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Life Cycle Assessment in Foundry Sand Reclamation – Comparison of Secondary Reclamation Processes

Samuel Keith Ghormley
University of Nebraska-Lincoln, samuel.ghormley@unl.edu

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LIFE CYCLE ASSESSMENT IN FOUNDRY SAND RECLAMATION – COMPARISON OF SECONDARY RECLAMATION PROCESSES

by

Samuel Keith Ghormley

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LIFE CYCLE ASSESSMENT IN FOUNDRY SAND RECLAMATION – COMPARISON OF SECONDARY RECLAMATION PROCESSES

Samuel Keith Ghormley, M.S.

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Advisor: Bruce I. Dvorak

Foundries represent a significant part of the base of the world's economy and as a sector are one of the largest consumers of energy and producers of solid waste in the United States. Sand casting foundries use approximately 5-10% of their total energy on sand handling processes. By adding a secondary sand reclamation process, foundries can expect to become more energy efficient as well as reducing solid waste from the foundry. To measure the broader environmental impacts, life cycle assessment (LCA) can be used. The goal of the current research was to examine a medium-sized foundry in the United States that sources its sand from a long distance away by using LCA techniques. A comparison was made between a sand reclamation train model without any secondary sand reclamation, secondary reclamation using a mechanical process, a thermal process, and a microwave process. An economic, energy balance, and full LCA analysis was conducted for each of these processes. It was found that in addition to being economically beneficial, the life cycle environmental impacts were also less for processes that included secondary reclamation. In eight of ten measured categories adding a secondary reclamation process reduced the environmental impact of the foundry. When comparing mechanical and thermal mechanisms for secondary reclamation it was found that thermal processes were more energy intensive at the foundry, but due to their lower

sand requirements their overall life cycle impacts are less than the mechanical reclamation model. It was determined that varying the transportation distance in the model created the largest change in the associated outputs for all processes.

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CHAPTER 1. INTRODUCTION

Foundries represent a significant part of the base of the world's economy. Metal parts made in foundries are vital to the automotive industry, construction projects, as end products, and as parts for larger equipment. Without foundries, industry as we know it would not function. Because foundries play such an integral role, it is imperative that they operate as efficiently as possible. In the past, efficiency goals focused almost entirely on economic and production metrics, but a shift toward sustainability means foundries need to reassess the way they view efficient operations.

The foundry industry is one of the largest consumers of energy in the United States. In 2010, ferrous foundries accounted for 5.5% of all energy use in the manufacturing sector (US EIA 2013). Foundries also are responsible for 4% of all municipal solid waste produced in the United States (US EPA 2016). The goal of becoming more energy efficient and reducing foundry waste will decrease the environmental impact caused by foundries. One area where improvements can be made is the sand handling train of processes.

Sand casting foundries use sand to form molds for their end products. Their sand handling processes cover all processes from the time virgin sand arrives at the foundry to when it leaves as spent foundry sand (SFS). The specific individual processes vary by foundry and can include core and mold mixing, curing, shakeout, and any subsequent reclamation processes. The sand handling processes account for 5-10% of the total energy use in a steel foundry (Keramida 2004) but contribute nearly all of the solid waste generated. Reducing solid waste at the foundry can be accomplished by modifying the sand handling process train to include one or more sand reclamation processes. These processes can be viewed as a tradeoff where there is an additional process requiring energy offset by a reduction in virgin sand purchase and SFS disposal. When looking at the impacts from a broader environmental viewpoint, the simple tradeoff seen at the foundry may not be wholly accurate because of transportation as well as other upstream and downstream impacts. To measure the broader impacts, life cycle assessment (LCA) can be used.

The goal of the current research was to perform an LCA on a medium-sized foundry in the United States that sources its sand from a long distance away and analyze those results. The specific objectives set were: 1) develop a model of the foundry using appropriate system boundaries, 2) analyze the environmental impacts of the model and compare those impacts when the process is modified by a secondary sand reclamation system, and 3) perform a sensitivity analysis on the model to determine important trends if important variables are altered.

1.1. Need For Research

LCA has been used to analyze the impacts caused by different foundry processes. These LCAs almost universally consider the entire foundry process including all metal processing. While this type of LCA is good for comparing distinct foundries and foundry processes, the volume of data necessary for the LCA is extensive and in many cases difficult to obtain. There was no research found that focused specifically on developing an LCA model for the sand casting portion of the foundry. By focusing on a smaller unit of the larger process, this research shows that using a carefully selected system boundary in a larger system can still provide all the benefits of a full LCA while requiring a more manageable amount of data. The results of this research is an LCA model which shows specific environmental impact comparisons for using various sand reclamation technologies.

1.2. Organization of Report

This report contains five chapters: literature review, research methodology, modelling, results and discussion, and final conclusions, as well as a section for supporting appendices. The literature review consists of a selection of literature both in and out of the foundry field that pertain to the current research. Research methodology covers an overview of the research, how and where data were collected, how they were prepared, and which programs and tools were used in their final analysis. The results and discussion section discusses how the collected data were organized into a usable theoretical model that offers an accurate simulation of the actual system as well as the output from the model. The results and discussion section was also prepared as a potential paper for submission to appropriate journals. A section of final conclusions synthesizes the output from the model and looks for important trends while seeking to offer guidance on the appropriate way to apply this information. Appendices include primary documents, schematics, calculation spreadsheets, and other supporting material.

CHAPTER 2. LITERATURE REVIEW

Before initial work began, a review of current literature was conducted. The review began with the Life Cycle Assessment (LCA) process and reporting methodologies followed by a brief overview of the sand handling process train. Individual sand reclamation processes were then reviewed. Review continued by examining LCAs conducted in the foundry sector. Once these sources were studied, knowledge gaps between existing research and the research to be conducted were identified. To fill these gaps, additional literature searches were made in the areas of LCA process comparisons, LCA uncertainty and sensitivity analysis reporting, and landfill use and solid waste reporting in LCA.

2.1. Life Cycle Assessment

Life Cycle Assessment is the "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle" (ISO 2006a). LCA can be used as a tool to determine the overall environmental impact of a product, process, or service. LCA goes beyond traditional means of analysis because it includes not only the primary components of the focus of the study, but also all upstream and downstream impacts. This kind of study provides a more complete understanding of how a product or process impacts the environment as well as human health.

An LCA is performed in four major stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation of results. As illustrated in the Figure 2.1. all stages interact with one another.

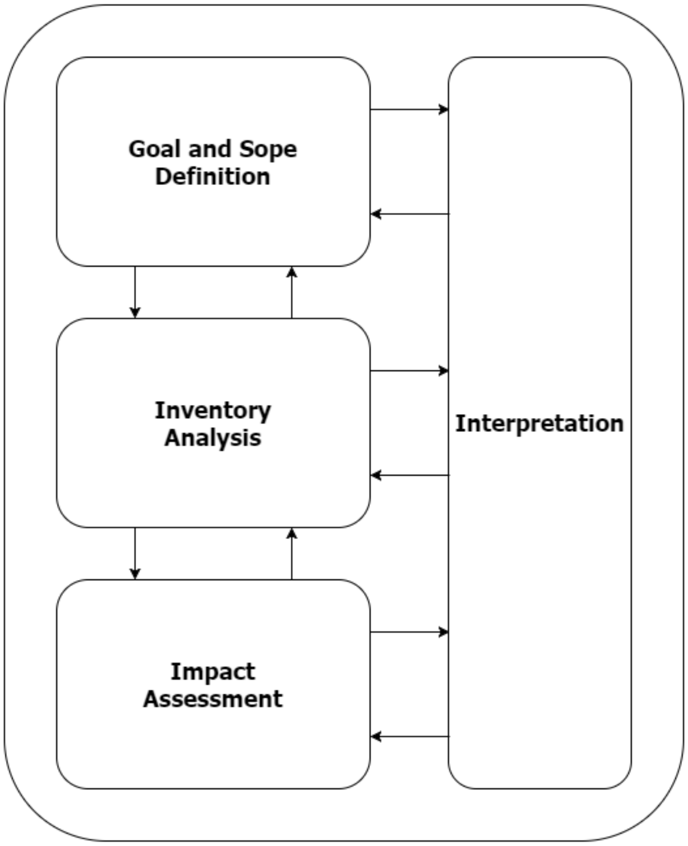


Figure 2.1. Life Cycle Assessment Framework

Interpretation of results should occur during the entire LCA process and is useful in refining all other stages. The process is iterative and only by having a well-defined end goal can useful results be attained.

Goal and scope definition is the basis for the rest of an LCA. The sheer volume of data and interconnecting processes that are involved in viewing a true life cycle of a product makes the analysis impossible without setting defined system boundaries. Defining a specific goal helps to determine the most appropriate processes to focus on and begin data collection. Defined boundaries will help to streamline the data collection process and to reach meaningful conclusions from the results of the assessment.

LCAs begin with raw material extraction and end with the final return to the environment either through chemical releases, or product disposal. This is known as “cradle to grave” assessment. Often due to unknown end of life considerations, an LCA can define other endpoints. One common endpoint is the completed product leaving the factory. This is known as “cradle to gate” analysis.

In addition to choosing system boundaries, it is also necessary to define a functional unit for the LCA. A functional unit is a quantified product or service that can be compared between similar processes. The functional unit aids in comparing environmental impacts between similar processes.

Life cycle inventory analysis (LCI) is the collection and preparation of the data necessary in order to meet the goals of the study. The data is collected for processes identified in the goal and scope step with particular care taken to remain within the defined boundaries. Whenever possible, this data is procured directly at the source, but when that is not possible representative data can be taken from industry standards or LCI databases such as Ecoinvent (Wernet et al. 2016). After data are collected, it is necessary to normalize all collected data to reference flows that correspond to one functional unit. Reference flows refer to the input necessary to produce one functional unit, or the output produced as the result of one functional unit. In addition to data collection and preparation, the quality and associated uncertainty related to each reference flow should be recorded.

Life cycle impact assessment (LCIA) is the step where all inputs and outputs to the system are analyzed to determine the overall environmental impact of the modeled system. The impacts are separated into impact categories. These can be chosen specifically to meet the stated goals of the LCA, or a specific methodology can be used for reporting a wide range of impacts. Impact categories generally report midpoint impacts which can then be used to describe endpoint impacts if desired. The initial impacts are simply the results of the LCI analysis. The midpoint impacts refer to how these can be initially characterized. The endpoint impacts refer to how these changes directly affect human or ecological health.

2.2. TRACI Methodology

The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) provides characterization factors to quantify potential impacts a process can have on specific impact categories. These factors are useful in describing LCIA results as well as for use in other industrial ecology, and sustainability metrics (US EPA 2012). TRACI describes seven discrete impact categories that can be used to compare the magnitude of environmental impacts in each category. The impact categories are:

- Ozone Depletion
- Climate Change
- Acidification
- Eutrophication
- Smog Formation
- Human Health Impacts
- Ecotoxicity

Each impact category is calculated from the total emissions in each applicable medium (air, water, and/or soil) and weighted based on the potential of each emission to cause the associated impact. The ozone depletion impact is measured using the ozone depletion potential of all air emissions as outlined by the EPA based on World Meteorological Organization standards (WMO 2003). Climate Change is based on the total CO_2 equivalent of air emissions outlined in the Intergovernmental Panel on Climate Change standards (IPCC 1996). Acidification is the measure of increasing concentration of H+ ions in the air and water media. The model is only concerned with total ion potential and does not include local environmental considerations that may affect the final impact (Wenzel et al. 1997, Wenzel & Hauschild 1997). Eutrophication considers air and water emissions of nitrogen and phosphorous. Smog formation is measured as the air emissions that act as precursors to ground level ozone. These chemicals have been specifically studied regionally for application in the TRACI model (Carter 1994, Carter 2007). The USEtox model (USEtox 2017) is used to track chemical emissions in air, water, and soil media and how they affect Human Health and Ecotoxicity. Human Health impacts due to respiratory effects are measured separately from the USETox model and instead are tracked by particulate matter, or precursors to particulate matter in air emissions. PM2.5 is used as the reference substance.

Aside from these main categories, resource depletion is also characterized as a separate category. Depending on the required level of reporting, several categories can also be broken down into sub-categories. For example, human health impacts can be separated into carcinogenic, non-carcinogenic, and respiratory in nature. When reporting results for TRACI impact categories, the magnitude of the impact is a unitless number defined as the entire environmental load produced by all production and consumption activities in the United States divided into the share of each individual.

There are other useful tools in describing LCIA results. Two of the more popular choices are Eco-indicator 99 (EI99) and ReCiPe. Each methodology covers a similar set of impact categories, but the reporting goal, as well as the regional applicability is different. EI99 is a methodology that was created in the Netherlands and uses an agreed upon set of characterization, normalization, and weighting values to produce endpoint impact indicators. ReCiPe reports 18 midpoint and 3 endpoint indicators. ReCiPe was developed to merge EI99 and another European methodology into an updated and more widely applicable methodology (Menoufi 2011). Neither of these choices were suitable for this research due to the regional applicability. The TRACI methodology is commonly used for LCAs conducted in the United States because it is regionally applicable and has been widely distributed by the US EPA. For these reasons, LCIA results are reported using the TRACI methodology in this research.

2.3. Sand Handling Process

Foundries that use sand casting techniques must plan for and design around the requirement of having enough sand to create the molds required by their steel throughput. Virgin sand is chosen and sourced from a location based on specific engineering qualities. Typical mold sand is silica based (>97% SiO_2) with a round grain shape and a density of approximately 93 lb/ft^3 (Brown 2000). Both the properties of the sand and the basic processes used through the life cycle of the sand will differ based on foundry products and technology available. The following description refers to a generalized resin bound mold and core system for a ferrous foundry based on research and experiences at Omaha Steel compiled in previous reports (Ghormley 2015, Nguyen 2016).

In this research sand handling will refer to the acquisition of virgin sand, all sand processes at the foundry, and the final disposition of the sand. To start the process, virgin sand is transported to the foundry and is usually stored in a large sand storage silo. From this silo it is mixed with reclaimed sand and various chemicals to form the molds and cores used in the steel casting process. The sand mixture in the molds is kept at a fixed ratio called the reclaim ratio. Reclaim ratios typically range from 70% reclaimed sand in basic systems to almost 95% reclaimed sand in foundries practicing advanced reclamation processes. The ratios can also vary based on the desired part quality or other specifications. After casting is complete, the molds will cool with the part inside them. The molds are then broken apart to retrieve the part. The remaining sand goes through a reclamation process consisting of one or more processes until it stored in a reclaimed sand silo.

There are multiple levels of sand reclamation and most foundries include one or more technology in their sand handling process. The goal of reclamation is to recondition used sand internally for the purpose of reusing it in new mold and core production. Primary reclamation refers to processes that occur right after the casting is removed from the mold. These include shakeout, magnetic separation, and other bulk sorting processes. The main goals of reclamation is to cool the sand, remove non-sand impurities, and sort the grains by size. As a whole, these processes have low energy requirements and produce reclaimed sand that can be used in reclaim ratios up to 70-80% based on data taken from the foundry being researched. Most foundries use at least some of these technologies in their sand handling processes.

Secondary reclamation processes occur after primary reclamation and are included to increase the sand reclamation ratio. These can be categorized broadly as either mechanical or thermal in nature. Mechanical reclamation systems include a variety of methods for sand treatment. Options include systems that vibrate, shock, use air scrubbing, or other means to return sand to a usable condition for reuse in mold and core making. Thermal reclamation is most often accomplished through use of a high temperature fluidized bed that is able to achieve nearly 100% reclamation rates. Microwave reclamation is an emerging technology that uses microwaves as the energy source to thermally reclaim the sand. Microwave reclamation has been shown to reach reclamation rates similar to thermal reclamation.

During the process of reclamation, there are sand losses due to spillage, the removal of fines by a baghouse collection system, and the loss of grains that do not meet the sorting criteria within the reclamation process. After all sand reclamation and losses have occurred, the remaining sand is transported to the reclaimed sand storage silo.

Sand in the reclaimed storage silo no longer matches the same desirable engineering qualities that the virgin sand possesses due to excess binder left over from the mold or due to heat fractures in the individual grains. This is why new molds and cores can not use only reclaimed sand. As can be seen in a simple mass balance, if new virgin sand is coming into the foundry, an equal amount of sand must leave the foundry. The sand from the reclaim silo is wasted at a certain rate to equalize the mass balance. The wasted sand, as well as any sand spillage and sand fines, is called spent foundry sand (SFS).

SFS can be defined as sand that is no longer suitable to be reused internally by a foundry in their mold and core making processes. When SFS leaves a foundry, the foundry must decide its final disposition. While there are reuse applications, it is estimated that less than 30 percent of the 10 million tons of SFS generated annually are reused in applications outside of foundries (US EPA 2016). These applications include flowable fill in construction projects, concrete and asphalt production, as well as other applications. While reuse is an attractive option for foundries, SFS reuse options are limited by geography and local needs of construction contractors. SFS that can not be reused is sent to landfills. Finding another method to reduce this waste is of great importance both for reduction in landfill usage, as well as for potential economic benefits foundries can expect to see.

2.4. Current Literature on Reclamation Technologies

There are many published studies related to making the foundry process cleaner and more economical, including the reclamation of sand. These include studies describing reclamation processes as Best Available Techniques (BAT) (Yilmaz et al. 2015), a process that agrees with lean principles (Torielli et al. 2011), or other similar descriptions. Research also shows that secondary sand reclamation, while a good economic option, is not necessarily a good environmental option (Yigit 2013). This research is useful but does not consider transport distances for virgin sand or for spent sand disposal. There is another area of research represented in the literature that focuses on new and novel methods of sand reclamation. These include mechanical disc grinding (Czapla and Danko 2013), advanced oxidation (Danko 2011), and microwave sand reclamation (Mathis and Plunger 2016).

While not specifically sand reclamation, beneficial foundry sand reuse shares the same end goal of SFS going to the landfill as sand reclamation. The reuse of SFS has been promoted for end uses including construction material (FHWA 2004) and soil amendments (US EPA 2014). The reuse of SFS has also been shown to be much more energy efficient as well as having less environmental impact in most categories (Carpenter and Gardner 2009).

2.5. Current Research in Foundry Sand LCA

Most foundry LCAs focus on the entire foundry, covering metal preparation, melting, pouring, and finishing as well as all mold making and sand reclamation processes as well. LCA research into the entire foundry system can give valuable insights into the environmental impacts caused not only by the overall process, but also how each sub-process contributes to the whole. Most research select system boundaries that include all foundry processes from cradle to grave, but only consider the metal production from cradle to gate excluding final disposition of metal products (Dalquist and Gutowski 2004; Yigit 2013; Masike and Chimbadzwa 2013).

Dalquist and Gutowski (2004) conducted an LCA comparison of the overall foundry environmental impacts between a selection of foundries in the U.S. and U.K.

Yigit (2013) specifically researched the environmental impact of secondary sand reclamation. The research concluded there was a net detriment in applying these techniques but the reduction of virgin sand excavation and transport was not part of the model. A model for economic and environmental cost was developed to model any process modifications that may occur (Saha 1996), however the LCA methodology was based around process costing, rather than environmental inventories available in current assessments.

2.6. LCAs Comparing Process Options

LCA is commonly used to compare similar systems and specific rules for conducting these studies exist (ISO 2006b). Applying LCA to a single situation with multiple process modification options is not specifically discussed in the ISO standard, but this kind of comparison meets the criteria laid out so using an LCA in this way is justified.

There are few examples in the available literature that focus specifically on process changes in the conducted LCAs. Because of this, a review of literature on this topic based in other industries was conducted. Doing this will allow insight into the methodology the researchers used and might provide useful parallels when analyzing the results of this LCA. LCAs on waste water treatment were conducted in recent research (Baresel et al. 2015; Blanco et al. 2016). Baresel et al. modeled wastewater reuse and the equipment necessary for this treatment. This research found that in some cases economy of scale can play an important role when looking at these technologies and reuse potential. This research has some parallels when looking at foundry sand recycle both internally and once it leaves the foundry. The research done by Blanco et al. (2016) investigated a process change in a wastewater treatment plant by adding an anaerobic digester for biogas recovery used in onsite heating. This process change results in two scenarios (with and without the digester) which are compared in the LCIA framework. In many ways, this research is analogous to the current research. Instead of the anaerobic digester, this research will model a modification in secondary sand reclamation.

2.7. Sensitivity and Uncertainty Reporting

Sensitivity and uncertainty analyses are grouped together in the ISO standard (2006b) as additional techniques that can improve LCIA interpretation. Sensitivity analysis can be performed in many ways that can be applied based on the end goal of the specific LCA (Bjorklund 2002). Scenario sensitivity analysis is described by Bjorklund as descriptions of possible future situations based on specific assumptions about how a system may change. This approach seemed to fit the current research.

Presenting results of sensitivity and uncertainty analyses can be difficult. Because there are several different levels of output data in a comparative LCIA sensitivity analysis including LCIA category, each sub process’s contribution, as well as total impacts for each process modification using multiple input sensitivities, representing all these data simultaneously presents a challenge. Using stacked and grouped bar column graphs as seen in Lardon et al. (2009) was found to be an effective method of displaying this information.

There are many ways to analyze and treat uncertainty in LCAs. In order to effectively report uncertainty both input uncertainty as well as software to analyze the data is required (Heijungs and Huijbregts 2004). To meet the requirement for input data, the Ecoinvent database can be used (Wernet et al. 2016). The Ecoinvent database tracked uncertainty of all entries throughout their development leaving a wide range of input data with associated uncertainty. Simapro, an LCA software package, is built with a robust uncertainty analysis set of tools that uses the Monte Carlo method to deliver good estimates of uncertainty in the model. Simapro also gives graphical methods of displaying this information as was shown in Guo and Murphy (2012).

2.8. Landfill Use and Solid Waste Reporting in LCA

One of the original purposes for the current research was the investigation of solid waste generated by foundry sand disposal. TRACI currently lacks a way to quantify a midpoint value for this category (US EPA 2012) so a review of literature relating to the characterization of solid waste in landfills was performed to help find the best way to report this factor. LCA studies of solid waste disposal generally examined toxicity in landfill emissions (Obersteiner et al. 2007; Hauschild et al. 2008) or were comparisons of disposal methods (Mendes et al. 2004; Ojoawo and Gbadamosi 2013).

Reporting toxicity in landfills has been examined in detail. The main discussion comes in how to collect and report accurate landfill data. Collecting data from landfills can be difficult and will depend on several factors including regional conditions, consumer habits, and many other variables. Efforts to standardize both the collection and reporting of this data is important in landfill research (Obersteiner et al. 2007). Another difficulty arises when looking at long term emissions from landfills. Depending on the time horizon chosen, the toxic releases from a landfill could potentially dominate all other categories which make results less descriptive of what an LCA is actually reporting. Hauschild et al. (2008) proposes the introduction of a stored impact which would account for the longer time horizon without remaining in the same impact category as the toxicity that would be observable in a foreseeable time.

Unlike most landfill studies, the current research focuses on a homogeneous waste that is largely inert and not subject to toxic releases. The industry's claim that SFS is "cleaner than dirt" has been tested using a microbial bioassay and the results have supported that claim (Bastian and Alleman 1998).

LCA studies comparing landfilling with other solid waste disposal methods are common. The studies reach different conclusions based on the processes evaluated, the composition of the waste, and the region examined. A study comparing incineration options with traditional landfilling in Sao Paolo determined that incineration options offered a better choice than the current landfilling option (Mendes et al. 2004). A similar study done in Nigeria found that landfilling represents a better option (Ojoawo and Gbadamosi 2013). These two studies show that regional differences as well as how the system is modeled greatly affect the LCA results.

Other literature discusses the effects of solid waste entering a landfill and the secondary impacts that will have when a landfill is forced to close prematurely. One researcher says that in addition to the land use required for a new disposal site, the site is often further from a municipality which can result in additional collection travel pressures (Kollikkathara et al. 2009).

The question of how to report land use changes due to landfilling was not found in the literature review conducted. The TRACI methodology for reporting LCA impacts is widely used and according to the TRACI User's Manual version 2.1., the TRACI framework does include land use impacts under the category of resource depletion. However, the current research into how to report land use is ongoing (US EPA 2012). None of the literature reviewed directly examined land use change due to landfill volumes.

CHAPTER 3. METHODS

This chapter outlines the stages of research from formation of the initial hypothesis, the sources and methods of data gathering, and the model development that led to the final form of the research. The first section is a background of the foundry and relevant information about foundry sand and reclamation technologies. Preliminary framework discusses setting a goal and planning the course of the research, the development of the model, and data collection. The cost and energy balance section considers the costs and impacts at the foundry level for each of the technologies being. The last section discusses the LCA development including the software and impact database used for calculating overall impacts.

3.1. Background

Initial work for this research began in the Summer of 2015. Omaha Steel Castings Company (OSCC) became involved with the University of Nebraska Lincoln's (UNL) Partners in Pollution Prevention (P3) Program. P3 interns assigned to OSCC examined the feasibility of developing a SFS reuse program.

Research into SFS reuse centered on statements made by the EPA (US EPA 2014) and guidelines given by the Federal Highway Administration (FHWA 2004). Citing these guidelines, the Nebraska Department of Roads (NDOR) was contacted about reuse opportunities in their road construction projects. NDOR agreed to run tests on used sand samples to determine their suitability in roadway projects (Appendices A and B), but ultimately found the samples unsuitable for their needs.

Further conversations with OSCC engineers revealed that the foundry was considering modifying their sand reclamation processes by adding a thermal reclamation system. Questions of how this equipment would affect current sand reclamation processes and what the economic and energy balance implications would be were discussed. An economic and energy balance would be investigated by a new P3 intern during the summer of 2016, but there were still questions as to how overall environmental impacts would change during the potential process modification. It was determined that conducting an LCA would provide the clearest results to that question. To that end, a study of the basic framework, research methods, and requirements for an LCA was undertaken. This time also served as a planning phase to determine what data would be needed, how to collect it, and initial system modeling.

In the summer of 2016, OSCC hired P3 intern Than Nguyen to assist in the modification of their sand handling system to include a secondary reclamation unit. Nguyen submitted a report to OSCC outlining his recommendation to modify their sand reclamation system by adding a mechanical reclamation process (Nguyen 2016). This decision was based on economic, environmental, and other business considerations. During this time period, Nguyen also was able to gather important data for this current research.

In refining the goal of the thesis, it was decided to compare multiple secondary reclamation systems with the current sand handling process at OSCC. It was determined that this would involve using LCA software to analyze models based on the current OSCC sand handling processes both as it is now and with potential process modifications. The results could then be compared to see the relative environmental impact of each technology. The comparison of the reduction of solid waste sent to the landfill to these impacts was also determined to be an important part of the thesis research.

3.1.1. Company Background and Process Description

OSCC is recognized as a leading producer of high-quality steel and stainless steel castings for a vast array of end users. Their mission is to provide flexible, cost effective solutions for their customers on time, every time while maintaining the highest standards of quality.

OSCC was founded in 1906 in Omaha, Nebraska. In the company's history they have produced structures for bridgework, truck bodies and trailers, locomotive and other railroad parts, and various proprietary castings for many companies including Caterpillar Tractor Co. Also, from 1941 to 1945 OSCC produced artillery shells and landing craft for the war effort. In 2012, OSCC moved their production facility to Wahoo, Nebraska. Their new facility is 150,000 square feet. They employ 88 factory workers and 30 office workers between two shifts per day. OSCC pours a wide variety of steels including corrosion resistant high alloy steels, heat resistant high alloys, Nickel-base alloys, and tool steels. On-site processes include mold pouring, weld stations, arc air stations, burning stations, finishing stations, heat treatment, tempering, quenching, and testing facilities. A simplified process flow diagram for OSCC's sand casting line is illustrated in Figure 3.1. This figure focuses on the sand handling processes and does not elaborate on the number and type of metal finishing processes. A more detailed description of these processes can be found in Section 3.1.2.

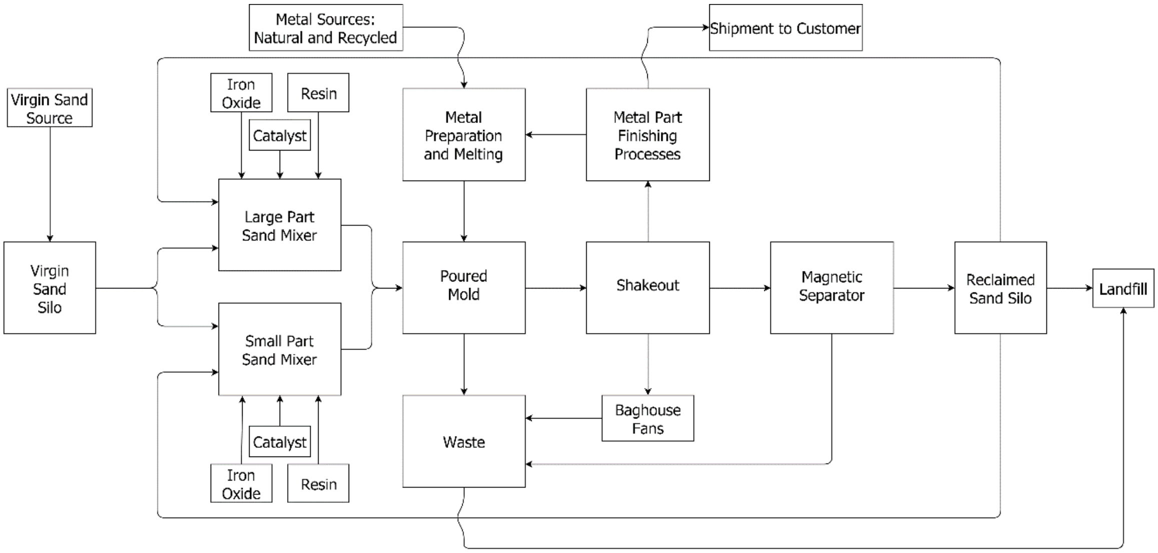


Figure 3.1. Omaha Steel Castings Company Process Flow Diagram

OSCC currently sources their virgin sand from the Unimin Corporation located in Oregon, IL. Transportation is done using semi-trucks carrying between 10 and 15 tons of virgin sand. The one-way trip is 425 miles. This sand vendor was chosen because their sand had a specific set of superior mechanical properties ideal for mold and core work at OSCC.

The foundry uses a Phenolic Urethane No Bake System (PUNB) for its main mold and core operations. The mold mixture consists of virgin sand, reclaimed sand, a two-part resin, a catalyst, and iron oxide which is mixed in a hopper before being poured into the pattern for cooling. The resin and catalyst are added to set the sand in place and give the mold tensile strength. The resin system in use is Pep Set Q I 4180 and Pep Set Q II 6180 from ASK Chemical (Dublin, OH). Resin is added in a proportion of 60% first part (4180) and 40% second part (6180). The catalyst is Pep Set Catalyst, also from ASK

Chemical. Iron Oxide, which is added to reduce occurrence of veining, metal penetration, and other defects (Showman and Scheller 2015), is purchased from Canfield & Joseph (St. Louis, MO).

3.1.2. Reclaimed Sand

After the mold has been poured and cooled it undergoes a shakeout process to separate the steel part from the rest of the sand. After shakeout, the steel part is taken for whatever finishing processes it requires. The rest of the sand from the mold is broken down and begins a process of reclamation.

Reclaimed sand is sand that has been used in at least one mold or core and is then reused in a new mold. In theory, this reclamation could be done indefinitely, but for practical reasons, not all sand can be reclaimed. Remaining organics from the binding process, other fines, such as the iron oxide, and sand particle fractures in the reclaimed sand lead to less than optimal conditions for curing the new mold and core. To compensate for this, new virgin sand can be added while an equal portion of reclaimed sand is wasted as SFS. This SFS can be beneficially reused outside the foundry as construction fill, an artificial soil base, or other applications (US EPA 2014). However, beneficial reuse is highly dependent on the general need in the local area. If there is not a need, the SFS is most commonly landfilled. OSCC currently sends all their SFS to a landfill.

Decreasing SFS involves increasing the amount of reclaimed sand that can be reused in the mold and core operations. This can be done by performing additional reclamation work after the initial shakeout. The proportion of reclaimed sand to virgin sand in the mold and core operation, also referred to as reclaim ratio, is of primary importance to this research. The goal of the foundry is to use as much reclaimed sand as possible in order to keep the cost of purchasing virgin sand low. The limiting factors to reclaim ratio are surface finish and mold strength. With too much reclaimed sand, the molds will not be strong enough and will fail during the pouring process. The reclaim ratio used at a foundry is based largely on operational conditions and experience.

Reclaim ratio in the mold and core operations can be increased by introducing processes that remove additional binder from the used sand. Reclaim ratios without using any reclamation processes will vary by the type of foundry and process but are generally close to 70:30 reclaim to virgin sand. Additional processes can raise that ratio to almost 100%, but 95% seems to be a reasonable upper limit when considering other system losses.

OSCC currently uses an 80% reclaim ratio using their primary reclamation processes. Primary reclamation can mean a number of different reclamation technologies, but for OSCC the two technologies that make up their primary reclamation are primary attrition and magnetic separation. Primary attrition is the separation and classification of sand beginning with shakeout and continuing to finer sizes. Slag and other unusable sand is separated during this process as well as sand fines which are collected by a baghouse fan system. As its name implies, Magnetic separation uses a magnet to collect any metal that passes through the primary attrition process, including most of the added iron oxide. The resulting sand is well sorted, but generally has a small amount of binder or other fines remaining on its grain surface. The sand is stored in a reclaimed sand silo and is reused or wasted as necessary.

3.1.3. Secondary Reclamation - Proposed Technology

To increase reclaim ratio, OSCC is interested in adding a secondary sand reclamation technology in their sand handling process train. Secondary reclamation's primary goal is to take sand that is sorted in primary reclamation and use a technique to "clean" it, restoring its properties to more closely resemble virgin sand. The secondary reclamation technologies vary widely but generally fall into either a mechanical or thermal category. For this research, there are three different technologies that will be studied.

To understand the results from these secondary technologies, one of the best indicators available to foundries is a test measuring loss on ignition (LOI). The LOI of a sand sample is a percentage difference in the weight of a sample before and after a prolonged igniting phase allows for the removal of all volatile substances. The LOI test is done onsite at OSCC to ensure the quality of their molds. LOI of a virgin sand sample generally ranges from 0.3-1.5%, depending on the source of the sand and how it was conditioned at the quarry. Reclaimed sand should have LOIs no greater than 3% (Brown 2000). The current LOI of reclaimed sand at OSCC is approximately 1.34%. Investing in additional reclamation technology that is able to lower the LOI of used sand means that it can be reused more times and will result in a mold with better strength when mixed with virgin sand.

3.1.3.1. Mechanical Reclamation

Mechanical reclamation is broadly used to describe a secondary reclamation process that cleans remaining binder from sand by friction. The friction can come from an outside force, such as a brush or grinding wheel, or more often from the sand itself as the grains come into contact at high speed and/or pressure. Mechanical reclamation machines vary widely in size and generally achieve LOIs of 0.5-1.5% (Danko et al. 2003).

The mechanical reclamation technology being considered at the OSCC foundry is a Two Cell Unit from Simpson Technologies capable of processing five tons of sand per hour. See Appendix C for a simplified process diagram. The unit is based on pneumatic sand reclamation technology that has been in use for many years (Smith 1982). The Simpson mechanical reclamation system utilizes two identical cells with vertical air blowers used to accelerate the sand onto cone shaped targets to remove binder before the sand is sorted.

3.1.3.2. Thermal Reclamation

Thermal reclamation uses high temperature to combust any remaining binder on the sand. Temperatures in the machine are kept at approximately 800 degrees Celsius to ensure complete combustion. The process leaves sand in a “better than new” condition. Thermal reclamation systems achieve LOIs of 0.1-0.3% (Danko et al. 2003).

Thermal reclamation systems have been in use in foundries for many years, but they did not see widespread use until improvements were made making them more economical than either mechanical reclamation or simply bypassing secondary reclamation. While the basic function of thermal reclamation is simple to understand, there are many obstacles to attaining a well-functioning system. Over the years many solutions have been proposed based on the same basic fluidized bed technology but most systems use a rotary drum to create a fluidized bed during combustion with some sort of cooling and sorting process after combustion is complete (Bailey 1993). The specific thermal reclamation system being considered is from EnviroAir, Inc. Appendix D has a process diagram.

In practice, modern thermal reclamation systems can achieve sand that is as clean as virgin sand which supports a 100% reuse rate. This, of course, is not operationally possible. Even under ideal reuse conditions, virgin sand must still be purchased to replace sand that is lost through particle fracturing, slag and other impurities, or simply as spillage during transport throughout the foundry. This waste sand either ends up in the baghouse system as fines, or in the dumpster as wasted sand. The ratio of this wasted sand depends on operating conditions, but based on gathered data from OSCC will be estimated as 5% of the total sand used in a mold.

3.1.3.3. Microwave Reclamation

Microwave reclamation uses microwaves to heat the remaining binder on the used sand causing it to volatilize. In this way it is identical to the thermal reclamation removal mechanism, only the heat source changes from external combustion to the binder itself releasing heat. The initial research and testing performed on microwave reclamation was done by M-Wave Consulting for Midwest Metal Products, Inc. (Mathis and Plunger 2016). The technology is based on the fact that remaining resin on used foundry sand will interact with microwaves at a lower temperature than sand. The goal of the process is to preheat the used sand into this range and then feed the used sand through a microwave processing section where the heat of the reaction will be sufficient for continuous reclamation. Monitoring the temperature of the sand and turning the microwave source on and off when necessary allows for a non-continuous energy output as opposed to both mechanical reclamation and thermal reclamation systems. Similar to thermal reclamation, the resulting sand is very low in impurities and can be used as if it was virgin sand. Appendix E has a sample of what a microwave reclamation system could look like.

While microwave reclamation was not considered for the initial foundry project, it will still be studied and compared in this study. As microwave reclamation develops into a tested technology with wider acceptance in the foundry industry, more specific, industry-wide data will become available for future studies. While no technical specifications are available for any specific size of unit, Dr. Milt Mathis, the principle researcher of the pilot study, was contacted and has agreed to supply information and data about their method for this study (M-Wave 2017).

3.2. Preliminary Framework

To properly conduct an LCA, a researcher must clearly state the goal of the research. A clear idea of the end result of the research saves time when laying the foundation for the rest of the work. After a goal is defined, relevant data must be collected. Collected data can then be used in the development of system boundaries and the working LCA model. The goal of this research is to conduct an LCA comparison of three potential process modifications at OSCC. The following section details the types of data collected, model development, model assumptions, and final system boundaries.

3.2.1. Data Sources

Data used throughout the entire research process consisted of three kinds of data: directly sampled data, industry standards, and process inventories from the Ecoinvent database, version 3.3 (Wernet et al. 2016). Whenever possible, directly sampled data were used. The source of these data were OSCC personnel, billing information, technical schematics, daily mass flow values, and other directly or indirectly gathered data based on the working foundry (Nguyen 2016).

Industry standards were used in cases where direct measurements were not possible, or data were too variable for direct measurement to be a feasible option. These types of data were used in calculating average weight and gas mileage in a fleet of semi trucks, and efficiency in sand processing. Industry standards also include rigorously sampled data published by trusted organizations such as the US EPA and similar entities. The relative accuracy of industry standards varies and is reflected in the data quality.

The Ecoinvent database version 3.3 (Ecoinvent) is the world's leading LCI database and is used as the basis for many LCA studies. It is built to allow for maximum consistency and transparency (Wernet et al. 2016). Data for Ecoinvent are collected by research institutes and industries, reviewed by expert staff, and loaded into the database with full transparency about sources and accuracy of the data. Sampling is a worldwide effort and when it is possible, specific regional datasets are included in the database. Ecoinvent was used to fill in data where no direct sampling was possible, or when the process was too complicated to sufficiently model using other data. This was done mainly for background processes such as the sand excavation process, electricity grid use, and to account for the larger transportation inputs and outputs.

All data were collected and organized into a Microsoft Excel (2016) spreadsheet. Whenever possible, raw data was preserved “as collected” with appropriate conversions made as separate calculations. The full list of raw data used in the model can be found in Appendix F.

3.2.2. Model Development

Initial modeling of sand flows occurred in 2015 when investigating the possibility of reusing SFS in other applications. In 2016, a more detailed model of the entire sand handling process was prepared. A simplified version of this model was shown in Figure 3.1. This model provided a good picture of the sand’s role within the foundry, the reclamation flow, and the inputs and flows that affect the sand handling process. When the choice to approach this problem from an LCA framework was made, the model was simplified by removing the steel production and finishing processes. The addition of energy and transportation costs were also incorporated into the model. The choice to model the split mixing system as a single flow mixer was also made. The resulting model is shown in Figure 3.2.

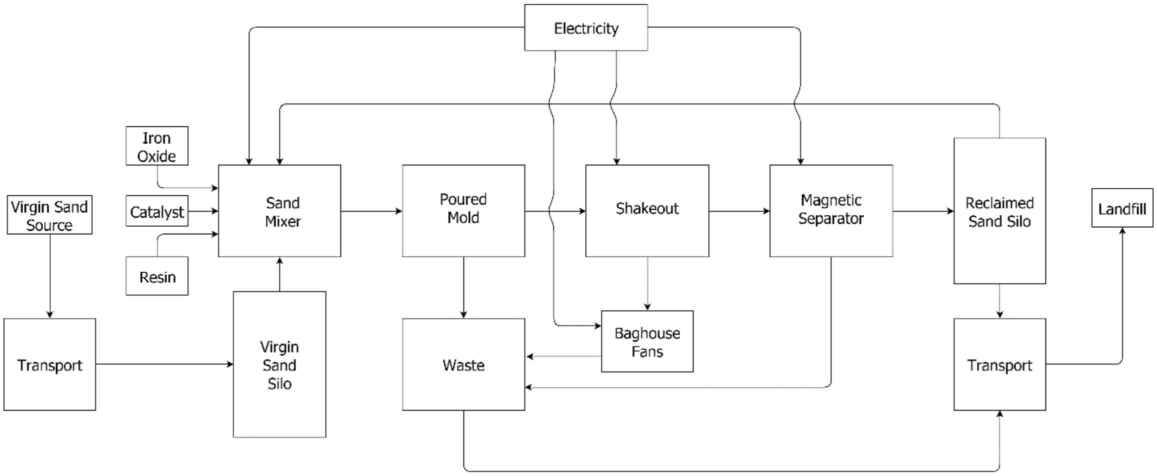


Figure 3.2. OSCC Current Process - Intermediate LCA Model Simplification

The final step of the system model is creating a specific model that is usable by LCA software. The final model is an aggregate of all processes and therefore less representational of the actual process flow. This model represents the sum total of inputs and outputs for the selected system boundary in a form that is usable by LCA software. The final version of the model can be seen in Figure 3.3.

3.2.3. Model Assumptions

The first assumption used for this research has to do with how the foundry processes will change upon addition of new technology. The assumption made was that any change in the sand handling train will not affect any other flows outside the system boundary. These include chemical additions during mold making, electric inputs for mixing, shakeout, and reclamation, as well as any unforeseen results elsewhere in the foundry.

