A Calculation of the Environmental Footprint of a Granular Activated Carbon Regeneration Facility

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ABSTRACT

The U.S. Environmental Protection Agency (EPA) Superfund Division is responsible for maintaining a high standard of environmental quality, and thus must deal with the environment impacts of its own remedial activities. The regeneration of granular activated carbon (GAC), a substance used to purify contaminated water, is one example of a remediation activity with substantial environmental impacts. The objective of my project is to calculate the environmental footprint of GAC regeneration at the Siemens Reactivation facility in Parker, Arizona. I calculated the electricity usage, natural gas usage, potable water usage, employee gasoline usage, and wastewater production using information from site diagrams, facility process maps, and literature searches. I converted these values into units of CO_2e, NO_x, SO_x, PM_{10}, and HAP using conversion values from the *EPA Methodology for Understanding and Reducing a Project's Environmental Footprint*. I found that the largest environmental impact resulted from natural gas consumption and electricity usage in the carbon regeneration building. The selection of context-dependent conversion factors greatly impacted the accuracy of my results. Using the results from my GAC environmental impact assessment, remedial project managers can more effectively apply green remediation principles to their projects.

KEYWORDS

remediation, carbon footprint, climate change, Environmental Protection Agency (EPA), Superfund

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) is responsible for monitoring and enforcing a high standard of environmental quality, and thus must also regulate the environmental impacts of its own remedial activities (EPA 2011a). The EPA Superfund program, established in response to human-induced environmental disasters in the 1970s, initiates and executes cleanup of abandoned hazardous waste sites, termed “Superfund” sites. The multistep Superfund cleanup process includes conducting rigorous site assessments, designing specific remediation strategies, and constructing contaminant profiles (EPA 2011b).

Remedial activities also have their own negative environmental impacts. The Superfund Program has acknowledged the potential environmental impact of its operations and as a result has developed a methodology to quantify the impacts of remediation projects and processes. This method outlines a process to estimate environmental impacts of specific remediation activities in all steps of the Superfund cleanup process (EPA 2012). The methodology investigates the extent of impacts associated with energy usage, water usage, material inputs, and waste discharge (ibid.). Superfund projects can last decades due to the complexity of projects and the EPA goal of sustained environmental protection in remediated sites (EPA 2011b). Consequently, these long-term cleanup projects can have substantial long-term environmental impacts (ibid.). For example, the Iron Mountain Mine cleanup project has cost nearly USD 55.5 million and has altered natural waterway trajectories to facilitate contaminant management (Region 9: Superfund 2011). EPA diverted streams loaded with heavy metals from the mine site to a water treatment plant. This diversion of water impacted the benthic invertebrate ecology and water quality of nearby riparian ecosystems (EPA 2004). These impacts were a direct result of the EPA-initiated remediation activities. The environmental footprint calculator used to estimate these and other impacts is currently being developed (Scheuermann, personal communication). Due to the novelty of the methodology and calculator, environmental impact values of many common remediation strategies incorporated in the footprint calculator are incomplete.

The regeneration of granular activated carbon (GAC) is one example of a Superfund site remediation activity whose calculated environmental footprint is incomplete. Activated carbon, a porous carbon-rich material, is used to filter harmful volatile organic compounds (VOCs) from contaminated water (Cannon et al. 1994). It has enormous adsorptive potential because it has the largest surface area to mass ratio of any known substance (Mohan and Singh 2005). When contaminated water is poured into a matrix of GAC, the contaminants are attracted to the GAC's large surface area and are captured in the matrix (ibid.). Activated carbon is produced by heating various materials like coal, coconut shells, and bone to temperatures of 1000 °C (Mohan and Singh 2005, Bayer 2005). After use in water treatment, GAC can be regenerated through exposure to temperatures up to 800 °C in the presence of a mildly oxidative atmosphere (provided by steam and/or carbon dioxide). The heat and oxidative conditions vaporize the VOCs, which may be vented to the atmosphere in low concentrations (San Miguel et al. 2001).

The regeneration of GAC plays an important role in decreasing the demand for creation of virgin, or previously unused, GAC (San Miguel et al. 2001). This recycling process has many ecological benefits such as reducing the need for new GAC, but the recycling process could possibly be inefficient and more polluting than creating new GAC. The comparison between the environmental impacts of new GAC and recycled GAC is crucial to choosing an alternative that best promotes environmental sustainability. A preliminary environmental footprint of GAC regeneration has already been calculated, but it only quantifies electricity usage, natural gas usage, water usage, and wastewater discharged, and does not account for many resource inputs of machines used in the regeneration process (Scheuermann, personal communication). Thus, there is a need to improve the estimated environmental footprint of the GAC regeneration process to better reflect all of its consequences.

The objective of my project is to refine the current calculations of the environmental footprint of GAC regeneration to provide a more accurate environmental assessment tool. This objective will help answer the broader research question of how ecologically sustainable remediation methods can be implemented in Superfund site remedy decision models. To accomplish this research objective, I will recalculate the results from the existing environmental impact analysis to double-check previously calculated values and to include categories that are inclusive of different emission categories. I will compile my results and present them to the EPA Superfund Division.

BACKGROUND

The Siemens Water Technologies Corporation Parker Reactivation Facility in Parker, Arizona reactivates spent carbon using a thermal regeneration process: spent GAC is heated in a reactivation furnace, vaporizing the contaminants on the carbon. These contaminants are filtered from the furnace exhaust and vented to the atmosphere at regulated levels (Siemens 2007). The facility processes both vapor phase and liquid phase carbon with and without chlorinated contaminants. This distinction is important because different types of spent GAC have different resource consumption requirements (ibid.).

In addition to the carbon regeneration facility, the Siemens facility has on-site support buildings including a carbon product warehouse, a drum storage warehouse, and administrative offices (ibid.). Activities that support the carbon regeneration facility are emissions monitoring, on-site and off-site wastewater treatment, employee transportation, and laboratory analysis (to determine the contaminant composition).

