiency of the AS or PAC sorbent at removing mercury would result in

overall differences in the life cycle analysis. In order to capture this uncertainty in sorbent efficiency an additional analysis was performed as follows.

## **Uncertainty**

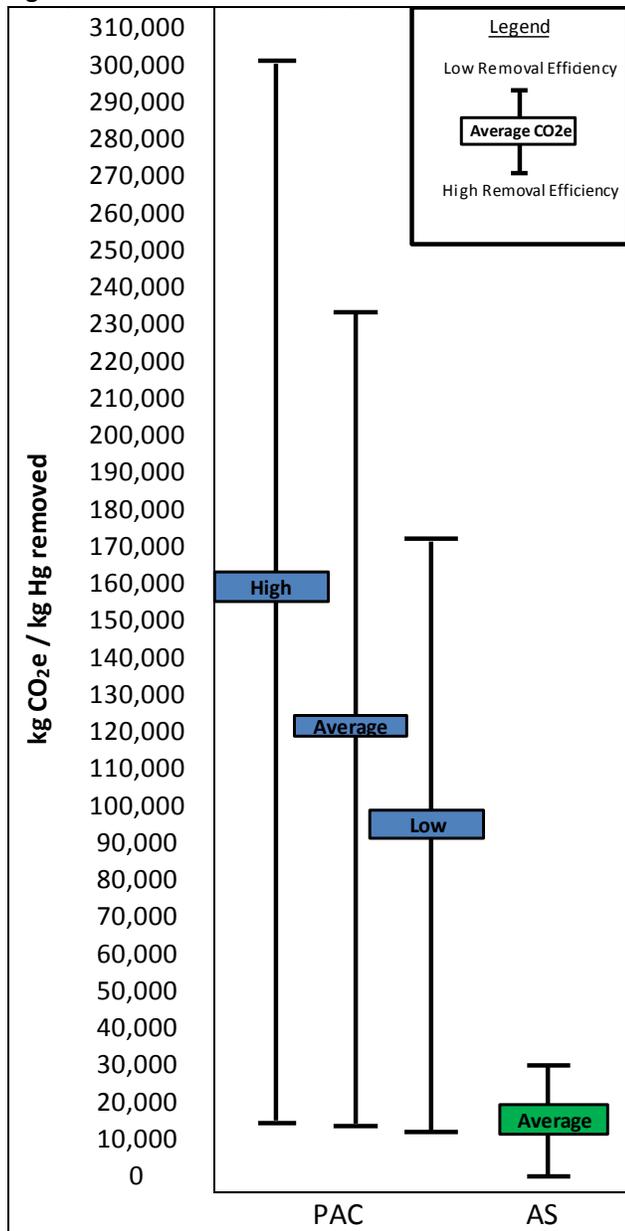
Types of uncertainty are divided into the following three categories: parameter, scenario, and model uncertainty. Parameter uncertainties, uncertainties regarding how well the chosen value represents the parameter in the product's life cycle, are discussed in the data source section. Given the relevancy of the Hg removal parameter an uncertainty analysis was done to bound the variation associated with this parameter. Scenario uncertainty, uncertainty due to methodological choices, is limited by using a standard approach for both process evaluations. Model uncertainties, uncertainty due to using approximations to represent actual operations, were limited to the extent possible by using representative data. To minimize the uncertainty between comparisons the overall range of results are compared rather than the ranges for each individual life cycle stage, as recommended by the WRI Product Standard.

## **Mercury Removal Efficiency Analysis**

As previously discussed the functional unit of sorbent is the mass of mercury removed. The conversion of results from mass of sorbent to mass of mercury removed was based on average industry data; however, individual flue gas stream compositions can vary significantly. Also the range of efficiency of mercury removal between AS and PAC may vary. The initial evaluation assumed that 1 kg of AS has the same removal efficiency as 1 kg of PAC; the following results demonstrate what the range of results would be assuming AS was less efficient than PAC in mercury removal.

Different mercury removal efficiencies correspond to lower or higher sorbent injection rates. The more efficient the sorbent is at removing mercury from the exhaust stream the lower the mass injection rate. Evaluating a typical range of mass injection rates (0.5 pounds per minute (lb/min) to 10 lb/min) for a nominal 1,000,000 acfm application, provides an upper and lower bound to the evaluation. Figure 4 and Table 4 show the literature values for PAC and the calculated value for AS with the potential variation expected due to the different sorbent removal efficiencies.