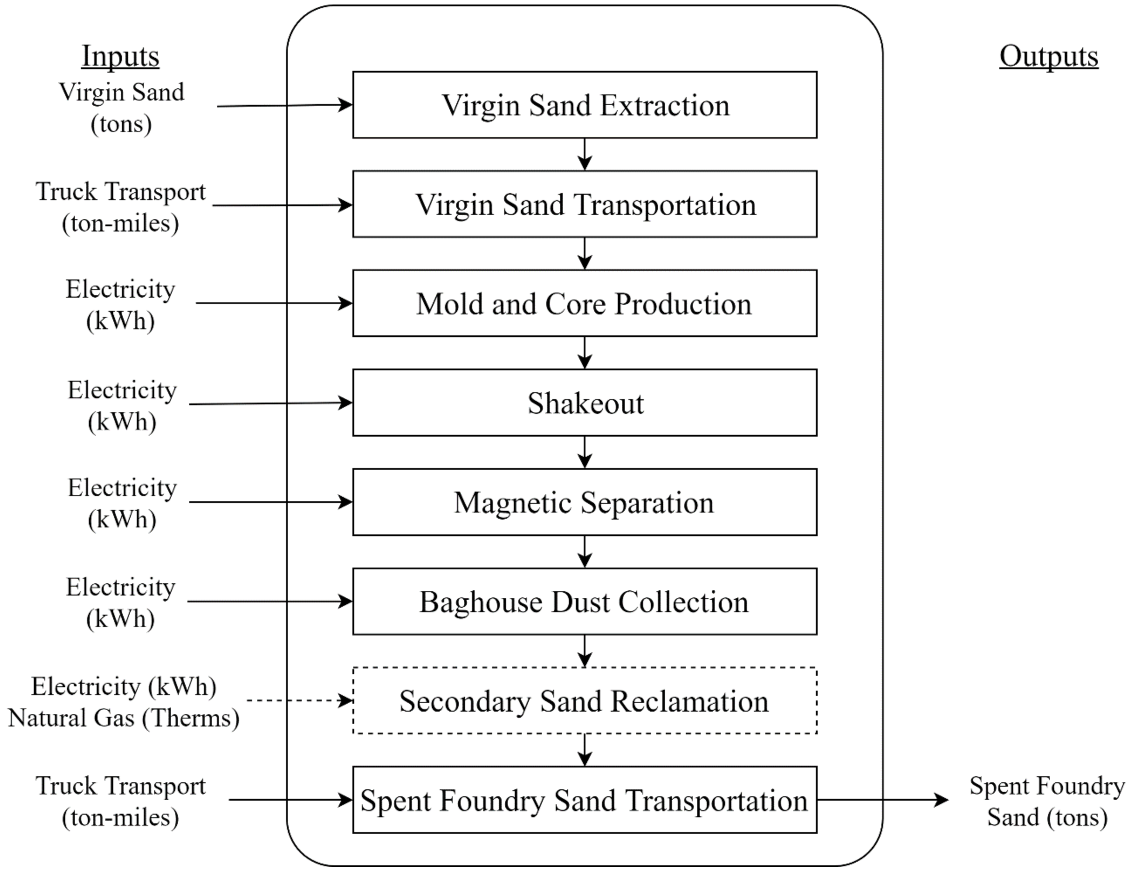


Figure 3.3. OSCC Current Process - Final LCA Model

Capital costs of equipment were not considered on the LCA scale. This is an assumption used in many LCA studies, including the reviewed literature in the foundry industry (Dalquist and Gutowski 2004; Yigit 2013). One time environmental impacts caused by the fabrication, delivery, and final disposal of the secondary reclamation equipment represent a smaller impact than the rest of the ongoing sand handling processes over the course of the equipment use phase.

While much research has been done discussing the long term effects of pollution caused by long term releases from landfills (Obersteiner et al. 2007; Hauschild et al. 2008) the assumption to ignore any affects caused by SFS once it entered the landfill was made. This assumption was made due to the largely inert nature of SFS. Within the industry it is promoted as being “cleaner than dirt”. Research done by both the EPA (2014), and Bastian and Alleman (1998) support this assumption as well.

3.2.4. System Boundaries

System boundaries were initially chosen to account for the entire foundry process. This model included cradle to grave analysis for the foundry sand, and cradle to gate analysis for steel production. These system boundaries are commonly used in foundry LCAs (Dalquist and Gutowski 2004, Yigit 2013) but were soon found to be inconsistent with the stated goals of the research. As discussed in the model assumptions, there would be no change in the steel production activities of the foundry. This means that any comparison between sand reclamation technologies would include the same, unchanging environmental impacts caused by the acquisition, melting, pouring, and processing of steel. By redrawing system boundaries to exclude the steel specific processes, the comparison between sand reclamation processes are more pronounced. This makes analysis and conclusions more targeted and useful.

In a similar way, it was assumed that resin, catalyst, and iron oxide inputs during the molding process would not change based on the secondary reclamation technology chosen. As with steel, these inputs would be duplicated in any comparison and could therefore be excluded from the system boundaries. Future research may benefit from examining the relationship between environmental impacts caused by these additives compared to the system model being researched.

The final description of system boundaries for the LCA can be described as a cradle to grave analysis of the sand used by a foundry. This includes initial extraction of the sand, transportation of the sand to the foundry, mixing, molding, shakeout, reclamation, and final transportation to the landfill.

3.3. Cost and Energy Balance

The cost and energy analysis performed for OSCC (Nguyen 2016) gave them an economic decision making tool when exploring secondary sand reclamation technologies, but lacked a clearer picture as to the larger environmental picture. Energy use and associated Greenhouse Gas (GHG) emissions were calculated, but this is only one aspect of total environmental impact. The cost of landfill disposal was considered in the model, but not what the volume of sand in the local landfill means in a long term environmental view. Similarly, the source and total energy was calculated and given as a bottom line value. The impact of the depletion of these resources as well as the pollutants caused during their life cycles is not shown in a simple cost and energy analysis.

The cost and energy balance performed was based largely on Nguyen's work with OSCC in 2016 (Nguyen 2016). Not included in Nguyen's original work was the electricity cost associated with the rest of the sand handling process including mixing, shakeout, magnetic separation, and baghouse dust fans. The original assumption was that since these values did not change, they could be ignored for clarity of presentation. For purposes of this research, their inclusion enables a better description of the breakdown of the total costs of processing foundry sand.

All calculations for the economic analysis were straight forward and can be seen in Appendix G. Finding annual economic cost was based on a sum total of virgin sand cost including both the sand itself and its transportation, all energy inputs based on the regional cost of electricity and/or natural gas, transportation of SFS to the landfill including both driver's wages and diesel fuel usage based on regional price average, landfill surcharges, and additional waste management services. These values were collected directly from the foundry's bills and invoices. Modifications to these values were made based on theoretical changes to the foundry's reclaim ratio. Price of new equipment as well as expected operating and maintenance costs were collected directly from company quotes. One key point to note is that total diesel usage includes calculated fuel used in all transportation whereas the fuel purchased includes only the fuel purchased for disposal of the SFS. Other fuel is included as a part of transportation fees.

The energy balance was performed using the same collected data and converting all energy inputs into MMBTU/year. Calculations can be found in Appendix G-4. The energy inputs that were included in the calculation were all diesel fuel used in virgin sand transport and SFS disposal, total electricity usage, and total natural gas usage. To find diesel usage, first, total mileage was calculated assuming one-way trips for virgin sand transport, two-way trips for SFS disposal, and two-way trips for the Waste Connections disposal service. This total mileage was converted to diesel consumption using industry standards for fuel economy for semi and dump trucks (University of Michigan 2016). Electricity totals were collected in the same manner as the economic balance. Natural gas usage was found using the quoted energy usage per ton and multiplying by the expected throughput of the thermal reclamation system. Each of these energy categories (gallons of diesel, kWh, and therms) were converted to MMBTUs using the conversion calculator found on the U.S. Energy Information Administration website (US EIA 2017).

Knowing the energy balance, it was decided to perform a quick estimate of GHG emission equivalent. Calculating GHG emissions is usually done using industry standards based on fossil fuels used, or other GHG producing activities. These activities often result in a variety of GHGs so the common way to report this value is using an equivalent mass of carbon dioxide, usually metric tons (MTCO$_2$e). In this case, values from the energy balance (gallons of diesel, kWh, and therms) could be used again with a different multiplier to find the GHG equivalent of that energy usage. The multipliers used were found in the EPA document found in Appendix H.

3.4. Life Cycle Assessment

To more fully explore the environmental impacts of implementing secondary sand reclamation technologies, a full LCA was conducted using Simapro (v8.2.3.0 PhD). Simapro is a widely used LCA software tool. When conducting an LCA the primary obstacles are data handling and presentation of results. Data handling includes collecting large sets of data, normalizing all the data, and multiplying by the impact inventory. The results from LCA are often presented as comparative graphs. Since LCIA results are often concerned with several different categories, the presentation of data can be difficult. Dedicated LCA software can aid in both data handling and presentation of results.

Simapro accomplishes both of these tasks effectively. Simapro includes a number of LCI databases that can be applied based on the needs of each specific LCA. The Ecoinvent database is one of the included databases and Simapro automatically keeps it up to date for the most accurate LCA results. Raw data can be entered into user created models and life cycle impacts are automatically calculated using the specified parameters and LCI database. Results can be analyzed in a variety of ways, including impact trees, uncertainty analysis, and impact specific reports.

Unlike the cost and energy models, the LCA model gives a larger environmental picture taking into account the effect upstream and downstream processing will have on the process. A detailed inventory of what chemical impacts can be found, their concentrations, and where they can be found are calculated from all given inputs. From these values, midpoint results are calculated and categorized based on given methodologies. These impact categories give a good idea of a more complete impact of the sand handling process and how introducing new technology will affect human health and the environment.

To keep the LCA as simple as possible while still achieving the desired goal, the system boundaries were carefully selected as detailed above. The final system model (Figure 3.3.) is the aggregate of all inputs necessary to produce molding sand. Before the required data are fed into Simapro, each input must be normalized to the functional unit. The normalizations were calculated within the Microsoft Excel spreadsheet. To compare the different reclamation technologies, multiple aggregate processes were defined in Simapro.

3.4.1. Life Cycle Inventory

The LCI phase was an ongoing process since the beginning of the initial research in 2015. As data were collected, they were entered in a raw form into a Microsoft Excel file. The method of retrieval and quality of data varied for each data point. This section discusses the most pertinent data to the LCA and how they were acquired.

In the cases where an Ecoinvent dataset is used, the title of that dataset is included in quotes. These titles have long and complex names with several abbreviations separated by a vertical slash. In all cases, the first section is the individual title of the dataset. In this section there is a bracketed abbreviation that indicates the regional source of the aggregate data. For purposes of this paper, the {RoW} set was chosen unless stated otherwise. This stands for “Rest of World” meaning the data is averaged over a larger region than some of the region specific codes. The second section is the family of processes the particular process belongs in. This section is generally self-explanatory and is used mostly as an organizing tool. The last section is the same for each dataset and explains that the default allocation was used and applied on a unit level, rather than a system level.

Raw sand extraction is a value that was taken as an average daily use of virgin sand by OSCC. Since billing information was available, finding a daily average was not difficult. However, the impacts caused by extraction are quite complex including everything from operating costs for the large equipment, to site construction and land transformation costs. Due to this complexity and inability to conduct onsite data collection, the Ecoinvent dataset “Sand {RoW}| gravel and quarry operation | Alloc Def, U” was used to identify impacts for this value.

The value for transportation for virgin sand was also modeled in the Ecoinvent database, but data collection was necessary as well. For input into the Simapro model, the units necessary were ton-miles. This unit of measure is a combination of both loaded weight of the transport vehicle and the total mileage travelled. The total mileage was found using the most direct route on google maps measuring from the Unimin Corporation near Oregon, IL to OSCC in Wahoo, NE. This value is 424 miles, but it can be expected to be at least 5 to 10 miles higher due to any detours, refueling stops, or other unforeseen occurrences during transit. It was determined that only a one-way trip would be modeled because the empty semi-trailer would not return, rather it would begin another haul outside of the system boundaries of this LCA.

To determine the weight of the loaded truck, both the weight of the virgin sand cargo, and the empty semi needed to be accounted for. The weight of the sand was found to be approximately 12 tons per load according to OSCC records. To find the weight of an empty semi tractor and trailer, an industry search of typical tractor and trailer weights showed a standard weight range of 32,000-37,000 pounds as seen in Appendix I (Celadon Trucking 2014). The Ecoinvent dataset “Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Def, U” was chosen for use in the Simapro model. The Ecoinvent database is a European undertaking and even though the model for transportation is based on EU standards of emissions, the assumption was made that it would be better to use these standards than try to find a closer model in a different database.

Electricity inputs are present in most of the sand handling equipment in the foundry. Nguyen was able to retrieve both the power requirements of this equipment and an average value for daily uptime usage. The collected data is listed in Table 3.1. Total process energy was normalized to the functional unit. To use this value in Simapro, the Ecoinvent dataset “Electricity, high voltage {MRO, US only}| production mix | Alloc

Def, U" was chosen. This process models the electricity mixture provided by the Midwest Reliability Organization (MRO) Region. As illustrated in Figure 3.4. the MRO region is where OSCC is located.

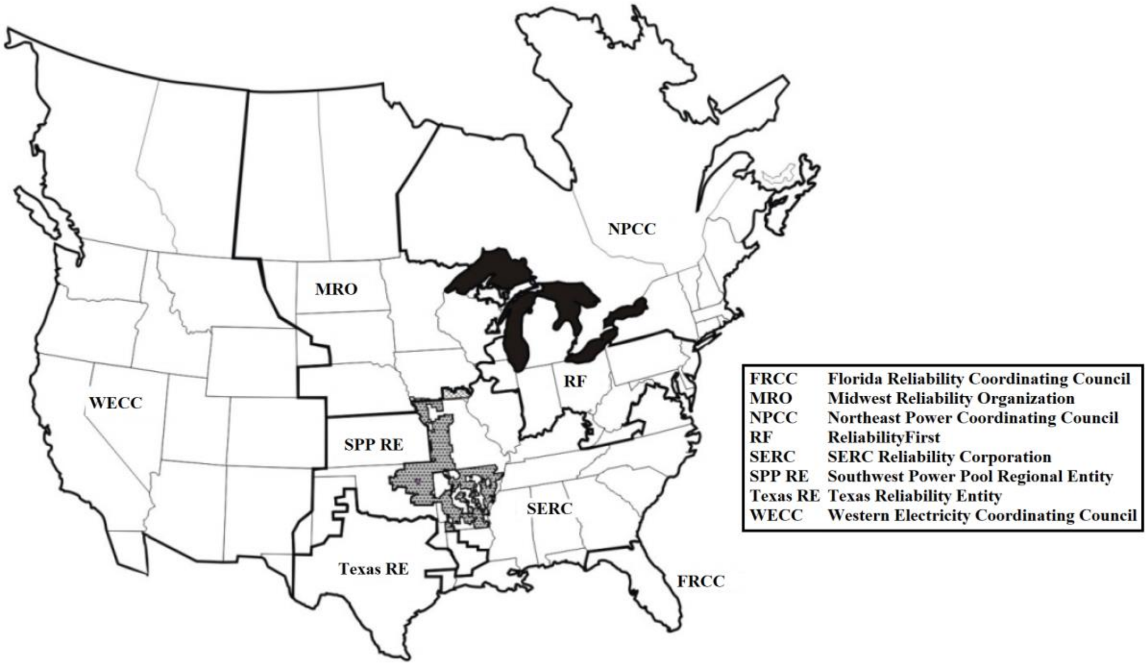


Figure 3.4. NERC Regions (taken from 2016 ERO Enterprise Compliance Monitoring and Enforcement Program Implementation Plan Version 2.5, North American Reliability Corporation, July 2016)

Table 3.1. Power and Energy Requirements for OSCC Sand Handling Processes

Process	**Power Requirement (kW)**	**Uptime (hours/day)**	**Energy Total (kWh/day)**
Mold/Core Mixers	33.6	5.5	184.8
Shakeout	0.75	10	7.5
Magnetic Separator	0.37	10	3.7
Baghouse Fans	0.03	16	0.48
Current Sand Handling Total			**196.48**
Mechanical Reclaimer	56	6.5	364
Thermal Reclaimer	10.9	6	65.4
Microwave Reclaimer	35	4	140

To show the sensitivity of the process change to different electricity fuel inputs, Ecoinvent datasets “Electricity, high voltage {NPCC, US only}| production mix | Alloc Def, U” and “Electricity, high voltage {WECC, US only}| production mix | Alloc Def, U” were chosen to model other regional power profiles. These were based on the Northeast Power Coordinating Council (NPCC) and Western Electricity Coordinating Council (WECC) respectively.

The only process that required a natural gas input was thermal reclamation. The amount of natural gas was found using the expected process uptime and the manufacturer provided specifications including an estimate of therms/ton of reclaimed sand. Using this total and the Ecoinvent dataset “Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at industrial furnace >100 kW|Alloc Def, U” the natural gas usage could be modeled in Simapro.

The final necessary data for the Simapro model were the transportation values for sand disposal. The same basic method was used for this as was used for transportation of virgin sand with a few modifications. OSCC disposes its SFS in Butler County Landfill in David City, NE (27 miles away). OSCC use their own dump truck to dispose of excess reclaimed sand from the storage silo, as well as a roll off service from Waste Connections that provides three services per week. The weight of both vehicles is estimated to be 14 tons from browsing industry forums. The estimated value of SFS taken in each load is estimated to be 10 tons. The total ton-miles for all landfill transportation is a summation of loaded mileage to the landfill as well as unloaded return mileage. This value is normalized and used with the same Ecoinvent dataset as the virgin sand transportation in the Simapro model.

Outside the Simapro model, data was also collected for the Butler County landfill in order to see what effect the disposal of SFS has on land use changes. To collect the data, direct communication with the landfill was made (Waste Connections 2017). The landfill occupies 160 acres of land, 106.4 of which is permitted for solid waste, with a total capacity of 15,597,445 cubic yards. The Nebraska Department of Environmental Quality (NDEQ) waste management section was contacted to obtain the most current year of annual solid waste loading data for the Butler County landfill. The data show an annual load of 542,596.24 tons from 3rd quarter 2016-2nd quarter 2017. Density of compacted municipal solid waste in the landfill varies depending on practices at the landfill. An average of 1,000 lbs/yd^3 will be used to approximate the volume of annual loading at the landfill (MDEQ 2007, US EPA 2016).

3.4.2. Life Cycle Impact Assessment

The LCIA was run using Simapro software with the data collected during the LCI phase. The TRACI methodology, version 2.1 (US EPA 2012) was chosen as the way the results would be reported. A separate Simapro model was created for the following scenarios: current process, addition of mechanical reclamation, addition of thermal reclamation, and addition of microwave reclamation.

Simapro software can show TRACI results of each individual model while showing the breakdown of impact contributions by each sub process in the model. Simapro also allows for comparison between any number of models simultaneously.

Both approaches were used to understand how the overall environmental impact changed between the different modelled scenarios.

Simapro offers a method of including or excluding long term impacts in the results. Long term impacts are impacts outside of a 100 year time horizon. After examining the results with and without long term impacts, it was decided not to include them in the model because they did not change the basic characterization of any particular category and did not change any of the major conclusions drawn from the LCA.

3.4.3. Sensitivity Analysis

LCA models are always based on a large pool of data, some of which is not directly sampled. Because of this, the results of running a model can be highly sensitive to certain variables.

To better show sensitivity trends in the developed models, it was decided to conduct two scenario sensitivity analyses (Bjorklund 2002). A scenario sensitivity analysis varies a single variable in a given model to see how that variable affects the LCIA. While this does not lead to a strict mathematical model of variable sensitivity, the method clearly illustrates the relationship between a given variable and each resulting impact category. In the case of LCAs, this is often enough to effectively communicate results.

When reviewing the inputs to the model, the two inputs that appeared to have the greatest impact on the model are the transportation distance from the virgin sand source to the foundry, and the process electricity use. The sensitivity due to transportation distance was simple to model. Three distances were chosen to represent a range of possible source locations. These distances are: 430 miles (current distance), 100 miles (a theoretical in-state source), and 5 miles (a source adjacent to the foundry).

To vary the sensitivity of electricity, the decision to change the electricity mix to simulate a move to “greener” electricity sources. Three regions as described by the North American Electric Reliability Corporation (NERC 2016) were chosen to model this (Figure 3.4.). The MRO region is where the modelled foundry is located. The MRO is highly reliant on coal-based power. The WECC region represents a more balanced energy portfolio with a high percentage of hydroelectric power. The NPCC region represents a region based primarily around nuclear and natural gas electricity generation leading to an impact profile that is “cleaner” than both the MRO and WECC regions in most categories. See Appendix J for a more thorough discussion of impacts.

3.4.4. Uncertainty Analysis

Uncertainty is an unavoidable aspect of LCA. With every measurement there is a new uncertainty value introduced and with as many measurements as are necessary in an LCA, the uncertainty will mount quickly. To ensure final transparency and utility of the results, tracking this uncertainty is an important part of the LCA process.

Uncertainty in an LCA originates in the LCI stage and comes from direct measurement variability as well as any variability tracked in any process datasets used during modeling. In the case of direct measurement it was decided to create a theoretical model based on values measured at OSCC. By making the model a theoretical foundry, the question of uncertainty in the measured values can be bypassed. Not including this uncertainty makes the final results less representative of the actual OSCC process, but still makes the results useful as a comparative tool.

Uncertainty caused by the Ecoinvent database variability has been well documented by the Ecoinvent team. Each entry in the Ecoinvent database is reported as a list of single number inputs and outputs. Uncertainty in these reported values are caused by temporal, geographic, or technological gaps in the LCI data (Guo and Murphy 2012). To compensate for this, each database entry also includes a pedigree matrix to represent data quality. This pedigree matrix enables Simapro to represent the single number values in the database as lognormal distributions.

The LCIA phase of the LCA is where uncertainty must be communicated. Simapro includes an option to calculate uncertainty using the Monte Carlo method. The Monte Carlo method is a tool that calculates a range of uncertainty for a given system by making multiple runs assigning a set of values based on the probability distributions of each LCI input. The method itself dates back to the mid-19th century and has been applied to many uncertainty applications (Harrison 2010).

Simapro can report results from the Monte Carlo analysis for a single process, or as a comparison of two processes. An uncertainty analysis run on one process can show the results as a distribution for each impact category. Running the uncertainty analysis on two processes can show which process had higher or lower impacts in each category. In every case, the Monte Carlo method was run in Simapro for 1,000 trials with a confidence interval of 0.95.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Introduction

The foundry industry is one of the largest consumers of energy in the United States. In 2010, ferrous foundries accounted for 5.5% of all energy use in the manufacturing sector (US EIA 2013). Foundries also are responsible for 4% of all municipal solid waste produced in the United States (US EPA 2016). The goal of becoming more energy efficient and reducing foundry waste will decrease the environmental impact caused by foundries. One area where improvements can be made is the sand handling train of processes.

Sand handling processes cover all processes from the time virgin sand arrives at the foundry to when it leaves the foundry as spent foundry sand (SFS). The processes vary by foundry and can include core and mold mixing, curing, shakeout, and any subsequent reclamation processes. The processes account for 5 to 10% of the total energy use in a steel foundry (Keramida 2004) but contribute nearly all of the solid waste generated. Reducing solid waste at the foundry can be accomplished by modifying the sand handling process train to include one or more sand reclamation processes. These processes can be viewed as a tradeoff where there is an additional process requiring energy offset by a reduction in virgin sand purchase and SFS disposal. When looking at the larger environmental impacts, this tradeoff becomes less clear. The goal of this research is to identify whether the overall environmental impacts would be improved if the sand handling process train was modified. To measure these impacts, life cycle assessment (LCA) was used.

LCA has been used extensively to study foundry processes (Dalquist and Gutowski 2004; Yigit 2013; Masike and Chimbadzwa 2013) but these studies usually focus on the entire foundry process. Since sand handling processes contribute a small portion of the total energy used in a steel foundry, there has been less research that focuses specifically on these processes. However, the amount of energy used over the entire life cycle of sand is a significant environmental burden. LCA was used to compare the current process train with process modifications using mechanical reclamation, thermal reclamation, and microwave reclamation additions.

It was determined from the LCA results that adding a secondary sand reclamation process results in an overall decrease in life cycle energy consumption. The increased energy requirement in the foundry is offset by the reduction in transportation of the virgin sand and SFS.

4.2. Background

The current research was modeled on a mid-sized foundry as a case study. To best approach the analysis, a model was created using this foundry's process train, real data collected from the foundry, as well as assumptions based on literature. While the actual process at the foundry fluctuates based on market activity and active orders, the model will be approached as a theoretical average which operates at a fixed level rate throughout the year. The following sections describe this model.

4.2.1. Foundry Information

The modeled foundry is located in a small Midwestern town. The foundry employs approximately 100 individuals working two shifts per day, five days per week.

The footprint of the foundry is 150,000 square feet. Sand casting is used to create a wide variety of parts from construction and automotive parts to bridgework. Each part is custom ordered by the customer including full specifications and alloy requested. The foundry pours a wide array of alloys including nickel based, corrosion and heat resistant, and tool steels.

Virgin sand for the foundry's mold and core production is sourced from a company 430 miles away. The foundry uses a Phenolic Urethane No Bake System (PUNB) for its main mold and core operations. The mold mixture consists of virgin sand, reclaimed sand, a two-part resin, a catalyst, and iron oxide which is mixed in a hopper before being poured into the pattern for curing. The resin and catalyst are added to set the sand in place and give the mold tensile strength. The resin system in use is Pep Set Q I 4180 and Pep Set Q II 6180 from ASK Chemical (Dublin, OH). Resin is added in a proportion of 60% first part (4180) and 40% second part (6180). The catalyst is Pep Set Catalyst, also from ASK Chemical. Iron Oxide, which is added to reduce occurrence of veining, metal penetration, and other defects (Showman and Scheller 2015), is purchased from Canfield & Joseph (St. Louis, MO).

4.2.2. Foundry Sand Reclamation

After a mold has been used it undergoes a shakeout process to separate the raw steel casting from the rest of the sand. After shakeout, the casting is taken for finishing processes. The sand from the mold is broken down and begins a process of reclamation.

The reclaimed sand can be reused in making new molds and cores. In theory, this reuse could be done indefinitely, but for practical reasons not all sand can be reclaimed.

Remaining organics from the binding process, other fines, such as the iron oxide, and sand particle fractures in the reclaimed sand lead to less than optimal conditions for curing the new mold and core. To compensate for this, new virgin sand is added while an equal portion of reclaimed sand is wasted as SFS. This SFS can be beneficially reused outside the foundry as construction fill, an artificial soil base, or in other applications (US EPA 2014). However, beneficial reuse is highly dependent on the general need in the local area. If there is not a need, the SFS is most commonly landfilled. The entirety of the modeled foundry's SFS is landfilled.

Decreasing SFS involves increasing the amount of reclaimed sand that can be reused in the mold and core operations. This can be done by performing additional reclamation work after the initial shakeout to remove remaining binder or other impurities. The percentage of reclaimed sand in the mold and core operation is of primary importance for this research. The goal of the foundry is to keep this percentage as high as possible without sacrificing surface finish and mold strength. The proportion of reclaimed to virgin sand is based largely on operational conditions and experience.

Reuse ratios without using any reclamation processes vary by the type of foundry and mold and core processes but are generally close to 70:30 reclaimed sand to virgin sand. By including additional processes concurrent or subsequent to shakeout, a foundry can increase this ratio to 75% or 80%. By using primary attrition and magnetic separation, the modeled foundry uses an 80% reclaim ratio.

4.2.3. Secondary Sand Reclamation Technology

Secondary sand reclamation is any additional process that is added to the sand handling system beyond primary attrition to increase the reclaim ratio. Additional energy is required for secondary reclamation but the increased reclaim ratio means the foundry needs less virgin sand and sand disposal. Secondary sand reclamation is often praised as a best management practice and shows a dedication to lean and sustainable manufacturing (Yilmaz et al. 2015; Torielli et al. 2011). However, from a total life cycle viewpoint it has been shown that the extra energy required by the reclamation processes outweigh any environmental benefit of reducing sand consumption (Yigit 2013). This research was based on a system boundary that did not include the transportation of virgin sand or the disposal of spent sand.

There are many secondary reclamation technologies available to steel foundries. They generally fall broadly under two categories: mechanical and thermal. Mechanical processes use friction to remove a portion of the remaining binder on sand grains. Thermal processes use heat to remove virtually all remaining binder from the sand.

The current research will compare the foundry's current process with three available secondary reclamation technologies. The first is a mechanical reclamation system, the second is a thermal reclamation system. Both these processes are similar to Smith (1982) and Bailey (1993), respectively. The last system to be compared is a microwave reclamation system. The technology uses a different energy transfer mechanism, but functionally performs similarly to other thermal reclamation techniques (Mathis and Plunger 2016).

4.2.4. Life Cycle Assessment

Life cycle assessment (LCA) is a method of evaluating a product, process, or service by examining all costs associated from raw material extraction to final disposal. The generally accepted method for conducting an LCA can be found in ISO 14040 and 14044 (ISO 2006a, 2006b). The basic steps include defining the goal and scope of the study, performing a life cycle inventory of all necessary data, using the results of the inventory stage to conduct an impact assessment, and interpreting these results. The results can be used to judge a product's overall environmental impact in a descriptive way that is easy to compare with similar processes.

4.3. Methods

The methodology used in this study follows the ISO standards 14040 and 14044 for conducting an LCA. Each step in the method will be described in the following sections.

4.3.1. Goal and Scope of the Study

The goal of this LCA is to compare life cycle impacts of the sand reclamation process at a modeled foundry with the same process modified with mechanical reclamation, thermal reclamation, or microwave reclamation technology. The assessment is also being presented to the modeled foundry as a tool in determining the best secondary reclamation technology for their proposed process modification. The results of the LCA can also be used to assist other foundries facing a similar decision. This LCA can also be used as supporting documentation when applying for grants to purchase the necessary equipment for a secondary reclamation system.

The functional unit chosen for this study is one ton of cured molding sand. Other studies such as (Dalquist and Gutowski 2004; Yigit 2013) use one ton of finished steel when studying foundry processes. One ton of cured sand was chosen for this study because only the sand handling processes were considered.

The process being studied includes only the sand handling processes inside a foundry as detailed in Figure 4.1. The sand and all related processes are being analyzed from cradle to grave. Not included in this study are the impacts caused by capital equipment construction and maintenance. Also not included are the resin, catalyst, and iron oxide inputs, as well as any associated outputs. These inputs are not considered because they would be kept at the current level of usage in all process modifications causing their impacts to cancel out during the comparison. These assumptions do not form the basis of a comprehensive LCA, but it does provide a good foundation for comparing the proposed technologies.

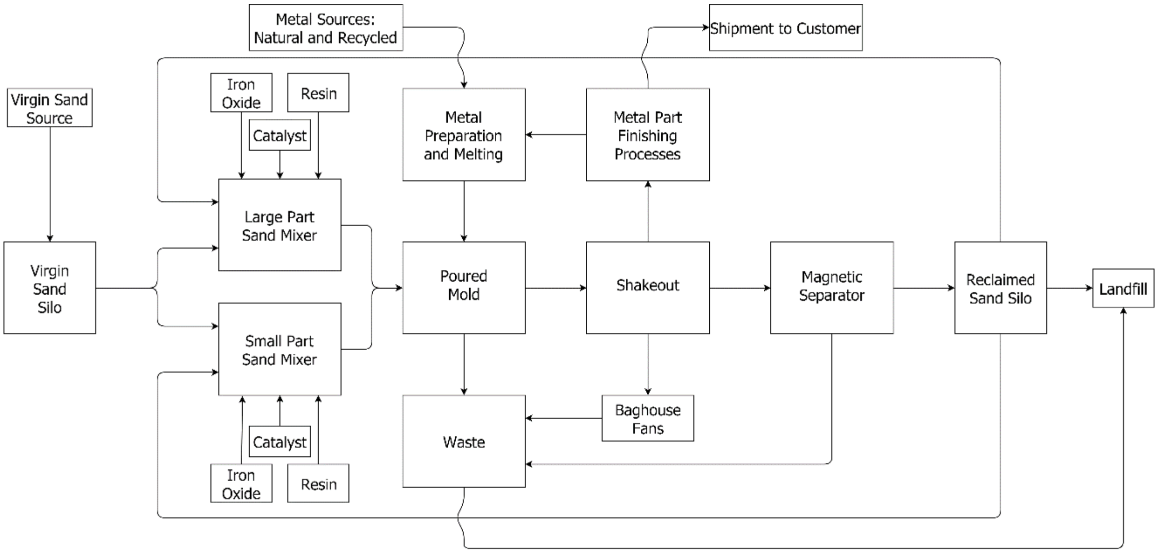


Figure 4.1. Foundry Sand Process Flow Chart

4.3.2. Life Cycle Inventory

The LCI portion of the LCA was conducted over the course of two years. Raw data from the foundry was collected on the unit process level. Values for virgin sand input was averaged over the course of a year as well as trash sent to the landfill. The measured values vary weekly depending on the number and type of jobs being fulfilled, but the stated 80% reclaim ratio was shown to be generally accurate. Data concerning equipment power usage and up time was collected through direct observation for all current processes. Energy use for new technologies was based on manufacturer's schematics and direct communication. Transportation distance between the virgin sand source, the foundry, and the landfill were found using Google Maps. The associated diesel usage was found using these distances and industry standards for truck fuel economy (University of Michigan 2016). A collection of pertinent collected data is listed in Table 4.1. A more complete listing of collected data and associated calculations can be found in Appendices F and G.

4.3.2.2. LCA Software

Using specialized computer software for analysis of data is common in LCAs. Simapro is widely used in professional and research applications for its wide range of data libraries and ease of use. The PhD version of Simapro (ver. 8.3.2) was chosen for the current research.

Table 4.1. Brief LCI Results

Constant Inputs	Annual Usage	Usage Per Functional Unit
Electricity Input (kWh)		
Sand Mixers	46,200	5.28
Shakeout	1,875	0.21
Magnetic Separator	925	0.11
Baghouse Fans	120	0.01
Diesel Usage (Gallons)		
Virgin Sand Transport	6,890	0.79
Spent Sand Disposal	1,820	0.21

New Process Inputs	Annual Usage	Usage Per Functional Unit
Mechanical Reclamation		
Electricity (kWh)	91,000	10.40
Thermal Reclamation		
Electricity (kWh)	16,350	1.87
Natural Gas (Therms)	10,965	1.25
Microwave Reclamation		
Electricity (kWh)	35,000	4.00

The quality of an LCA is entirely dependent on the quality of data it draws from. For this reason the Ecoinvent v3.3 database was chosen for this research. Although Ecoinvent data are mostly based on European sampling, the quality of the data makes it a better choice than other libraries available in Simapro. The question of whether to use multiple databases was considered, but the decision to use only one was made to avoid any error associated with data collection differences between each database.

To analyze the data, an aggregate model for the entire life cycle was developed. The processes that were included in the aggregate include virgin sand production at the mine, truck transportation from the mine to the foundry, mold and core mixing, shakeout, magnetic separation, and truck transportation from the foundry to the landfill. Added to this list are inputs for the potential secondary reclamation technologies if necessary. The LCA model used in Simapro can be seen in Figure 4.2. All inputs are collected, normalized to the functional unit, and added together. This results in three main inputs: sand (ton), transport (ton-mile), and electricity (kWh). For the thermal reclamation model an additional input of natural gas (therm) is added. One aggregate model was created for each scenario for a total of four: current process, mechanical reclamation option, thermal reclamation option, and microwave reclamation option. At some foundries a combination of processes may be found to best meet reclamation needs. The current research was based on the constraint that the foundry would only be able to implement one technology.

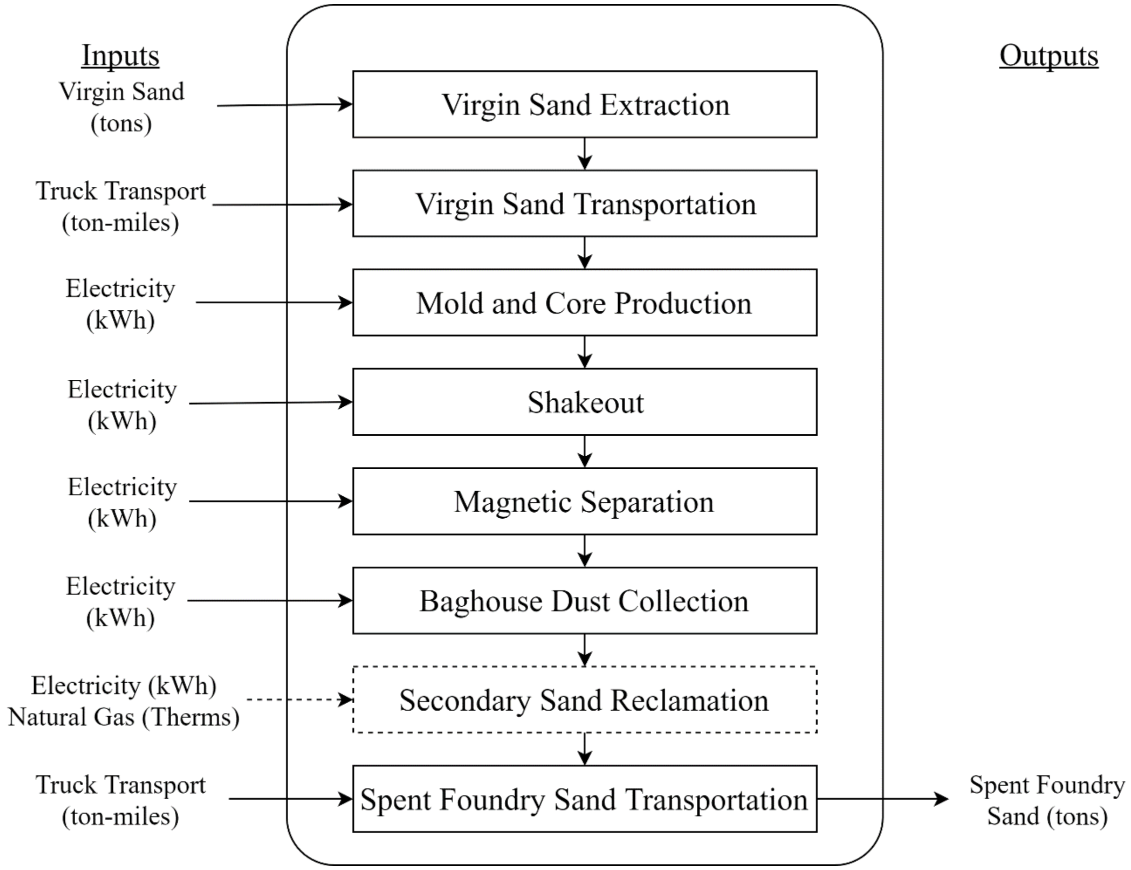


Figure 4.2. Aggregate LCA Simapro Model

4.3.3. Life Cycle Impact Assessment

In the LCIA, the Tool for Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) Methodology v2.1 (US EPA 2012) was used. The TRACI methodology is commonly used within the U.S. as a way to report environmental impacts. TRACI was available as a reporting tool in Simapro and enabled all calculations and comparisons to be completed within the program.

Outside of the TRACI analysis, it was determined that the LCIA should attempt to convey impacts due to land use change. Reducing the SFS entering the landfill represents a positive ecological impact that doesn’t necessarily fall under a TRACI impact category. The current version of the TRACI methodology accounts for resource depletion which includes fossil resources, water use, and land use. In the case of fossil fuel use, a method has been developed, but how to report land and water use are still being researched (US EPA 2012).

Because land use was identified as one of the key midpoint impacts of this model, a basic method of quantifying land use change was developed. An information request was made to the landfill being used by the foundry. Correspondence received indicates a footprint for the landfill (106.4 acres), as well as the total headspace (15,597,445 yd^3) (Waste Connections 2017). Knowing these parameters as well as the volume of SFS being landfilled lets a correlation be made between SFS and land use. A high and low estimate of total annual land use change was determined to show how much farmland would be consumed for landfill space in relation to the functional unit.

While solid waste has not been modeled directly as an impact category in TRACI, the toxicity of waste in the landfill is discussed (Obersteiner et al. 2007, Hauschild et al. 2008). The composition of the SFS is relatively inert. Chemical composition of a SFS sample tested by the Nebraska Department of Roads (NDOR) (Appendix A) found that the sample consisted almost entirely of silica sand and iron oxide. The pH and other contaminants were also reported at a level that is as clean or cleaner than most soils. Because of this, only land usage impacts were added to the LCIA.

4.4. Results and Discussion

Since one of the major stated goals of the research was to offer the modeled foundry as well as other foundries a comparison tool to pick the best reclamation strategy, it was determined that the study would include more than a simple LCA comparison. Analysis was conducted in four stages: economic and energy balance, the LCA study, a land usage study, and an exploration of the sensitivity of the model to change.

4.4.1. Economic and Energy Balance

The economic and energy balance was based on current cost of sand use from cradle to grave using the same system boundaries as the LCA. This cost and energy result was compared with the same system if modified by one of the secondary sand reclamation technologies under consideration. In this analysis, it was assumed that labor and materials not included in the system boundaries will be constant across all processes and therefore not included in the analysis. Estimates of the probable payback period, annual cost savings, annual energy savings, and reduction in greenhouse gas (GHG) emissions will be presented. A brief summary of the operating cost comparison results can be seen in Table 4.2. and Figure 4.3.