The facility is currently undergoing a permitting process and has released a permit application that includes information about the layout and specifications of their machines and buildings (Siemens 2007). This permit application was a major source of information for my study.

METHODS

I separated the environmental impacts into six components: (1) electricity impacts, (2) natural gas impacts, (3) water impacts, (4) transportation impacts, (5) laboratory analysis, and (6) treatment chemicals. I calculated CO_2 emissions, NO_x emissions, SO_x emissions, PM_{10} emissions, and hazardous air pollutant (HAP) emissions for each component. I used Excel spreadsheets to organize my data.

General assumptions

Data in the process maps from the Siemens permit application was separated by carbon phase (vapor versus liquid) and carbon chlorination (non-chlorinated versus chlorinated). I assumed a breakdown of 25% liquid phase non-chlorinated carbon, 25% liquid phase chlorinated carbon, 25% vapor phase non-chlorinated carbon, and 25% vapor phase chlorinated carbon (Scheuermann, personal communication).

I applied a 0.9 capacity factor to all processes in the regeneration building by multiplying final spent carbon and resource consumption estimates by 0.9 (Scheuermann, personal communication). This capacity factor accounts for downtime due to equipment maintenance and holidays. The 0.9 capacity factor was not applied to warehouse/office electricity and water consumption, transportation, or lab analysis - I incorporated system downtime for these activities using other methods.

I assumed 100% of energy consumption in warehouses and office buildings originated from grid electricity and not natural gas (Scheuermann, personal communication).

I worked in collaboration with EPA employees to assign reasonable assumptions whenever data was lacking.

Spent carbon data collection

I found the rate of spent carbon processing (in lb/hr) from process maps in the permit application (Siemens 2007). I converted this value into lb/year by multiplying by 24 hr/day and 365 days/year.

(1a) Electricity usage data collection and analysis

Wet electrostatic precipitator (WESP)

I found the power requirements (in kVA, kilo Volt Ampere) of the Clean Gas Systems (CGS) WESP from the permit application (Siemens 2007). I assumed the apparent power (VA) equaled real power (watts) and used a 1:1 conversion between kVA and kW. The listed power requirements were for a 7200 actual cubic feet per minute (acfm) WESP, while the facility's actual exhaust flow rate was 6717 acfm (this value was collected from the process maps). I prorated the power consumption by exhaust rate to calculate the actual power consumption. I then multiplied the power consumption (in kW) by 8760 hr/year to calculate the annual electricity demand (in kWh).

Induced draft (ID) fan

I found the power requirements (in brake horsepower, bhp) of the Barron Industries Induced Draft (ID) fan from the permit application (Siemens 2007). I prorated the power requirements according to the actual exhaust flow rate (8039 acfm versus the 8420 acfm listed in the permit ID fan performance conditions) and applied a 90% motor efficiency to calculate the facility's ID fan power requirements (Scheuermann, personal communication). I converted the power requirements from bhp to kW (using a conversion factor of 746 watts/bhp, EPA 2012) and multiplied by 8760 hr/yr to calculate the annual energy consumption in kWh.

On-site wastewater treatment plant (WWTP)

I found the wastewater flow rate (in gal/min) to the on-site WWTP in the permit application process maps (Siemens 2007). I multiplied the flow rate by one half of the estimated electricity demand (in kWh/gal) of a municipal wastewater treatment plant (EPA 2010) to calculate the annual electricity demand (in kWh). I assumed the Siemens on-site WWTP would have half the electricity demand of a municipal WWTP because it is a pre-treatment plant for treating wastewaters before discharge to the local publicly owned treatment works (POTW) and would therefore have a lower power requirement (Scheuermann, personal communication).

Continuous emissions monitoring system (CEMS)

I found the power requirements (in Voltage-Amps, VA) of the four emissions monitoring devices in the permit application (Siemens 2007) and from device manuals (Siemens 2001). I assumed apparent power (VA) equaled real power (watts) and applied a 1:1 VA:watt conversion factor to calculate power requirements of the devices (in watts). I summed the power requirements of all four devices to calculate the total CEMS power requirement and divided by

1000 to calculate power in kW. Finally, I multiplied by 8760 hr/yr to calculate the annual electricity demand (in kWh).

Drum and carbon product storage warehouses

I found the dimensions of the office buildings in the permit application (Siemens 2007) and multiplied the length by the width to calculate the total area (in ft^2). I then multiplied this area by a conversion factor of 5.38 kWh/ft^2. I calculated this conversion factor by dividing a conversion factor from the literature (in units of USD/ft^2 annually spent on energy, E Source 2007) by the 2007 price of electricity for industrial customers (EIA 2011). I reduced this final value by 50% because the warehouses at the Siemens facility are not intensively heated or cooled (Scheuermann, personal communication).

Administrative offices

I found the dimensions of the office buildings in the permit application (Siemens 2007) and multiplied the length by the width to calculate the total area (in ft^2). I calculated a energy density conversion factor (in kwh/ft^2) from E Source 2006: "office buildings in the U.S. use an average of 17 kilowatt-hours (kWh) of electricity and 32 cubic feet of natural gas per square foot annually." I assumed 100% of the facility's energy requirements were supplied by electricity (Scheuermann, personal communication) and added the cited 32 ft^3 natural gas/ft^2 to the 17 kWh/ft^2. I converted "32 ft^3 of natural gas" into 9 kWh/ft^2 by multiplying by 1,000 Btu/ft^3 natural gas and 3412 Btu/kWh (APS 2012). I multiplied the area by this conversion factor (26 kWh/ft^2) to calculate the annual energy consumption of the office buildings.

Miscellaneous fans, pumps, and motors

Carbon regeneration equipment not included in the above calculations was powered by fans, pumps, and motors. I quantified their electricity consumption by calculating the electricity consumption of all fans (excepting the ID fan), pumps, and motors.