**Figure 4: Variations in GHG Emissions Due to Sorbent Mercury Removal Efficiency**



**TABLE 4  
LCA Results in Terms of Mercury Removed**

Removal Efficiency	AS kg CO <sub>2</sub> e/kg Hg removed	PAC kg CO <sub>2</sub> e/kg mercury removed		
		Literature Values		
		High	Average	Low
High Efficiency (0.5 lb/min injection rate)	2,700	16,400	12,900	10,200
Average Efficiency (5.25 lb/min injection rate)	13,700	157,600	121,500	92,300
Low Efficiency (10 lb/min injection rate)	24,700	298,800	230,000	174,400

The GHG values shown in Table 4 represent the LCA results for PAC and AS at the anticipated range of efficiencies, where efficiency is inversely proportional to injection rate. Across the range of possible efficiencies and injection rates, and assuming equal injection rates of both products, the PAC GHG footprint per unit of Hg removal ranges from 3.8 to 12.0 times that of AS given the range of PAC literature values.

Note that the variation in ratio of PAC:AS GHG footprint at equal injection rates, across that range of injection rates, is primarily driven by the GHG impacts of the electricity consumed for sorbent injection during the use phase. Because this power is assumed to be somewhat independent of injection rate, and is rather driven by the power needed to disperse the injection air and product into the exhaust flow, it is a higher proportion of the life cycle impacts at lower injection rates.

There is a slight overlap between the most efficient PAC and the least efficient AS impacts. However it is notable that the footprint of AS at average injection rates is roughly equal to the footprint of literature average PAC at low injection rates (5.25 lb/min and 0.5 lb/min, respectively). Also, the footprint of AS at high injection rates is roughly double the footprint of literature average PAC at low injection rates, indicating that PAC injection would have to roughly double to equal the AS footprint (thus 10 lb/min vs. 1 lb/min, respectively). Thus, it can be concluded that PAC would have to be approximately 10 times as efficient in removal of Hg to have equal life cycle GHG LCA emissions per unit of Hg removed.

**Avoided Emissions: Benefit of Fly Ash Reuse**

Avoided emissions are considered emission reductions that are indirectly caused by market responses to the product’s life cycle. Avoided emissions cannot be subtracted from the total inventory results and still be in compliance with the WRI Product Standard, however that can be reported separately as discussed below. Rather than using the attributed approach, the consequential approach was done to evaluate the potential avoided emissions associated with the re-use of fly ash. This approach assumes that the reduction of GHG emissions would be a consequence of a shift in demand for Portland concrete.

Although the use of fly ash is outside the specific process boundaries of the life cycle analysis of sorbents for mercury removal, the co-benefit associated with the opportunity to use fly ash from power plants that use AS as a sorbent provides an additional GHG reduction by potentially avoiding the emissions associated with producing Portland cement. The large benefit is mostly due to the leveraging of the mass of sorbent to the mass of fly ash generated. This is because the mass of sorbent is typically ½ to 2 percent of the total fly ash mass generated, which could be reused.

Based on literature review approximately 0.91 kg CO<sub>2</sub>e per kg Portland cement (Athena Institute, 2006) is emitted during extraction and production of Portland cement. If the fly ash generated during use with AS was used as a replacement for Portland cement, an equivalent proportion of CO<sub>2</sub>e could be avoided from the cement production process, assuming a 1:1 displacement of Portland cement with fly ash. Table 5 summarizes the potential avoided GHG emissions per mass of sorbent used assuming range of AS content in fly ash (0.5 to 2 percent).

TABLE 5  
GHG Displaced through Beneficial Reuse of Fly Ash

Functional Unit	AS Content in Fly Ash		
	0.5 %	1 %	2 %
kg CO <sub>2</sub> e Displaced / kg AS used	-182	-91	-46

As noted above, AS market share could reach 50 million pounds per year. Based on the estimated average injection dosage that would result in 1 percent concentration of AS in fly ash, and assuming that 50 percent of the resulting fly ash would be beneficially used for cement production, use of AS would result in avoided emissions of 1.03 million metric tons per year from cement plants.

## Conclusions

Although there is a wide range of GHG emissions for both AS and PAC, on average, the life-cycle GHG emissions of AS is an order of magnitude lower than life-cycle GHG emissions associated with PAC. In order for PAC to have equivalent life-cycle GHG emissions per unit of mercury removed, it would need to be about 10 times more efficient than AS in removal of mercury. A potential added benefit of using AS is the potential for fly-ash reuse in cement manufacturing which results in avoided GHG emissions that would be one to two orders of magnitude greater than the life-cycle GHG emissions of AS.

## Disclosure

CH2M HILL maintains a minority ownership in Novinda. Nonetheless, this study is an objective analysis performed in accordance with industry standards.

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