Table 4.2. Cost Comparison of Three Secondary Reclamation Technologies

		Secondary Reclamation Technology		
Annual Expenses	Current Practice	Mechanical	Thermal	Microwave
New Equipment O&M Costs	-	$2,000	$15,000	$10,000
Virgin Sand Transportation	$52,500	$36,750	$18,375	$18,375
Virgin Sand Purchase	$36,875	$25,813	$12,906	$12,906
Reclamation Cost	$2,456	$7,006	$10,401	$4,206
Landfill Surcharges	$8,297	$3,319	-	-
Landfill Transportation	$3,074	$1,230	-	-
Waste Management Service	$19,500	$19,500	$19,500	$19,500
Total	**$122,702**	**$95,617**	**$76,182**	**$64,987**
Savings from Current Practice	-	$27,085	$46,520	$57,715
New Equipment Purchase	-	$300,000	$700,000	$500,000
Simple Payback Period (years)	-	11.1	15.0	8.7

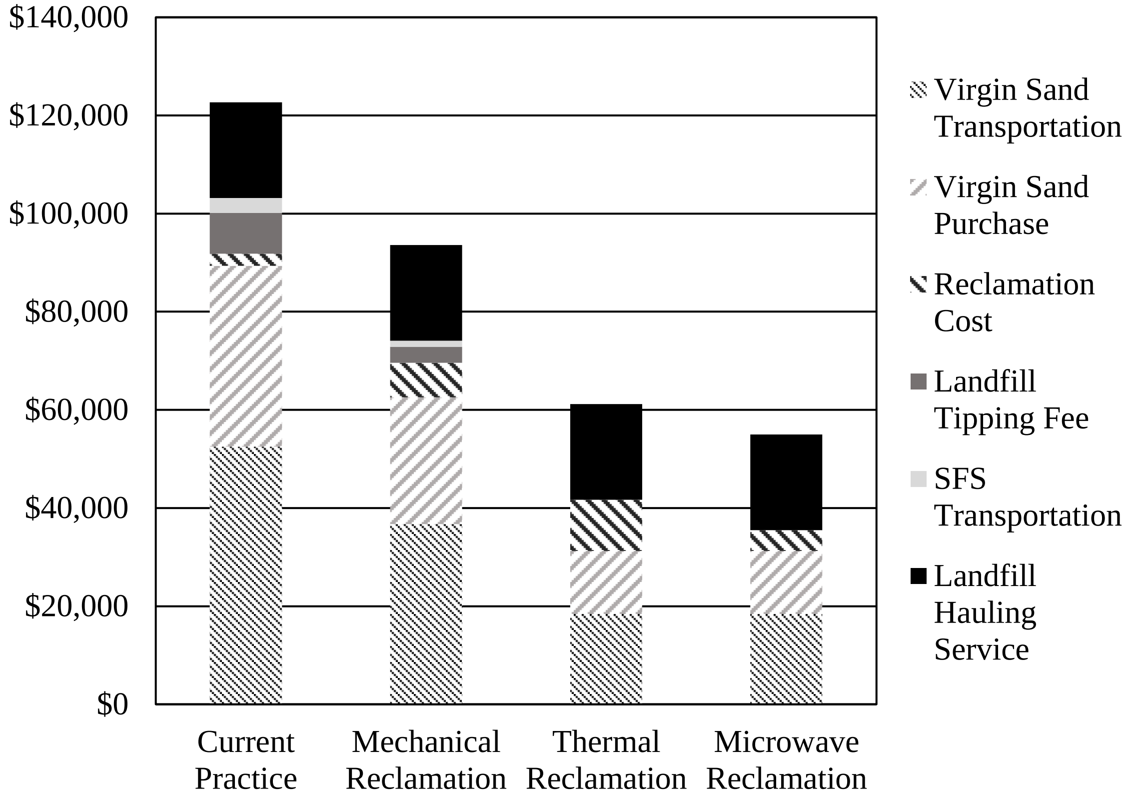


Figure 4.3. Comparison of Annual Cost Contribution by Process

This economic analysis, while greatly simplified compared to the LCA, can still highlight important trends. The most apparent trend is that total annual operating cost decreases as new reclamation technology is introduced. It is also important to note that energy usage cost at the foundry will increase when the equipment is added. The net decrease in annual cost can be readily explained by the reduction of virgin sand purchased. As shown in Figure 4.3. the current cost of purchasing and transporting virgin sand constitutes 73% of the total life cycle operating cost. By increasing the reclaimed sand percentage, the virgin sand requirement can be decreased by 30% in the case of mechanical reclamation and by 65% in the case of the thermal or microwave systems.

This in turn leads to savings in virgin sand purchase costs, virgin sand transport costs, and SFS transport and disposal costs.

Conducting a simplified energy balance also allows for further insight into the proposed process modification. Only foreground energy usage and associated emissions were considered in this analysis including total diesel usage for delivery and disposal of sand, electricity used during sand handling and reclamation phases, and natural gas usage in the thermal reclamation process modification. From these totals, conversions can be made using EPA standards to find a comparison of total MMBTU (US EIA 2017) or the resulting equivalent GHG emissions (US EPA 2016). Energy inputs are listed in Table 4.3. and the resulting comparisons are illustrated in Figures 4.4.a. and 4.4.b.

Table 4.3. Total Annual Foreground Energy Usage for Secondary Sand Reclamation Process Alternatives

	Current	Mechanical	Thermal	Microwave
Electricity (kWh)	49120	140120	65470	84120
Diesel (gal)	8706	6327	3708	3708
Natural Gas (therms)	-	-	10965	-

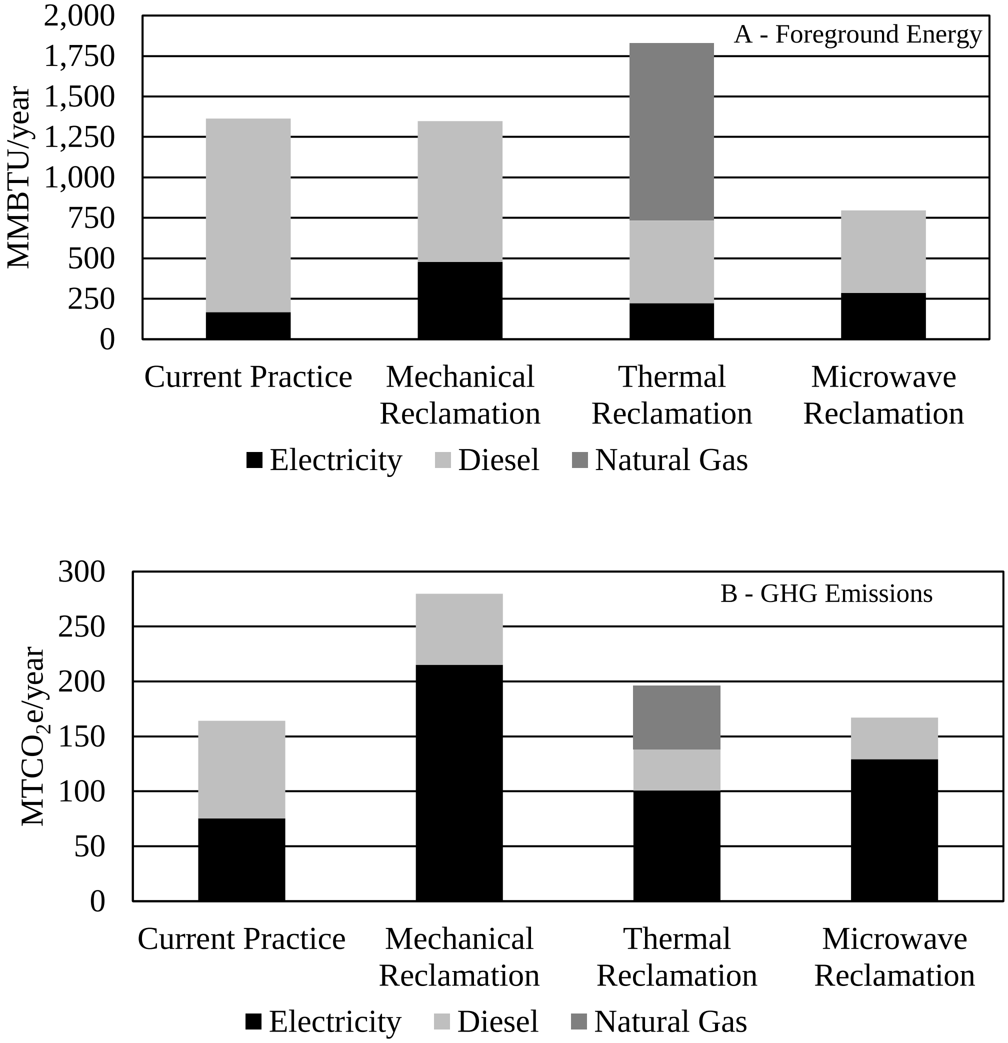


Figure 4.4. Total Foreground Energy and Equivalent GHG Emissions for Secondary Sand Reclamation Process Alternatives

The results of the energy balance offer an interesting view of the process modification. In terms of pure energy, the only process modification that saves a significant amount of energy compared to the current process is by adding a microwave reclamation unit. In the other cases, while the reclamation ratio increase may lead to less diesel consumption, the additional energy required by the mechanical reclamation or thermal reclamation process leads to only a slight net benefit in the case of mechanical reclamation or a net increase in total energy required in the case of thermal reclamation.

When considering the total equivalent GHG emissions, the comparison becomes even more complicated. In all cases, the GHG emissions caused by electricity and natural gas usage during secondary reclamation are larger than the GHG emissions savings created by reducing diesel fuel usage during virgin sand and SFS transportation. As illustrated in Figure 4.4.b., the contribution of electricity alone ranges from 46% in the current case up to over 75% of the total in the case of mechanical reclamation and microwave reclamation. Because the GHG emissions caused by diesel combustion are less impactful than electricity, it makes it difficult for any electrically powered process to result in any net decrease in GHG emissions.

The overall results of the economic and energy balance show that while the addition of secondary reclamation equipment may be cost efficient and reduce diesel fuel usage, the overall GHG emissions produced during the entire sand process increase with the addition of this new equipment. This result is in agreement with earlier research (Yigit 2013). It is important to remember that these results were based on direct energy use only and while GHG emissions from energy usage are an important indicator, they do not represent total environmental impact. A better assessment should include a broader range of impacts such as human health, chemical releases, and resource depletion.

4.4.2. Life Cycle Assessment Results

After all aggregate models were created in Simapro, total impacts were reported using the TRACI methodology. Each model could be analyzed separately, but because the system boundaries were drawn specifically to enable comparison between the process alternatives, results from a single model would not offer useful data when viewed alone.

Results of the comparison were charted in Simapro using the weighting and normalization factors of the TRACI methodology. These results were further refined in Microsoft Excel to show the contribution of each input to the total model impact in each category. Each of the subsequent figures is made in a similar format. The x-axis shows individual impact categories corresponding to the seven categories of the TRACI methodology. In the case of human health impacts, the category is split into three parts: Carcinogenic, Non-Carcinogenic, and Respiratory. An additional category of Fossil Fuel Depletion is also included in the output categories. The y-axis is a normalized unitless value representing the entire environmental impact caused by industry in the United States divided by the population. For each impact category, the comparison of each process will be slightly different. To show the difference, a cluster of four bars is shown for each impact category. These are labeled as C (current process), M (mechanical reclamation), T (thermal reclamation), and Mi (microwave reclamation). Figure 4.5. shows this comparison using standard TRACI weighting and normalization. Figure 4.6. shows the same comparison using 100% characterization of each category. The comparison was calculated by taking the maximum TRACI impact value for each impact category and using that value as the 100% value for that category. The resulting chart shows comparative details with more clarity in all impact categories regardless of their normalized values. For this reason characterization graphs will be used for the remainder of the report.

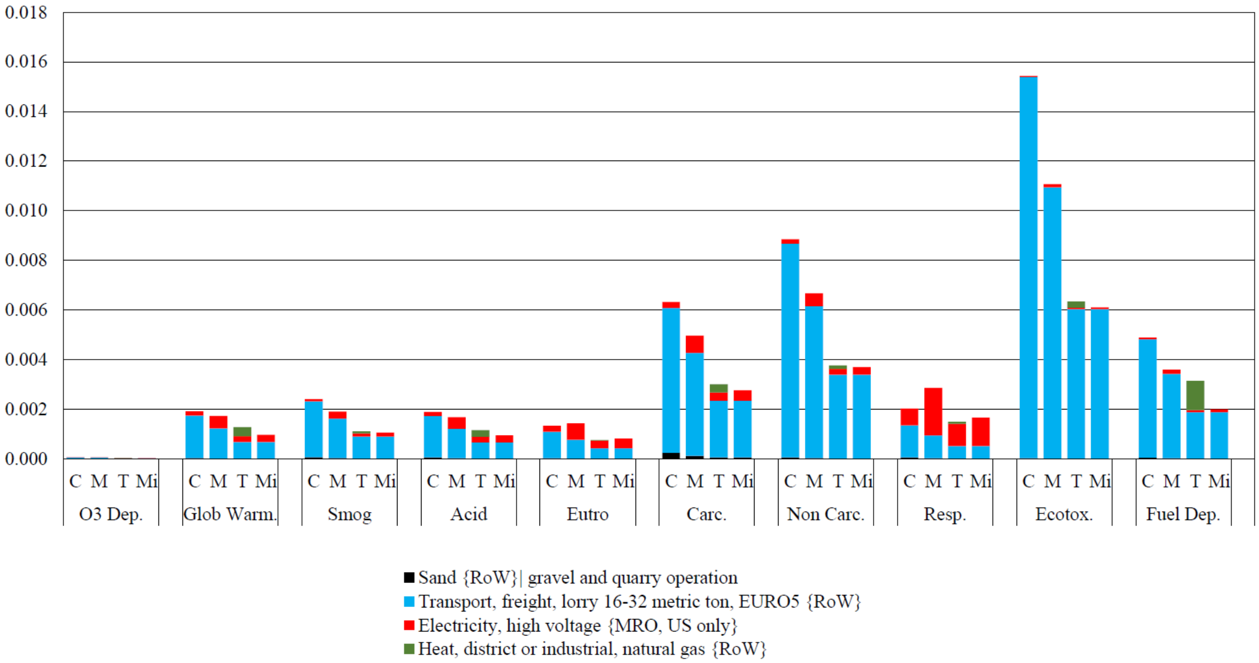


Figure 4.5. Comparison of Four Process Alternatives Using Standard TRACI Weighting and Normalization

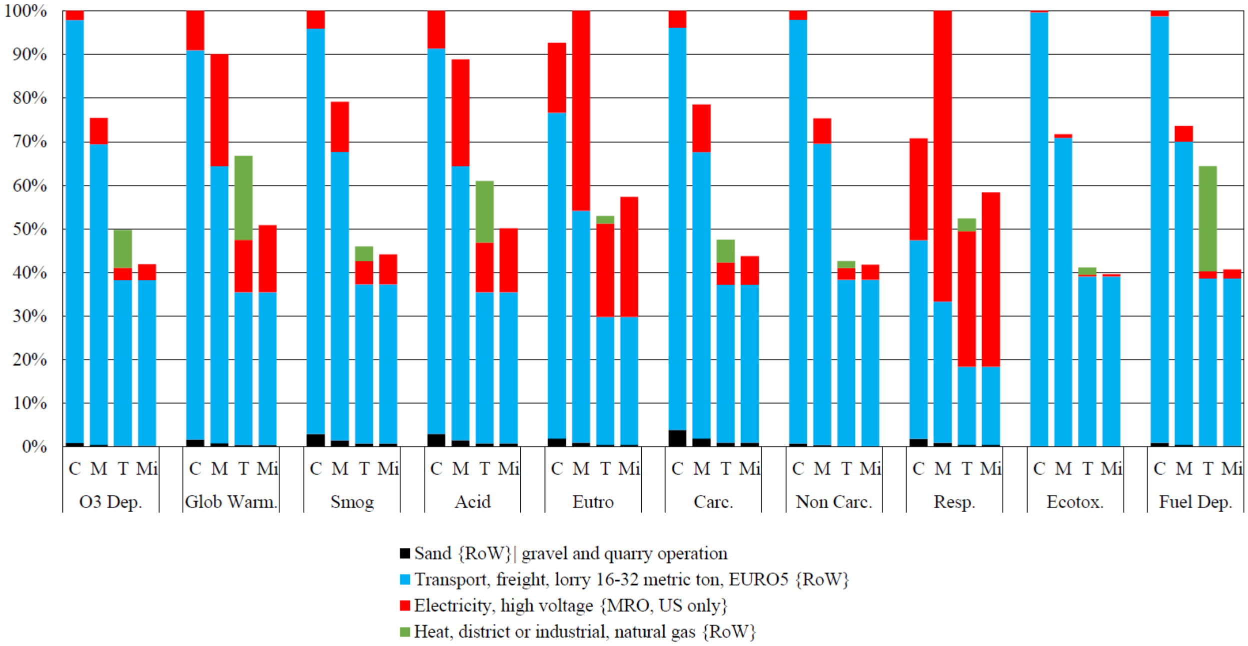


Figure 4.6. Comparison of Four Process Alternatives' TRACI Impact Characterization

Figures 4.5. and 4.6. offer important information as to the overall impacts of each process and which sub-processes are most responsible for those impacts. The standard TRACI normalization and weighting (Figure 4.5.) shows that the most impactful categories relative to overall industrial impacts are ecotoxicity and human health (carcinogenics, non-carcinogenics, and respiratory categories). Other categories, such as ozone depletion and global warming are of much less overall importance when discussing this process modification.

The 100% characterization (Figure 4.6.) aids in showing which sub-processes are most important in each impact category by normalizing each impact category by the maximum value in that category. The resulting graph clearly shows which process has the greatest environmental impact in that category as well as highlighting the contribution of each sub process to the total impact. In all cases but respiratory where the electricity sub-process contributes a significant portion, the transportation sub-process causes the greatest portion of the impact and in some cases almost the entire impact. There are a few categories where electricity plays an important role. As mentioned before, electricity is responsible for 30-70% of the respiratory impact. Eutrophication, acidification, and global warming also see larger impacts caused by electricity use, but to a smaller degree than respiratory impact. The impact caused by sand excavation is negligible compared to the other inputs.

The more important question of overall environmental impact when considering each process modification can be found by looking at these results. There is a general trend in worst to best for each impact category. The current process usually performs the worst in every category followed by the mechanical reclamation modification with microwave reclamation and thermal reclamation performing near the top in each case. The two categories where this does not happen is eutrophication and respiratory. As mentioned before, these are two categories where the electricity sub-process has a larger impact. In these two categories, the order changes with mechanical reclamation performing worse than the current process with microwave reclamation and thermal reclamation still performing the best.

4.4.3. Land Use Analysis Results

As is intuitively expected, each secondary reclamation process results in a lower amount of waste at the landfill than the current process. To better illustrate this result, the impact will be examined in terms of land use change and the lifespan of the landfill.

The land use change can be thought of as the footprint of a landfill that is necessary to support the disposal of SFS. Given the annual volume of spent foundry sand, the density of spent sand, the total headspace of the landfill, and the corresponding landfill footprint, the annual landfill footprint change caused by SFS disposal can be calculated as shown in Appendix G-6. The current practice contributes a 487 ft^2/year change in landfill footprint. Mechanical reclamation improves this to 365 ft^2/year with thermal and microwave processes performing the best causing a change of only 223 ft^2/year. In all cases when the change in landfill footprint is compared with the total landfill footprint of 106.4 acres (160 including all infrastructure), the annual SFS disposal represents a very small portion of the landfill area.

Changes to the landfill lifespan can also be calculated. According to information from the Nebraska Department of Environmental Quality (NDEQ), the landfill's annual intake for the past year was 542,596.24 tons (NDEQ 2017). To change this mass to volume, a conversion factor of 1,000 lbs/yd^3 for compacted municipal waste in the landfill was used (MDEQ 2007, US EPA 2016). Using that conversion, the annual intake is approximately 1.1 million cubic yards. When compared to the total landfill headspace (15,597,445 yd^3) the lifespan of an equivalent empty landfill can be estimated as 14.4 years at the current level of intake. If the level of intake was reduced through the incorporation of a secondary reclamation technology, the lifespan of the equivalent landfill would be increased by 1.3 days in the case of mechanical reclamation and 2.9 days in the case of thermal or microwave reclamation. A summary of results can be seen in Table 4.4.

Table 4.4. Summary of Landfill Disposal Changes

	SFS Produced (tons/year)	SFS Disposal ($yard^3$/year)	Land Use Change (ft^2/year)	Increase to Landfill Lifespan (days)
Current	1,500	1,089	487	0.0
Mechanical	1,125	817	365	1.3
Thermal	688	499	223	2.9
Microwave	688	499	223	2.9

4.4.4. Life Cycle Assessment Sensitivity

The impacts shown in Section 4.4.2. indicate a specific trend in which processes would have the lowest life cycle environmental impacts. This was found to be true given the specific modelling assumptions that were detailed in the life cycle inventory. It was decided to conduct a scenario sensitivity analysis as described by Bjorklund (2002). It was determined that two variables, distance to virgin sand source and electricity grid source mixture, should be investigated in the analysis.

4.4.4.1. Sensitivity to Regional Electricity Generation Mixture

Electricity generation mixture was chosen as a sensitivity variable for two main reasons. The first is to find out if a foundry’s location in the United States would greatly affect the LCA due to electricity usage. The second was to see if there would be a significant change in the results if a specific area would move to a “greener” electricity mixture in the future. To show how the electricity grid source mixture impacts the overall LCIA, the Simapro model was run using three different electricity source mixtures described by the North American Electric Reliability Corporation (NERC 2016): Western Electricity Coordinating Council (WECC), Northeast Power Coordinating Council (NPCC), and Midwest Reliability Organization (MRO). These mixes were chosen because their data are available in the Ecoinvent library, as well as each representing a range of different electricity source mixtures.

MRO was chosen as the primary region for the model because the modeled foundry is located there. The MRO region relies heavily on coal and lignite for the majority of its power. NPCC generates a majority of their electricity from natural gas and nuclear power plants. WECC is more balanced with the highest hydroelectric percentage of the three. A breakdown of these electricity sources can be seen in Appendix J. When compared using the TRACI methodology the three mixes produce different impact profiles. The coal-heavy production in the MRO region leads to high global warming, smog, and respiratory effect impact scores while the almost coal-free production in the NPCC region has the lowest impact in all categories except ozone depletion, ecotoxicity, and fossil fuel depletion.

Because of this range in impacts and because electricity plays an important role in determining the overall impact of the sand reclamation process, a comparison of the overall process was made changing the electricity mix used, as illustrated in Figure 4.7.

This figure follows the same format as those previously used, but there is now a cluster of three bars for each process alternative in each impact category. In order from left to right, these bars represent the MRO, NPCC, and WECC regional mixes, respectively.

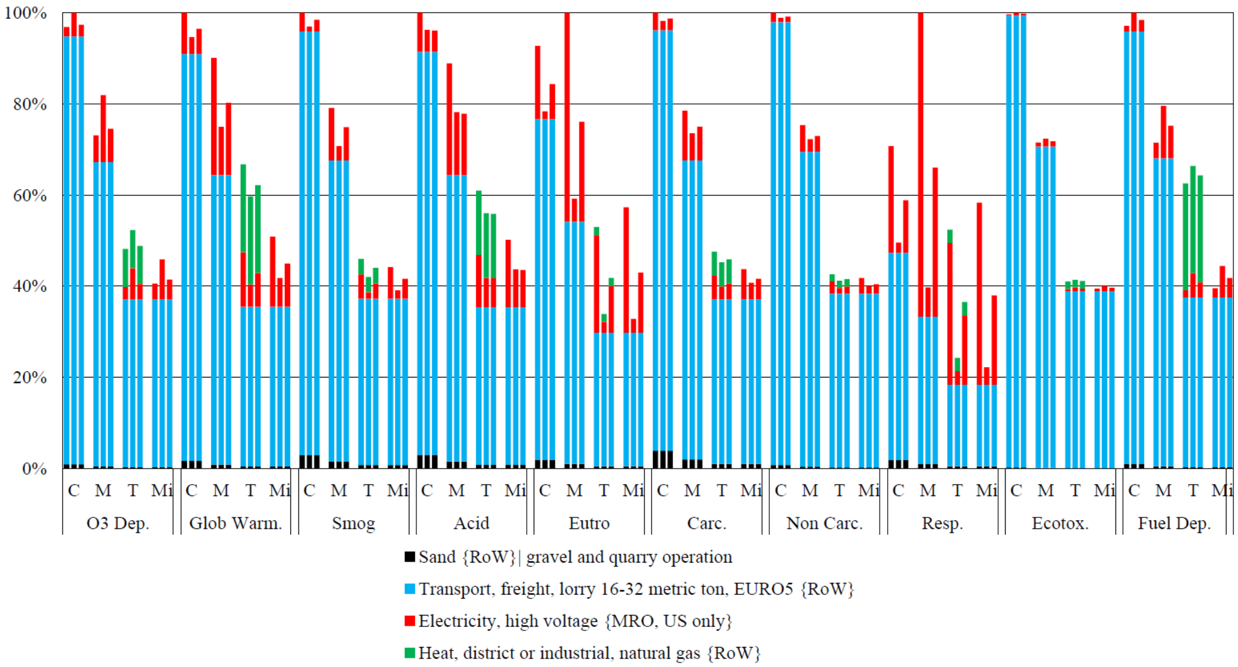


Figure 4.7. Process Sensitivity to Regional Electricity Generation (MRO, NPCC, and WECC Regions)

While the impact can be seen to change in all categories, the difference is slight in most cases due to the low sub-process contribution of electricity. The only time there is a definite change in which process modification has a larger impact is in the eutrophication and respiratory impact categories. In these cases, using the NPCC electricity mix lessens the impact of mechanical reclamation’s electricity use making it better than the current process. In all other cases, the benefits of moving to lower fossil fuel using electric mixtures is negligible.

4.4.4.2. Sensitivity to Distance from Virgin Sand Source

To study the sensitivity of the sand handling process to distance from the foundry was a simple process. New distances of 100 miles and 5 miles were chosen to show a wide range of possible distances. 100 miles represents a theoretical in-state source of virgin sand where 5 miles was chosen to represent a case where the foundry would be extremely close to the source of their virgin sand. New aggregate processes were created in the Simapro model by duplicating the original models and changing the transportation distance in the input data. Figure 4.8. shows the generated output. As before, each impact category has a cluster of three bars for each process alternative in each impact category. In order from left to right, this cluster of bars represent distance from the virgin sand source to the foundry: 430 miles, 100 miles, and 5 miles, respectively.

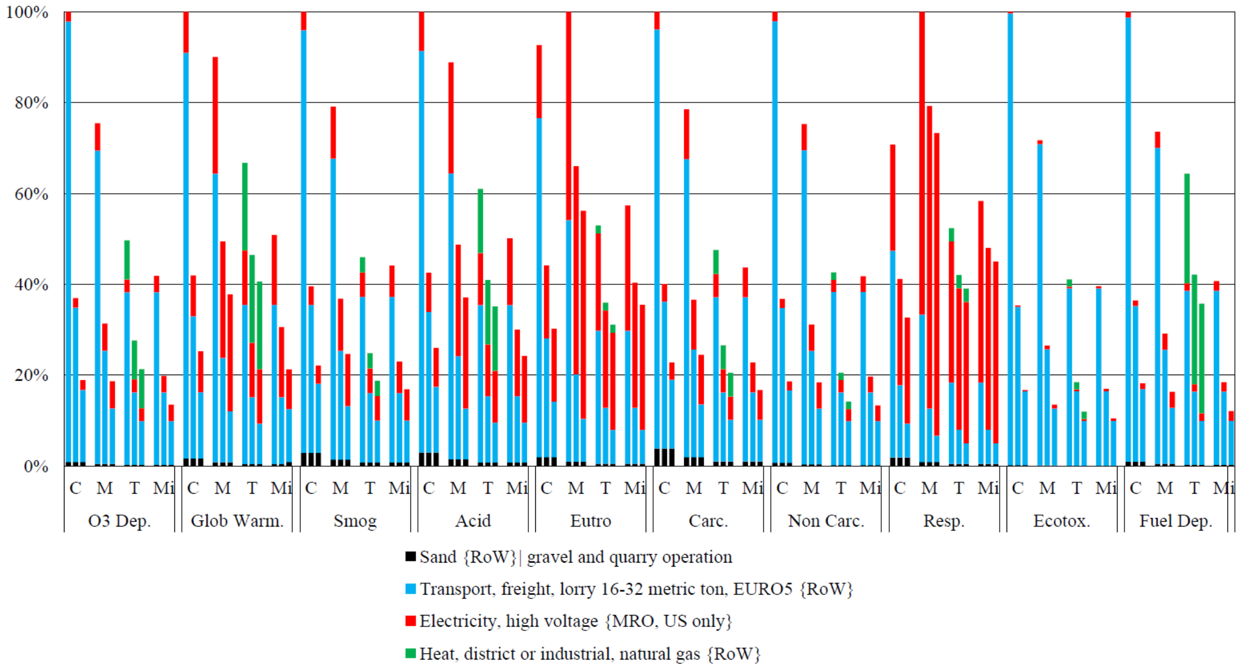


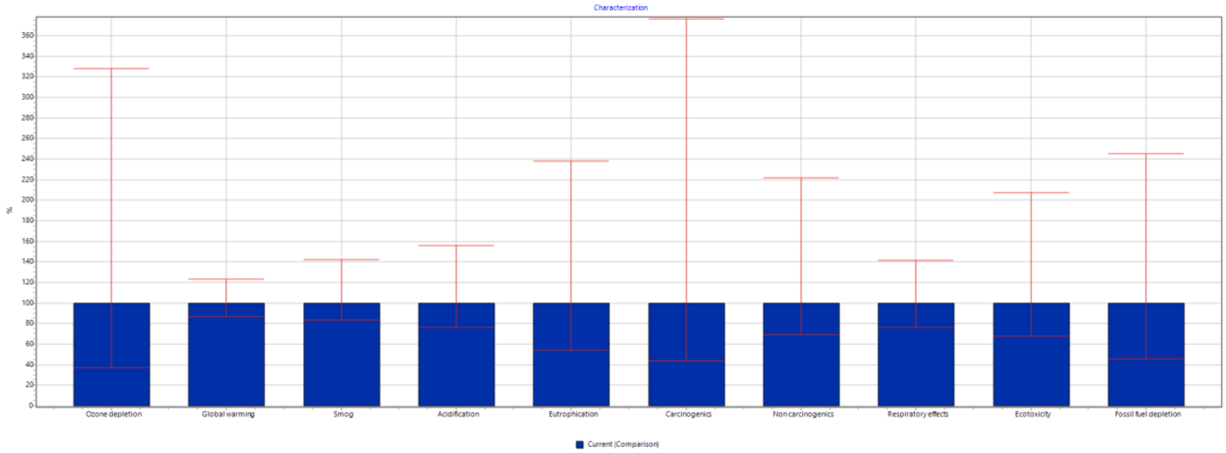
Figure 4.8. Process Sensitivity to Geographical Location of Virgin Sand Source (430, 100, and 5 Miles to Source)

Unlike the change in electricity mix, the impact caused by choosing a nearer sand source is clearly evident in all cases. While the same basic trend of impacts associated with each technology does not change, two trends are apparent. First is that comparing the current process at 100 miles with the proposed technologies at 430 miles shows that in every case the current process impacts are comparable to or less than those of the proposed technologies. The second thing to notice is that as the distance decreases the difference between each process becomes smaller and in some extreme cases, the current process performs better than any of the process modifications.

4.4.5. Uncertainty Analysis

Before the results of the model can be accepted, a study of uncertainty in the model must be done. Uncertainty analyses were run using the Monte Carlo function in Simapro set at 1,000 trials with a confidence interval of 0.95. A separate analysis was performed for each individual model. In addition, comparison analyses were run for all possible scenario pairings. A discussion of the most important findings can be found here with a more complete set of results found in Appendix K.

The output of the single model uncertainty analysis in Simapro includes error distributions for each impact category as well as a single graph showing error bars for all categories simultaneously. As can be seen on the 100% characterization graph of the current process (Figure 4.9.) the outliers range from 90% to 120% for global warming to 45% to 375% for carcinogenics. The categories with high uncertainty, such as carcinogenics, are usually due to a few specific data sets which are highly variable making an accurate estimate of a mean value quite difficult. Output for each process can be found in Appendices K-1 through K-4.



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

Figure 4.9. Current Process Uncertainty

To better understand these large uncertainty intervals, it is informative to look at an uncertainty analysis for each specific impact category. For these single category graphs, the x-axis shows the midpoint impact score specific to each category. The scores are separated into small ranges and a tally of each result is taken. The y-axis shows the probability of each range of results. A complete record of these individual results can be found in Appendices K-1 through K-4.

When comparing two process models in the uncertainty analysis, each impact category is scored separately during each iteration and whichever process has the higher impact is tracked. The final result is a graph of each impact with a sliding percentage scale to show which process had a higher percentage of higher impacts. As an example, Figure 4.10. shows a comparison between the current process and the mechanical reclamation process.

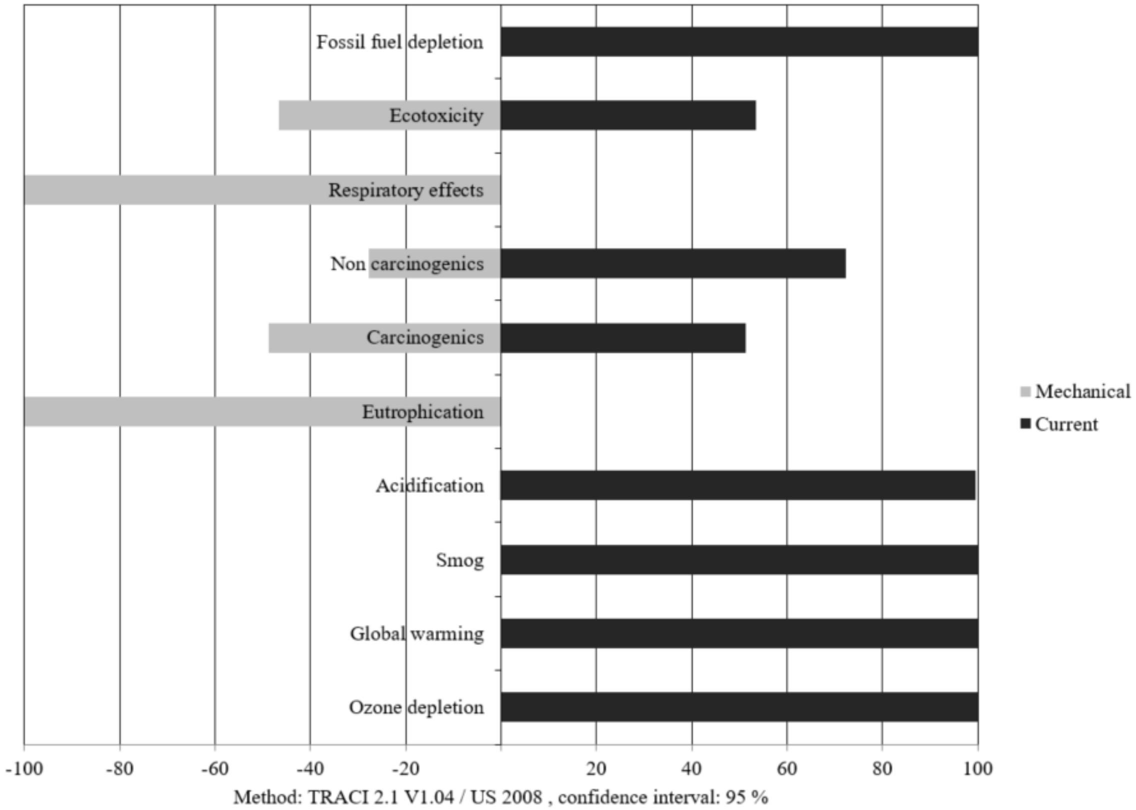


Figure 4.10. Comparison of Current Process and Mechanical Reclamation Using the Monte Carlo Method

The right side of the graph represents the current process. The bars showing 100% to the right mean that for every iteration of the Monte Carlo method, the current process had a larger impact than mechanical reclamation in that category. Given what has been shown in this research, most of the results of this comparison are not surprising. The two impact areas where mechanical reclamation had a larger effect than the current process were Eutrophication and Respiratory effects. This is shown to happen 100% of the time in the uncertainty analysis. This shows that those results, while close in magnitude are still statistically significant.

The three impact categories that do not have a clear leader in impact are Carcinogenics, Non carcinogenics, and Ecotoxicity. These three categories have also been shown to have higher uncertainty compared to some of the other categories. This graph shows that while there is a clear difference between these categories when using the average values in the database, they are not statistically different.

When reviewing the results of the other comparisons (Appendix K-5), the trend of the data is that a majority of the time the differences shown in the LCIA are statistically significant, even if the magnitude of that difference is small. To examine this further, one additional comparison will be viewed. The thermal reclamation and microwave reclamation processes generally performed the best and were often extremely close in magnitude. Figure 4.11. shows this uncertainty comparison.

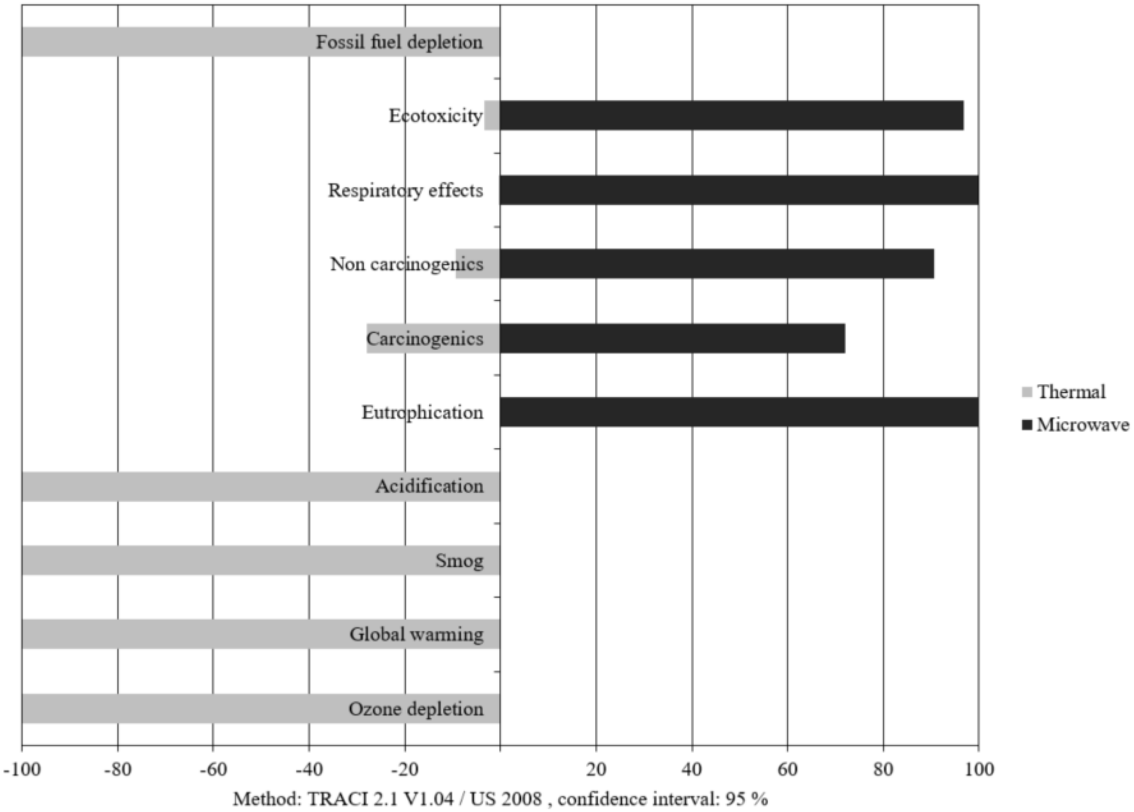


Figure 4.11. Comparison of Thermal Reclamation and Microwave Reclamation Using the Monte Carlo Method

For each impact category one of the two processes are clearly better or worse with possible exceptions for the Carcinogenic, Non carcinogenic, and Exotoxicity impacts. This is a qualitative way to show that even though the processes are close in overall magnitude, there is still statistical significance in their difference. These outliers are similar to the results in Figure 4.10. and are not surprising because of their high uncertainty.

4.5. Discussion

It is common practice in energy efficiency assessments to perform simple calculations based on energy consumption at the point of use to find GHG emissions. While GHG is a useful metric, it is important to consider other environmental impacts from a broader life cycle view. The simple energy analysis performed for this research shows a one particular result for the GHG impact, but when the larger LCA picture is considered, the GHG category (Global Warming) is only one of several important impacts. When viewing GHG reduction results, it is important to consider whether other impact categories should be considered as well.

When considering the energy balance and the resulting Figures (4.3.a and b) it is evident that a direct relationship between raw energy content and environmental impact does not exist. One way to think about this discrepancy is to think of every fuel as having an energy density per emission value. This value is essentially a ratio between MMBTU and $MTCO_2e$ within one unit of fuel. For these three inputs the result would be: diesel having 13.5 $MMBTU/MTCO_2e$, electricity having 2.2 $MMBTU/MTCO_2e$, and natural gas having 18.9 $MMBTU/MTCO_2e$. The low value of electricity is evident when looking at how much GHG it contributes compared to the relatively clean burning natural gas. Of course, these values are based on non-life cycle values of energy content and only consider GHG emissions, not other harmful emissions caused, especially by diesel fuel combustion. Future research could examine this question within an LCA framework to determine a specific environmental impact per one unit of energy as a way to compare the environmental impact of different fuel sources.

The land use analysis performed has shown that although a seemingly large amount of waste produced at the foundry represents only a small sum compared to the size of the landfill being used by the foundry. In addition to this, in the Midwest the required land space for a landfill is relatively easy to find and generally not very expensive when compared with more urban areas on the East and West coasts of the United States. In those situations, the landfill disposal fees and land use change may be more of a driving factor when considering the alternative reclamation technologies.

The impacts caused by the transportation of sand from the distributor to the foundry and then the foundry to the landfill is the largest single contributor to almost every impact category in the final analysis. This can be easily explained because the distance between the foundry and the sand source, as well as the landfill, is also large. As the sensitivity analysis showed, choosing a closer virgin sand source can drastically reduce the environmental impacts of the entire sand handling process. As previously stated, at very close distances, the main environmental impact driver is no longer transportation in many cases. When this happens, the additional energy required by the secondary reclamation processes make them perform worse than the current process in several impact categories. This extreme case is similar to the system modeled by Yigit (2013) and similar results are found in this research.

As alternative green energy sources become more widely available, there is a better chance that foundries can purchase their electricity from a cleaner source. However, when reviewing the results of the electrical sensitivity study, this would result in only a small benefit in most of the measured impact categories. Switching to a cleaner energy source may reduce impacts, but a foundry seeking to reduce their total environmental impact would be better served looking in other areas first, such as transportation distances to both virgin sand source and landfill. A combination of both a cleaner electricity source and finding a closer virgin sand source would have the largest environmental benefit than taking either action separately.

When reviewing the economic, energy, LCA, and land use analyses performed in this research together, it gives a foundry a solid set of decision making tools when approaching a process change. Depending on the foundry’s goals, values, and financial situation, the importance of each individual analysis could be weighted differently. However, this research has also shown that in most cases, the LCA and land use analyses generally follow the simple economic analysis that was performed.

CHAPTER 5. CONCLUSIONS

5.1. Introduction

Ferrous foundries represent a large total environmental load in the United States manufacturing sector and while the foundry sand processes represent a small portion of this total, their overall energy and environmental impacts are significant. The goal of this research was to perform a life cycle assessment (LCA) on a medium-sized foundry in the United States that sources its sand from a long distance away and analyze those results. To accomplish this goal, several objectives needed to be completed. The first objective was to develop a system model. This objective was completed and a model for the foundry was developed using system boundaries that specifically targeted the sand handling process chain. The second objective was to analyze the model using LCA. This objective was completed using several tools, such as Simapro LCA software, the Ecoinvent database, and the TRACI impact methodology. Four models were developed and analyzed to develop a good comparison tool based on LCA. The third and last objective was to perform a sensitivity analysis on the model. This was accomplished by varying a single input and analyzing the results. This was done for both virgin sand transportation distance and electricity mixture.