I summed all the fans, pumps, and motors identified from process diagrams in the permit application (Siemens 2007). I assumed fans, pumps, and motors all operated at 5 hp (Scheuermann, personal communication). I converted 5 hp into kWh/yr by multiplying by 8760 hr/yr and 0.746 kW/hp (EPA 2012). I multiplied the total number of items by the per unit energy consumption (in kWh/yr) to calculate the estimated annual electricity usage.

(1b) Electricity emissions conversion

Energy composition

I found the electricity fuel blend supplied to the facility (in terms of percentage of power mix – e.g. % coal, % natural gas, % renewable energy) (APS 2009). I then converted the resource mix to footprint conversion factors by multiplying total emissions (in lb/ MWh) (EPA 2012) by the fraction of power mix. I summed all of these emissions by type of emission (CO_2e, NO_x, PM_{10}, etc.) to calculate the emissions per kWh of electricity supplied in this region of Arizona.

Electricity generation impact

I summed the electricity consumption (in kWh) of all activities listed above to calculate the annual electricity consumption. I converted kWh into MWh by multiplying by MWh/1000 kWh and multiplied this total consumption by the emissions conversion factors calculated in the previous section titled “Energy composition” to calculate emissions (in lb/yr) of CO_2, NO_x, SO_x, PM_{10}, and HAP.

(2a) Natural gas data collection and analysis

Reactivation furnace and afterburner burners

I found the natural gas flow rate (in standard cubic feet per minute, scfm) into the reactivation furnace and the afterburner in the Siemens permit application (Siemens 2007). I converted scfm into annual usage by multiplying by 60min/hr and 8760 hr/yr.

For comparison purposes, I also calculated burner annual natural gas consumption using manufacturer's information from the permit application (Siemens 2007). The permit application provided the number of burners in the furnace and afterburner as well as the rate of natural gas consumption per burner in scf/hr. I calculated the annual natural gas usage by multiplying the number of burners by the per burner rate of natural gas consumption and by 8760 hr/yr.

Small boiler

The natural gas flow rate of the small boiler was not provided in the process maps. However, the steam production rate (in lb/hr) of the boiler was given. I used tables that quantify heat quantities and temperature/pressure relationships, steam tables, to determine the energy (in Btu/lb) required to heat the steam (Spirax 2012). I converted the steam production rate into annual natural gas consumption by multiplying the steam production rate (in lb/hr) by the energy requirement (in Btu/lb), an assumed boiler efficiency (Scheuermann, personal communication), 8760 hr/yr, and the energy content of natural gas (Btu/scf) (APS 2012).

(2b) Natural gas emissions conversion

Natural gas impact

I summed the natural gas consumption of the burners and boilers to calculate the annual natural gas usage of the facility (in scf). I multiplied this quantity by emissions conversion factors (in lb/scf) from the EPA methodology (EPA 2012) to calculate emissions of CO_2, NO_x, SO_x, PM_{10}, and HAP. I applied conversion factors for both natural gas production and natural gas usage.

(3a) Water usage data collection and analysis

Potable water usage

Carbon regeneration system. I summed the flow rates (in gal/min) of all consumers of potable water in the facility (Siemens 2007). I converted this quantity into gal/yr by multiplying by 60 min/hr and 8760 hr/yr.

Other industrial uses. I found the weekly truck traffic in the permit application (Siemens 2007). I assumed that 2 trucks/day carried GAC in bulk and 1 truck/day carried GAC in drums. I assumed each truck carried 30 drums. I assumed truck wash-down required 1000 gallons per truck and drum wash-down required 10 gallons per drum. I multiplied the number of bulk trucks per week by 260 working days/yr to calculate annual truck traffic and multiplied by 1000 gal/truck to calculate the annual water usage for truck wash-down. I converted one drum truck/day into annual drum truck wash-down water consumption by multiplying by 30 drums/truck, 260 working days/yr, and 10 gal/drum. I estimated water consumption of general maintenance to be 500 gal/day. I multiplied this quantity by 260 working days/yr to calculate annual water usage due to general maintenance. I summed the water consumption from drum wash-down, truck wash-down, and general maintenance to calculate the annual water usage from other industrial uses. All of these assumptions were reasonable estimates made in collaboration with Karen Scheuermann of EPA Region 9.

Administrative offices. I found the dimensions of administrative office space in the permit application (Siemens 2007). I multiplied the length by the width of the buildings to calculate the total area (in ft^2). I multiplied the area by the average annual corporate water usage (m^3 water/m^2 office space) to calculate the annual water usage in m^3/yr (Seneviratne 2007). I then multiplied this quantity by 264 gal/m^3 to calculate the annual water usage in gal/yr.

Wastewater production

Carbon regeneration system. I found the wastewater flow rate (in gal/min) to the off-site POTW in the facility process maps (Siemens 2007). I multiplied by 60 min/hour and by 8760 hr/yr to calculate the annual discharge to the POTW.

Administrative offices. I assumed water loss in office water use activities was negligible and that wastewater produced through office use was the same as potable water domestic use (Scheuermann, personal communication).

(3b) Water emissions conversion

Potable water production impact

I summed water usage of the carbon regeneration system, other industrial uses, and office use to calculate the total annual water usage in the facility (in gal). I divided by 1000 to convert to thousands of gallons (galx1000). I then multiplied this quantity by emissions conversion factors (in lb/galx1000) from the EPA methodology (EPA 2012) to calculate annual emissions of CO_2, NO_x, SO_x, PM_{10}, and HAP.

Off-site wastewater treatment impact

I summed wastewater production of the carbon regeneration system and office use to calculate the total annual water usage in the facility (in gal). Wastewater produced from “other industrial uses” flows into sumps that lead to the carbon regeneration system and would thus be included in wastewater calculations. I divided this quantity by 1000 to convert to galx1000. I then multiplied this quantity by emissions conversion factors (in lb/galx1000) from the EPA methodology (EPA 2012) to calculate annual emissions of CO_2, NO_x, SO_x, and PM_{10}. HAP emission conversion factors were unavailable for off-site wastewater treatment.