5.2. Findings

The main findings of this report are summarized below:

1) Although total operational costs associated with secondary reclamation technologies were less than that of the current practice, the simple payback periods were relatively long (9-15 years) due to the required capital investment.

2) Major operational cost savings are due to a reduction in virgin sand purchase and hauling fees. Increased energy required for the secondary reclamation processes are much smaller than the decrease in cost due to virgin sand purchase and transport.

3) When looking at the energy inputs and associated green house gas emissions when changing the model, there is a general overall increase when adding secondary reclamation processes to the system. This simplified model was shown to be inadequate from a full life cycle perspective because it did not encompass full life cycle energy usage and did not consider other impact categories like a full LCA.

4) The LCA comparison of the four processes showed a relative order of environmental impacts that is consistent in eight out of ten of the reported impact categories. The general trend is that the lowest environmental impacts are the thermal and microwave reclamation processes, followed by mechanical reclamation, with the current process having the highest impacts. The exceptions to this order occur in the respiratory and eutrophication impact categories where mechanical reclamation has higher impacts than the current process. This is because in these categories electricity has a larger contribution to the overall impact.

5) Transportation impacts dominate the overall life cycle impacts with electricity constituting a significant portion in only the respiratory and eutrophication

categories. Quarry processes and natural gas usage are smaller impacts that do not largely affect the major conclusions of the LCA.

6) Landfill impacts were found to be very small. This could be due to the combination of modeling a mid-sized foundry going to a large landfill. This finding could be significantly different if modeling a large foundry in a location with limited landfill space.

7) The sensitivity of the LCA was shown to rely heavily on virgin sand transportation distance. Finding a closer source of foundry sand will greatly reduce all impacts. It might also be possible to reduce these impacts by finding a more efficient method of transportation, whether by rail or by upgrading the truck fleet. It was also shown that at longer transportation distances the environmental benefits of introducing a secondary reclamation process is much more important than if a foundry is able to source its sand from a close distance.

8) It was shown that the sensitivity of the LCA due to the electricity grid mixture was low. In general there was no major change in any of the findings by changing to a more eco-friendly electricity source mixture. This is largely due to the fact that the electricity portion of the total impact is much smaller than it is for transportation.

9) It was found that while LCA data are inherently uncertain, the developed model was able to produce consistent results. This shows that the results of the model are a reliable representation of the expected impacts. The uncertainty present is not enough to change any of the major findings of this research.

5.3. Foundry Specific Recommendations

Secondary reclamation is considered a BMP in modern foundries, but it is an expensive process to implement. This research shows that in addition to an economic benefit, there is a total life cycle reduction in environmental impacts as well as a reduction in solid waste being sent to the landfill. By showing that secondary sand reclamation can reduce environmental impacts, this research can possibly support rebate or grant applications that fall under energy efficiency, pollution prevention, or solid waste reduction. Finding available rebates or grants will also help foundries cover the large initial purchase price of secondary reclamation technology.

The model based on microwave reclamation pilot data was shown to outperform two existing common secondary reclamation options. Microwave reclamation uses less total energy than mechanical and thermal reclamation leading to lower operating costs and a smaller environmental impact. It also reconditions sand to a better than new state leading to low virgin sand consumption and reduced SFS disposal. Foundries should follow the development of microwave reclamation as a technology to see if full sized systems perform as well as the initial pilot test data.

The sensitivity analysis performed in the report can assist foundries in finding effective ways to reduce their environmental impacts. It was shown that shifting to cleaner energy can reduce overall impacts, but not enough to justify any extensive shift in how energy is procured. As regional energy grids shift to more eco-friendly energy mixes, this will benefit the foundry, but not in any appreciable way. In contrast, the sand handling process is very sensitive to the distance from the foundry to their sand source.

This means the most effective way for foundries to reduce their sand handling environmental impact is to find a sand source that is as close to their foundry as possible. It also shows that while choosing a thermal or microwave system is always a better choice at long distances, the improvement becomes less pronounced and may disappear altogether with a closer sand source. Conversely, a foundry that must procure their sand from a distant location will benefit the most from implementing a process that will enable the highest reclaim ratio possible.

Although this research was based on a model of one specific set of foundry processes, the results may prove to be useful for other foundries considering a modification to their sand handling process. The choice on whether or not to implement additional reclamation technology must be examined considering a wide range of factors including local energy costs, transportation distances between the foundry, the virgin sand quarry, and the final sand disposition, as well as landfill availability and tipping fees. This will be a value judgment that is different for every foundry. When making this determination, this research has shown that LCA can be effectively used as a comparative tool when considering process modification.

5.4. Areas of Future Research

Limitations of the model and lack of data were problematic during this research. Future research should look to address these areas to improve the existing model.

The system boundaries in this research did not include the sand binder, catalyst, and iron oxide additives. The environmental impacts caused by the release of these chemicals is important to consider and should be included in future research. By including these it would be possible to get a better idea of the total impacts of the sand casting process. This would allow for comparisons between different foundries using different casting processes.

One significant limitation of the TRACI methodology for the current research is the lack of life cycle impacts due to the resource depletion of land. For this research, the necessity of including land use in the assessment was apparent from the beginning, but for other research, the need might not be as apparent. The solution used in this research only considered land area change. A true life cycle view would require a more detailed model. Future research may wish to see if land use changes are as limited as the current model shows by developing a better model, or by applying the TRACI model when it is developed.

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Appendix A: Nebraska Department of Roads Foundry Sand Laboratory Results

Bulk Specific Gravity & Absorption AASHTO T 84

Sample #	Specific Gravity	Absorption
MF15-4	2.602	0.44
MF15-5	2.756	1.69

Sieve Analysis (% Passing) AASHTO T 27

Sample #	#10	#30	#40	#50	#100	#200
MF15-4	**100**	**99**	**89**	**54**	**7**	**1**
MF15-5			**100**	**95**	**62**	**44**

Electrochemical Analysis

Lab ID	pH	Resistivity at 15.5°C, ohm-cm	Sulfates, ppm	Chlorides, ppm
MF15-4	7.5	10,389	70	34
MF15-5	6.9	1,093	156	349
NDOR Requirements*	5-10	3,000 Min.	200 Max.	100 Max.
Test Method	AASHTO T 289	AASHTO T 288	AASHTO T 291	AASHTO T 290

*Requirements for Granular Backfill for use in Mechanically Stabilized Earth (MSE) Walls.

X-Ray Fluorescence Analysis

Sample ID	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3
MF15-4	0.15	3.39	82.49	0.97	0.273	0.0935	11.98
MF15-5	0.339	14.62	29.34	0.549	0.614	0.252	51.91

Moisture Density Relations AASHTO T 99

Sample ID	Maximum Dry Density, pcf	Optimum Moisture %
MF15-4	102.0	15.0

Direct Shear of Soils AASHTO T 236

Sample ID	Friction Angle	Cohesion, psf
MF15-4*	33.6°	36

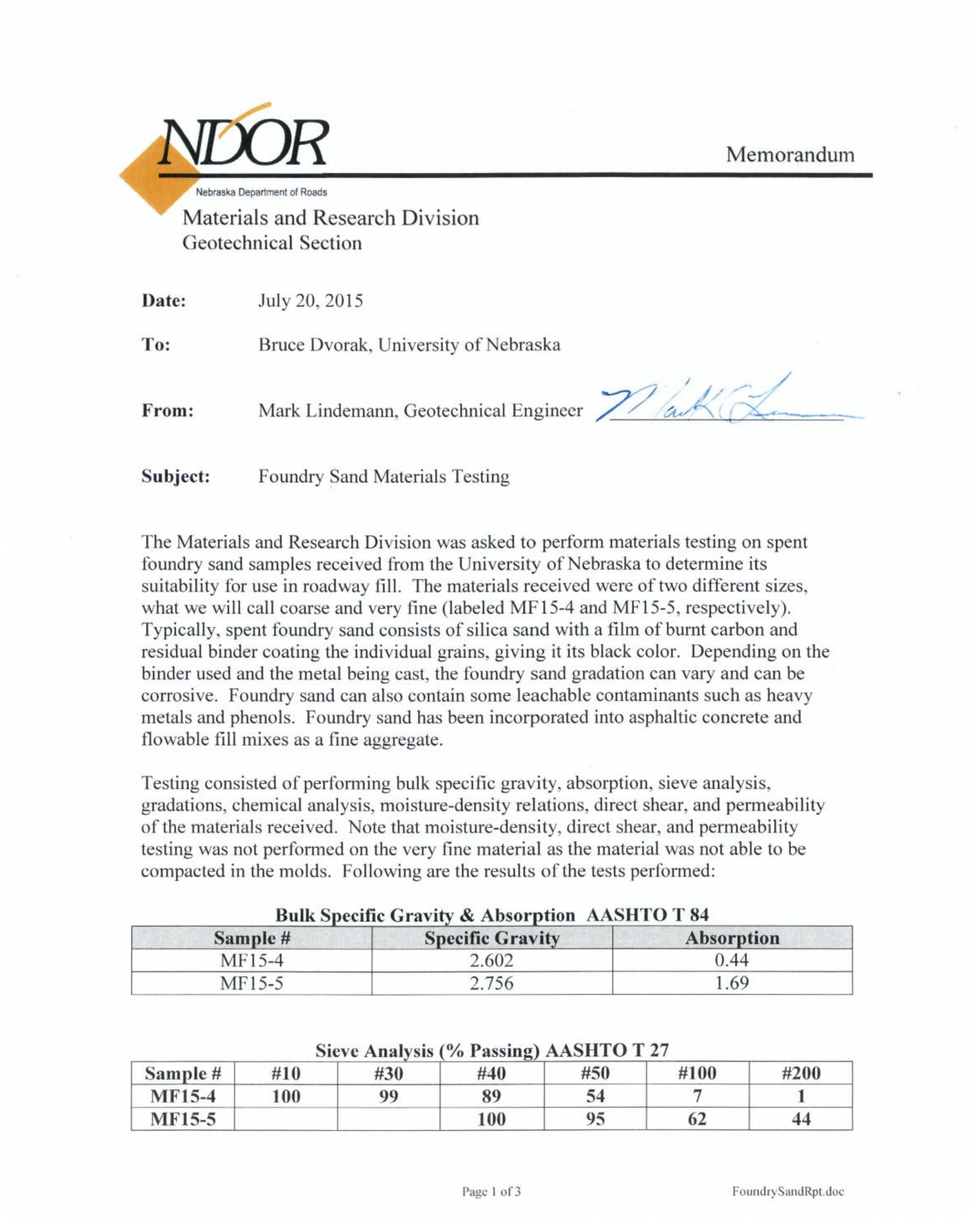
*Sample molded at 95% of Maximum Dry Density.

Constant Head Permeability of Soils AASHTO T 215

Sample ID	Hydraulic Conductivity, k (cm/sec)
MF15-4*	1.3

*Sample molded at 95% of Maximum Dry Density.

Appendix B: Complete Nebraska Department of Roads Foundry Sand Laboratory Report



NDOR

Nebraska Department of Roads

Memorandum

Materials and Research Division
Geotechnical Section

Date: July 20, 2015

To: Bruce Dvorak, University of Nebraska

From: Mark Lindemann, Geotechnical Engineer

Subject: Foundry Sand Materials Testing

The Materials and Research Division was asked to perform materials testing on spent foundry sand samples received from the University of Nebraska to determine its suitability for use in roadway fill. The materials received were of two different sizes, what we will call coarse and very fine (labeled MF15-4 and MF15-5, respectively). Typically, spent foundry sand consists of silica sand with a film of burnt carbon and residual binder coating the individual grains, giving it its black color. Depending on the binder used and the metal being cast, the foundry sand gradation can vary and can be corrosive. Foundry sand can also contain some leachable contaminants such as heavy metals and phenols. Foundry sand has been incorporated into asphaltic concrete and flowable fill mixes as a fine aggregate.

Testing consisted of performing bulk specific gravity, absorption, sieve analysis, gradations, chemical analysis, moisture-density relations, direct shear, and permeability of the materials received. Note that moisture-density, direct shear, and permeability testing was not performed on the very fine material as the material was not able to be compacted in the molds. Following are the results of the tests performed:

Bulk Specific Gravity & Absorption AASHTO T 84

Sample #	Specific Gravity	Absorption
MF15-4	2.602	0.44
MF15-5	2.756	1.69

Sieve Analysis (% Passing) AASHTO T 27

Sample #	#10	#30	#40	#50	#100	#200
MF15-4	**100**	**99**	**89**	**54**	**7**	**1**
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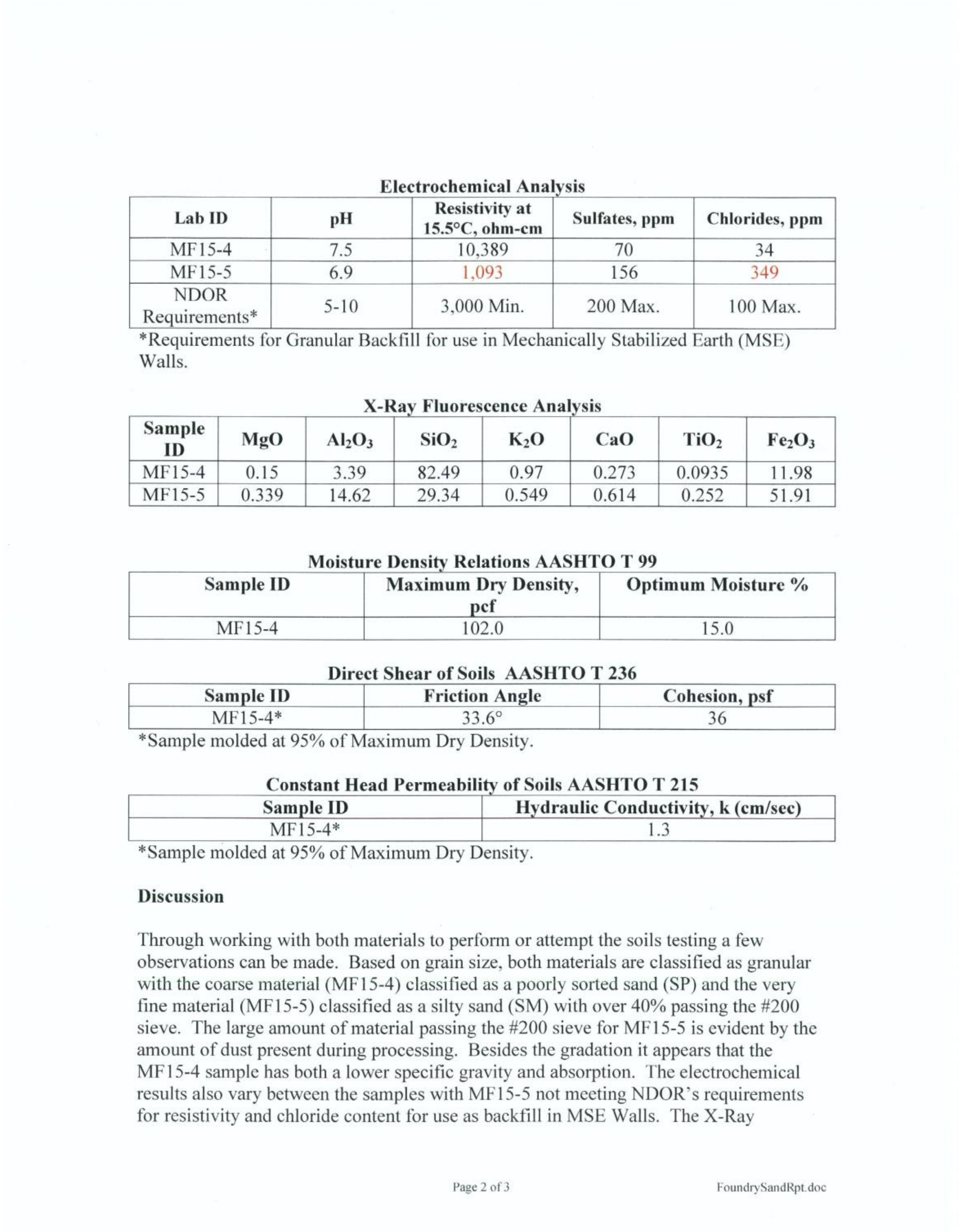

Electrochemical Analysis

Lab ID	pH	Resistivity at 15.5°C, ohm-cm	Sulfates, ppm	Chlorides, ppm
MF15-4	7.5	10,389	70	34
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NDOR Requirements*	5-10	3,000 Min.	200 Max.	100 Max.

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Direct Shear of Soils AASHTO T 236

Sample ID	Friction Angle	Cohesion, psf
MF15-4*	33.6°	36

*Sample molded at 95% of Maximum Dry Density.

Constant Head Permeability of Soils AASHTO T 215

Sample ID	Hydraulic Conductivity, k (cm/sec)
MF15-4*	1.3

*Sample molded at 95% of Maximum Dry Density.

Discussion

Through working with both materials to perform or attempt the soils testing a few observations can be made. Based on grain size, both materials are classified as granular with the coarse material (MF15-4) classified as a poorly sorted sand (SP) and the very fine material (MF15-5) classified as a silty sand (SM) with over 40% passing the #200 sieve. The large amount of material passing the #200 sieve for MF15-5 is evident by the amount of dust present during processing. Besides the gradation it appears that the MF15-4 sample has both a lower specific gravity and absorption. The electrochemical results also vary between the samples with MF15-5 not meeting NDOR's requirements for resistivity and chloride content for use as backfill in MSE Walls. The X-Ray

Fluorescence data also shows that MF15-5 also is predominantly made of iron oxide at over 50% while sample MF15-4 is mostly silica.

As stated earlier the AASHTO tests T 99, T 236, and T 215 were not performed on MF15-5. This was due to the inability to work or compact the material once water was added. When MF15-5 was saturated for the specific gravity and absorption test, the fines of the material was observed to float in the water. It was also observed that the material behaves like an elastic silt material in that it is very sensitive and unstable with the addition of water. Due to the coarser nature of MF15-4, the T 99, T 236, and T 215 tests were able to be performed. It was observed though that the moisture-density and friction angle results were on the lower end values of typical granular soil of the same gradation. The elastic behavior was still observed with MF15-4 but it was not as sensitive as MF15-5. The AASHTO T 215 test provided hydraulic conductivity results that indicate very good drainage characteristics.

Based on the behavioral properties of both the foundry sands tested, the NDOR Materials & Research Division would not incorporate these materials as roadway fill or backfill. The undesirable elastic behavior and sensitivity to the addition of water, along with corrosion and chemical leaching potential make the material unsuitable for our uses.

If you have any further questions and comments, please contact us at your convenience.

cc: Mick Syslo
file

Appendix C: Simplified Schematic of Two Cell Mechanical Reclamation Unit by Simpson Technologies

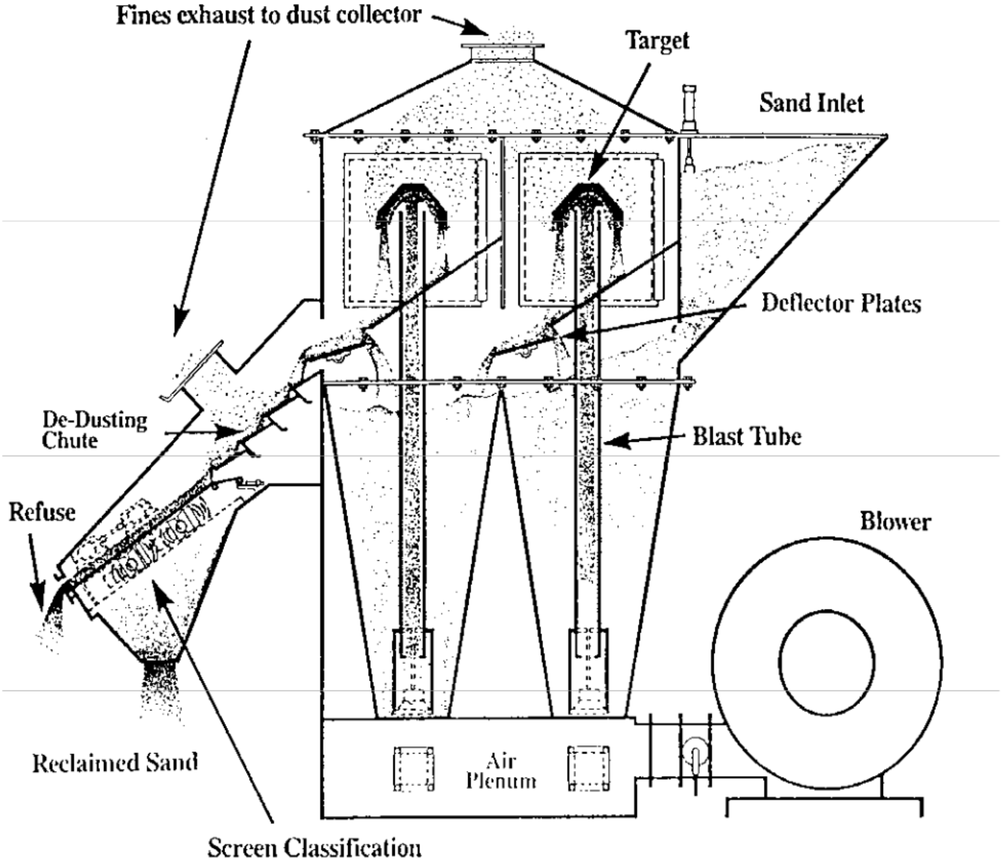
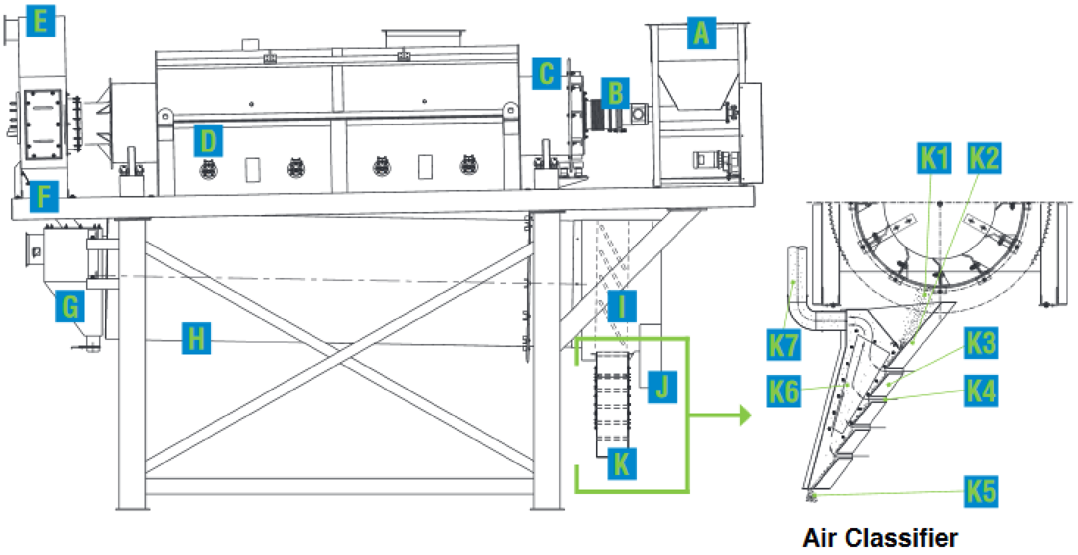


Figure C-1. Two Cell Mechanical Reclamation System, From Simpson Technologies

Appendix D: Simplified Schematic of Thermal Reclamation Unit by EnviroAir, Inc.

Functional Description



A	Waste foundry sand is fed into the input hopper by a conveyor, elevator or pneumatic transporter
B	Sealed screw feeder feeds the sand at a constant rate into the rotary retort
C	The waste sand is heated to 1200 to 1500°F inside the rotary retort evaporating moisture and oxidizing organic binders
D	Gas-fired burners heat the retort from the outside. This indirect heat prevents flame impingement on the sand grains.
E	Retort exhaust gases are collected in the retort exhaust hood and discharged to a dust collector
F	Transfer chute
G	Cooling air is collected in the cooling drum exhaust hood and discharged to a dust collector
H	Heat from the reclaimed sand is transferred to the cooling air in the rotary cooling drum. Sand leaves the cooling drum 10 to 30°F above ambient temperature.
I	Reclaimed sand is filtered through a 20-mesh screen on the end of the cooling drum
J	Metal and other oversize materials flow over the filter screen and out the reject chute
K	Reclaimed sand flows through the air classifier to remove fines

Air Classifier

K1	Screened openings in the cooling drum filter reclaimed sand into the air classifier
K2	Adjustable slot in classifier infeed hopper to distribute the sand across the classifier
K3	Sand flows down inclined surface inside the classifier
K4	Room air enters the classifier and flows through the cascading sand to remove unwanted fines from the reclaimed sand
K5	Reclaimed sand drops from classifier into a conveyor or pneumatic transporter
K6	Sand fines are captured in the upward moving airflow and are exhausted from the classifier
K7	Classifying air and fines are discharged to a dust collector. A damper is provided to adjust the classifying air flow rate to control the AFS fineness number of the reclaimed sand.

Figure D-1. Thermal Sand Reclamation System, From EnviroAir, Inc.

Appendix E: Conceptual Process Flow of Microwave Reclamation Unit by M;-Wave Consulting

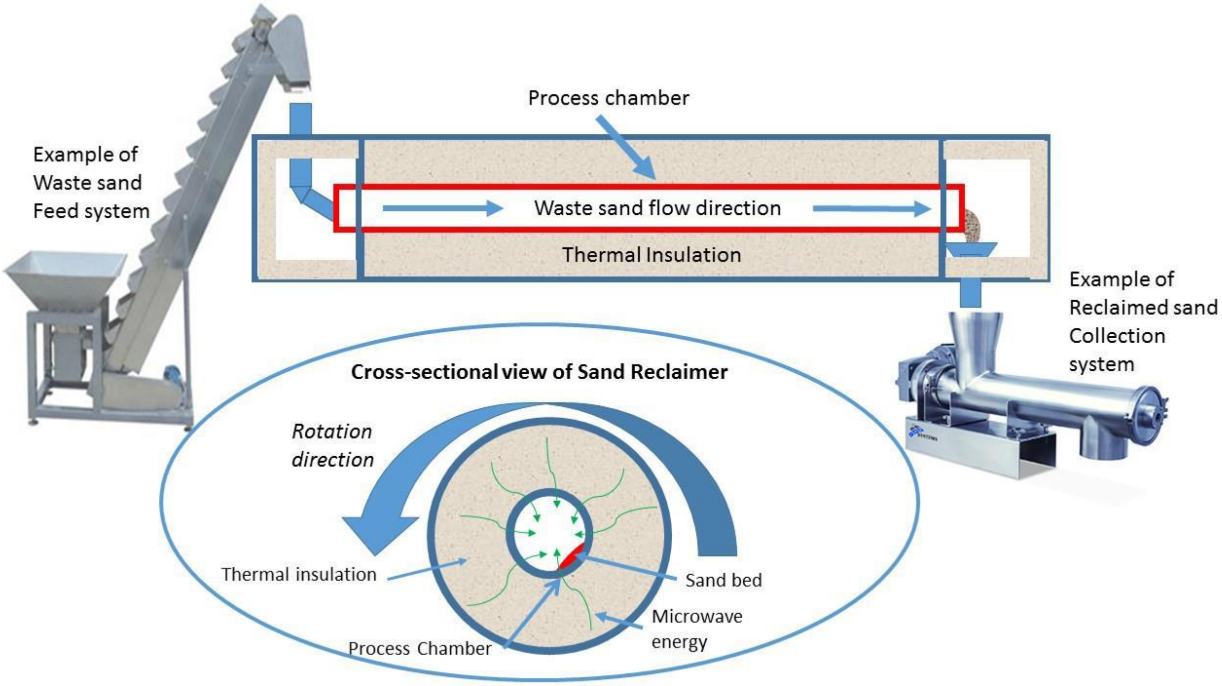


Figure E-1. Simplified Microwave Foundry Sand Reclamation System, From M-Wave Consulting

Appendix F: Raw Data

	Unit	Value	Source
Facility Information			
Days in Operation	days/year	250.00	Reported by Foundry
Hours in Operation	hours/day	16.00	Reported by Foundry
Utility Rates			
Electricity Rate	$/kWh	0.05	Extracted from Bills (Wahoo Utilities)
Natural Gas Rate	$/therm	0.65	Extracted from Bills (Wahoo Utilities)
Virgin Sand Transport			
Source Distance	miles/trip	430.00	Measured using Google Earth
Virgin Sand Usage	tons/day	5.00	Directly Measured (Nguyen, 2016)
Virgin Sand Cost	$/ton	29.50	Extracted from Bills
Freight Charge	$/ton	42.00	Extracted from Bills
Freight Capacity	tons/trip	12.00	Directly Measured (Nguyen, 2016)
Empty Semi Weight	tons	16.00	Industry Average (Celadon Trucking)
Semi Gas Mileage	miles/gallon	6.50	Industry Average (University of Michigan)
Spent Foundry Sand Disposal			
SFS Produced	tons/day	6.00	Directly Measured (Nguyen, 2016)
SFS OSCC Landfill	tons/day	2.50	Directly Measured (Nguyen, 2016)
SFS Landfill Service	tons/day	3.50	Directly Measured (Nguyen, 2016)
Disposal Distance	miles/trip	54.00	Measured using Google Earth
Tipping Fee	$/ton	13.28	Extracted from Bills
Freight Fee	$/service	125.00	Extracted from Bills
Services	service/year	156.00	Extracted from Bills
Driver Rate	$/trip	30.00	Reported by Foundry
Truck Gas Mileage	miles/gallon	6.50	Industry Average (University of Michigan)
Truck Capacity	tons/trip	10.00	Directly Measured (Nguyen, 2016)
Diesel Fuel Cost	$/gallon	2.31	Nebraska Energy Office
Empty Truck Weight	tons	14.00	Industry Average (Web search)
Mold and Core Sand Mixture			
Catalyst	tons/day	0.03	Directly Measured (Nguyen, 2016)
Resin	tons/day	0.32	Directly Measured (Nguyen, 2016)
Iron Oxide	tons/day	0.45	Directly Measured (Nguyen, 2016)
Reclaimed Sand	tons/day	30.00	Directly Measured (Nguyen, 2016)
Common Electricity Usage			
Mold/Core Mixers	kW	33.60	From Equipment
Mold/Core Mixers Uptime	hours/day	5.50	Directly Measured (Nguyen, 2016)
Shakeout	kW	0.75	From Equipment
Shakeout Uptime	hours/day	10.00	Directly Measured (Nguyen, 2016)
Magnetic Separator	kW	0.37	From Equipment
Magnetic Separator Uptime	hours/day	10.00	Directly Measured (Nguyen, 2016)
Baghouse Fans	kW	0.03	From Equipment
Baghouse Fans Uptime	hours/day	16.00	Directly Measured (Nguyen, 2016)
Secondary Reclamation Equipment Additional Energy			
Mechanical Reclamation Electric Usage	kW	56.00	Quoted Specifications (Simpson Technologies)
Mechanical Reclamation Throughput	tons/hour	5.00	Quoted Specifications (Simpson Technologies)
Thermal Reclamation Gas Usage	therms/ton	7.31	Quoted Specifications (EnviroAir, Inc.)
Thermal Reclamation Electric Usage	kW	10.90	Quoted Specifications (EnviroAir, Inc.)
Thermal Reclamation Throughput	tons/hour	1.00	Quoted Specifications (EnviroAir, Inc.)
Microwave Reclamation Electric Usage	kW	35.00	Estimate (M-Wave Consulting)
Microwave Reclamation Throughput	tons/hour	1.00	Design Criteria (M-Wave Consulting)
Landfill Information			
Footprint of Landfill	acres	106.40	Reported by Landfill
Footprint of Landfill (Including Offices)	acres	160.00	Reported by Landfill
Total Volume of Landfill	yard^3	15,597,445.00	Reported by Landfill
Total Municipal Waste Flow to Landfill	tons/year	542,596.24	NDEQ Records
Density of Spent Sand	pounds/ft^3	102.00	Measured by NDOR
Average Density of Landfill Waste	pounds/yard^3	1,000.00	Reported by MDEQ

Appendix G: Sample Calculations

All example calculations use data from thermal reclamation model except where indicated.

G-1: General Data

G-1.1) Operating Days

$$5\,\frac{days}{week} * 50\,\frac{weeks}{year} = 250\,\frac{days}{year}$$

G-1.2) Total Cured Mold and Core Sand

$$35\,\frac{tons}{day} * 250\,\frac{days}{year} = 8{,}750\,\frac{tons}{year}$$

G-2: Process Data

G-2.1. Virgin Sand Acquisition and Transportation

G-2.1.a) Virgin Sand Usage - Total virgin sand purchased and transported to foundry.

$$Virgin\ Sand\ Requirement\ \left(\frac{tons}{day}\right) * Operating\ Days\ \left(\frac{days}{year}\right) = \left(\frac{tons}{day}\right)$$

$$1.75\frac{tons}{day} * 250\frac{days}{year} = 437.5\frac{tons}{year}$$

G-2.1.b) Virgin Sand Trips - Number of one-way deliveries from the virgin sand source to the foundry.

$$\frac{Virgin\ Sand\ Usage\ \left(\frac{tons}{year}\right)}{Freight\ Capacity\ \left(\frac{tons}{trip}\right)} = \left(\frac{Trips}{year}\right)$$

$$\frac{437.5\frac{tons}{year}}{12\frac{tons}{trip}} = 36.5\ trips/year$$

G-2.1.c) Virgin Sand Mileage - Total one-way mileage from all virgin sand deliveries.

$$Virgin\ Sand\ Trips\ \left(\frac{trips}{year}\right) * Source\ Distance\ \left(\frac{miles}{trip}\right) = \left(\frac{miles}{year}\right)$$

$$36.5\ \left(\frac{trips}{year}\right) * 430\ \left(\frac{miles}{trip}\right) = \ 15{,}677\ \left(\frac{miles}{year}\right)$$

G-2.2. Sand Handling Processes

G-2.2.a) Mold and Core Mixers - Total electrical power usage of mold and core mixers.

$$Mixer\ Power\ (kW) * Mixer\ Uptime\ \left(\frac{hours}{day}\right) * Operating\ Days\ \left(\frac{days}{year}\right) = (kWh/year)$$

$$33.6\ kW * 5.5\frac{hours}{day} * 250\frac{days}{year} = 46{,}200\frac{kWh}{year}$$

G-2.2.b) Shakeout - Total electrical power usage of shakeout equipment.

$$Shakeout\ Power\ (kW) * Shakeout\ Uptime\ \left(\frac{hours}{day}\right) * Operating\ Days\ \left(\frac{days}{year}\right) = (kWh/year)$$

$$0.75\ kW * 10\frac{hours}{day} * 250\frac{days}{year} = 1{,}875\frac{kWh}{year}$$

G-2.2.c) Magnetic Separator - Total electrical power usage of magnetic separator.

$$Magnetic\ Separator\ Power\ (kW) * Magnetic\ Separator\ Uptime\ \left(\frac{hours}{day}\right) * Operating\ Days\ \left(\frac{days}{year}\right) = (kWh/year)$$

$$0.37\ kW * 10\frac{hours}{day} * 250\frac{days}{year} = 925\frac{kWh}{year}$$

G-2.2.d) Baghouse Fans - Total electrical power usage of dust collection system.

$$Fan\ Power\ (kW) * Fan\ Uptime\ \left(\frac{hours}{day}\right) * Operating\ Days\ \left(\frac{days}{year}\right) = (kWh/year)$$

$$0.03\ kW * 16\frac{hours}{day} * 250\frac{days}{year} = 120\frac{kWh}{year}$$

G-2.2.e) Process Electricity - Total electrical power usage of additional secondary sand reclamation system. Mechanical, Thermal, or Microwave options only.

$$Process\ Power\ (kW) * Process\ Uptime\ \left(\frac{hours}{day}\right) * Operating\ Days\ \left(\frac{days}{year}\right) = \left(\frac{kWh}{year}\right)$$

$$10.9\ kW * 6\frac{hours}{day} * 250\frac{days}{year} = 16{,}350\frac{kWh}{year}$$

G-2.2.f) Process Natural Gas - Total natural gas usage of secondary sand reclamation system. Thermal option only.

$$Gas\ Requirement\ \left(\frac{therms}{ton}\right) * Process\ Rate\ \left(\frac{tons}{hour}\right) * Process\ Uptime\ \left(\frac{hours}{day}\right) * Operating\ Days\ \left(\frac{days}{year}\right) = \left(\frac{therms}{year}\right)$$

$$7.31\frac{therms}{ton} * 1\frac{ton}{hour} * 6\frac{hours}{day} * 250\frac{days}{year} = 10{,}965\frac{therms}{year}$$

G-2.3. Spent Foundry Sand Generation and Transportation

G-2.3.a) Spent Sand Produced - Total sand wasted by the foundry. Example calculation uses mechanical reclamation model data.

$$4.5\frac{tons}{day} * 250\frac{days}{year} = 1{,}125\frac{tons}{year}$$

G-2.3.b) Spent Sand to Landfill - Wasted sand transported using foundry equipment and personnel to the landfill. Example calculation uses mechanical reclamation model data.

$$1\frac{ton}{day} * 250\frac{days}{year} = 250\frac{tons}{year}$$

G-2.3.c) Landfill Trips - Number of two-way trips made from the foundry to the landfill to drop off spent sand. Example calculation uses mechanical reclamation model data.

$$\frac{Spent\ Sand\ to\ Landfill\ \left(\frac{tons}{year}\right)}{Truck\ Capacity\ \left(\frac{tons}{trip}\right)} = \left(\frac{trips}{year}\right)$$

$$\frac{250\frac{tons}{year}}{10\frac{tons}{trip}} = 25\frac{trips}{year}$$

G-2.3.d) Landfill Mileage - Total two-way mileage during landfill trips made by foundry personnel. Example calculation uses mechanical reclamation model data.

$$Landfill\ Trips\ \left(\frac{trips}{year}\right) * 2 * Landfill\ Distance\ \left(\frac{miles}{trip}\right) = \left(\frac{miles}{year}\right)$$

$$25\frac{trips}{year} * 2 * 27\frac{miles}{trip} = 1{,}350\frac{miles}{year}$$

G-2.3.e) Waste Management Disposal - Wasted sand collected by waste management service. Example calculation uses mechanical reclamation model data.

$$Spent\ Sand\ Produced\ \left(\frac{tons}{year}\right) - Spent\ Sand\ to\ Landfill\ \left(\frac{tons}{year}\right) = \left(\frac{tons}{year}\right)$$

$$1{,}125\,\frac{tons}{year} - 250\,\frac{tons}{year} = 875\,\frac{tons}{year}$$

G-2.3.f) Waste Management Services - Number of waste pick up services performed by waste management service.

$$3\,\frac{services}{week} * 52\,\frac{weeks}{year} = 156\,\frac{services}{year}$$

G-2.3.g) Waste Management Mileage - Total two-way mileage from foundry to landfill during waste management collection services.

$$Waste\ Management\ Services\ \left(\frac{services}{year}\right) * 2 * Disposal\ Distance\ \left(\frac{miles}{service}\right) = \left(\frac{miles}{year}\right)$$

$$156\,\frac{services}{year} * 2 * 27\,\frac{miles}{service} = 8{,}424\,\frac{miles}{year}$$

G-3: Economic Analysis

G-3.1) Virgin Sand Purchase - Cost of virgin sand from supplier.

$$Virgin\ Sand\ Usage\ \left(\frac{tons}{year}\right) * Virgin\ Sand\ Cost\ \left(\frac{\$}{ton}\right) = \left(\frac{\$}{year}\right)$$

$$437.5\frac{tons}{year} * 29.5\frac{\$}{ton} = \frac{\$12{,}906}{year}$$

G-3.2) Virgin Sand Transportation Fee - Cost of transporting virgin sand from supplier to foundry.

$$Virgin\ Sand\ Usage\ \left(\frac{tons}{year}\right) * Freight\ Cost\ \left(\frac{\$}{ton}\right) = \left(\frac{\$}{year}\right)$$

$$437.5\frac{tons}{year} * 42\frac{\$}{ton} = \frac{\$18{,}375}{year}$$

G-3.3) Electricity Cost - Total electricity cost of all sand handling processes.

$$\Bigg(Mold\ and\ Core\ Mixers\ \left(\frac{kWh}{year}\right) + Shakeout\ \left(\frac{kWh}{year}\right) + Magnetic\ Separator\ \left(\frac{kWh}{year}\right) + Baghouse\ Fans\ \left(\frac{kWh}{year}\right) + Process\ Electricity\ \left(\frac{kWh}{year}\right)\Bigg) * Electricity\ Rate\ \left(\frac{\$}{kWh}\right) = \left(\frac{\$}{year}\right)$$

$$\left(46{,}200\frac{kWh}{year} + 1{,}875\frac{kWh}{year} + 925\frac{kWh}{year} + 120\frac{kWh}{year} + 16350\frac{kWh}{year}\right) * 0.05\frac{\$}{year} = \frac{\$3{,}274}{year}$$

G-3.4) Natural Gas Cost - Total cost of natural gas use in sand handling processes. Applicable to thermal model only.

$$Process\ Natural\ Gas\ \left(\frac{therms}{year}\right) * Natural\ Gas\ Rate\ \left(\frac{\$}{therm}\right) = \left(\frac{\$}{year}\right)$$

$$10{,}965\frac{therms}{year} * 0.65\frac{\$}{therm} = \frac{\$7{,}127}{year}$$

G-3.5) Waste Management Cost - Annual cost of waste management pick up service.

$$Waste\ Management\ Services\ \left(\frac{services}{year}\right) * Service\ Fee\ \left(\frac{\$}{service}\right) = \left(\frac{\$}{year}\right)$$

$$156\,\frac{services}{year} * 125\,\frac{\$}{service} = \frac{\$19{,}500}{year}$$

G-3.6) Landfill Cost - Dumping fee at landfill for all spent sand transported by foundry personnel. Example calculation uses mechanical reclamation model data.

$$Spent\ Sand\ to\ Landfill\ \left(\frac{tons}{year}\right) * Landfill\ Disposal\ Fee\ \left(\frac{\$}{ton}\right) = \left(\frac{\$}{year}\right)$$

$$250\,\frac{tons}{year} * 13.275\,\frac{\$}{ton} = \frac{\$3{,}319}{year}$$

G-3.7) Landfill Transportation Cost - All costs associated with transportation of spent sand to the landfill including consumed diesel fuel and driver's wages. Example calculation uses mechanical reclamation model data.

$$\left(\frac{Landfill\ Mileage\left(\frac{miles}{year}\right)}{Truck\ Gas\ Mileage\ \left(\frac{miles}{gallon}\right)} * Diesel\ Fuel\ Rate\ \left(\frac{\$}{gallon}\right)\right) + \left(Landfill\ Trips\ \left(\frac{trips}{year}\right) * Driver\ Rate\ \left(\frac{\$}{trip}\right)\right) = \left(\frac{\$}{year}\right)$$

$$\left(\frac{1{,}350\,\frac{miles}{year}}{6.5\,\frac{miles}{gallon}} * 2.31\,\frac{\$}{gallon}\right) + \left(25\,\frac{trips}{year} * 30\,\frac{\$}{trip}\right) = \frac{\$1{,}230}{year}$$

G-3.8) Total Annual Cost - Total annual costs for operating the sand handling model. Model costs includes new process operation and maintenance, virgin sand transportation and purchase, all process electricity, process natural gas (if applicable), landfill disposal, landfill transportation, and waste management services. Example calculation uses mechanical reclamation model data.

$$\sum Cost\ \left(\frac{\$}{year}\right) = \left(\frac{\$}{year}\right)$$

$$\frac{\$2{,}000}{year} + \frac{\$36{,}750}{year} + \frac{\$25{,}812.50}{year} + \frac{\$7{,}006}{year} + \frac{\$3{,}318.75}{year} + \frac{\$1{,}229.77}{year} + \frac{\$19{,}500}{year} = \frac{\$95{,}617.02}{year}$$

G-3.9) Savings from Current Practice - Difference between current process annual cost and process modification annual cost. Example calculation uses mechanical reclamation model data.

$$Current\ Total\ Cost\ \left(\frac{\$}{year}\right) - Process\ Modification\ Total\ Cost\ \left(\frac{\$}{year}\right) = \left(\frac{\$}{year}\right)$$

$$\frac{\$122{,}702.30}{year} - \frac{\$95{,}617.02}{year} = \frac{\$27{,}085.28}{year}$$

G-3.10) Simple Payback - Number of years necessary for annual savings to meet initial equipment modification cost. Example calculation uses mechanical reclamation model data.

$$\frac{New\ Equipment\ Cost\ (\$)}{Annual\ Savings\ \left(\frac{\$}{year}\right)} = (years)$$

$$\frac{\$300{,}000}{\$27{,}085.28/year} = 11.1\ years$$

G-4: Energy Balance and GHG Estimate

G-4.1) Virgin Sand Diesel Usage - Diesel consumption for all one-way trips from virgin sand source to the foundry. Example calculation uses mechanical reclamation model data.

$$\frac{Virgin\ Sand\ Mileage\ \left(\frac{miles}{year}\right)}{Truck\ Gas\ Mileage\ \left(\frac{miles}{gallon}\right)} = \left(\frac{gallons}{year}\right)$$

$$\frac{31{,}354\,\frac{miles}{year}}{6.5\,\frac{miles}{gallon}} = 4{,}824\,\frac{gallons}{year}$$

G-4.2) Waste Management Diesel Usage - Diesel consumption for all two-way trips from the foundry to the landfill taken by the waste management service.

$$\frac{Waste\ Management\ Services\ \left(\frac{services}{year}\right) * Landfill\ Distance\ \left(\frac{miles}{service}\right)}{Truck\ Gas\ Mileage\ \left(\frac{miles}{gallon}\right)} = \left(\frac{gallons}{year}\right)$$

$$\frac{156\,\frac{services}{year} * 54\,\frac{miles}{service}}{6.5\,\frac{miles}{gallon}} = 1{,}296\,\frac{gallons}{year}$$

G-4.3) Landfill Diesel Usage - Diesel consumption for all two-way trips from the foundry to the landfill taken by foundry personnel. Example calculation uses mechanical reclamation model data.

$$\frac{Landfill\ Mileage\ \left(\frac{miles}{year}\right)}{Truck\ Gas\ Mileage\ \left(\frac{miles}{gallon}\right)} = \left(\frac{gallons}{year}\right)$$

$$\frac{1{,}350\,\frac{miles}{year}}{6.5\,\frac{miles}{gallon}} = 208\,\frac{gallons}{year}$$

G-4.4) Total Diesel Usage - Sum of all diesel usage used by a process model. Example calculation uses mechanical reclamation model data.

$$Virgin\ Sand\ Diesel\ Usage\ \left(\frac{gallons}{year}\right) + Waste\ Management\ Diesel\ Usage\ \left(\frac{gallons}{year}\right) + Landfill\ Diesel\ Usage\ \left(\frac{gallons}{year}\right) = \left(\frac{gallons}{year}\right)$$

$$4{,}824\frac{gallons}{year} + 1{,}296\frac{gallons}{year} + 208\frac{gallons}{year} = 6{,}328\frac{gallons}{year}$$

G-4.5) Equivalent Energy - Total energy used in process model by diesel consumption, electricity usage, and natural gas usage if applicable. Conversion factors taken from EIA energy calculator[1].

$$\sum X * Conversion\ Factor = \left(\frac{MMBTU}{year}\right)$$

X = Diesel Usage, Natural Gas Usage, Electricity Usage

$$\left(\left(3{,}708\frac{gallons}{year} * 137{,}381\frac{BTU}{gallon}\right) + \left(10{,}965\frac{therms}{year} * 99{,}976.1\frac{BTU}{therm}\right) + \left(65{,}470\frac{kWh}{year} * 3{,}412\frac{BTU}{kWh}\right)\right) * \frac{1\ MMBTU}{10^6 BTU} = 1{,}829\frac{MMBTU}{year}$$

G-4.6) Equivalent Greenhouse Gas Emissions - Total CO_2 equivalent emissions caused by diesel consumption, electricity usage, and natural gas usage if applicable. Conversion factors taken from EPA emission factors literature[2].

$$\sum X * Conversion\ Factor = \left(\frac{MTCO2e}{year}\right)$$

X = Diesel Usage, Natural Gas Usage, Electricity Usage

$$\left(3{,}708\frac{gallons}{year} * 0.01018\frac{MTCO2e}{gallon}\right) + \left(10{,}965\frac{therms}{year} * 0.005302\frac{MTCO2e}{therm}\right) + \left(65{,}470\frac{kWh}{year} * 0.00153636\frac{MTCO2e}{kWh}\right) = 196.5\frac{MTCO2e}{year}$$

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[1] **US EIA (Energy Information Administration) (2017), Energy Conversion Calculators,** https://www.eia.gov/energyexplained/index.cfm?page=about_energy_conversion_calculator **(2.22.2017).**

[2] **United States Environmental Protection Agency (2014), Emission Factors for Greenhouse Gas Inventories,** https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf **(3.16.2017)**

G-5: Simapro Model Input Calculations

G-5.1) Normalization to Functional Unit - Functional unit is 1 ton of cured mold and core sand. Each input variable must be normalized to this functional unit.

$$\frac{Variable\ Annual\ Total\ \left(\frac{x}{year}\right)}{Total\ Cured\ Mold\ and\ Core\ Sand\ \left(\frac{tons}{year}\right)} = \left(\frac{x}{ton}\right)$$

G-5.2) Sand {RoW}| gravel and quarry operation | Alloc Def, U - Simapro title of category. Uses Ecoinvent v3.3 data to account for quarry operations from raw extraction to final sand preparation for transport.

$$Virgin\ Sand\ Purchased\ \left(\frac{tons}{day}\right) * Operation\ Days\ \left(\frac{days}{year}\right) = \left(\frac{tons}{year}\right)$$

$$1.75\frac{tons}{day} * 250\frac{days}{year} = 437.5\frac{tons}{year}$$

Normalization:

$$\frac{437.5\frac{tons}{year}}{8750\frac{tons}{year}} = 0.05\frac{tons}{ton}$$

G-5.3) Electricity, high voltage {MRO, US only}| production mix | Alloc Def, U - Simapro title of category. Uses Ecoinvent 3.3 data to account for the electricity generation, transport, and use at the foundry.

$$Mold\ and\ Core\ Mixers\ \left(\frac{kWh}{year}\right) + Shakeout\ \left(\frac{kWh}{year}\right) + Magnetic\ Separator\ \left(\frac{kWh}{year}\right) + Baghouse\ Fans\ \left(\frac{kWh}{year}\right) + Process\ Electricity\ \left(\frac{kWh}{year}\right) = \left(\frac{kWh}{year}\right)$$

$$46{,}200\frac{kWh}{year} + 1{,}875\frac{kWh}{year} + 925\frac{kWh}{year} + 120\frac{kWh}{year} + 16350\frac{kWh}{year} = 65{,}470\frac{kWh}{year}$$

Normalization:

$$\frac{65{,}470\frac{kWh}{year}}{8750\frac{tons}{year}} = 7.5\frac{kWh}{ton}$$

G-5.4) Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at industrial furnace >100 kW|Alloc Def, U - Simapro title of category. Uses Ecoinvent 3.3 data to account for natural gas extraction, transportation, and use at the foundry.

$$Total\ Natural\ Gas\ \left(\frac{Therms}{year}\right)$$

$$10{,}965\,\frac{therms}{year}$$

Normalization:

$$\frac{10{,}965\,\frac{therms}{year}}{8{,}750\,\frac{tons}{year}} = 1.25\,\frac{therms}{ton}$$

G-5.5) Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Def, U - Simapro title of category. Uses Ecoinvent 3.3 data to account for all sand transportation to and from the foundry. Example calculations use mechanical reclamation model data.

G-5.5.a) Virgin Sand Transport

$$\big(Empty\ Semi\ (tons) + Virgin\ Sand\ (tons)\big) * Virgin\ Sand\ Mileage\ \left(\frac{miles}{year}\right) = \left(\frac{ton - miles}{year}\right)$$

$$(16\ tons + 12\ tons) * 31{,}354\ miles = 877{,}912\ \frac{ton - miles}{year}$$

G-5.5.b) Landfill Transport

$$\left(\big(Empty\ Truck\ (tons) + Spent\ Sand\ (Tons)\big) * Landfill\ One - Way\ Mileage\ \left(\frac{miles}{year}\right)\right) + \left(Empty\ Truck\ (tons) * Landfill\ One - Way\ Mileage\ \left(\frac{miles}{year}\right)\right) = \left(\frac{ton - miles}{year}\right)$$

$$\left((14\ tons + 10\ tons) * 675\frac{miles}{year}\right) + \left(14\ tons * 675\frac{miles}{year}\right) = 25{,}650\ \left(\frac{ton - miles}{year}\right)$$

G-5.5.c) Waste Management Transport

$$\left(\left(Empty\ Truck\ (tons) + Spent\ Sand\ (Tons)\right) * Waste\ Management\ One - Way\ Mileage\ \left(\frac{miles}{year}\right)\right) + \left(Empty\ Truck\ (tons) * Waste\ Management\ One - Way\ Mileage\ \left(\frac{miles}{year}\right)\right) = \left(\frac{ton - miles}{year}\right)$$

$$\left((14\ tons + 10\ tons) * 4{,}212\frac{miles}{year}\right) + \left(14\ tons * 4{,}212\frac{miles}{year}\right) = 160{,}056\ \left(\frac{ton - miles}{year}\right)$$

G-5.5.d) Total Transport

$$Virgin\ Sand\ Transport\ \left(\frac{ton - mile}{year}\right) + Landfill\ Transport\left(\frac{ton - mile}{year}\right) + Waste\ Management\ Transport\left(\frac{ton - mile}{year}\right) = \left(\frac{ton - mile}{year}\right)$$

$$877{,}912\frac{ton - mile}{year} + 25{,}650\frac{ton - mile}{year} + 160{,}056\frac{ton - mile}{year} = 1{,}063{,}618\left(\frac{ton - mile}{year}\right)$$

Normalization:

$$\frac{1{,}063{,}618\ \frac{ton - mile}{year}}{8{,}750\frac{tons}{year}} = 121.6\frac{ton - mile}{ton}$$

G-6: Simapro Model Input Calculations

G-6.1) Spent Sand Volume - Spent sand volume being sent to the landfill.

$$\frac{Spent\ Sand\ Produced\ \left(\frac{tons}{year}\right) * 2{,}000\ \left(\frac{lbs}{ton}\right)}{Density\ of\ Spent\ Sand\ \left(\frac{lbs}{ft^3}\right) * 27\frac{ft^3}{yard^3}} = \left(\frac{yard^3}{year}\right)$$

$$\frac{1{,}125\ \left(\frac{tons}{year}\right) * 2{,}000\ \left(\frac{lbs}{ton}\right)}{102\ \left(\frac{lbs}{ft^3}\right) * 27\frac{ft^3}{yard^3}} = 817\left(\frac{yard^3}{year}\right)$$

G-6.2) Spent Sand Volume Reduction - Reduction of spent sand being sent to the landfill by implementing a secondary sand reclamation technology. Difference between spent sand volume of current practice and each reclamation process.

$$Spent\ Sand\ Volume_{Current}\left(\frac{yard^3}{year}\right) - Spent\ Sand\ Volume_{Mechanical}\left(\frac{yard^3}{year}\right) = \left(\frac{yard^3}{year}\right)$$

$$1{,}089.3\ \left(\frac{yard^3}{year}\right) - 817\left(\frac{yard^3}{year}\right) = 272.3\left(\frac{yard^3}{year}\right)$$

G-6.3) Spent Sand Landfill Footprint Usage - Spent sand equivalent landfill footprint usage. Based on total landfill headspace and land area coverage.

$$Spent\ Sand\ Volume\ \left(\frac{yard^3}{year}\right) * \frac{Landfill\ Footprint\ (acres)}{Landfill\ Headspace\ (yard^3)} * 43{,}560\frac{ft^2}{acre} = \left(\frac{ft^2}{year}\right)$$

$$817\ \left(\frac{yard^3}{year}\right) * \frac{160\ (acres)}{15{,}597{,}445\ (yard^3)} * 43{,}560\frac{ft^2}{acre} = 365.1\left(\frac{ft^2}{year}\right)$$

G-6.4) Current Landfill Loading - Volume of annual waste going to landfill.

$$\frac{Waste\ Flow\ to\ Landfill\left(\frac{tons}{year}\right) * 2{,}000\left(\frac{lbs}{ton}\right)}{Average\ Density\ of\ Waste\ \left(\frac{lbs}{yard^3}\right)} = \left(\frac{yard^3}{year}\right)$$

$$\frac{543{,}596.24\left(\frac{tons}{year}\right)*2{,}000\left(\frac{lbs}{ton}\right)}{1{,}000\ \left(\frac{lbs}{yard^3}\right)}=1{,}087{,}192\left(\frac{yard^3}{year}\right)$$

G-6.5) Current Landfill Lifespan - What is the lifespan of an equivalent empty landfill given current annual loading.

$$\frac{Landfill\ Headspace\ (yard^3)}{Current\ Landfill\ Loading\ \left(\frac{yard^3}{year}\right)}=(years)$$

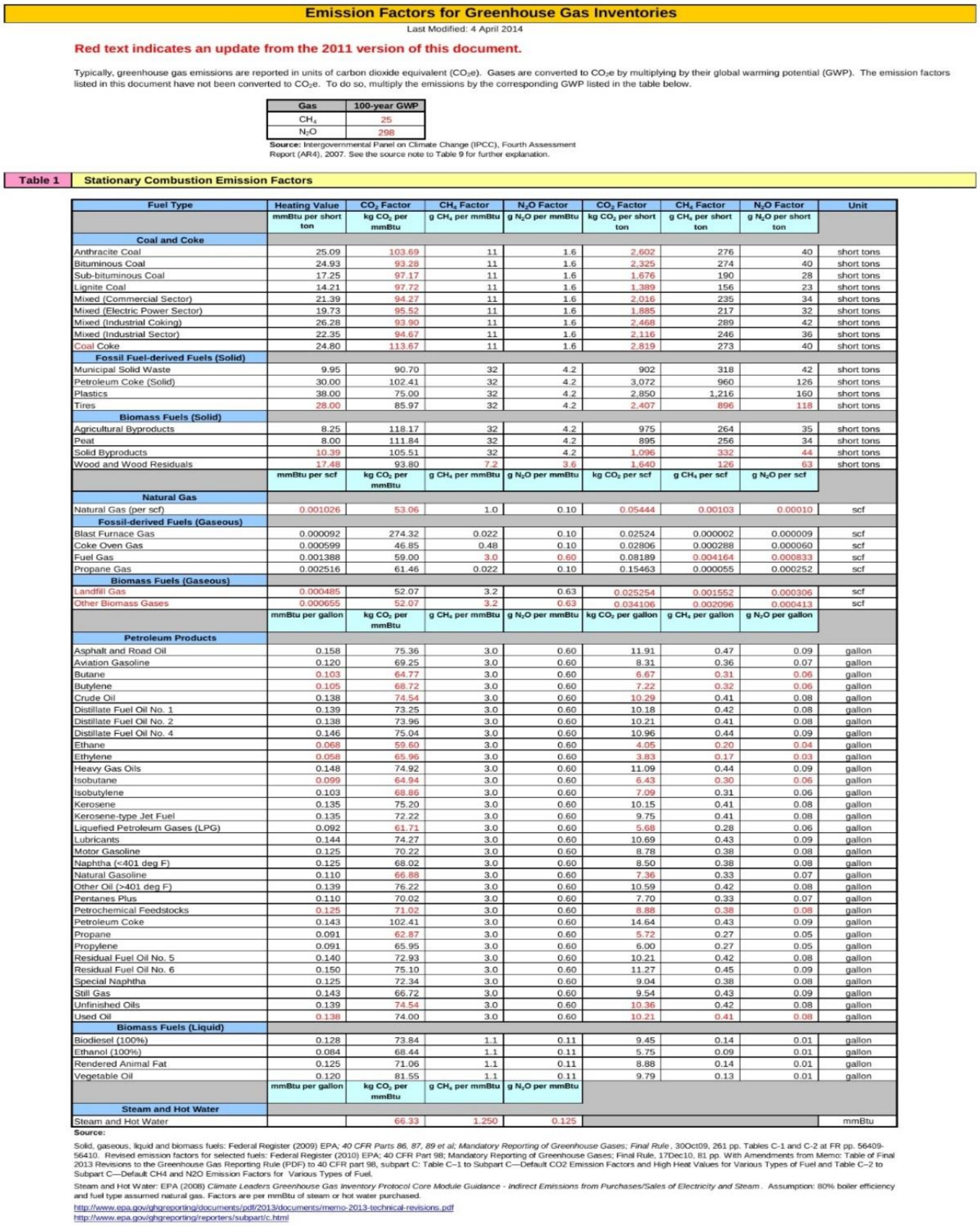
$$\frac{15{,}597{,}445\ (yard^3)}{1{,}087{,}192\ \left(\frac{yard^3}{year}\right)}=14.3\ (years)$$

G-6.6) Landfill Lifespan Increase - Increase in landfill lifespan if secondary reclamation was implemented at the foundry. Exact values in spreadsheet produce a more accurate result than the rounding presented here for clarity. Value here corresponds with spreadsheet value.

$$\left(\frac{Landfill\ Headspace\ (yard^3)}{Current\ Landfill\ Loading\ \left(\frac{yard^3}{year}\right)-Spent\ Sand\ Volume\ Reduction\ \left(\frac{yard^3}{year}\right)}\right.$$
$$\left.-\ Current\ Landfill\ Lifespan\ (years)\right)*365\left(\frac{days}{year}\right)=(days)$$

$$\left(\frac{15{,}597{,}445\ (yard^3)}{1{,}087{,}192\left(\frac{yard^3}{year}\right)-272.3\ \left(\frac{yard^3}{year}\right)}-14.3\ (years)\right)*365\left(\frac{days}{year}\right)=1.3\ (days)$$

Appendix H: Environmental Protection Agency Greenhouse Gas Conversion Tool



Emission Factors for Greenhouse Gas Inventories

Last Modified: 4 April 2014

Red text indicates an update from the 2011 version of this document.

Typically, greenhouse gas emissions are reported in units of carbon dioxide equivalent (CO_2e). Gases are converted to CO_2e by multiplying by their global warming potential (GWP). The emission factors listed in this document have not been converted to CO_2e. To do so, multiply the emissions by the corresponding GWP listed in the table below.

Gas	100-year GWP
CH_4	25
N_2O	298

Source: Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4), 2007. See the source note to Table 9 for further explanation.

Table 1 **Stationary Combustion Emission Factors**

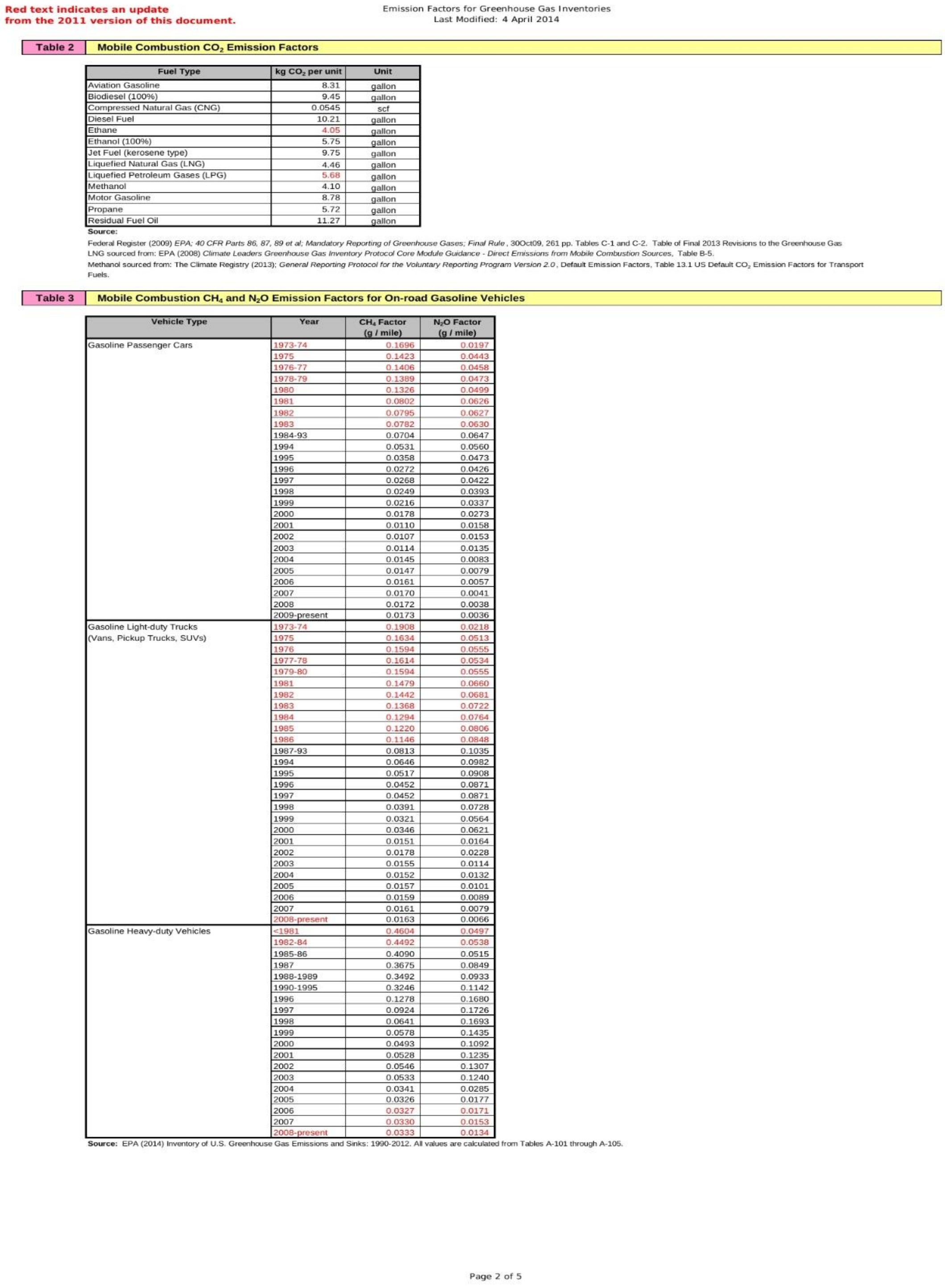
Fuel Type	Heating Value	CO_2 Factor	CH_4 Factor	N_2O Factor	CO_2 Factor	CH_4 Factor	N_2O Factor	Unit
	mmBtu per short ton	kg CO_2 per mmBtu	g CH_4 per mmBtu	g N_2O per mmBtu	kg CO_2 per short ton	g CH_4 per short ton	g N_2O per short ton	
Coal and Coke								
Anthracite Coal	25.09	103.69	11	1.6	2,602	276	40	short tons
Bituminous Coal	24.93	93.28	11	1.6	2,325	274	40	short tons
Sub-bituminous Coal	17.25	97.17	11	1.6	1,676	190	28	short tons
Lignite Coal	14.21	97.72	11	1.6	1,389	156	23	short tons
Mixed (Commercial Sector)	21.39	94.27	11	1.6	2,016	235	34	short tons
Mixed (Electric Power Sector)	19.73	95.52	11	1.6	1,885	217	32	short tons
Mixed (Industrial Coking)	26.28	93.90	11	1.6	2,468	289	42	short tons
Mixed (Industrial Sector)	22.35	94.67	11	1.6	2,116	246	36	short tons
Coal Coke	24.80	113.67	11	1.6	2,819	273	40	short tons
Fossil Fuel-derived Fuels (Solid)								
Municipal Solid Waste	9.95	90.70	32	4.2	902	318	42	short tons
Petroleum Coke (Solid)	30.00	102.41	32	4.2	3,072	960	126	short tons
Plastics	38.00	75.00	32	4.2	2,850	1,216	160	short tons
Tires	28.00	85.97	32	4.2	2,407	896	118	short tons
Biomass Fuels (Solid)								
Agricultural Byproducts	8.25	118.17	32	4.2	975	264	35	short tons
Peat	8.00	111.84	32	4.2	895	256	34	short tons
Solid Byproducts	10.39	105.51	32	4.2	1,096	332	44	short tons
Wood and Wood Residuals	17.48	93.80	7.2	3.6	1,640	126	63	short tons
	mmBtu per scf	kg CO_2 per mmBtu	g CH_4 per mmBtu	g N_2O per mmBtu	kg CO_2 per scf	g CH_4 per scf	g N_2O per scf	
Natural Gas								
Natural Gas (per scf)	0.001026	53.06	1.0	0.10	0.05444	0.00103	0.00010	scf
Fossil-derived Fuels (Gaseous)								
Blast Furnace Gas	0.000092	274.32	0.022	0.10	0.02524	0.000002	0.000009	scf
Coke Oven Gas	0.000599	46.85	0.48	0.10	0.02806	0.000288	0.000060	scf
Fuel Gas	0.001388	59.00	3.0	0.60	0.08189	0.004164	0.000833	scf
Propane Gas	0.002516	61.46	0.022	0.10	0.15463	0.000055	0.000252	scf
Biomass Fuels (Gaseous)								
Landfill Gas	0.000485	52.07	3.2	0.63	0.025254	0.001552	0.000306	scf
Other Biomass Gases	0.000655	52.07	3.2	0.63	0.034106	0.002096	0.000413	scf
	mmBtu per gallon	kg CO_2 per mmBtu	g CH_4 per mmBtu	g N_2O per mmBtu	kg CO_2 per gallon	g CH_4 per gallon	g N_2O per gallon	
Petroleum Products								
Asphalt and Road Oil	0.158	75.36	3.0	0.60	11.91	0.47	0.09	gallon
Aviation Gasoline	0.120	69.25	3.0	0.60	8.31	0.36	0.07	gallon
Butane	0.103	64.77	3.0	0.60	6.67	0.31	0.06	gallon
Butylene	0.105	68.72	3.0	0.60	7.22	0.32	0.06	gallon
Crude Oil	0.138	74.54	3.0	0.60	10.29	0.41	0.08	gallon
Distillate Fuel Oil No. 1	0.139	73.25	3.0	0.60	10.18	0.42	0.08	gallon
Distillate Fuel Oil No. 2	0.138	73.96	3.0	0.60	10.21	0.41	0.08	gallon
Distillate Fuel Oil No. 4	0.146	75.04	3.0	0.60	10.96	0.44	0.09	gallon
Ethane	0.068	59.60	3.0	0.60	4.05	0.20	0.04	gallon
Ethylene	0.058	65.96	3.0	0.60	3.83	0.17	0.03	gallon
Heavy Gas Oils	0.148	74.92	3.0	0.60	11.09	0.44	0.09	gallon
Isobutane	0.099	64.94	3.0	0.60	6.43	0.30	0.06	gallon
Isobutylene	0.103	68.86	3.0	0.60	7.09	0.31	0.06	gallon
Kerosene	0.135	75.20	3.0	0.60	10.15	0.41	0.08	gallon
Kerosene-type Jet Fuel	0.135	72.22	3.0	0.60	9.75	0.41	0.08	gallon
Liquefied Petroleum Gases (LPG)	0.092	61.71	3.0	0.60	5.68	0.28	0.06	gallon
Lubricants	0.144	74.27	3.0	0.60	10.69	0.43	0.09	gallon
Motor Gasoline	0.125	70.22	3.0	0.60	8.78	0.38	0.08	gallon
Naphtha (<401 deg F)	0.125	68.02	3.0	0.60	8.50	0.38	0.08	gallon
Natural Gasoline	0.110	66.88	3.0	0.60	7.36	0.33	0.07	gallon
Other Oil (>401 deg F)	0.139	76.22	3.0	0.60	10.59	0.42	0.08	gallon
Pentanes Plus	0.110	70.02	3.0	0.60	7.70	0.33	0.07	gallon
Petrochemical Feedstocks	0.125	71.02	3.0	0.60	8.88	0.38	0.08	gallon
Petroleum Coke	0.143	102.41	3.0	0.60	14.64	0.43	0.09	gallon
Propane	0.091	62.87	3.0	0.60	5.72	0.27	0.05	gallon
Propylene	0.091	65.95	3.0	0.60	6.00	0.27	0.05	gallon
Residual Fuel Oil No. 5	0.140	72.93	3.0	0.60	10.21	0.42	0.08	gallon
Residual Fuel Oil No. 6	0.150	75.10	3.0	0.60	11.27	0.45	0.09	gallon
Special Naphtha	0.125	72.34	3.0	0.60	9.04	0.38	0.08	gallon
Still Gas	0.143	66.72	3.0	0.60	9.54	0.43	0.09	gallon
Unfinished Oils	0.139	74.54	3.0	0.60	10.36	0.42	0.08	gallon
Used Oil	0.138	74.00	3.0	0.60	10.21	0.41	0.08	gallon
Biomass Fuels (Liquid)								
Biodiesel (100%)	0.128	73.84	1.1	0.11	9.45	0.14	0.01	gallon
Ethanol (100%)	0.084	68.44	1.1	0.11	5.75	0.09	0.01	gallon
Rendered Animal Fat	0.125	71.06	1.1	0.11	8.88	0.14	0.01	gallon
Vegetable Oil	0.120	81.55	1.1	0.11	9.79	0.13	0.01	gallon
	mmBtu per gallon	kg CO_2 per mmBtu	g CH_4 per mmBtu	g N_2O per mmBtu				
Steam and Hot Water								
Steam and Hot Water		66.33	1.250	0.125				mmBtu

Source:

Solid, gaseous, liquid and biomass fuels: Federal Register (2009) EPA; *40 CFR Parts 86, 87, 89 et al; Mandatory Reporting of Greenhouse Gases; Final Rule*, 30Oct09, 261 pp. Tables C-1 and C-2 at FR pp. 56409-56410. Revised emission factors for selected fuels: Federal Register (2010) EPA; 40 CFR Part 98; Mandatory Reporting of Greenhouse Gases; Final Rule, 17Dec10, 81 pp. With Amendments from Memo: Table of Final 2013 Revisions to the Greenhouse Gas Reporting Rule (PDF) to 40 CFR part 98, subpart C: Table C–1 to Subpart C—Default CO2 Emission Factors and High Heat Values for Various Types of Fuel and Table C–2 to Subpart C—Default CH4 and N2O Emission Factors for Various Types of Fuel.

Steam and Hot Water: EPA (2008) *Climate Leaders Greenhouse Gas Inventory Protocol Core Module Guidance - Indirect Emissions from Purchases/Sales of Electricity and Steam*. Assumption: 80% boiler efficiency and fuel type assumed natural gas. Factors are per mmBtu of steam or hot water purchased.

http://www.epa.gov/ghgreporting/documents/pdf/2013/documents/memo-2013-technical-revisions.pdf
http://www.epa.gov/ghgreporting/reporters/subpart/c.html



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Emission Factors for Greenhouse Gas Inventories
Last Modified: 4 April 2014

Table 2 Mobile Combustion CO_2 Emission Factors

Fuel Type	kg CO_2 per unit	Unit
Aviation Gasoline	8.31	gallon
Biodiesel (100%)	9.45	gallon
Compressed Natural Gas (CNG)	0.0545	scf
Diesel Fuel	10.21	gallon
Ethane	4.05	gallon
Ethanol (100%)	5.75	gallon
Jet Fuel (kerosene type)	9.75	gallon
Liquefied Natural Gas (LNG)	4.46	gallon
Liquefied Petroleum Gases (LPG)	5.68	gallon
Methanol	4.10	gallon
Motor Gasoline	8.78	gallon
Propane	5.72	gallon
Residual Fuel Oil	11.27	gallon

Source:

Federal Register (2009) *EPA; 40 CFR Parts 86, 87, 89 et al; Mandatory Reporting of Greenhouse Gases; Final Rule*, 30Oct09, 261 pp. Tables C-1 and C-2. Table of Final 2013 Revisions to the Greenhouse Gas

LNG sourced from: EPA (2008) *Climate Leaders Greenhouse Gas Inventory Protocol Core Module Guidance - Direct Emissions from Mobile Combustion Sources*, Table B-5.

Methanol sourced from: The Climate Registry (2013); *General Reporting Protocol for the Voluntary Reporting Program Version 2.0*, Default Emission Factors, Table 13.1 US Default CO_2 Emission Factors for Transport Fuels.

Table 3 Mobile Combustion CH_4 and N_2O Emission Factors for On-road Gasoline Vehicles

Vehicle Type	Year	CH_4 Factor (g / mile)	N_2O Factor (g / mile)
Gasoline Passenger Cars	1973-74	0.1696	0.0197
	1975	0.1423	0.0443
	1976-77	0.1406	0.0458
	1978-79	0.1389	0.0473
	1980	0.1326	0.0499
	1981	0.0802	0.0626
	1982	0.0795	0.0627
	1983	0.0782	0.0630
	1984-93	0.0704	0.0647
	1994	0.0531	0.0560
	1995	0.0358	0.0473
	1996	0.0272	0.0426
	1997	0.0268	0.0422
	1998	0.0249	0.0393
	1999	0.0216	0.0337
	2000	0.0178	0.0273
	2001	0.0110	0.0158
	2002	0.0107	0.0153
	2003	0.0114	0.0135
	2004	0.0145	0.0083
	2005	0.0147	0.0079
	2006	0.0161	0.0057
	2007	0.0170	0.0041
	2008	0.0172	0.0038
	2009-present	0.0173	0.0036
Gasoline Light-duty Trucks (Vans, Pickup Trucks, SUVs)	1973-74	0.1908	0.0218
	1975	0.1634	0.0513
	1976	0.1594	0.0555
	1977-78	0.1614	0.0534
	1979-80	0.1594	0.0555
	1981	0.1479	0.0660
	1982	0.1442	0.0681
	1983	0.1368	0.0722
	1984	0.1294	0.0764
	1985	0.1220	0.0806
	1986	0.1146	0.0848
	1987-93	0.0813	0.1035
	1994	0.0646	0.0982
	1995	0.0517	0.0908
	1996	0.0452	0.0871
	1997	0.0452	0.0871
	1998	0.0391	0.0728
	1999	0.0321	0.0564
	2000	0.0346	0.0621
	2001	0.0151	0.0164
	2002	0.0178	0.0228
	2003	0.0155	0.0114
	2004	0.0152	0.0132
	2005	0.0157	0.0101
	2006	0.0159	0.0089
	2007	0.0161	0.0079
	2008-present	0.0163	0.0066
Gasoline Heavy-duty Vehicles	<1981	0.4604	0.0497
	1982-84	0.4492	0.0538
	1985-86	0.4090	0.0515
	1987	0.3675	0.0849
	1988-1989	0.3492	0.0933
	1990-1995	0.3246	0.1142
	1996	0.1278	0.1680
	1997	0.0924	0.1726
	1998	0.0641	0.1693
	1999	0.0578	0.1435
	2000	0.0493	0.1092
	2001	0.0528	0.1235
	2002	0.0546	0.1307
	2003	0.0533	0.1240
	2004	0.0341	0.0285
	2005	0.0326	0.0177
	2006	0.0327	0.0171
	2007	0.0330	0.0153
	2008-present	0.0333	0.0134

Source: EPA (2014) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012. All values are calculated from Tables A-101 through A-105.

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Table 4 **Mobile Combustion CH_4 and N_2O Emission Factors for On-road Diesel and Alternative Fuel Vehicles**

Vehicle Type	Vehicle Year	CH_4 Factor (g / mile)	N_2O Factor (g / mile)
Diesel Passenger Cars	1960-1982	0.0006	0.0012
	1983-1995	0.0005	0.0010
	1996-present	0.0005	0.0010
Diesel Light-duty Trucks	1960-1982	0.0011	0.0017
	1983-1995	0.0009	0.0014
	1996-present	0.0010	0.0015
Diesel Medium- and Heavy-duty Vehicles	1960-present	0.0051	0.0048
Gasoline Motorcycles	1960-1995	0.0899	0.0087
	1996-present	0.0672	0.0069
CNG Light-duty Vehicles		0.7370	0.0500
CNG Heavy-duty Vehicles		1.9660	0.1750
CNG Buses		1.9660	0.1750
LPG Light-duty Vehicles		0.0370	0.0670
LPG Heavy-duty Vehicles		0.0660	0.1750
LNG Heavy-duty Vehicles		1.9660	0.1750
Ethanol Light-duty Vehicles		0.0550	0.0670
Ethanol Heavy-duty Vehicles		0.1970	0.1750
Ethanol Buses		0.1970	0.1750

Source: EPA (2014) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012. All values are calculated from Tables A-104 through A-106.

Table 5 **Mobile Combustion CH_4 and N_2O Emission Factors for Non-road Vehicles**

Vehicle Type	CH_4 Factor (g / gallon)	N_2O Factor (g / gallon)
LPG Non-Highway Vehicles	0.50	0.22
Residual Oil Ships and Boats	0.11	0.57
Diesel Ships and Boats	0.06	0.45
Gasoline Ships and Boats	0.64	0.22
Diesel Locomotives	0.80	0.26
Gasoline Agricultural Equip.	1.26	0.22
Diesel Agricultural Equip.	1.44	0.26
Gasoline Construction Equip.	0.50	0.22
Diesel Construction Equip.	0.57	0.26
Jet Fuel Aircraft	0.00	0.30
Aviation Gasoline Aircraft	7.06	0.11
Biodiesel Vehicles	0.57	0.26
Other Diesel Sources	0.57	0.26
Other Gasoline Sources	0.50	0.22

Source: EPA (2014) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012. All values are calculated from Table A-107.
Note: LPG non-highway vehicles assumed equal to other gasoline sources. Biodiesel vehicles assumed equal to other diesel sources.

Table 6 **Electricity Emission Factors**

eGRID Subregion	Total output emission factors			Non-baseload emission factors		
	CO_2 Factor (lb CO_2 /MWh)	CH_4 Factor (lb CH_4 /MWh)	N_2O Factor (lb N_2O /MWh)	CO_2 Factor (lb CO_2/MWh)	CH_4 Factor (lb CH_4/MWh)	N_2O Factor (lb N_2O/MWh)
AKGD (ASCC Alaska Grid)	1,256.87	0.02608	0.00718	1,387.37	0.03405	0.00693
AKMS (ASCC Miscellaneous)	448.57	0.01874	0.00368	1,427.76	0.05997	0.01180
AZNM (WECC Southwest)	1,177.61	0.01921	0.01572	1,210.44	0.02188	0.00986
CAMX (WECC California)	610.82	0.02849	0.00603	932.82	0.03591	0.00455
ERCT (ERCOT All)	1,218.17	0.01685	0.01407	1,181.70	0.02012	0.00763
FRCC (FRCC All)	1,196.71	0.03891	0.01375	1,277.42	0.03873	0.01083
HIMS (HICC Miscellaneous)	1,330.16	0.07398	0.01388	1,690.72	0.10405	0.01912
HIOA (HICC Oahu)	1,621.86	0.09930	0.02241	1,588.23	0.11948	0.02010
MROE (MRO East)	1,610.80	0.02429	0.02752	1,755.66	0.03153	0.02799
MROW (MRO West)	1,536.36	0.02853	0.02629	2,054.55	0.05986	0.03553
NEWE (NPCC New England)	722.07	0.07176	0.01298	1,106.82	0.06155	0.01207
NWPP (WECC Northwest)	842.58	0.01605	0.01307	1,340.34	0.04138	0.01784
NYCW (NPCC NYC/Westchester)	622.42	0.02381	0.00280	1,131.63	0.02358	0.00244
NYLI (NPCC Long Island)	1,336.11	0.08149	0.01028	1,445.94	0.03403	0.00391
NYUP (NPCC Upstate NY)	545.79	0.01630	0.00724	1,253.77	0.03683	0.01367
RFCE (RFC East)	1,001.72	0.02707	0.01533	1,562.72	0.03593	0.02002
RFCM (RFC Michigan)	1,629.38	0.03046	0.02684	1,744.52	0.03231	0.02600
RFCW (RFC West)	1,503.47	0.01820	0.02475	1,982.87	0.02450	0.03107
RMPA (WECC Rockies)	1,896.74	0.02266	0.02921	1,808.03	0.02456	0.02289
SPNO (SPP North)	1,799.45	0.02081	0.02862	1,951.83	0.02515	0.02690
SPSO (SPP South)	1,580.60	0.02320	0.02085	1,436.29	0.02794	0.01210
SRMV (SERC Mississippi Valley)	1,029.82	0.02066	0.01076	1,222.40	0.02771	0.00663
SRMW (SERC Midwest)	1,810.83	0.02048	0.02957	1,964.98	0.02393	0.02965
SRSO (SERC South)	1,354.09	0.02282	0.02089	1,574.37	0.02652	0.02149
SRTV (SERC Tennessee Valley)	1,389.20	0.01770	0.02241	1,873.83	0.02499	0.02888
SRVC (SERC Virginia/Carolina)	1,073.65	0.02169	0.01764	1,624.71	0.03642	0.02306
US Average	1,232.35	0.02414	0.01826	1,520.20	0.03127	0.01834

Source: EPA Year 2010 eGRID 9th edition Version 1.0 February 2014.
Note: Total output emission factors are used for quantifying emissions from purchased electricity. Non-baseload emission factors are used for quantifying the emission reductions from purchased green power.

This is a representational map; many of the boundaries shown on this map are approximate because they are based on companies, not on strictly geographical boundaries.
Source: EPA Year 2010 eGRID 9th edition Version 1.0 February 2014.