(4a) Transportation data collection and analysis

I found the number of facility employees in the permit application (Siemens 2007). I assumed half of the employees lived in Parker, AZ, and half of the employees lived in Lake Havasu, AZ, the nearest large city (Scheuermann, personal communication). I used Google maps to estimate the distance from the center of the two cities to the location of the facility (Google

2012). I averaged the two distances to calculate the average employee distance to the facility (in miles). I converted this quantity to gallons gasoline consumed per year by multiplying average employee distance to facility (mi) by number of employees and dividing by the average fuel efficiency of a passenger car (EPA 2012).

(4b) Transportation emissions conversion

I multiplied this quantity by emissions conversion factors (in lb/gal gasoline) from the EPA methodology (EPA 2012) to calculate emissions of CO_2, NO_x, SO_x, PM_{10}, and HAP. I applied conversion factors for both gasoline production and gasoline usage.

(5a) Laboratory analysis data collection and analysis

I assumed 100 facility clients per year require a set laboratory analyses. I assumed a set of laboratory analyses included metals analysis (USD 150/analysis), VOC analysis (USD 50/analysis), semi-volatile organic compound (SVOC) analysis (USD 125/analysis), general chemistry analysis (USD 150/analysis), and an analysis customized to the type of spent carbon (USD 150/analysis). I summed the costs of the five analyses to calculate the cost of a set of analyses. I multiplied this quantity by 100 customers/year to calculate the annual lab analysis cost. All assumptions and lab analysis costs were reasonable estimates made in collaboration with Karen Scheuermann of EPA Region 9.

(5b) Laboratory analysis emissions conversion

I multiplied the annual lab analysis cost by emissions conversion factors (in lb/USD) from the EPA methodology (EPA 2012) to calculate emissions of CO_2, NO_x, SO_x, PM_{10}, and HAP.

(6a) Treatment chemicals data collection and analysis

I found the caustic (sodium hydroxide (NaOH)) input rate (lb/hr) in the Siemens permit application (Siemens 2007). I multiplied this quantity by 8760 hr/yr to calculate the annual NaOH input (in lb).

(6b) Treatment chemicals emissions conversion

I multiplied the annual NaOH input by emissions conversion factors (in lb out/lb in) from the EPA methodology (EPA 2012) to calculate emissions of CO_2, NO_x, SO_x, PM_{10}, and HAP.

Total footprint calculation of recycled and virgin GAC

I summed all emissions for electricity generation, natural gas production, natural gas usage, potable water production, off-site wastewater treatment, gasoline production, gasoline usage, lab analysis, and NaOH production to calculate the facility's annual emissions of CO_2, NO_x, SO_x, PM_{10}, and HAP. I divided these emission values (in lb/year) by the annual amount of spent carbon processed (in lb/year) to calculate the pounds of emissions per pound of spent carbon.

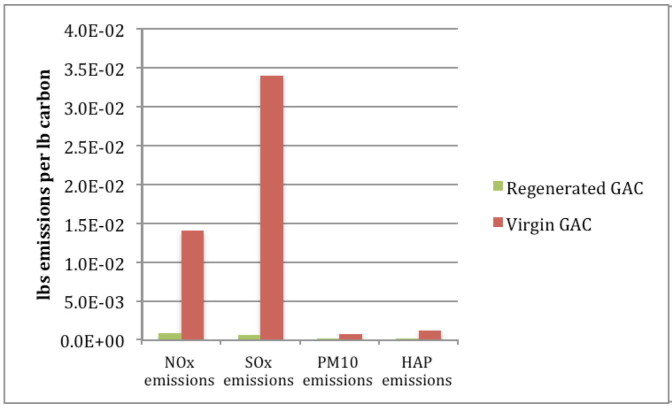
I found the annual emissions of CO_2, NO_x, SO_x, PM_{10}, and HAP from generating virgin GAC in the EPA methodology (EPA 2012).

RESULTS

Overall GAC Regeneration Footprint and Comparison to Virgin GAC Production

Per pound of spent carbon processed, the Siemens carbon regeneration facility emitted 0.70 pounds of CO_2, 8.1×10^{-4} pounds of NO_x, 5.7×10^{-4} pounds of SO_x, 6.0×10^{-5} pounds of PM_{10}, and 1.6×10^{-5} pounds of HAP (Table 1). Producing one pound of virgin GAC emitted 8.5 pounds of CO_2, 0.014 pounds of NO_x, 0.034 pounds of SO_x, 0.00078 pounds of PM_{10}, and 0.0012 pounds of HAP (Table 2). Figure 1 compares the emissions of regenerating GAC to emissions of producing virgin GAC.

Natural gas usage and production resulted in the largest CO_2 emissions, comprising 85% of the total CO_2 footprint (Figure 2).



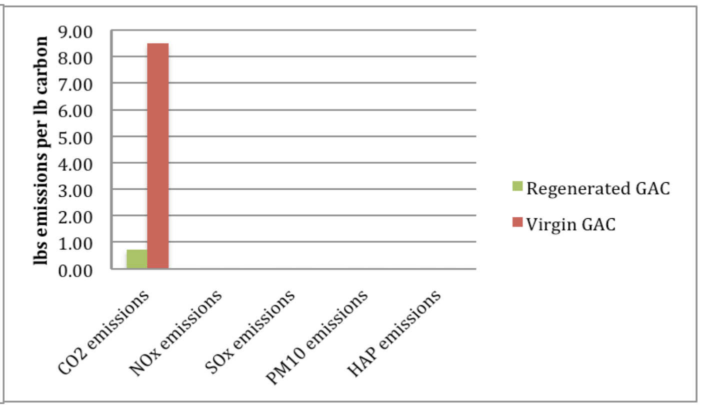


Fig. 1a. Emissions of recycled and virgin GAC.

Fig 1b. Enlargement of NO_x, SO_x, PM_{10}, and HAP Emissions.

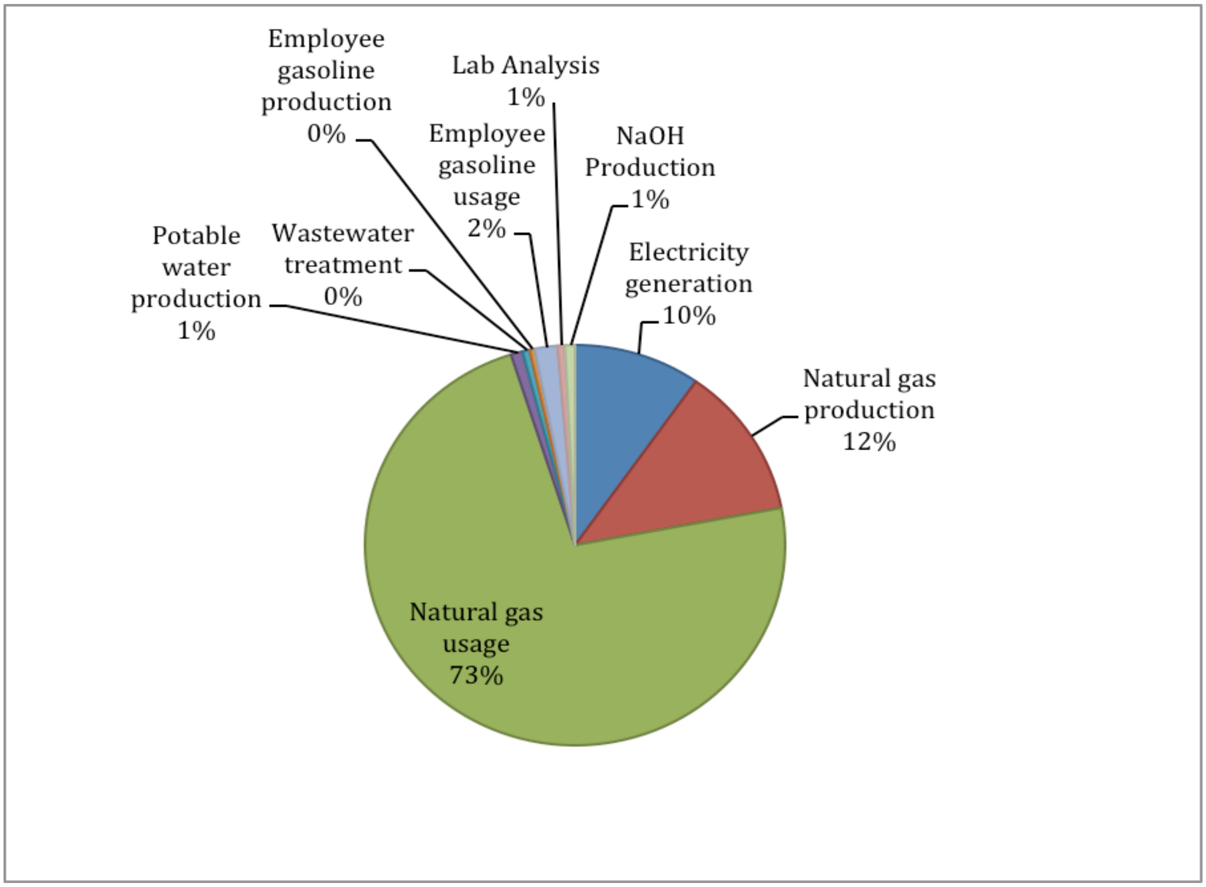


Fig. 2. CO_2 emissions breakdown by activity. 0% represents <0.1%.

Table 1. GAC regeneration footprint.

Activity	Quantity		Annual CO_2 emissions (lb)	Annual NO_x emissions (lb)	Annual SO_x emissions (lb)	Annual PM_{10} emissions (lb)	Annual HAP emissions (lb)
Electricity generation	883	MWh	1,094,193	2321	5038	53	228
Natural gas production	62,667	cu.ft.x1000	1,378,683	2319	2883	45	3.8
Natural gas usage	62,667	cu.ft.x1000	8,209,428	6267	3.9	476	5.3
Potable water production	20,073	galx1000	100,363	195	118	321	0.3
Wastewater treatment	14,182	galx1000	62,399	227	213	NP	NP
Employee gasoline production	10,010	gal	44,044	80	190	5.2	1.6
Employee gasoline usage	10,010	gal	196,196	1101	45	5.4	0.4
Lab Analysis	62,500	USD	62,500	300	225	25.0	8.1
NaOH Production	51,187	lb	87,018	154	333	31.2	0.8
Total emissions (lb)			11,234,824	12,963	9,049	963	249
Pounds emissions per pound of spent carbon (lb)			0.70	8.1E-04	5.7E-04	6.0E-05	1.6E-05

NP - Not Provided

Table 2. Virgin GAC footprint (for comparison).

	CO_2	NO_x	SO_x	PM_{10}	HAP
Pounds emissions per pound of virgin GAC (lb)	8.5	0.014	0.034	0.00078	0.0012

Electricity Consumption Breakdown and Impacts

Annually, the WESP consumed 78,840 kWh, the ID fan consumed 551,880 kWh, the WWTP consumed 4,598 kWh, the CEMS consumed 18,567 kWh, the drum storage warehouse consumed 77,538 kWh, the carbon product storage warehouse consumed 34,462 kWh, the administrative offices consumed 116,064 kWh, and the fans/pumps/motors consumed 1,176 kWh (Table 3). The largest electricity consumer was the ID fan, which comprised 62% of the total energy usage. The next largest consumers were the administrative offices (13%), the warehouses (13% combined), and the WESP (9%) (Figure 3).

Table 3. Electricity consumption.