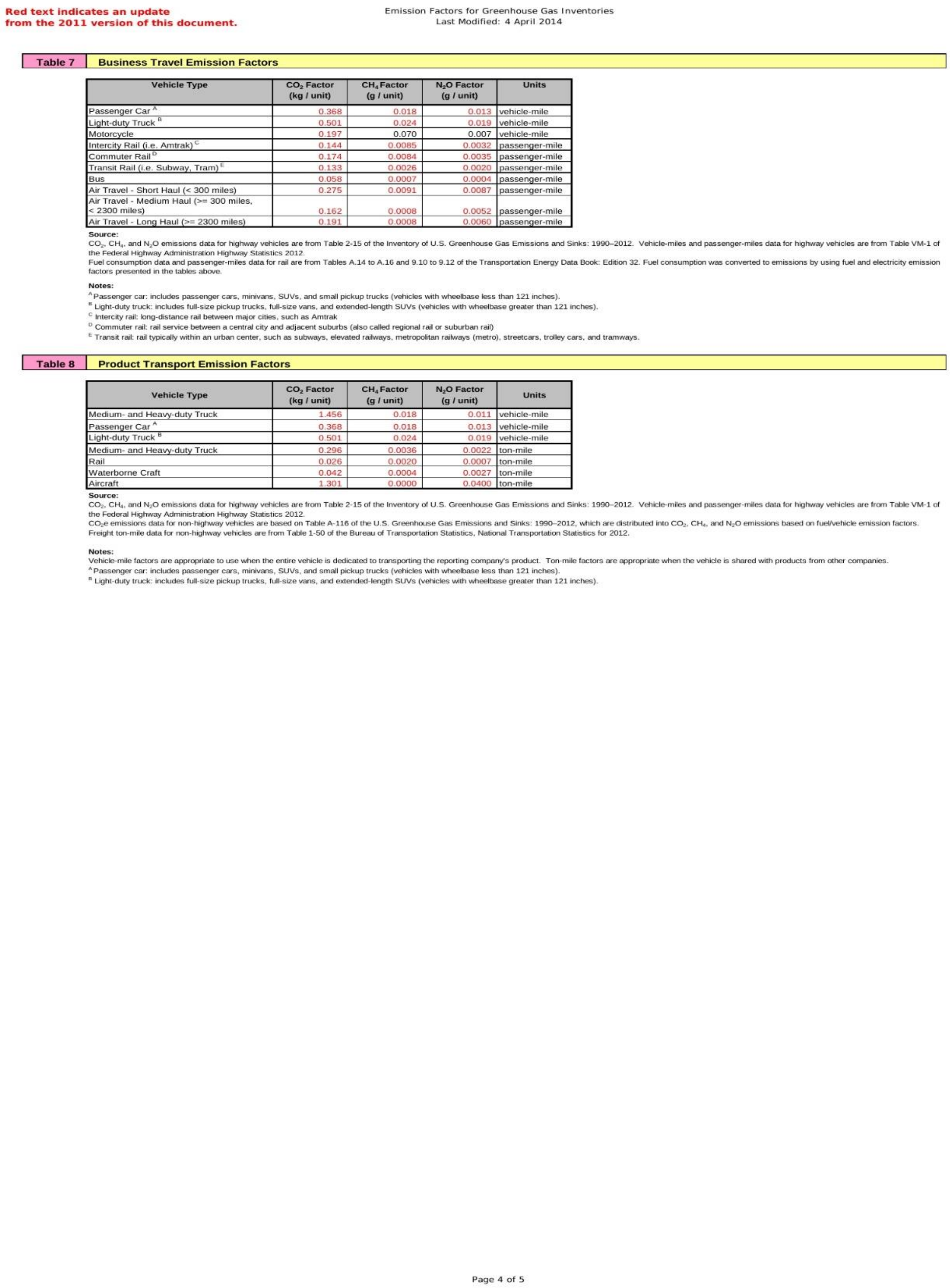

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Table 7 Business Travel Emission Factors

Vehicle Type	CO_2 Factor (kg / unit)	CH_4 Factor (g / unit)	N_2O Factor (g / unit)	Units
Passenger Car [A]	0.368	0.018	0.013	vehicle-mile
Light-duty Truck [B]	0.501	0.024	0.019	vehicle-mile
Motorcycle	0.197	0.070	0.007	vehicle-mile
Intercity Rail (i.e. Amtrak) [C]	0.144	0.0085	0.0032	passenger-mile
Commuter Rail [D]	0.174	0.0084	0.0035	passenger-mile
Transit Rail (i.e. Subway, Tram) [E]	0.133	0.0026	0.0020	passenger-mile
Bus	0.058	0.0007	0.0004	passenger-mile
Air Travel - Short Haul (< 300 miles)	0.275	0.0091	0.0087	passenger-mile
Air Travel - Medium Haul (>= 300 miles, < 2300 miles)	0.162	0.0008	0.0052	passenger-mile
Air Travel - Long Haul (>= 2300 miles)	0.191	0.0008	0.0060	passenger-mile

Source:

CO_2, CH_4, and N_2O emissions data for highway vehicles are from Table 2-15 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012. Vehicle-miles and passenger-miles data for highway vehicles are from Table VM-1 of the Federal Highway Administration Highway Statistics 2012.

Fuel consumption data and passenger-miles data for rail are from Tables A.14 to A.16 and 9.10 to 9.12 of the Transportation Energy Data Book: Edition 32. Fuel consumption was converted to emissions by using fuel and electricity emission factors presented in the tables above.

Notes:

[A] Passenger car: includes passenger cars, minivans, SUVs, and small pickup trucks (vehicles with wheelbase less than 121 inches).

[B] Light-duty truck: includes full-size pickup trucks, full-size vans, and extended-length SUVs (vehicles with wheelbase greater than 121 inches).

[C] Intercity rail: long-distance rail between major cities, such as Amtrak

[D] Commuter rail: rail service between a central city and adjacent suburbs (also called regional rail or suburban rail)

[E] Transit rail: rail typically within an urban center, such as subways, elevated railways, metropolitan railways (metro), streetcars, trolley cars, and tramways.

Table 8 Product Transport Emission Factors

Vehicle Type	CO_2 Factor (kg / unit)	CH_4 Factor (g / unit)	N_2O Factor (g / unit)	Units
Medium- and Heavy-duty Truck	1.456	0.018	0.011	vehicle-mile
Passenger Car [A]	0.368	0.018	0.013	vehicle-mile
Light-duty Truck [B]	0.501	0.024	0.019	vehicle-mile
Medium- and Heavy-duty Truck	0.296	0.0036	0.0022	ton-mile
Rail	0.026	0.0020	0.0007	ton-mile
Waterborne Craft	0.042	0.0004	0.0027	ton-mile
Aircraft	1.301	0.0000	0.0400	ton-mile

Source:

CO_2, CH_4, and N_2O emissions data for highway vehicles are from Table 2-15 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012. Vehicle-miles and passenger-miles data for highway vehicles are from Table VM-1 of the Federal Highway Administration Highway Statistics 2012.

CO_2e emissions data for non-highway vehicles are based on Table A-116 of the U.S. Greenhouse Gas Emissions and Sinks: 1990–2012, which are distributed into CO_2, CH_4, and N_2O emissions based on fuel/vehicle emission factors.

Freight ton-mile data for non-highway vehicles are from Table 1-50 of the Bureau of Transportation Statistics, National Transportation Statistics for 2012.

Notes:

Vehicle-mile factors are appropriate to use when the entire vehicle is dedicated to transporting the reporting company's product. Ton-mile factors are appropriate when the vehicle is shared with products from other companies.

[A] Passenger car: includes passenger cars, minivans, SUVs, and small pickup trucks (vehicles with wheelbase less than 121 inches).

[B] Light-duty truck: includes full-size pickup trucks, full-size vans, and extended-length SUVs (vehicles with wheelbase greater than 121 inches).

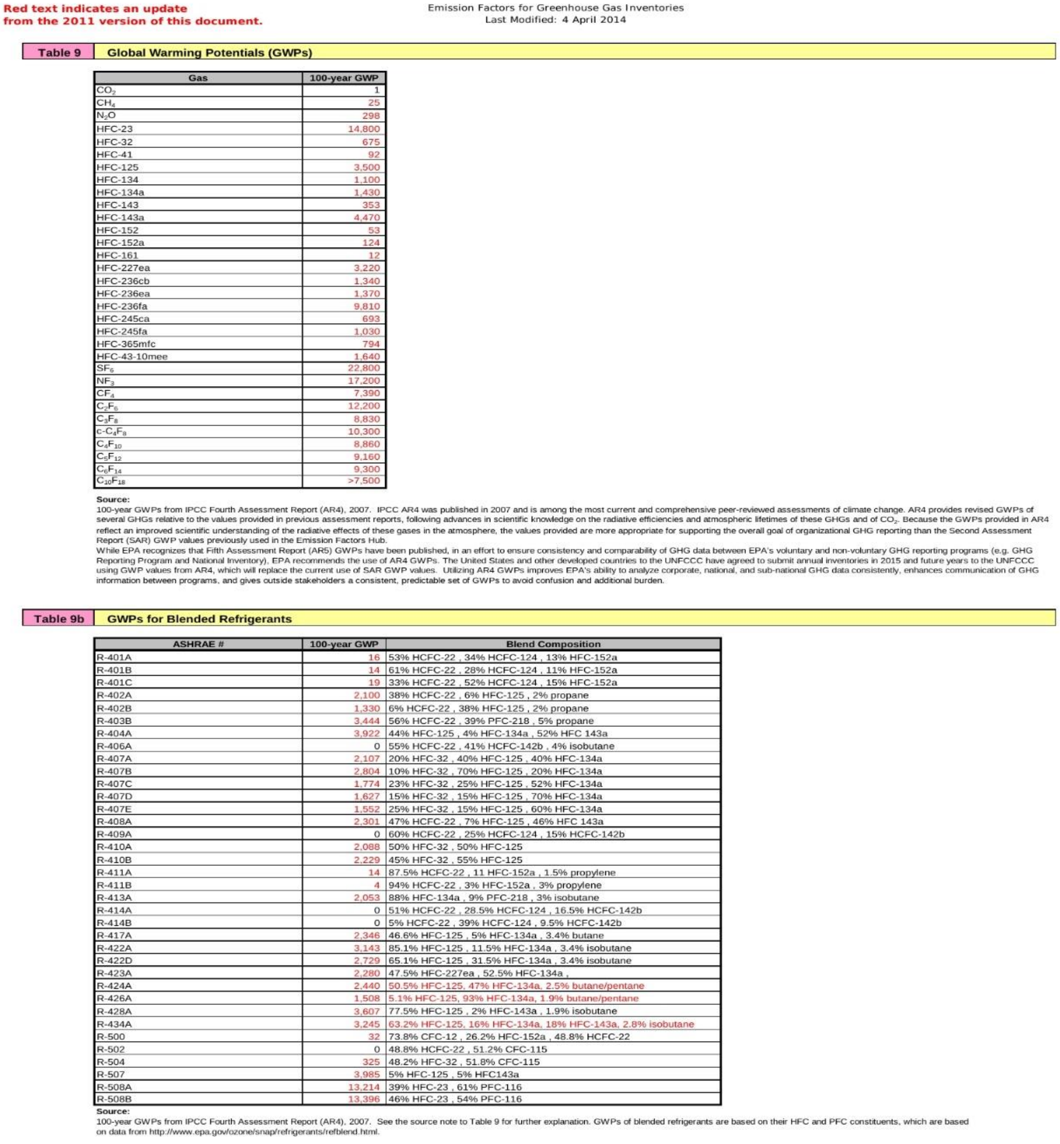

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Table 9 **Global Warming Potentials (GWPs)**

Gas	100-year GWP
CO_2	1
CH_4	25
N_2O	298
HFC-23	14,800
HFC-32	675
HFC-41	92
HFC-125	3,500
HFC-134	1,100
HFC-134a	1,430
HFC-143	353
HFC-143a	4,470
HFC-152	53
HFC-152a	124
HFC-161	12
HFC-227ea	3,220
HFC-236cb	1,340
HFC-236ea	1,370
HFC-236fa	9,810
HFC-245ca	693
HFC-245fa	1,030
HFC-365mfc	794
HFC-43-10mee	1,640
SF_6	22,800
NF_3	17,200
CF_4	7,390
C_2F_6	12,200
C_3F_8	8,830
$c\text{-}C_4F_8$	10,300
C_4F_{10}	8,860
C_5F_{12}	9,160
C_6F_{14}	9,300
$C_{10}F_{18}$	>7,500

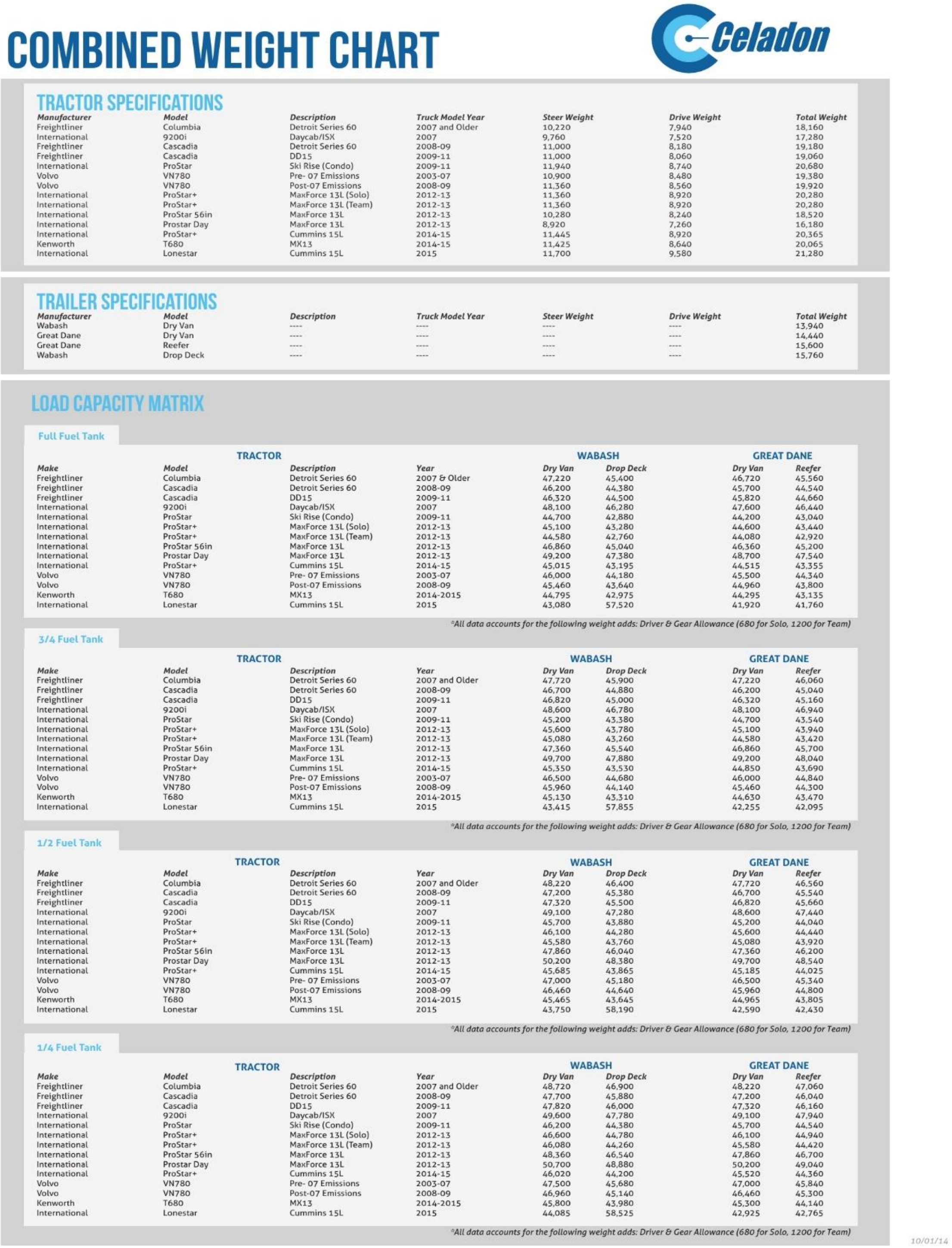
Source:
100-year GWPs from IPCC Fourth Assessment Report (AR4), 2007. IPCC AR4 was published in 2007 and is among the most current and comprehensive peer-reviewed assessments of climate change. AR4 provides revised GWPs of several GHGs relative to the values provided in previous assessment reports, following advances in scientific knowledge on the radiative efficiencies and atmospheric lifetimes of these GHGs and of CO_2. Because the GWPs provided in AR4 reflect an improved scientific understanding of the radiative effects of these gases in the atmosphere, the values provided are more appropriate for supporting the overall goal of organizational GHG reporting than the Second Assessment Report (SAR) GWP values previously used in the Emission Factors Hub.
While EPA recognizes that Fifth Assessment Report (AR5) GWPs have been published, in an effort to ensure consistency and comparability of GHG data between EPA's voluntary and non-voluntary GHG reporting programs (e.g. GHG Reporting Program and National Inventory), EPA recommends the use of AR4 GWPs. The United States and other developed countries to the UNFCCC have agreed to submit annual inventories in 2015 and future years to the UNFCCC using GWP values from AR4, which will replace the current use of SAR GWP values. Utilizing AR4 GWPs improves EPA's ability to analyze corporate, national, and sub-national GHG data consistently, enhances communication of GHG information between programs, and gives outside stakeholders a consistent, predictable set of GWPs to avoid confusion and additional burden.

Table 9b **GWPs for Blended Refrigerants**

ASHRAE #	100-year GWP	Blend Composition
R-401A	16	53% HCFC-22 , 34% HCFC-124 , 13% HFC-152a
R-401B	14	61% HCFC-22 , 28% HCFC-124 , 11% HFC-152a
R-401C	19	33% HCFC-22 , 52% HCFC-124 , 15% HFC-152a
R-402A	2,100	38% HCFC-22 , 6% HFC-125 , 2% propane
R-402B	1,330	6% HCFC-22 , 38% HFC-125 , 2% propane
R-403B	3,444	56% HCFC-22 , 39% PFC-218 , 5% propane
R-404A	3,922	44% HFC-125 , 4% HFC-134a , 52% HFC 143a
R-406A	0	55% HCFC-22 , 41% HCFC-142b , 4% isobutane
R-407A	2,107	20% HFC-32 , 40% HFC-125 , 40% HFC-134a
R-407B	2,804	10% HFC-32 , 70% HFC-125 , 20% HFC-134a
R-407C	1,774	23% HFC-32 , 25% HFC-125 , 52% HFC-134a
R-407D	1,627	15% HFC-32 , 15% HFC-125 , 70% HFC-134a
R-407E	1,552	25% HFC-32 , 15% HFC-125 , 60% HFC-134a
R-408A	2,301	47% HCFC-22 , 7% HFC-125 , 46% HFC 143a
R-409A	0	60% HCFC-22 , 25% HCFC-124 , 15% HCFC-142b
R-410A	2,088	50% HFC-32 , 50% HFC-125
R-410B	2,229	45% HFC-32 , 55% HFC-125
R-411A	14	87.5% HCFC-22 , 11 HFC-152a , 1.5% propylene
R-411B	4	94% HCFC-22 , 3% HFC-152a , 3% propylene
R-413A	2,053	88% HFC-134a , 9% PFC-218 , 3% isobutane
R-414A	0	51% HCFC-22 , 28.5% HCFC-124 , 16.5% HCFC-142b
R-414B	0	5% HCFC-22 , 39% HCFC-124 , 9.5% HCFC-142b
R-417A	2,346	46.6% HFC-125 , 5% HFC-134a , 3.4% butane
R-422A	3,143	85.1% HFC-125 , 11.5% HFC-134a , 3.4% isobutane
R-422D	2,729	65.1% HFC-125 , 31.5% HFC-134a , 3.4% isobutane
R-423A	2,280	47.5% HFC-227ea , 52.5% HFC-134a ,
R-424A	2,440	50.5% HFC-125, 47% HFC-134a, 2.5% butane/pentane
R-426A	1,508	5.1% HFC-125, 93% HFC-134a, 1.9% butane/pentane
R-428A	3,607	77.5% HFC-125 , 2% HFC-143a , 1.9% isobutane
R-434A	3,245	63.2% HFC-125, 16% HFC-134a, 18% HFC-143a, 2.8% isobutane
R-500	32	73.8% CFC-12 , 26.2% HFC-152a , 48.8% HCFC-22
R-502	0	48.8% HCFC-22 , 51.2% CFC-115
R-504	325	48.2% HFC-32 , 51.8% CFC-115
R-507	3,985	5% HFC-125 , 5% HFC143a
R-508A	13,214	39% HFC-23 , 61% PFC-116
R-508B	13,396	46% HFC-23 , 54% PFC-116

Source:
100-year GWPs from IPCC Fourth Assessment Report (AR4), 2007. See the source note to Table 9 for further explanation. GWPs of blended refrigerants are based on their HFC and PFC constituents, which are based on data from http://www.epa.gov/ozone/snap/refrigerants/refblend.html.

Appendix I: Celadon Trucking Average Fleet Weight



COMBINED WEIGHT CHART

Celadon

TRACTOR SPECIFICATIONS

Manufacturer	*Model*	*Description*	*Truck Model Year*	*Steer Weight*	*Drive Weight*	*Total Weight*
Freightliner	Columbia	Detroit Series 60	2007 and Older	10,220	7,940	18,160
International	9200i	Daycab/ISX	2007	9,760	7,520	17,280
Freightliner	Cascadia	Detroit Series 60	2008-09	11,000	8,180	19,180
Freightliner	Cascadia	DD15	2009-11	11,000	8,060	19,060
International	ProStar	Ski Rise (Condo)	2009-11	11,940	8,740	20,680
Volvo	VN780	Pre- 07 Emissions	2003-07	10,900	8,480	19,380
Volvo	VN780	Post-07 Emissions	2008-09	11,360	8,560	19,920
International	ProStar+	MaxForce 13L (Solo)	2012-13	11,360	8,920	20,280
International	ProStar+	MaxForce 13L (Team)	2012-13	11,360	8,920	20,280
International	ProStar 56in	MaxForce 13L	2012-13	10,280	8,240	18,520
International	Prostar Day	MaxForce 13L	2012-13	8,920	7,260	16,180
International	ProStar+	Cummins 15L	2014-15	11,445	8,920	20,365
Kenworth	T680	MX13	2014-15	11,425	8,640	20,065
International	Lonestar	Cummins 15L	2015	11,700	9,580	21,280

TRAILER SPECIFICATIONS

Manufacturer	*Model*	*Description*	*Truck Model Year*	*Steer Weight*	*Drive Weight*	*Total Weight*
Wabash	Dry Van	----	----	----	----	13,940
Great Dane	Dry Van	----	----	----	----	14,440
Great Dane	Reefer	----	----	----	----	15,600
Wabash	Drop Deck	----	----	----	----	15,760

LOAD CAPACITY MATRIX

Full Fuel Tank

TRACTOR				WABASH		GREAT DANE	
Make	*Model*	*Description*	*Year*	*Dry Van*	*Drop Deck*	*Dry Van*	*Reefer*
Freightliner	Columbia	Detroit Series 60	2007 & Older	47,220	45,400	46,720	45,560
Freightliner	Cascadia	Detroit Series 60	2008-09	46,200	44,380	45,700	44,540
Freightliner	Cascadia	DD15	2009-11	46,320	44,500	45,820	44,660
International	9200i	Daycab/ISX	2007	48,100	46,280	47,600	46,440
International	ProStar	Ski Rise (Condo)	2009-11	44,700	42,880	44,200	43,040
International	ProStar+	MaxForce 13L (Solo)	2012-13	45,100	43,280	44,600	43,440
International	ProStar+	MaxForce 13L (Team)	2012-13	44,580	42,760	44,080	42,920
International	ProStar 56in	MaxForce 13L	2012-13	46,860	45,040	46,360	45,200
International	Prostar Day	MaxForce 13L	2012-13	49,200	47,380	48,700	47,540
International	ProStar+	Cummins 15L	2014-15	45,015	43,195	44,515	43,355
Volvo	VN780	Pre- 07 Emissions	2003-07	46,000	44,180	45,500	44,340
Volvo	VN780	Post-07 Emissions	2008-09	45,460	43,640	44,960	43,800
Kenworth	T680	MX13	2014-2015	44,795	42,975	44,295	43,135
International	Lonestar	Cummins 15L	2015	43,080	57,520	41,920	41,760

**All data accounts for the following weight adds: Driver & Gear Allowance (680 for Solo, 1200 for Team)*

3/4 Fuel Tank

TRACTOR				WABASH		GREAT DANE	
Make	*Model*	*Description*	*Year*	*Dry Van*	*Drop Deck*	*Dry Van*	*Reefer*
Freightliner	Columbia	Detroit Series 60	2007 and Older	47,720	45,900	47,220	46,060
Freightliner	Cascadia	Detroit Series 60	2008-09	46,700	44,880	46,200	45,040
Freightliner	Cascadia	DD15	2009-11	46,820	45,000	46,320	45,160
International	9200i	Daycab/ISX	2007	48,600	46,780	48,100	46,940
International	ProStar	Ski Rise (Condo)	2009-11	45,200	43,380	44,700	43,540
International	ProStar+	MaxForce 13L (Solo)	2012-13	45,600	43,780	45,100	43,940
International	ProStar+	MaxForce 13L (Team)	2012-13	45,080	43,260	44,580	43,420
International	ProStar 56in	MaxForce 13L	2012-13	47,360	45,540	46,860	45,700
International	Prostar Day	MaxForce 13L	2012-13	49,700	47,880	49,200	48,040
International	ProStar+	Cummins 15L	2014-15	45,350	43,530	44,850	43,690
Volvo	VN780	Pre- 07 Emissions	2003-07	46,500	44,680	46,000	44,840
Volvo	VN780	Post-07 Emissions	2008-09	45,960	44,140	45,460	44,300
Kenworth	T680	MX13	2014-2015	45,130	43,310	44,630	43,470
International	Lonestar	Cummins 15L	2015	43,415	57,855	42,255	42,095

**All data accounts for the following weight adds: Driver & Gear Allowance (680 for Solo, 1200 for Team)*

1/2 Fuel Tank

TRACTOR				WABASH		GREAT DANE	
Make	*Model*	*Description*	*Year*	*Dry Van*	*Drop Deck*	*Dry Van*	*Reefer*
Freightliner	Columbia	Detroit Series 60	2007 and Older	48,220	46,400	47,720	46,560
Freightliner	Cascadia	Detroit Series 60	2008-09	47,200	45,380	46,700	45,540
Freightliner	Cascadia	DD15	2009-11	47,320	45,500	46,820	45,660
International	9200i	Daycab/ISX	2007	49,100	47,280	48,600	47,440
International	ProStar	Ski Rise (Condo)	2009-11	45,700	43,880	45,200	44,040
International	ProStar+	MaxForce 13L (Solo)	2012-13	46,100	44,280	45,600	44,440
International	ProStar+	MaxForce 13L (Team)	2012-13	45,580	43,760	45,080	43,920
International	ProStar 56in	MaxForce 13L	2012-13	47,860	46,040	47,360	46,200
International	Prostar Day	MaxForce 13L	2012-13	50,200	48,380	49,700	48,540
International	ProStar+	Cummins 15L	2014-15	45,685	43,865	45,185	44,025
Volvo	VN780	Pre- 07 Emissions	2003-07	47,000	45,180	46,500	45,340
Volvo	VN780	Post-07 Emissions	2008-09	46,460	44,640	45,960	44,800
Kenworth	T680	MX13	2014-2015	45,465	43,645	44,965	43,805
International	Lonestar	Cummins 15L	2015	43,750	58,190	42,590	42,430

**All data accounts for the following weight adds: Driver & Gear Allowance (680 for Solo, 1200 for Team)*

1/4 Fuel Tank

TRACTOR				WABASH		GREAT DANE	
Make	*Model*	*Description*	*Year*	*Dry Van*	*Drop Deck*	*Dry Van*	*Reefer*
Freightliner	Columbia	Detroit Series 60	2007 and Older	48,720	46,900	48,220	47,060
Freightliner	Cascadia	Detroit Series 60	2008-09	47,700	45,880	47,200	46,040
Freightliner	Cascadia	DD15	2009-11	47,820	46,000	47,320	46,160
International	9200i	Daycab/ISX	2007	49,600	47,780	49,100	47,940
International	ProStar	Ski Rise (Condo)	2009-11	46,200	44,380	45,700	44,540
International	ProStar+	MaxForce 13L (Solo)	2012-13	46,600	44,780	46,100	44,940
International	ProStar+	MaxForce 13L (Team)	2012-13	46,080	44,260	45,580	44,420
International	ProStar 56in	MaxForce 13L	2012-13	48,360	46,540	47,860	46,700
International	Prostar Day	MaxForce 13L	2012-13	50,700	48,880	50,200	49,040
International	ProStar+	Cummins 15L	2014-15	46,020	44,200	45,520	44,360
Volvo	VN780	Pre- 07 Emissions	2003-07	47,500	45,680	47,000	45,840
Volvo	VN780	Post-07 Emissions	2008-09	46,960	45,140	46,460	45,300
Kenworth	T680	MX13	2014-2015	45,800	43,980	45,300	44,140
International	Lonestar	Cummins 15L	2015	44,085	58,525	42,925	42,765

**All data accounts for the following weight adds: Driver & Gear Allowance (680 for Solo, 1200 for Team)*

10/01/14

Appendix J: Discussion of Electricity Grid Source Mixtures and Resultant TRACI Environmental Impacts

The North American Electric Reliability Corporation (NERC) has split the United States and Canada into eight regional entities which are monitored to ensure reliability standards are met and bulk power is reliably delivered throughout North America. These regions have been modeled in the Ecoinvent database so that an average electricity mixture for that region can be applied to LCA models. The three regions modeled in this report are the Midwest Reliability Organization (MRO), the Northwest Power Coordinating Council (NPCC), and the Western Electricity Coordinating Council (WECC).

These regions offer a wide range of geographic location as well as electricity fuel sources. The MRO was chosen as a modeled region because it is where Omaha Steel Castings Company (OSCC) is located. The WECC was chosen because it represents a large portion of the western the United States. The NPCC was chosen because it represents the Northeast portion of the United States and uses a much different power mixture than the Midwest. An argument could be made for including the ReliabilityFirst (RF) region in this research because that region contains a large number of foundries. The reason the RF region was not included was that its electricity source mixture was very similar to the MRO region, relying heavily on coal for the majority of its power. The exact proportion of electricity sources as they are modeled in Ecoinvent can be seen in Figure J-1.

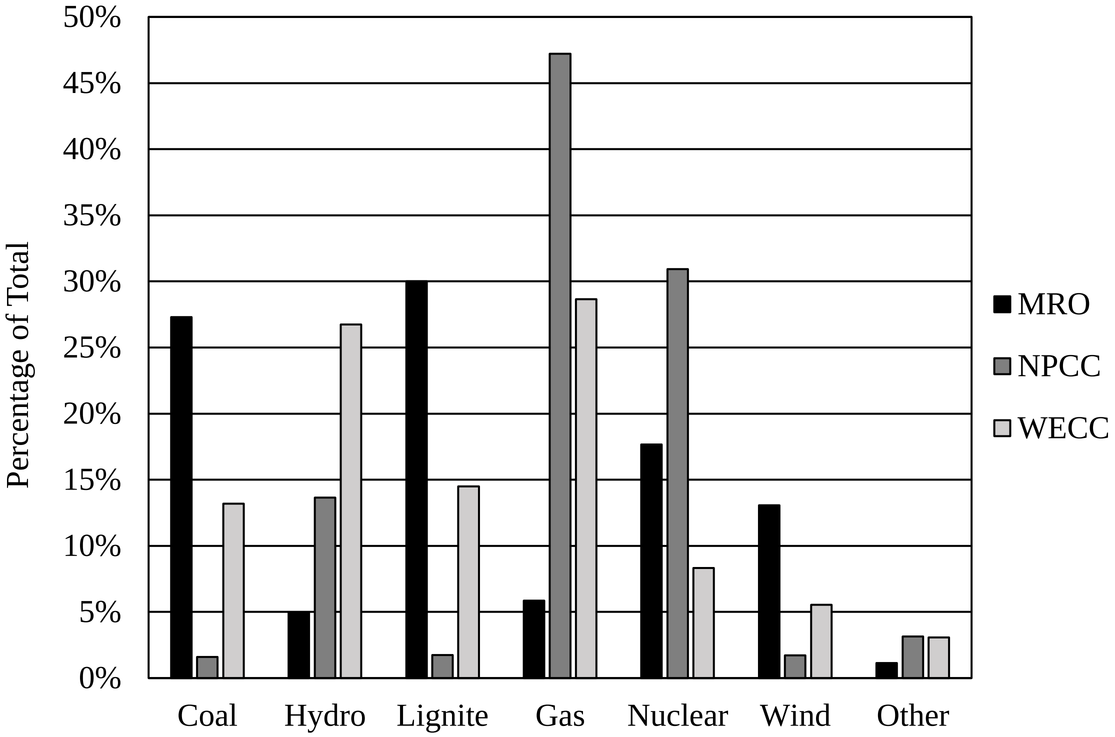


Figure J-1. Ecoinvent Electricity Source Mixture by Region

Because the source mixtures vary so much, the resultant environmental impacts will vary as well. To see how each region compares to the other, a simple comparison was done in Simapro. Figure J-2. shows the LCIA for generating 1 MJ of high voltage electricity in each region. As can be seen in the figure, not only are there differences in the impacts for each region, but also differences in each impact area. The coal-heavy MRO performs poorly in human health, smog, and greenhouse gas production as might be expected, but it actually performs quite well in ecotoxicity, fossil fuel depletion, and ozone depletion. In most categories, the predominantly nuclear and gas mixture of the NPCC has the smallest LCIA footprint. This result was supported in the sensitivity analysis of this research (Section 4.4.4.1) and is an important concept to understand when making environmental decisions in different regions in the United States or the world. It is important to know where your power comes from.

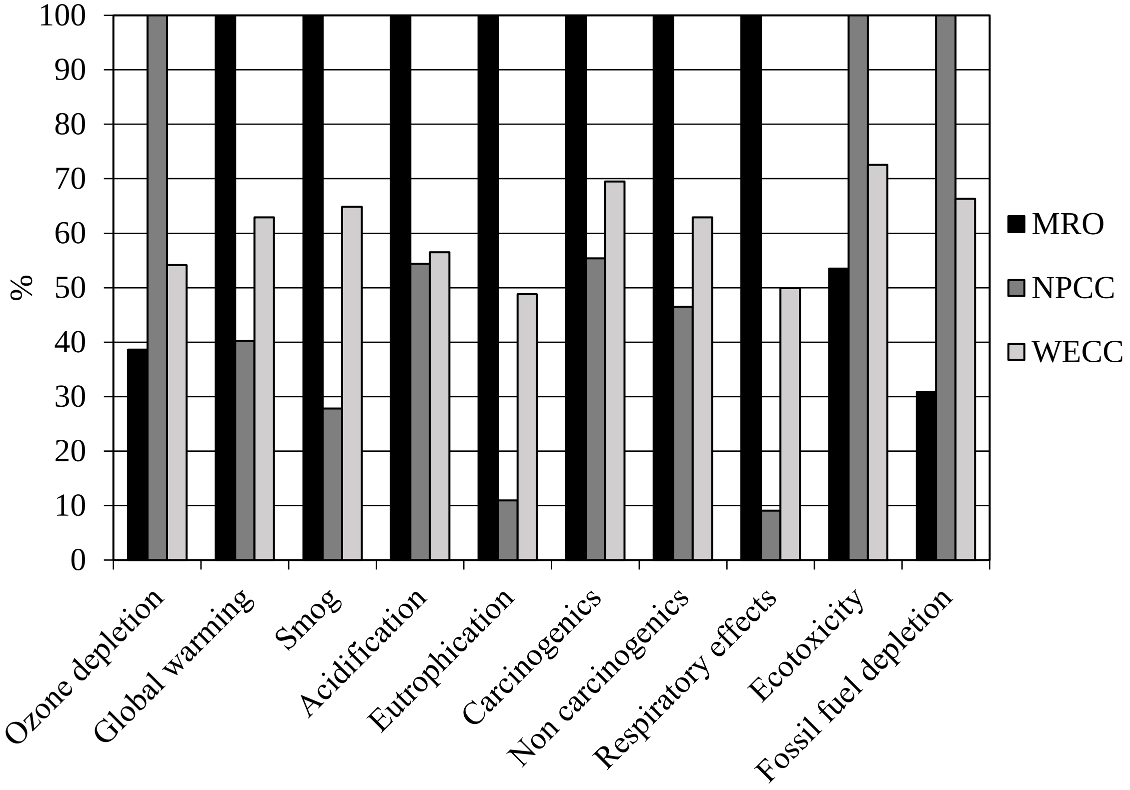


Figure J-2. LCIA Comparison of 1 MJ of High Voltage Electricity for the MRO, NPCC, and WECC Regions.

Appendix K: Uncertainty Analysis Results

Appendix K-1: Current Process Impact Uncertainty

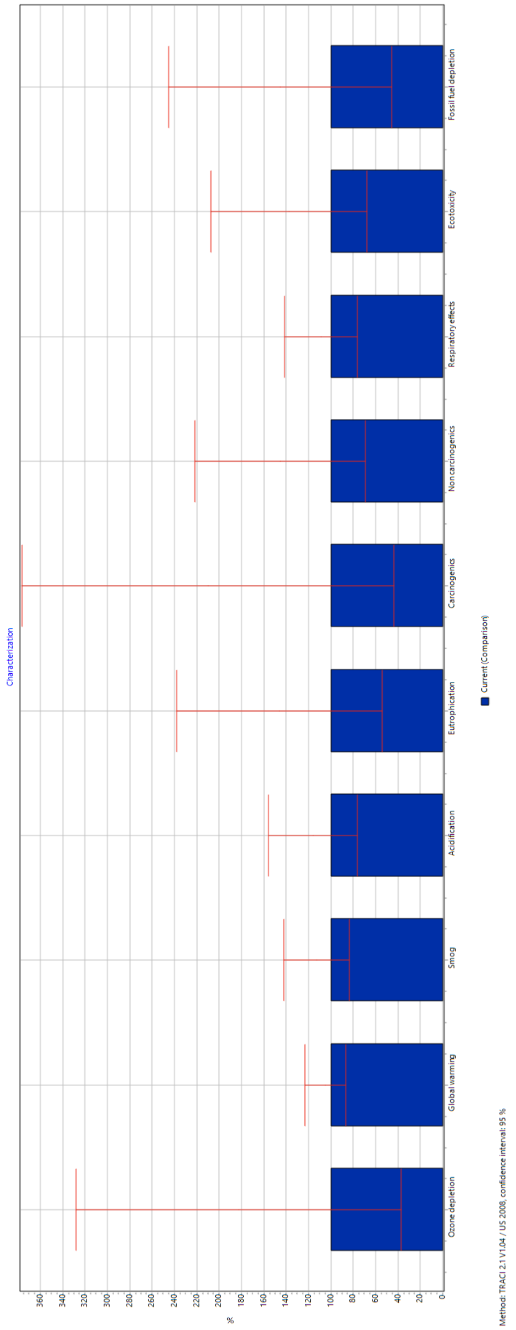


Figure K-1.1. Current Process - Overall Impact Uncertainty

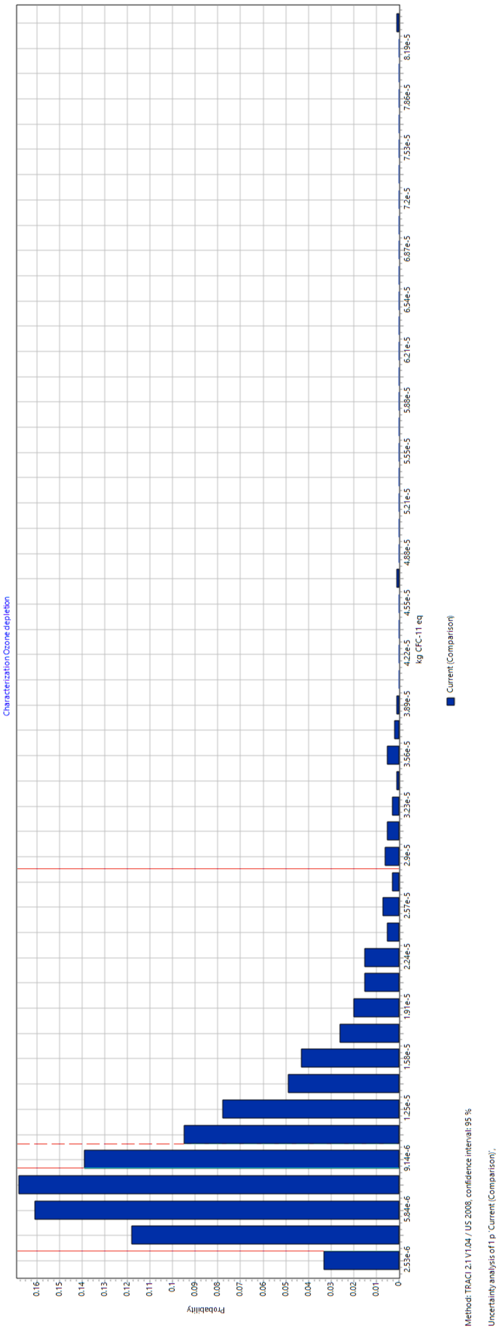
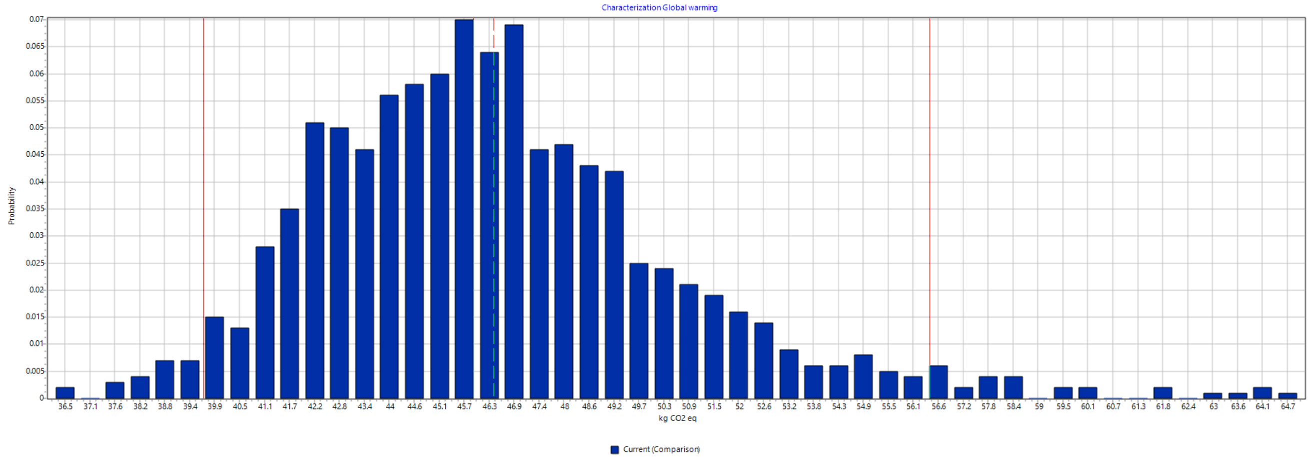


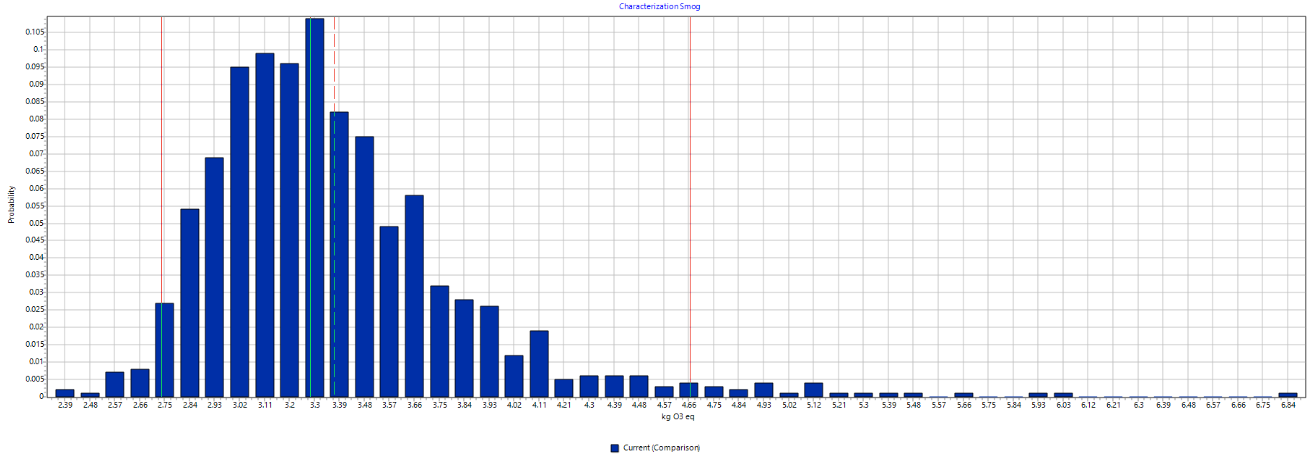
Figure K-1.2. Current Process - Ozone Depletion Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

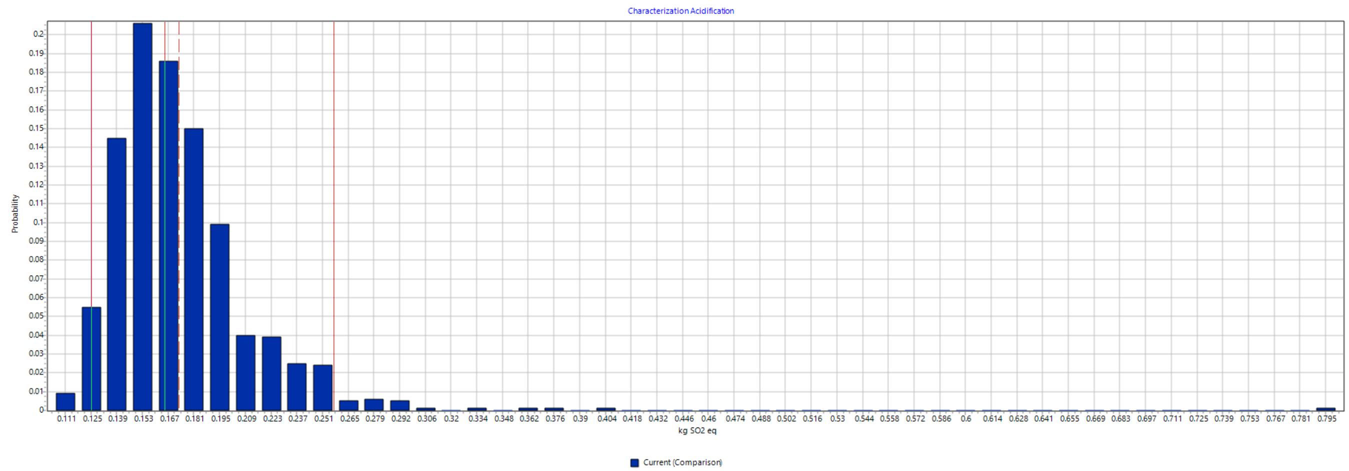
Figure K-1.3. Current Process - Global Warming Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

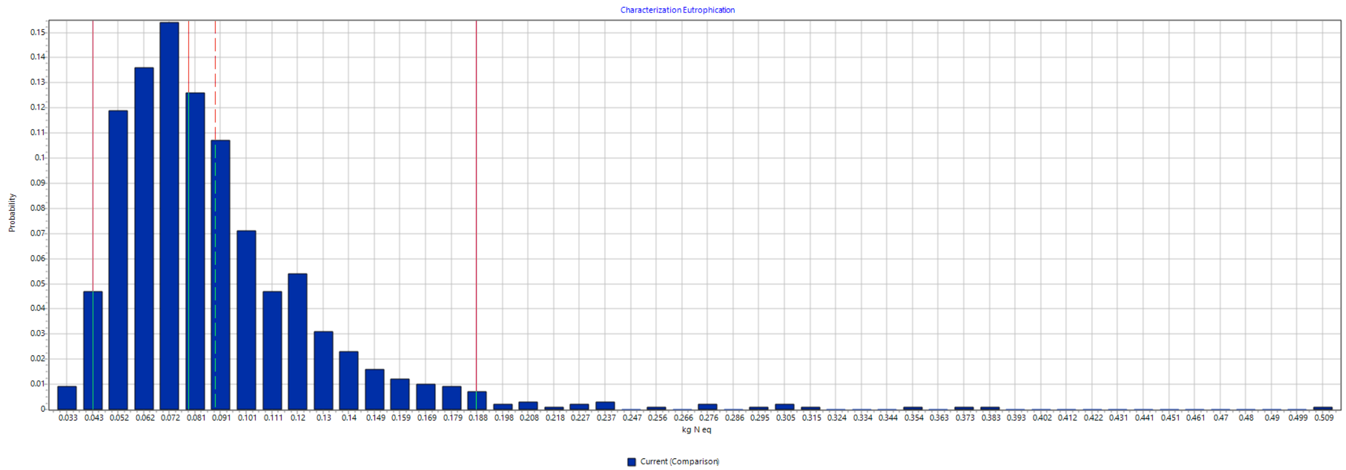
Figure K-1.4. Current Process - Smog Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

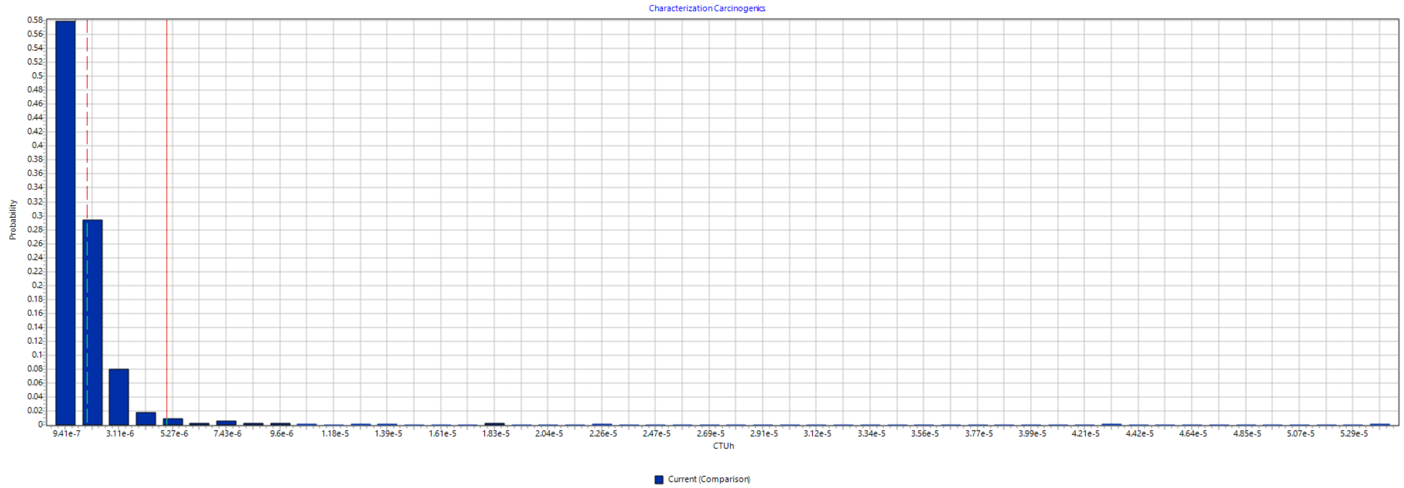
Figure K-1.5. Current Process - Acidification Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

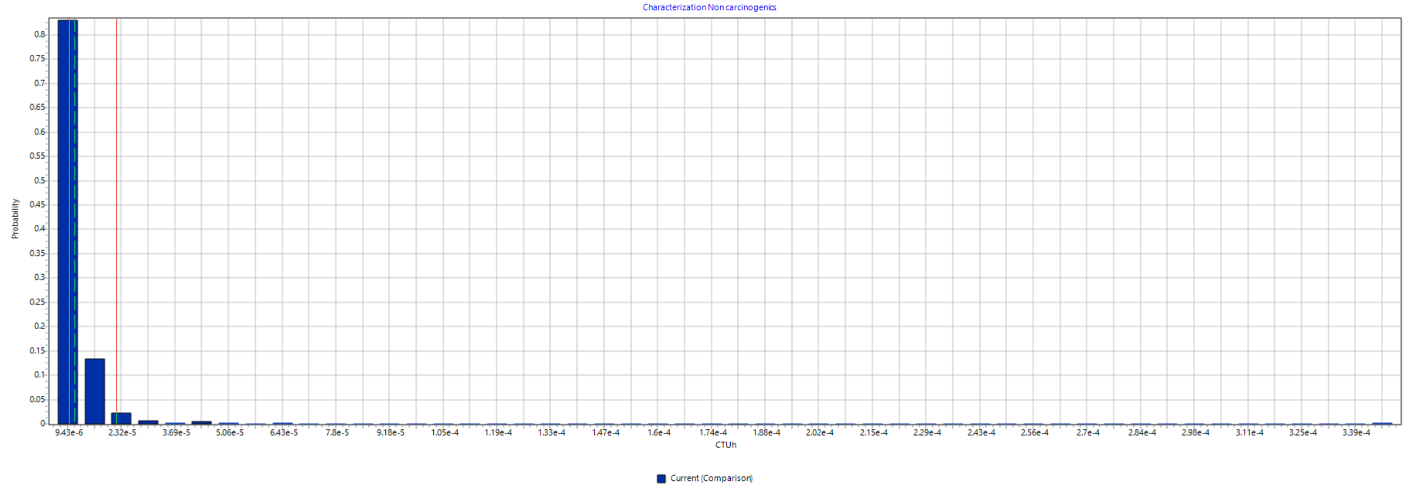
Figure K-1.6. Current Process - Eutrophication Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

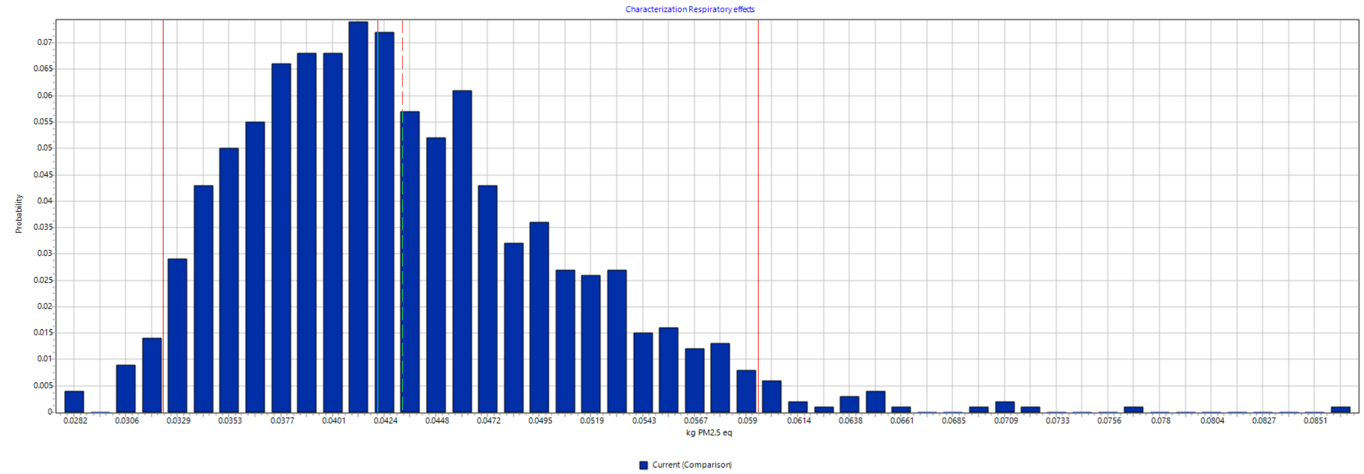
Figure K-1.7. Current Process - Carcinogenics Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

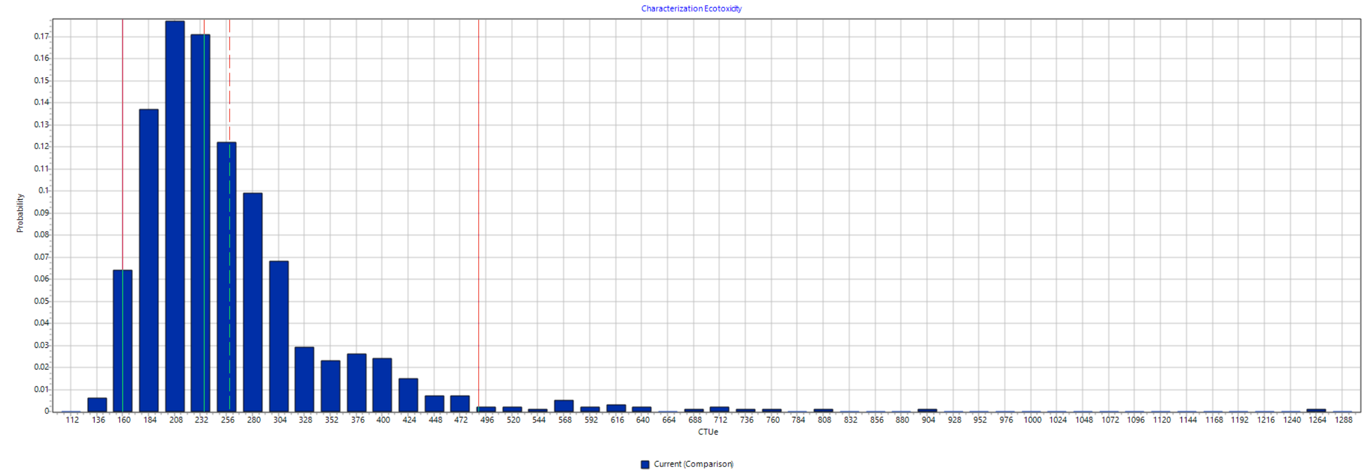
Figure K-1.8. Current Process - Non-Carcinogenics Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

Figure K-1.9. Current Process - Respiratory Effects Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Current (Comparison)',

Figure K-1.10. Current Process - Exotoxicity Uncertainty

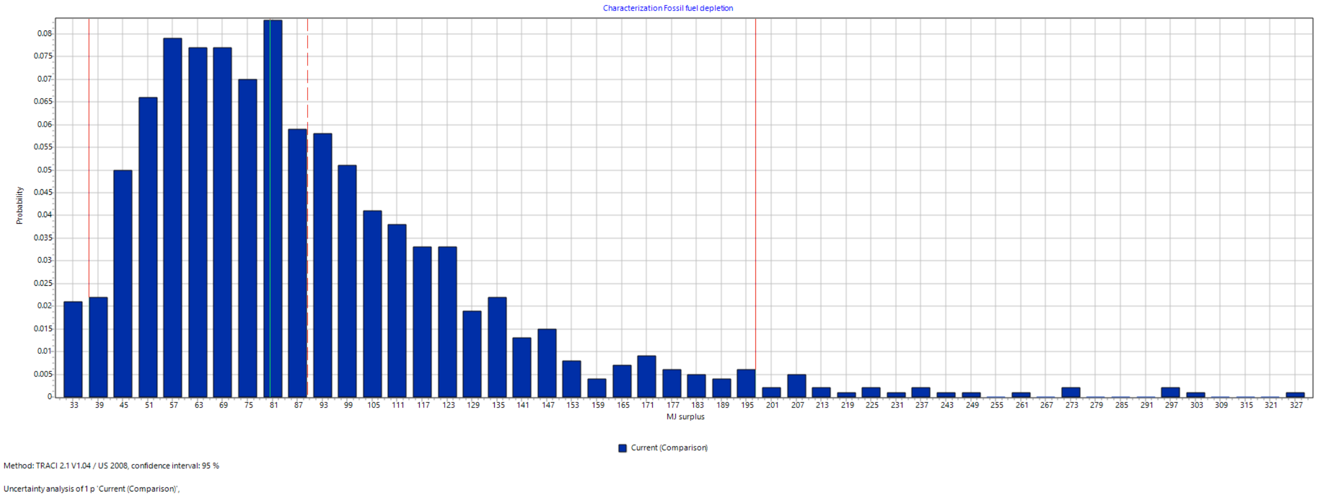


Figure K-1.11. Current Process - Fossil Fuel Depletion Uncertainty

Appendix K-2: Mechanical Reclamation Impact Uncertainty

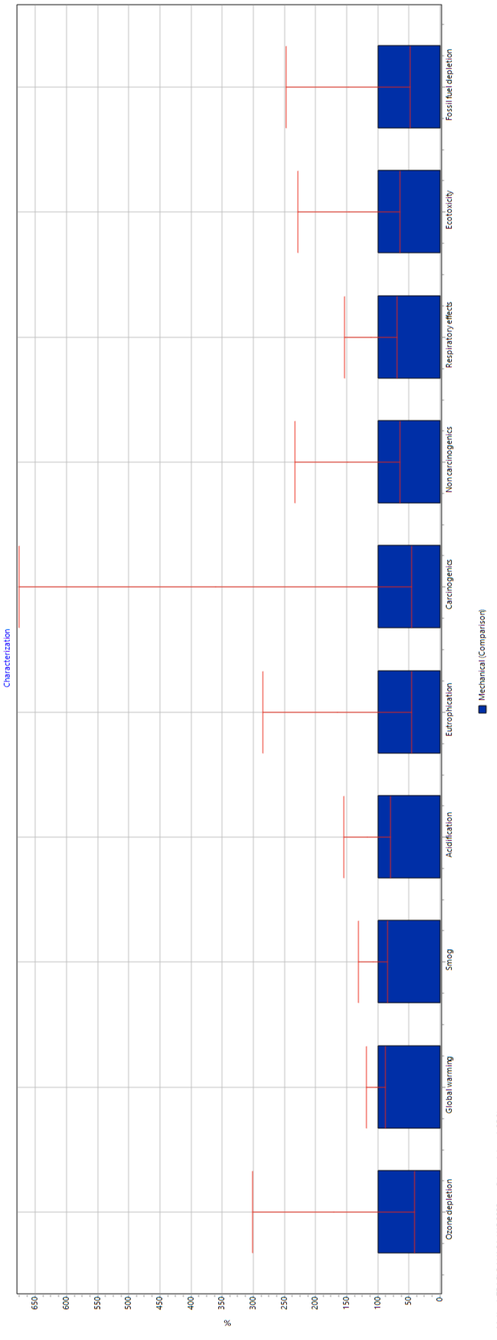


Figure K-2.1. Mechanical Reclamation - Overall Impact Uncertainty

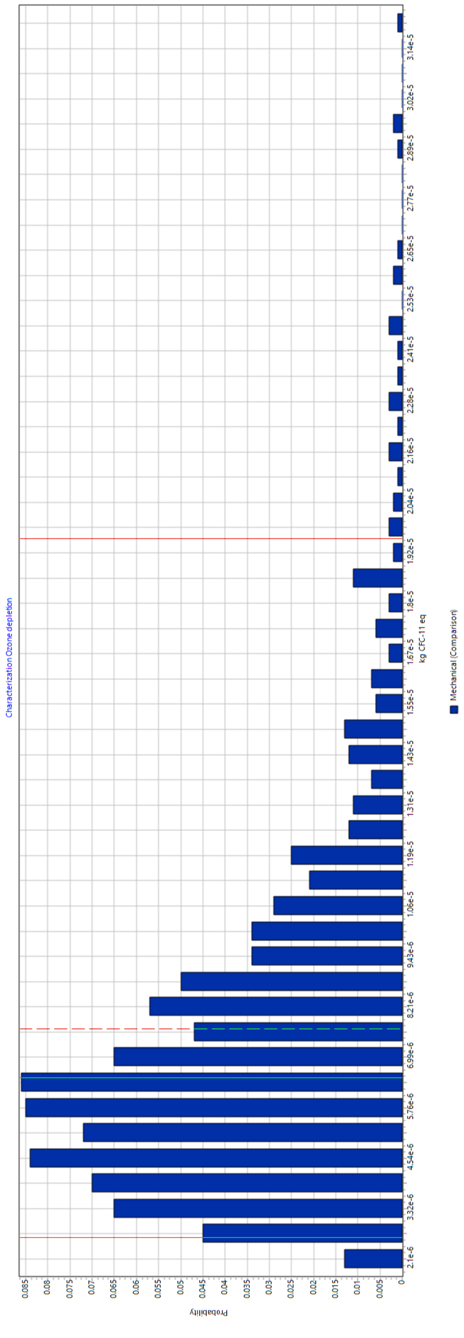
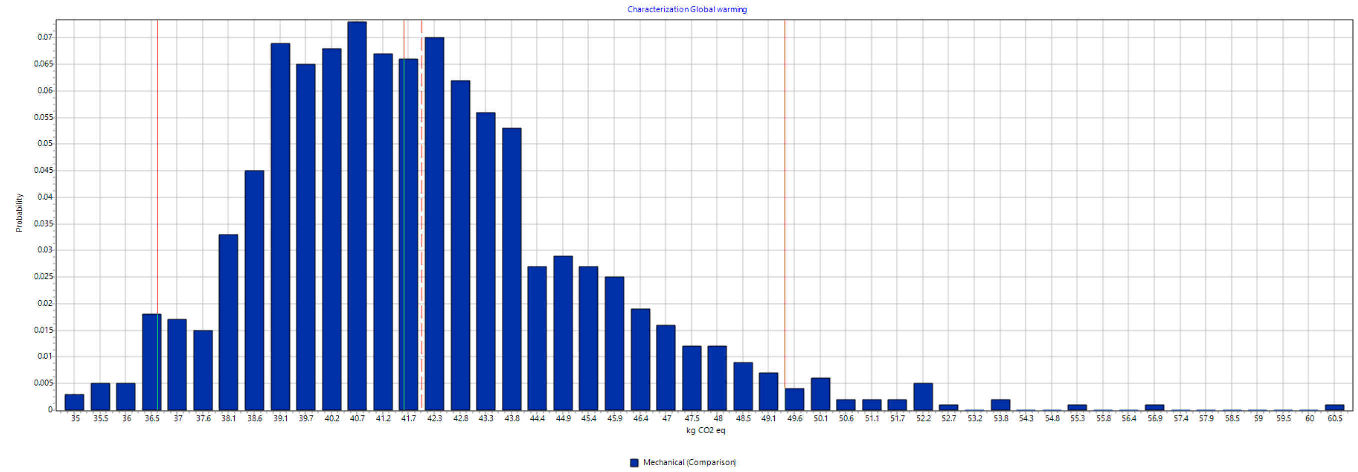


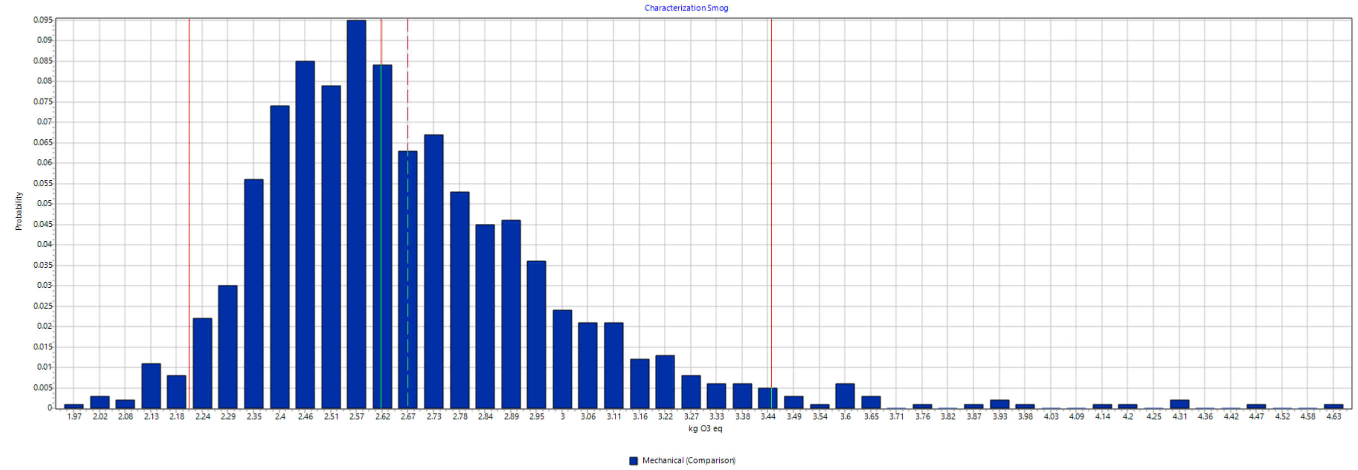
Figure K-2.2. Mechanical Reclamation - Ozone Depletion Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Mechanical (Comparison)',

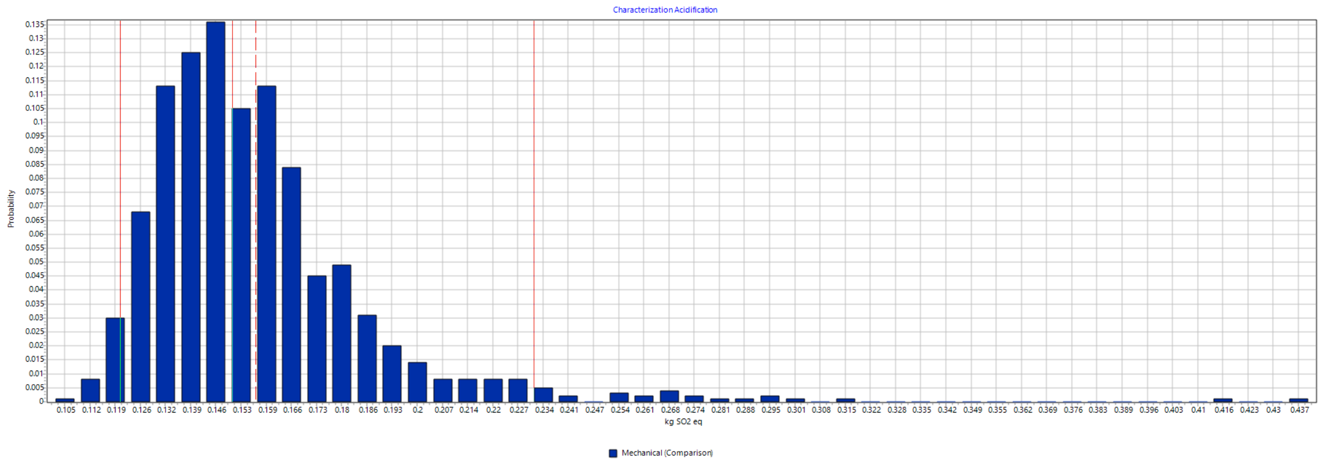
Figure K-2.3. Mechanical Reclamation - Global Warming Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Mechanical (Comparison)',

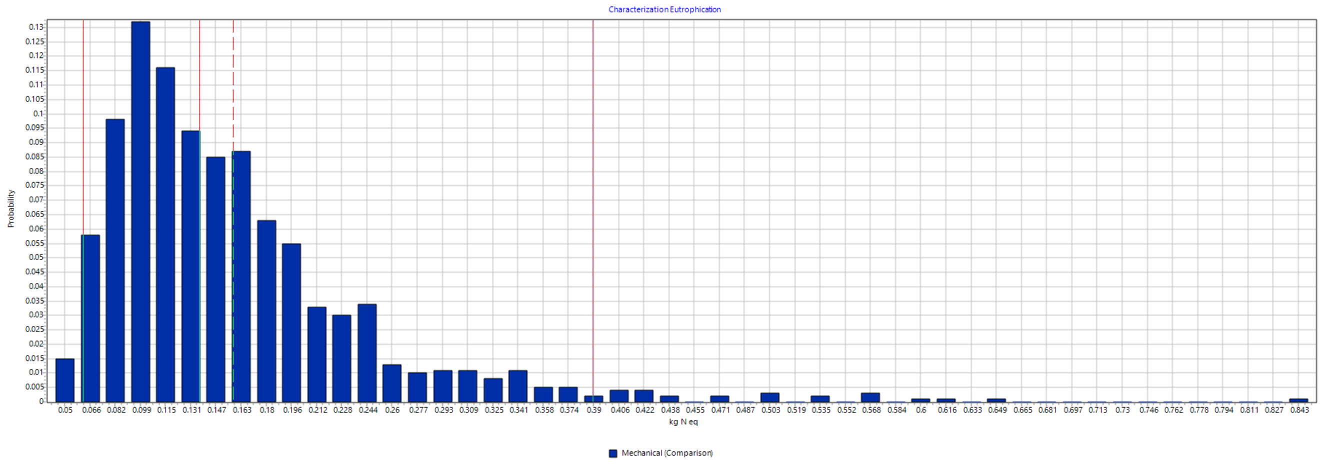
Figure K-2.4. Mechanical Reclamation - Smog Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Mechanical (Comparison)',

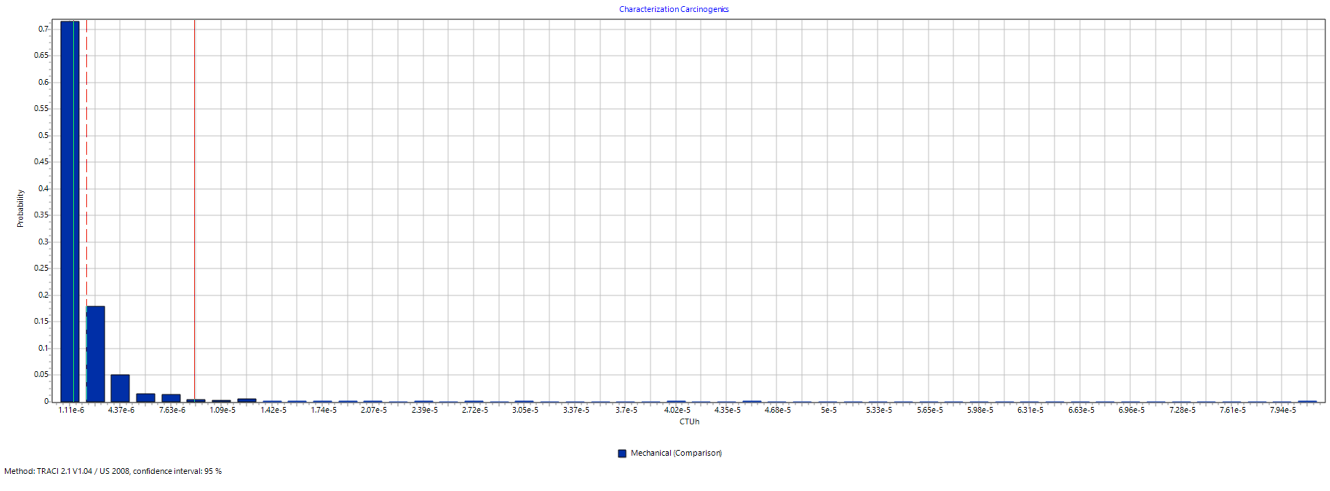
Figure K-2.5. Mechanical Reclamation - Acidification Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Mechanical (Comparison)',

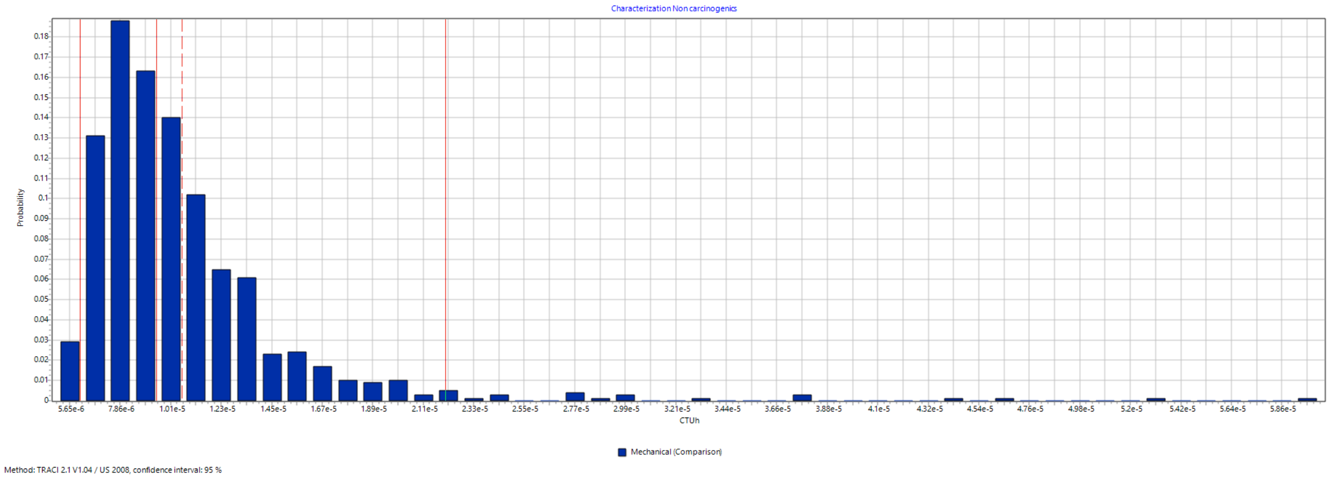
Figure K-2.6. Mechanical Reclamation - Eutrophication Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Mechanical (Comparison)',

Figure K-2.7. Mechanical Reclamation - Carcinogenics Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Mechanical (Comparison)',

Figure K-2.8. Mechanical Reclamation - Non-Carcinogenics Uncertainty

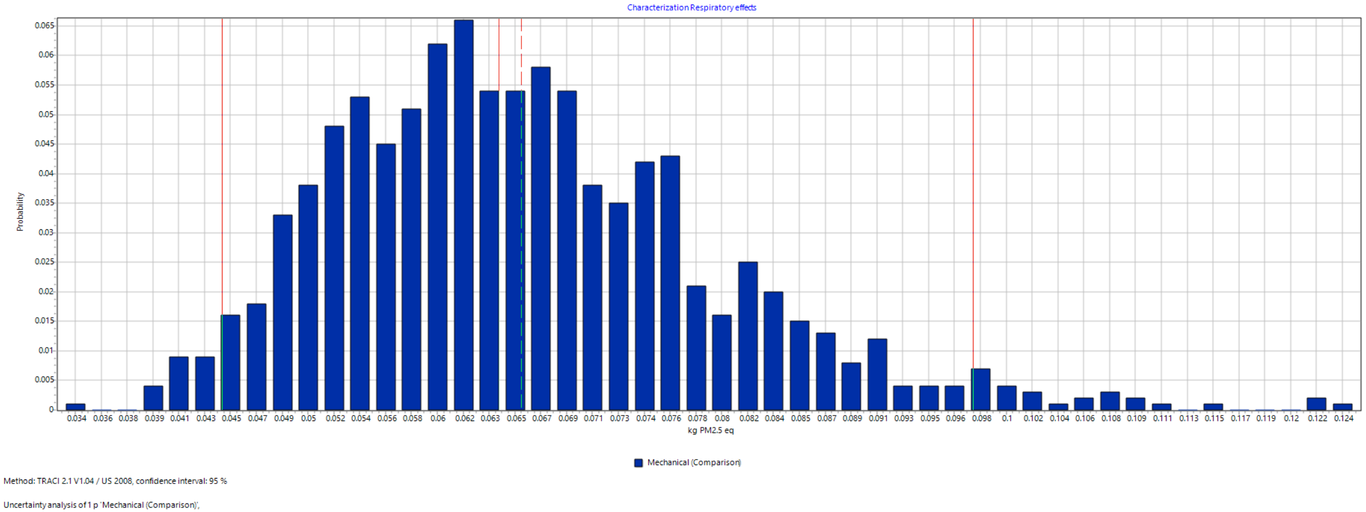


Figure K-2.9. Mechanical Reclamation - Respiratory Effects Uncertainty

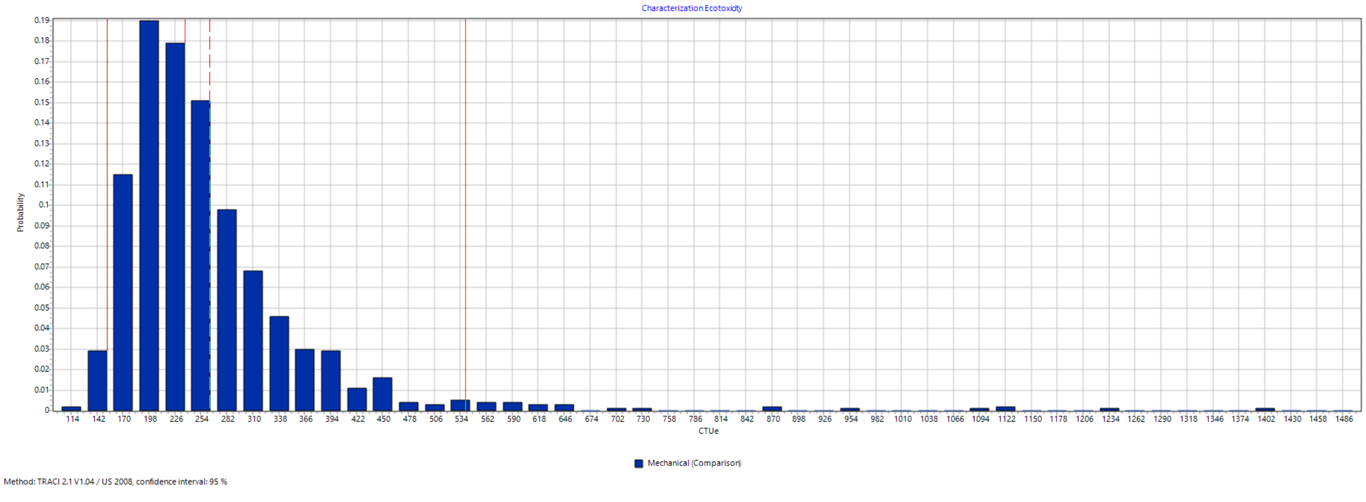


Figure K-2.10. Mechanical Reclamation - Ecotoxicity Uncertainty

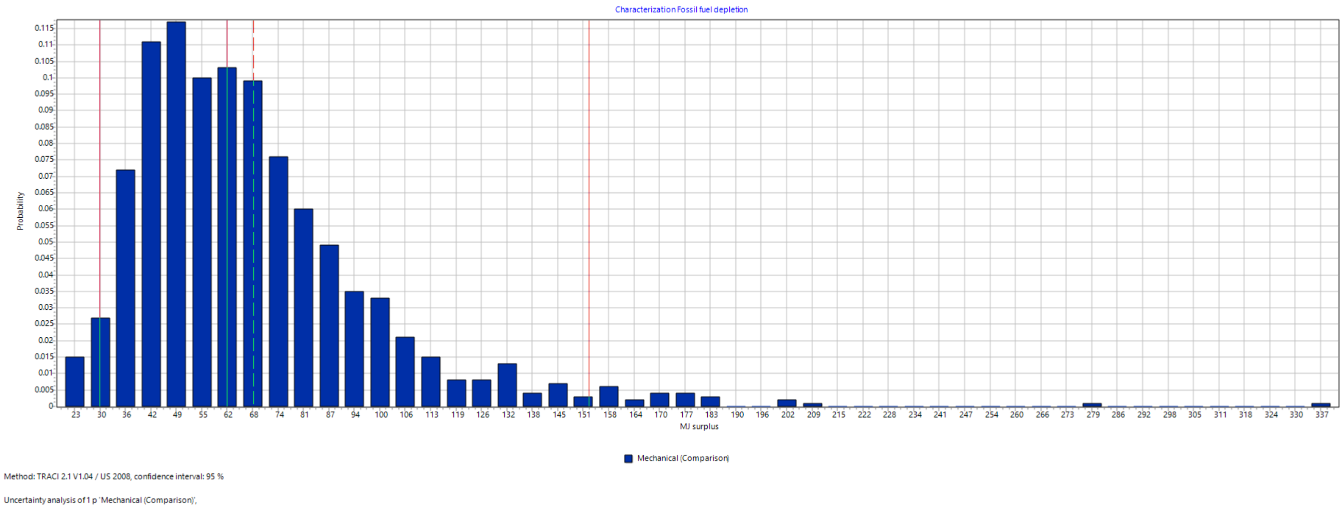
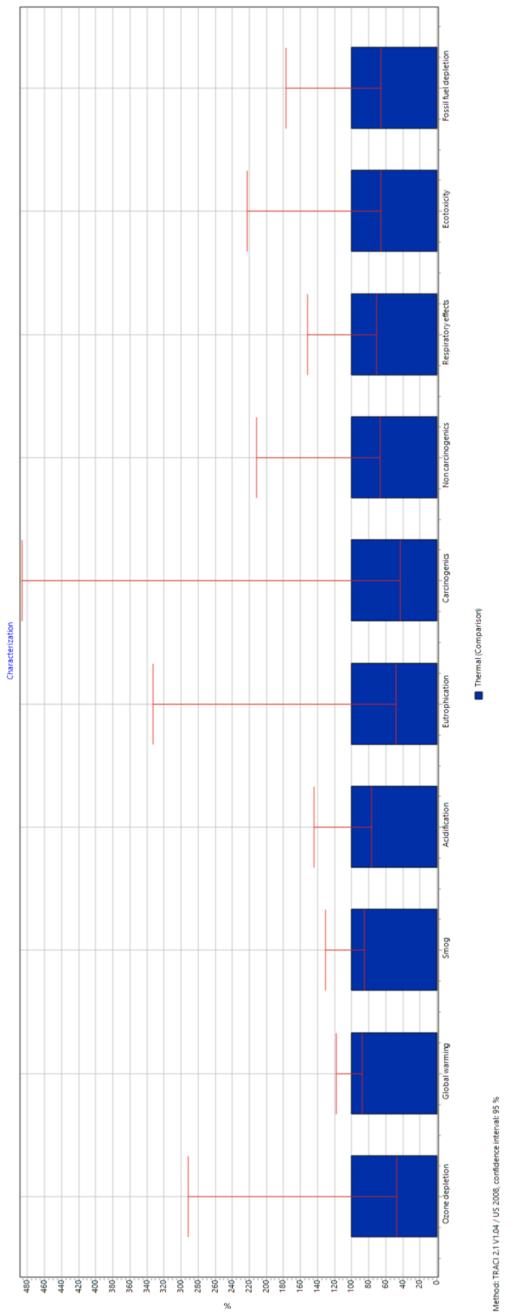