Item	Annual electricity usage (kWh)
Wet Electrostatic Precipitator (WESP	78840
Induced Draft (ID) Fan	551880
Wastewater Treatment Plant (WWTP)	4598
Continuous Emissions Monitoring System (CEMS)	18567
Drum Storage Warehouse	77538
Carbon Product Storage Warehouse	34462
Administrative Offices	116064
Fans, Pumps, Motors	1176
Total:	883126

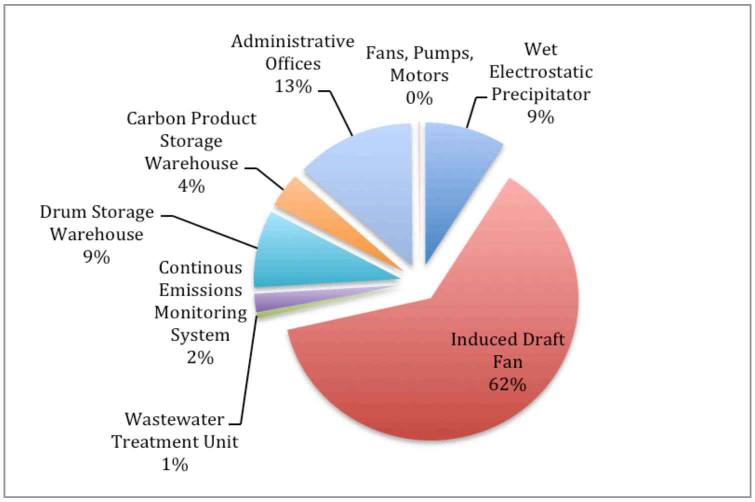


Fig. 3. Electricity consumption by activity. 0% represents <0.2%.

Natural Gas Consumption Breakdown and Impacts

Annually, the burners in the reactivation furnace consumed 20,577,000 ft^3 of natural gas, the small boiler consumed 7,440,000 ft^3 of natural gas, and the burners in the afterburner consumed 34,650,000 ft^3 of natural gas (Table 4). The largest natural gas consumer was the afterburner, which accounted for 55% of all consumption (Figure 4).

Table 4. Natural gas consumption.

Item	Annual natural gas usage (ft^3 x 1000)
Burners in Furnace	20577
Small Boiler	7440
Burners in Afterburner	34650
Total:	62667

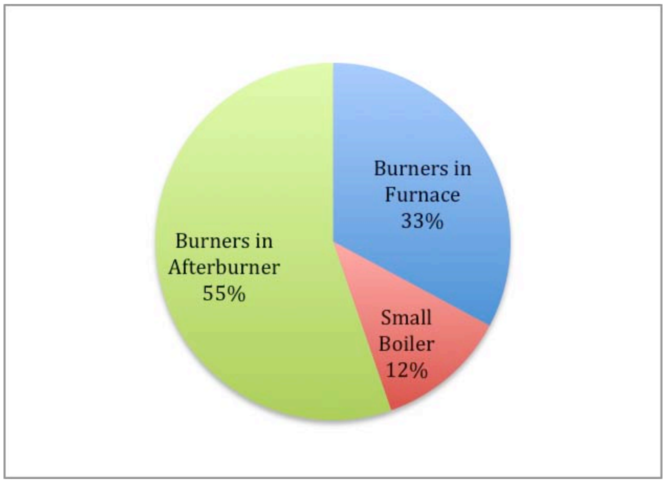


Fig. 4. Natural gas consumption by activity.

Water Consumption Breakdown and Impacts

Potable water

Annually, the carbon regeneration system consumed 19,108,000 gallons of water, other industrial site uses consumed 781,000 gallons of water, and administrative offices consumed 184,000 gallons of water (Table 5). The carbon regeneration system consumed the most water and accounted for 95% of the water consumption (Figure 5).

Table 5. Potable water usage.

Item	Annual flow rate (galx1000)
Carbon Regeneration System	19108
Other Industrial Site Uses	781
Administrative Offices	184
Total:	20073

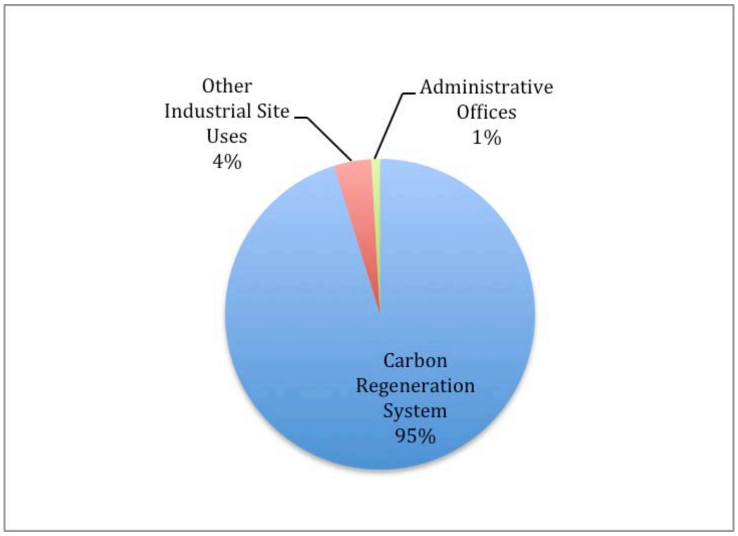


Fig. 5. Potable water consumption by activity.

Wastewater

Annually, the carbon regeneration facility produced 13,998,000 gallons of wastewater and administrative uses produced 184,000 gallons of wastewater (Table 6). The largest producer was the carbon regeneration facility, which accounted for 99% of the wastewater production (Figure 6).

Table 6. Water discharged to POTW.

Item	Annual flow rate (galx1000)
Carbon Regeneration Facility	13998
Administrative Offices	184
Total:	14182

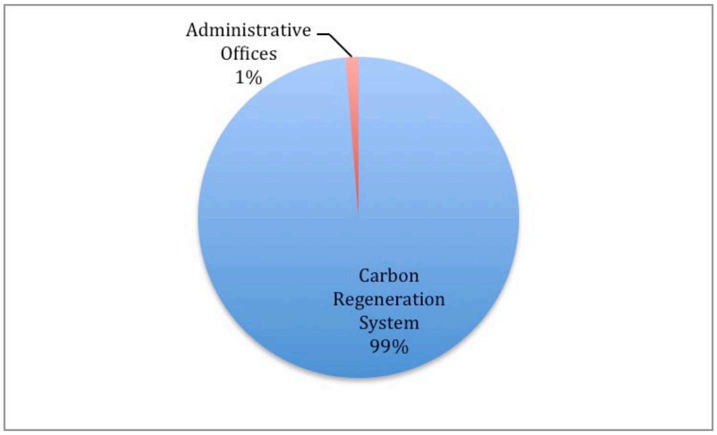


Fig. 6. Wastewater production by activity.

Transportation, Lab Analysis, and NaOH Breakdown and Impacts

Annually, employee transportation consumed 10,010 gallons of gasoline, laboratory analyses cost USD 62,500, and the regeneration facility consumed 51,187 lb of NaOH (Table 7). The units of these values are not comparable.

Table 7. Transportation, lab analyses, treatment chemicals.

Item	Amount	Unit
Transportation	10010	gal gasoline
Laboratory analyses	62500	USD spent
Treatment chemicals	51,187	lb NaOH

DISCUSSION

I found that the majority of the carbon footprint of the Siemens Reactivation facility resulted from natural gas usage and electricity usage in the carbon regeneration building. Because the Siemens facility has direct control over the operation of the carbon regeneration facility, there is great potential to reduce environmental impacts through efficiency measures. The choice of conversion values I used from the literature had the potential to change my calculated results greatly. When I reviewed my methods, I found that values for the same environmental impact that were calculated using two different estimation methods differed greatly, causing me to doubt the validity of derived values.

Electricity Usage

Machines in the regeneration building were the largest electricity consumers in the Siemens Reactivation facility. This pattern follows the national trend – 23 percent of electricity consumed in the United States is from industrial motor-driven systems (Consortium for Energy Efficiency (CEE) 2009).

The Induced Draft fan was the largest consumer of electricity in the facility, accounting for 62% of electricity consumption. Increasing the efficiency of the ID fan by purchasing a more efficient fan or optimizing its control system has the greatest potential for reducing electricity consumption. The ID fan pulls exhaust from the wet electrostatic precipitator through the air pollution control system to the stack that vents to the atmosphere. The fan is the largest consumer of energy and optimizing its control system can potentially reduce its electricity consumption by 40% (Mandi 2008). Another study found that incorporating more efficient motor systems like those in fans has the potential to decrease motor system demand by 11 – 18 percent (CEE 2009). Nationwide, this would result in emissions reductions of 15-26 million metric tons of carbon per year (ibid.).

Natural Gas Consumption

Natural gas consumption in the regeneration facility contributed to 73% of the aggregated carbon dioxide emissions. Industrial activities account for 33% of natural gas consumption nationally and 6% of natural gas consumption in Arizona (EIA 2012). Because industrial facilities comprise a substantial proportion of national natural gas consumption, reducing facility natural gas consumption has the potential to affect a large portion of national natural gas demand.

The cited natural gas consumption values underestimate the fraction of industry natural gas usage because they do not account for electricity generation. National electricity generation environmental impacts are primarily attributed to large users of electricity such as industrial facilities. Accounting for electricity generation, industrial activities in Arizona consume substantially more natural gas than the cited 6%. 68% of Arizona natural gas consumption is from electricity generation (ibid.) and industrial sources consume 16% of electricity in Arizona (EIA 2011). Multiplying 68% by 16% and adding this quantity to 6% increases the Arizona proportion of industrial natural gas consumption to 17%.

In part 2a of my analysis, I calculated burner natural gas consumption using two different methods for comparison purposes. The burner natural gas usage calculated from manufacturer's information sheets was roughly three times as high as the flow rate calculated from the process diagrams (Appendix A). The difference between these two estimates indicates that there are inconsistencies in the methods that I used. One source of error could have originated from the assumption that the burners work at 90% capacity, a rough estimate from an EPA employee (Scheuermann, personal communication). This 90% capacity factor is assumed for the entire facility.

Water Usage

I found that carbon impacts associated with water consumption were more than one order of magnitude smaller than electricity and natural gas impacts. Because the magnitude of water consumption impacts at the facility is small compared to impacts from electricity and natural gas usage, water efficiency measures will have a small effect on the overall environmental impact. However, implementing water efficiency measures would have a small, but favorable impact on the environmental footprint. A study conducted by the City of San Jose examined 15 industrial facilities that have implemented water efficiency measures. These facilities were able to reduce their water use by 25% to 90% and most were able pay back the initial costs of their conservation measures in less than one year (CA DWR 1994).

Lack of data from the facility resulted in imprecise water usage calculations. The permit application did not quantify many of the carbon regeneration system water flows (e.g. to the top of the packed bed scrubber, to the top of the Venturi scrubber, to the cooling tower) and many on-site water consuming activities were implied but not explicitly listed in the application (e.g. carbon drum wash-down, truck wash down, general maintenance) (Siemens 2007). These values were estimated with back of the envelope calculations and are the least supported by published data.

Overall Environmental Impact Calculations

Industrial and commercial activities account for approximately two-thirds of energy usage in the U.S (McLean-Conner 2009). Reductions in overall environmental impact in facilities like the Siemens carbon regeneration facility would have a substantial impact on national electricity consumption.

One assumption that affected both the electricity consumption and the natural gas consumption was the assumption that 100% of building energy came from electricity and 0% of building energy originated from natural gas (E Source 2007). Modifying this assumption would have a significant impact on the aggregated carbon dioxide emissions. A larger proportion of electricity in the energy composition would lead to substantially higher carbon dioxide emissions, as the process of producing electricity is more carbon-intensive (Deru 2007, EGRID 2007).

Methods Assessment

The original footprint only included CO_2 emissions. My new calculation also included NO_x emissions, SO_x emissions, PM_{10} emissions, and HAP emissions. Table 8 shows the results of the previous study compared to my study (Scheuermann 2011). The new carbon footprint of regenerating GAC is larger (0.70lb CO_2 versus 0.57lb CO_2), which could indicate that the new calculation included carbon emissions that were not previously quantified. Table 9 shows the items quantified in my study versus the previous study.

Table 8. Carbon emissions results of previous and new footprint calculations. NO_x emissions, SO_x emissions, PM_{10} emissions, and HAP emissions were not quantified in the previous calculation.

	Quantity		**Units**	**Annual CO2 Emissions (lb)**	
	Previous Calculation	**New Calculation**		**Previous Calculation**	**New Calculation**
Electricity Usage	660	883	MWh	1,016,757	1,094,193
Natural Gas Usage	52,667	62,667	cu.ft.x1000	6,425,369	1,378,683
Water Usage	16,680	20,073	galx1000	83,399	100,363
Wastewater Discharged	14,182	14,182	galx1000	62,399	62,399
Total Emissions (lb)				7,587,925	2,635,638
Pounds emissions per pound of spent carbon (lb)				0.57	0.70

Table 9. Items quantified in original and new environmental footprint. A checkmark indicates the analysis was completed for that item in that calculation.

Resource type	**Item**	**Original Calculation**	**New Calculation**
Electricity	Wet Electrostatic Precipitator	✓	✓
	Induced Draft Fan	✓	✓
	Wastewater Treatment Unit	✓	✓
	Continuous Emissions Monitoring System		✓
	Drum Storage Warehouse	✓	✓
	Carbon Product Storage Warehouse	✓	✓
	Administrative Offices	✓	✓
	Fans, Pumps, Motors		✓
Natural Gas	Burners in Furnace	✓	✓
	Small Boiler	✓	✓
	Burners in Afterburner	✓	✓
Water	Carbon Regeneration System	✓	✓
	Other Industrial Site Uses	✓	✓
	Administrative Offices	✓	✓
Other	Transportation		✓
	Laboratory analyses		✓
	Treatment chemicals		✓

Limitations

My study focused on one facility in Arizona; consequently, the generalizability of my results may be limited. Though the setup of each thermal reactivation facility is generally the same (EPA 2000), differences in location can affect transportation patterns (Neff 2005), electricity sources, and electricity and natural gas usage (Druckman 2008, Ratti 2005). These variations must be accounted for in a general environmental impact assessment of GAC regeneration.

The accuracy of my results was also impacted by the availability of context-dependent conversion factors for the calculations. Many conversion factors (e.g. energy consumption of an office building) were taken from national averages and tailored with rough estimates and assumptions (e.g. the on-site WWTP consumes half the average electricity of a typical WWTP). The accuracy of these assumptions has the potential to significantly affect the results.

Natural gas consumption, one of the largest contributors to the environmental footprint, is calculated directly from process drawings, which are assumed to be highly representative of the facility's resource flows (Scheuermann, personal communication). Thus, I am confident that variability in other impact categories (electricity and water) will have a small impact on the total carbon dioxide emissions with respect to the natural gas impact.

Future Directions

One improvement to my study would be to expand my system boundaries to include more environmental impact categories. Environmental impacts omitted from my analysis include hazardous waste generation and land use change impacts of regeneration activities.

Another improvement would be to investigate assumptions used in my calculations. For example, I assumed the on-site WWTP required half the electricity usage of a standard WWTP. In reality, the electricity consumption of the WWTP could be substantially higher or lower, depending on the treatment required (information on on-site wastewater treatment was not publicly available). I could also install water consumption, electricity consumption, and natural gas consumption meters at facility to determine the actual facility, warehouse, and office resource consumption. Installing meters would also provide the opportunity to quantify the impact of activities that are not detailed in the permit application.

A comprehensive impact assessment of carbon regeneration requires analyzing a diversity of carbon regeneration facilities. An aggregate, precise impact assessment is impossible without analysis of multiple, differentially located thermal GAC regeneration facilities. Having a diverse portfolio of regeneration types (including thermal regeneration) will help remedial project managers to make more informed, actionable decisions about remediation design. Regeneration environmental impacts must also be compared to the impacts of used GAC disposal. A recalculation of the environmental impact will be necessary as regeneration practices change with improving technologies.

Broader Implications/ Conclusions

There are substantial environmental impacts associated with regenerating GAC. Prominent sources of carbon dioxide emissions were the electricity usage associated with the ID fan and the natural gas usage associated with burner operation. However, these environmental impacts are substantially less than those of generating virgin GAC. Overall, generating new GAC releases over eight times as much carbon dioxide equivalents as generating new GAC (Table 1). This conclusion should encourage remedial project managers to use regenerated GAC in their remediation projects.

By including more accurate and thorough impact calculations, decision-makers can more effectively apply green remediation principles to their projects. Comprehensive environmental footprint calculations also identify opportunities to modify processes to reduce environmental impacts and suggest which specific aspects of these processes have the highest potential for improvement. My study advances the ongoing process to improve EPA remediation projects through modifying remediation processes and presenting more environmentally sustainable remediation alternatives.

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ABBREVIATIONS AND ACRONYMS

acfm	actual cubic feet per minute
bhp	brake horsepower
Btu	British thermal unit
CEMS	continuous emissions monitoring system
EPA	environmental protection agency
GAC	granular activated carbon
HAP	hazardous air pollutant
ID	induced draft
kWh	kilowatt hour
NO_x	oxides of nitrogen
PM_{10}	particulate matter with a diameter of 10 microns or less
POTW	publicly owned treatment works
scfm	standard cubic feet per minute
SO_x	oxides of sulfur
SVOC	semi-volatile organic compound
VA	volt-ampere
VOC	volatile organic compound
WESP	wet electrostatic precipitator
WWTP	wastewater treatment plant