Figure K-2.11. Mechanical Reclamation - Fossil Fuel Depletion Uncertainty

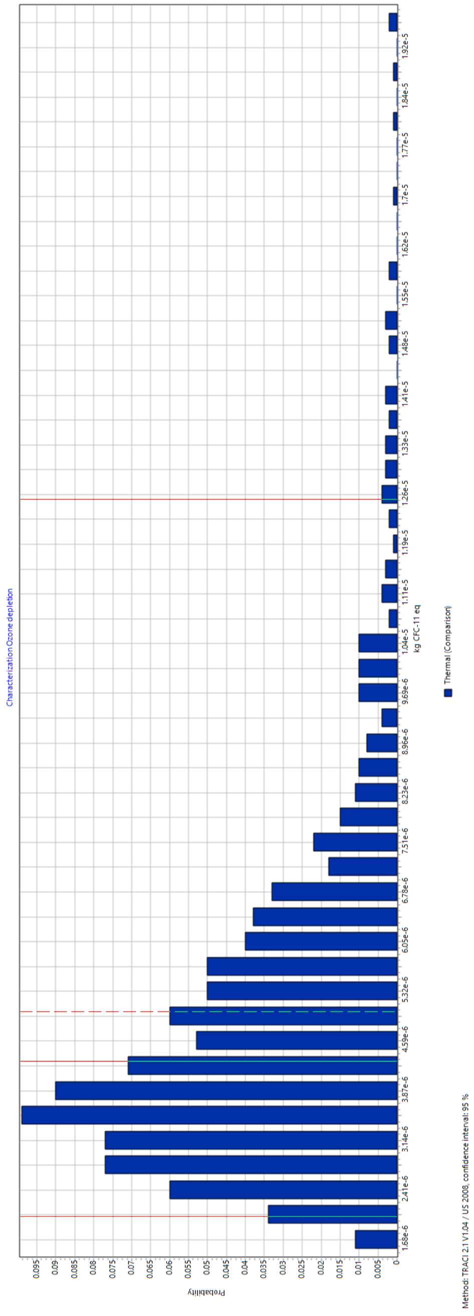
Appendix K-3: Thermal Reclamation Impact Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Thermal (Comparison)',

Figure K-3.1. Thermal Reclamation - Overall Impact Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Thermal (Comparison)',

Figure K-3.2. Thermal Reclamation - Ozone Depletion Uncertainty

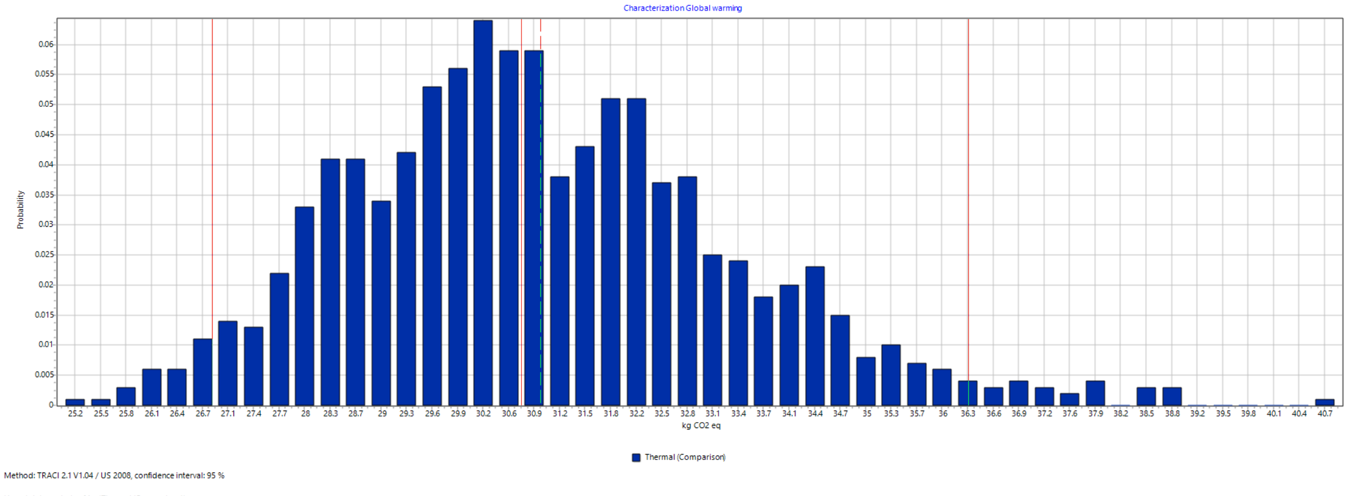


Figure K-3.3. Thermal Reclamation - Global Warming Uncertainty

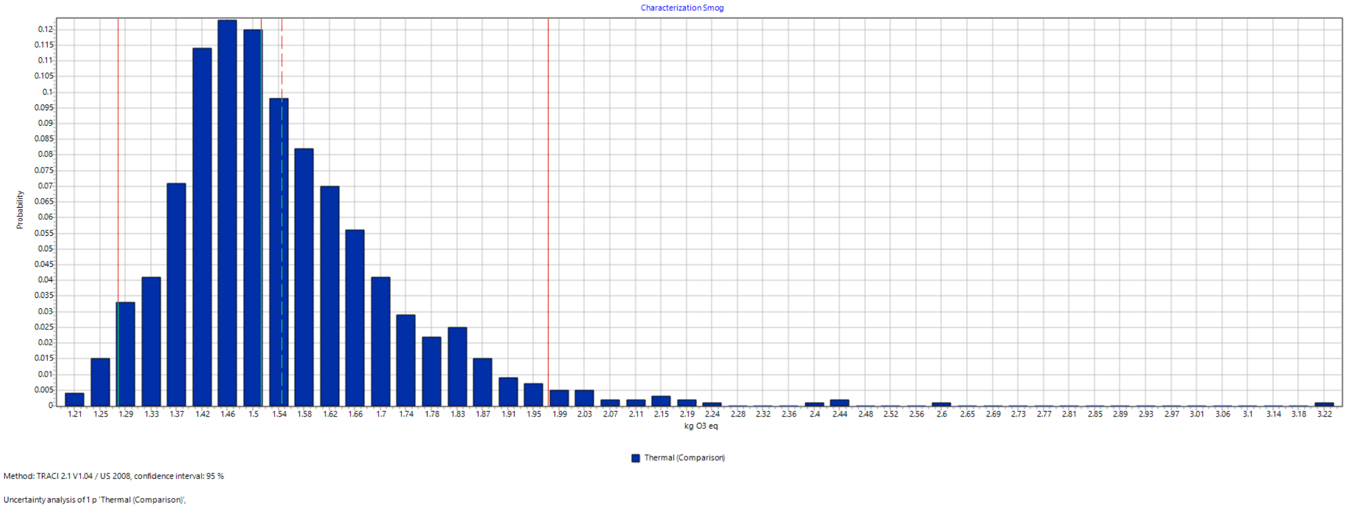


Figure K-3.4. Thermal Reclamation - Smog Uncertainty

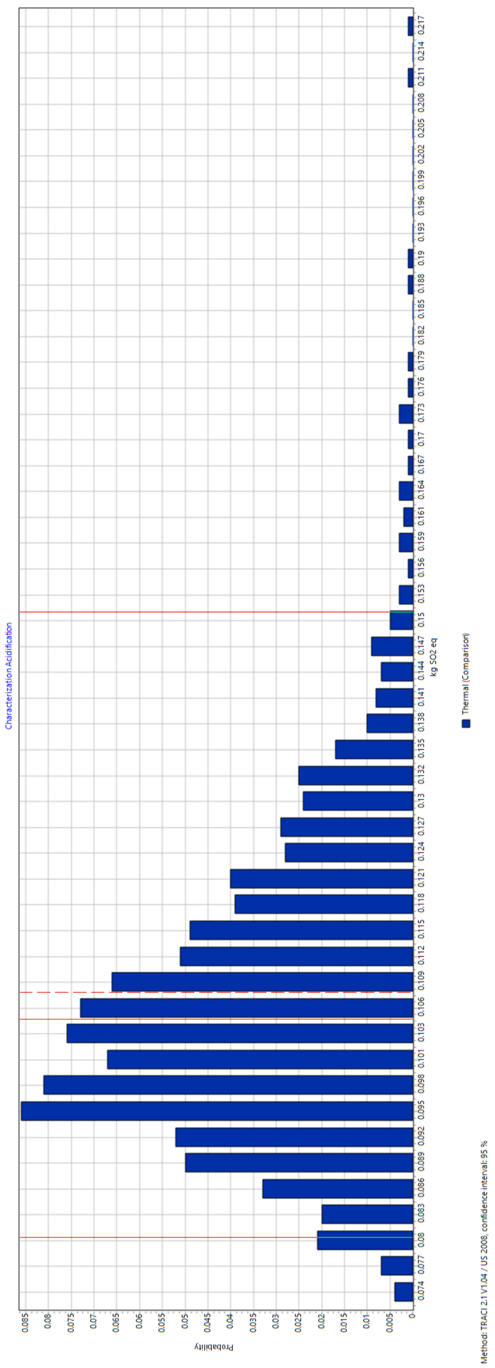


Figure K-3.5. Thermal Reclamation - Acidification Uncertainty

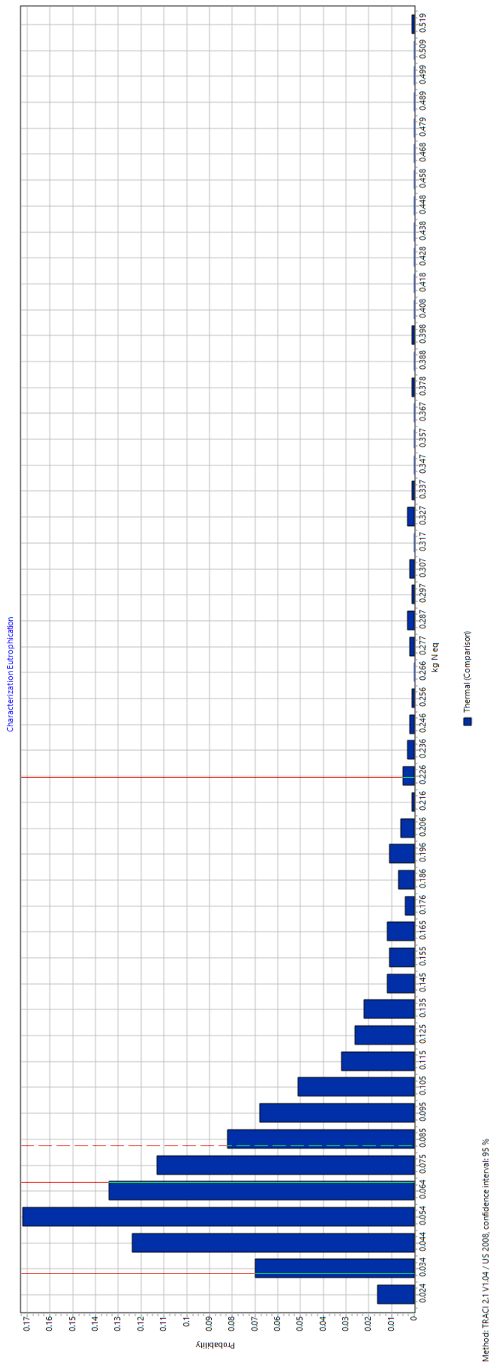
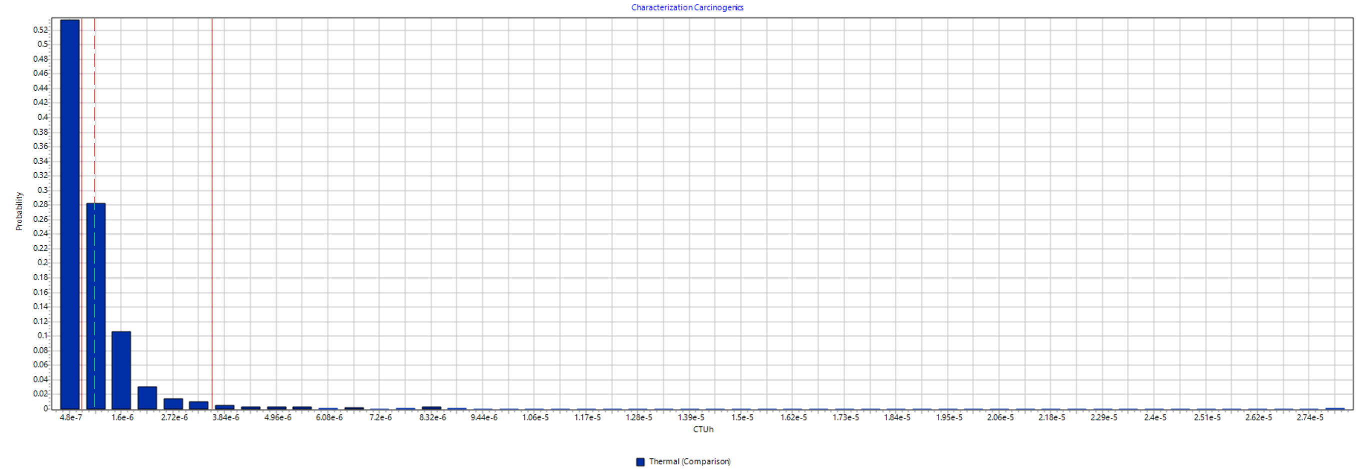


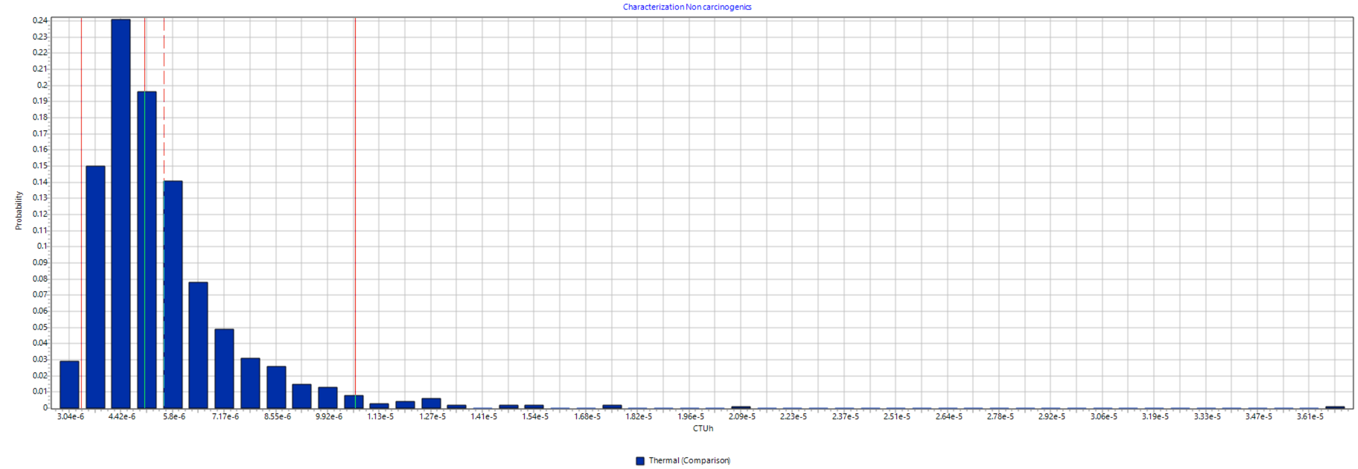
Figure K-3.6. Thermal Reclamation - Eutrophication Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Thermal (Comparison)',

Figure K-3.7. Thermal Reclamation - Carcinogenics Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Thermal (Comparison)',

Figure K-3.8. Thermal Reclamation - Non-Carcinogenics Uncertainty

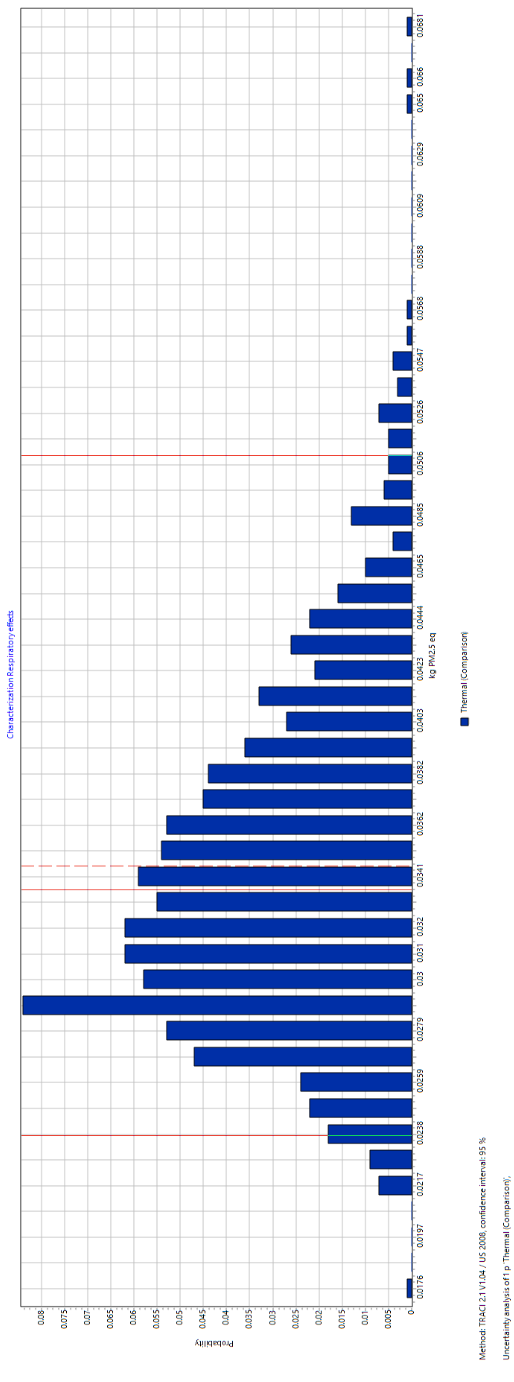


Figure K-3.9. Thermal Reclamation - Respiratory Effects Uncertainty

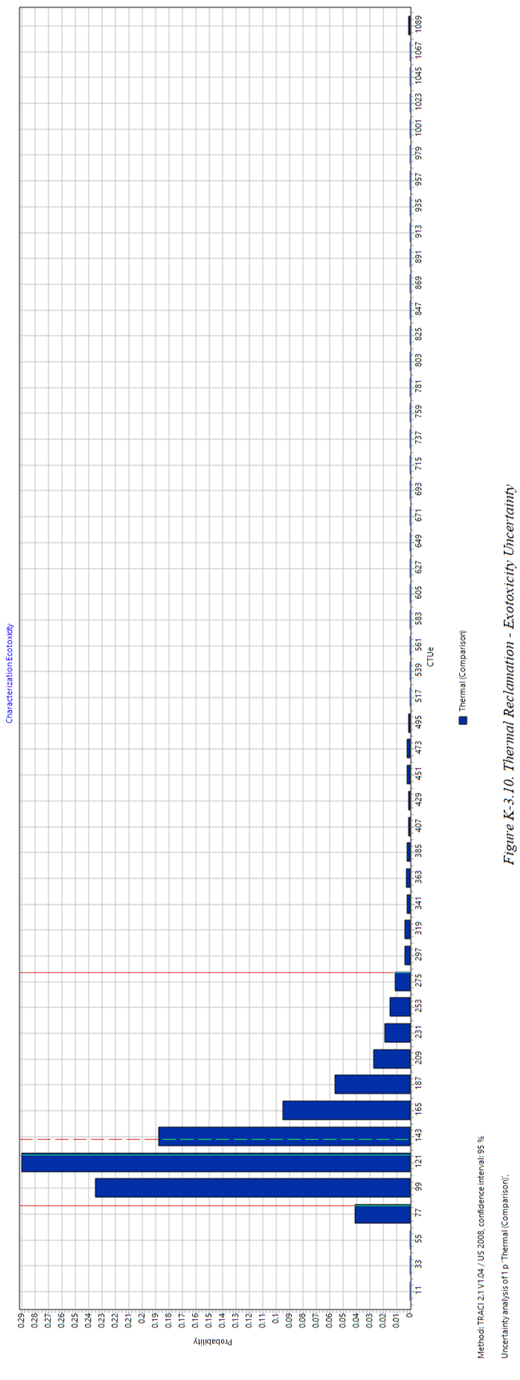


Figure K-3.10. Thermal Reclamation - Exotoxicity Uncertainty

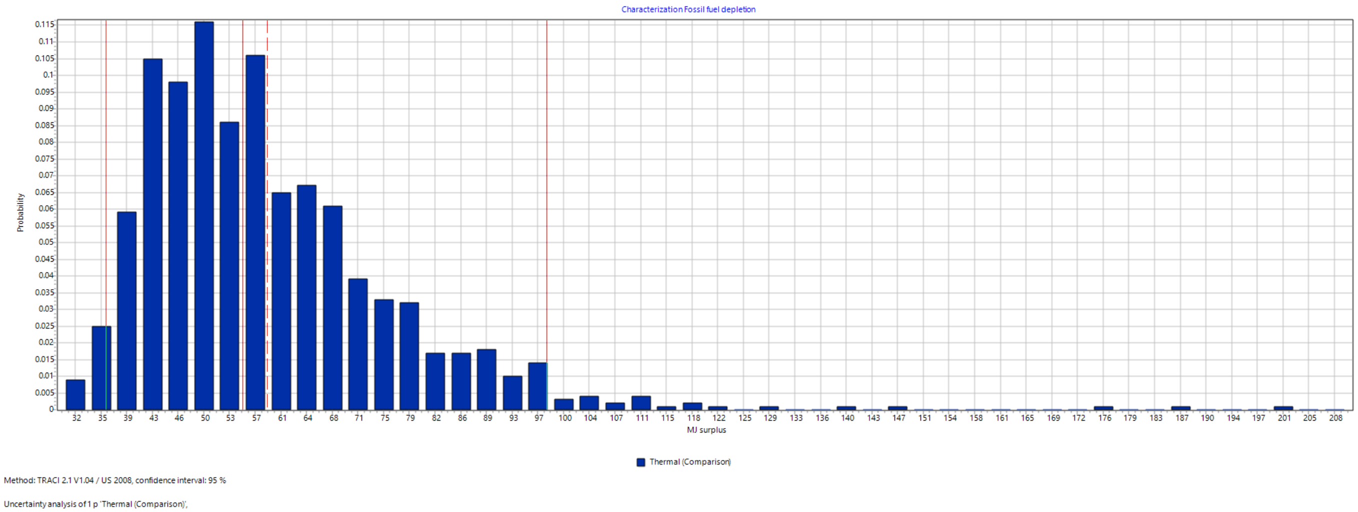
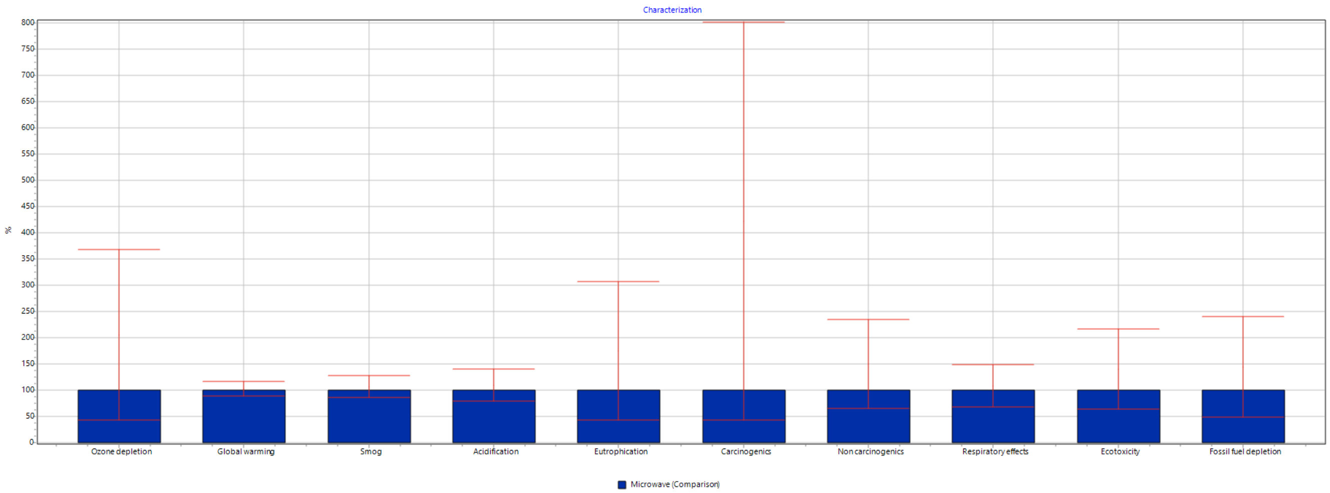


Figure K-3.11. Thermal Reclamation - Fossil Fuel Depletion Uncertainty

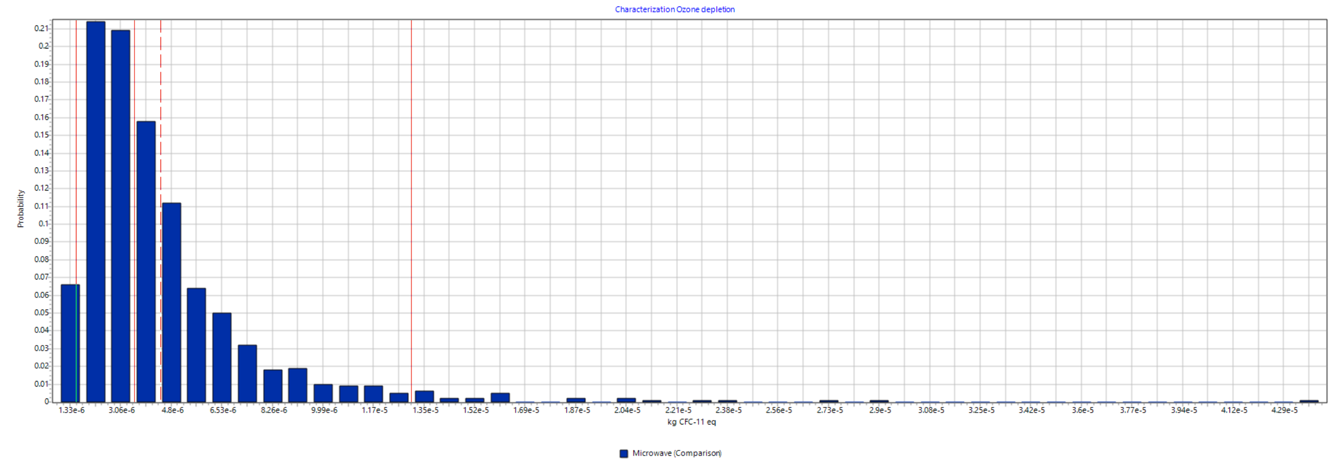
Appendix K-4: Microwave Reclamation Impact Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Microwave (Comparison)',

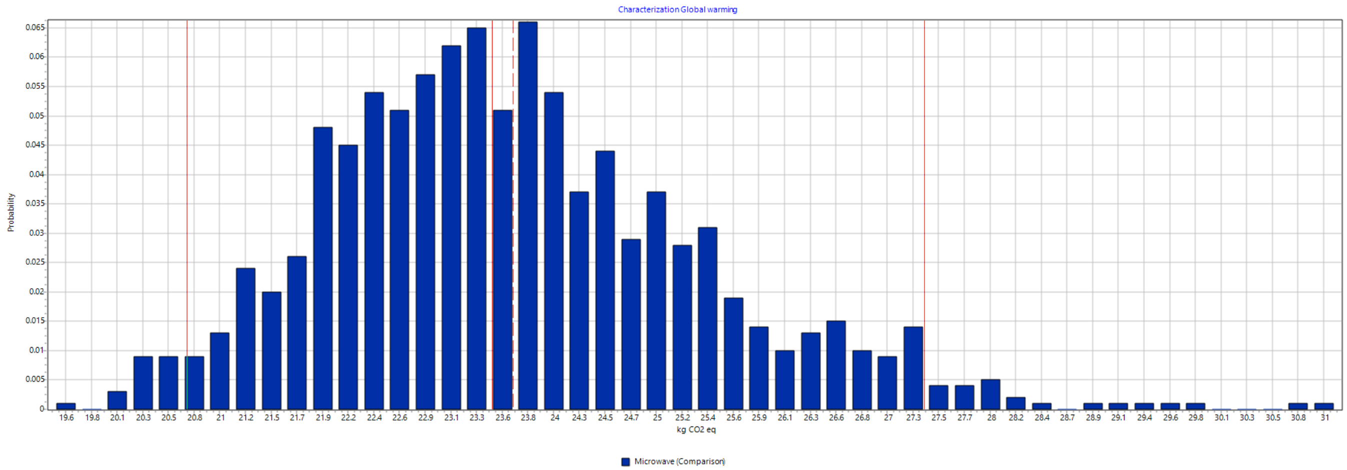
Figure K-4.1. Microwave Reclamation - Overall Impact Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Microwave (Comparison)',

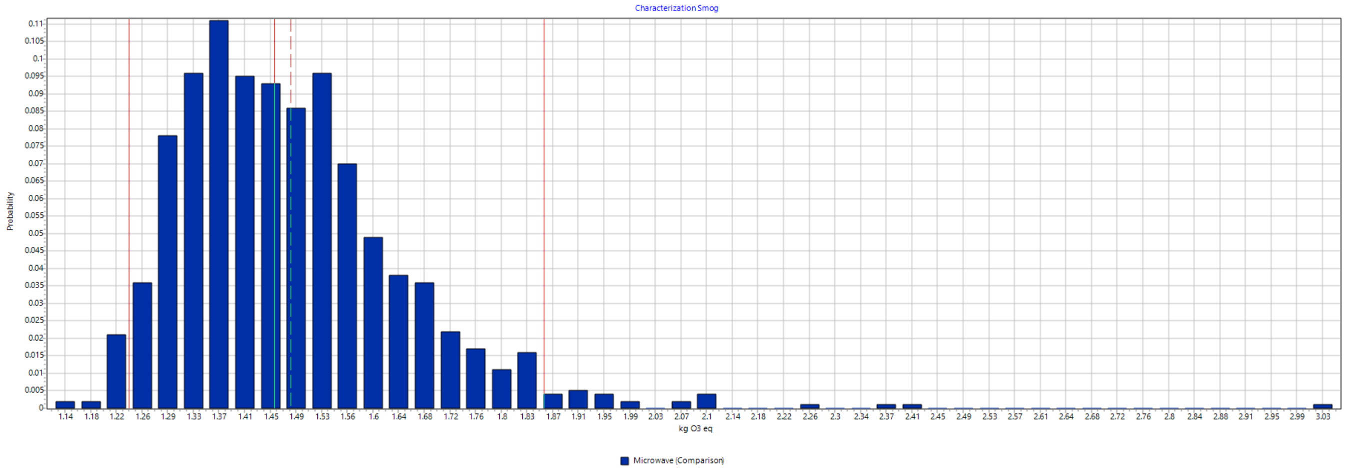
Figure K-4.2. Microwave Reclamation - Ozone Depletion Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Microwave (Comparison)',

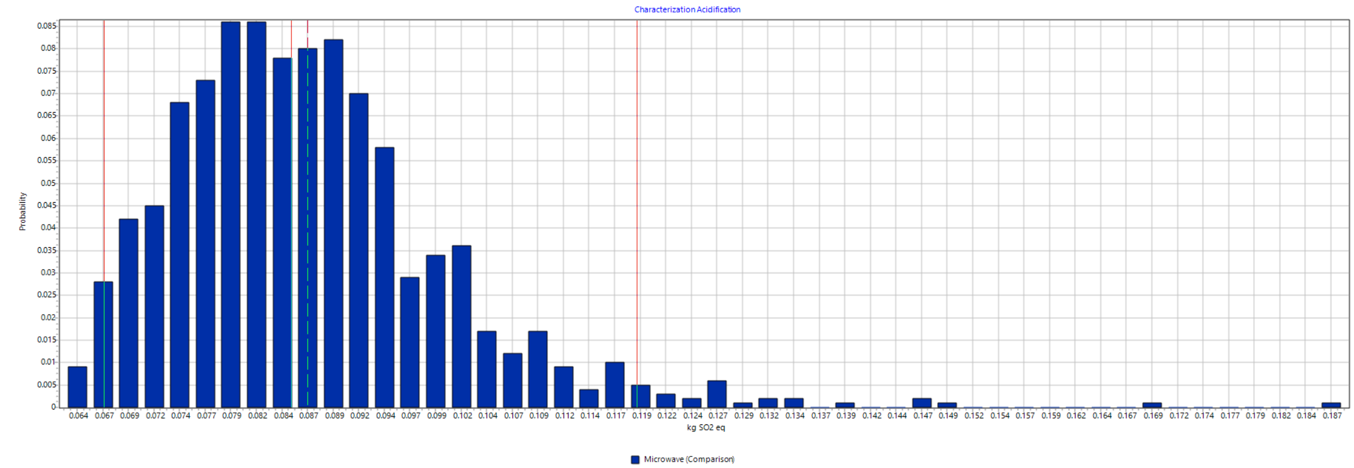
Figure K-4.3. Microwave Reclamation - Global Warming Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Microwave (Comparison)',

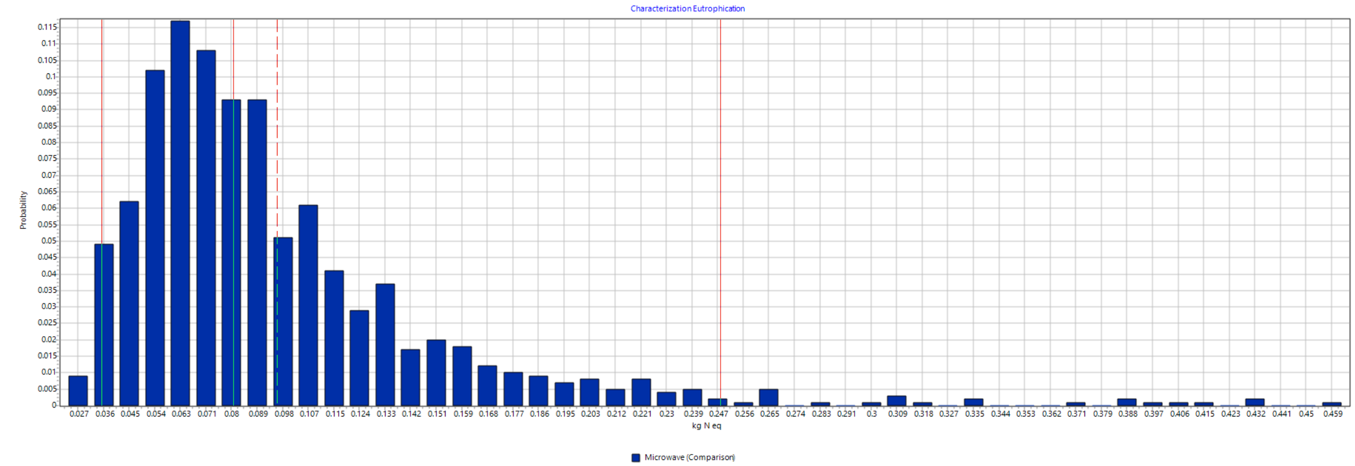
Figure K-4.4. Microwave Reclamation - Smog Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Microwave (Comparison)',

Figure K-4.5. Microwave Reclamation - Acidification Uncertainty



Method: TRACI 2.1 V1.04 / US 2008, confidence interval: 95 %

Uncertainty analysis of 1 p 'Microwave (Comparison)',

Figure K-4.6. Microwave Reclamation - Eutrophication Uncertainty

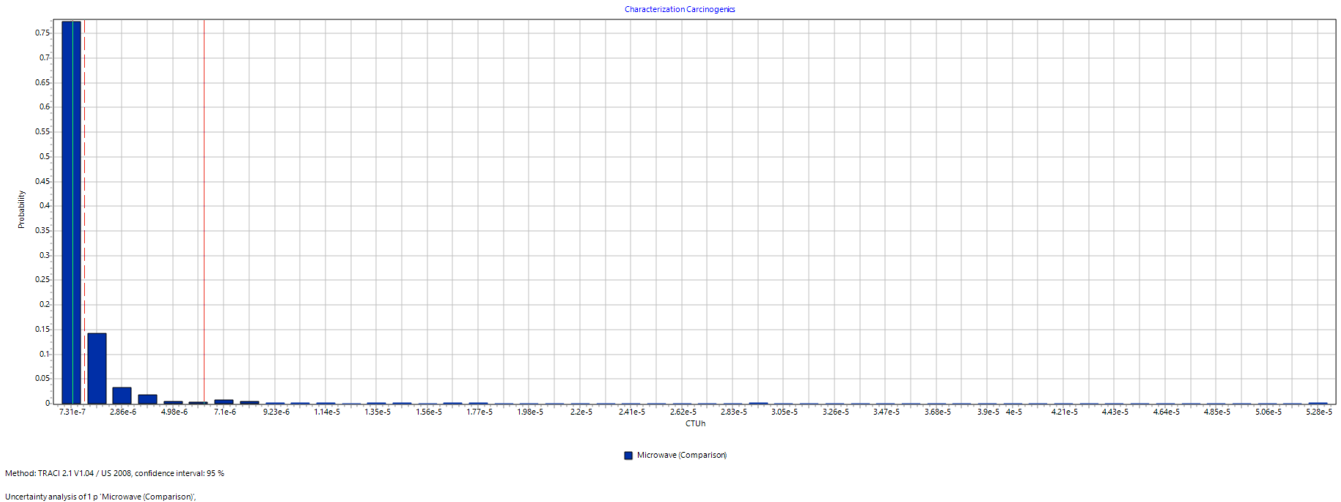


Figure K-4.7. Microwave Reclamation - Carcinogenics Uncertainty

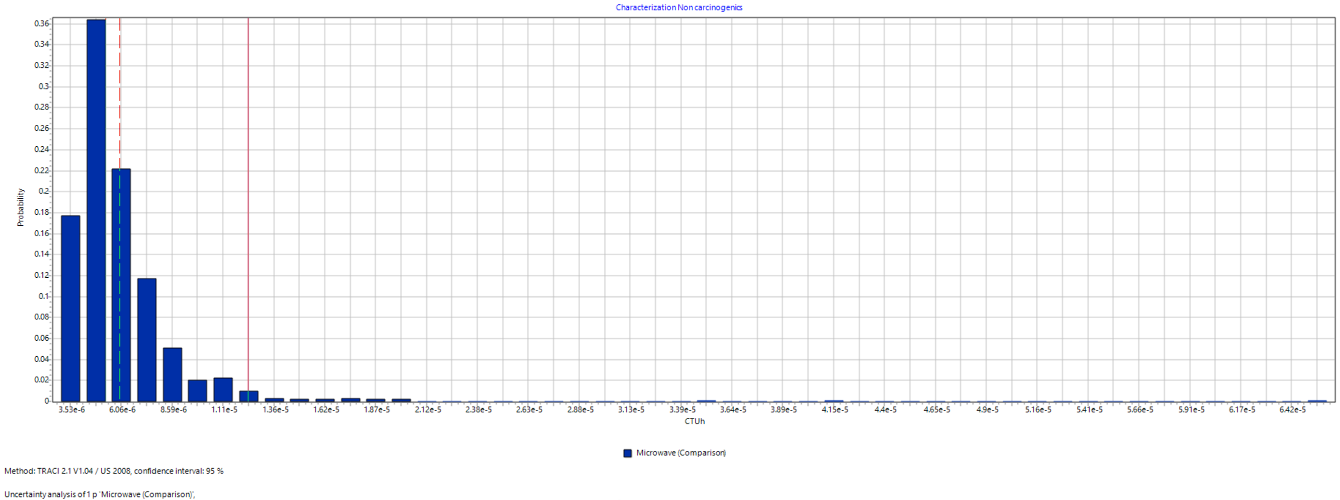


Figure K-4.8. Microwave Reclamation - Non-Carcinogenics Uncertainty

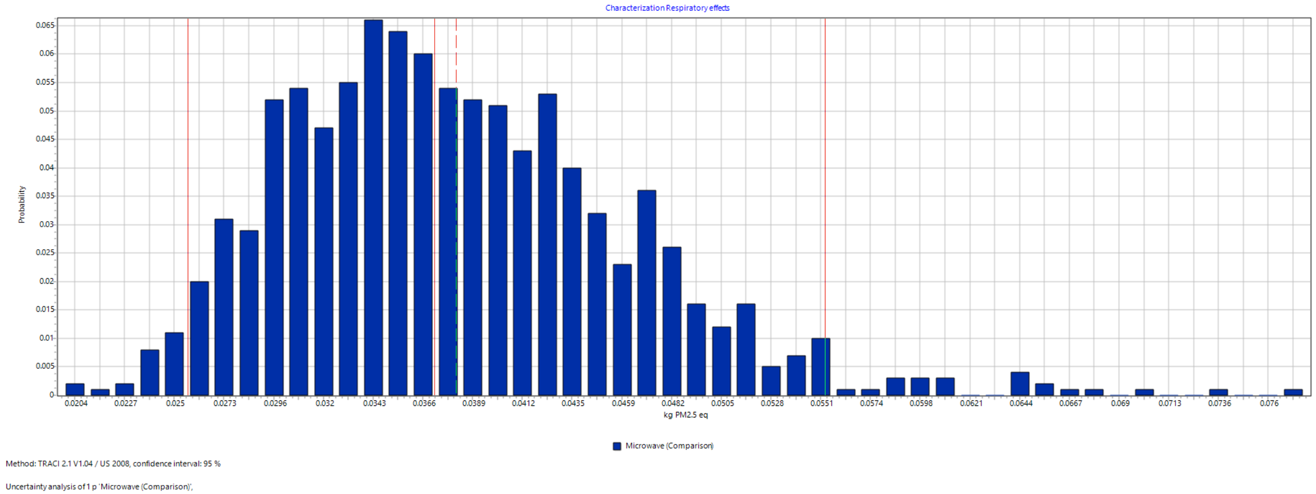


Figure K-4.9. Microwave Reclamation - Respiratory Effects Uncertainty

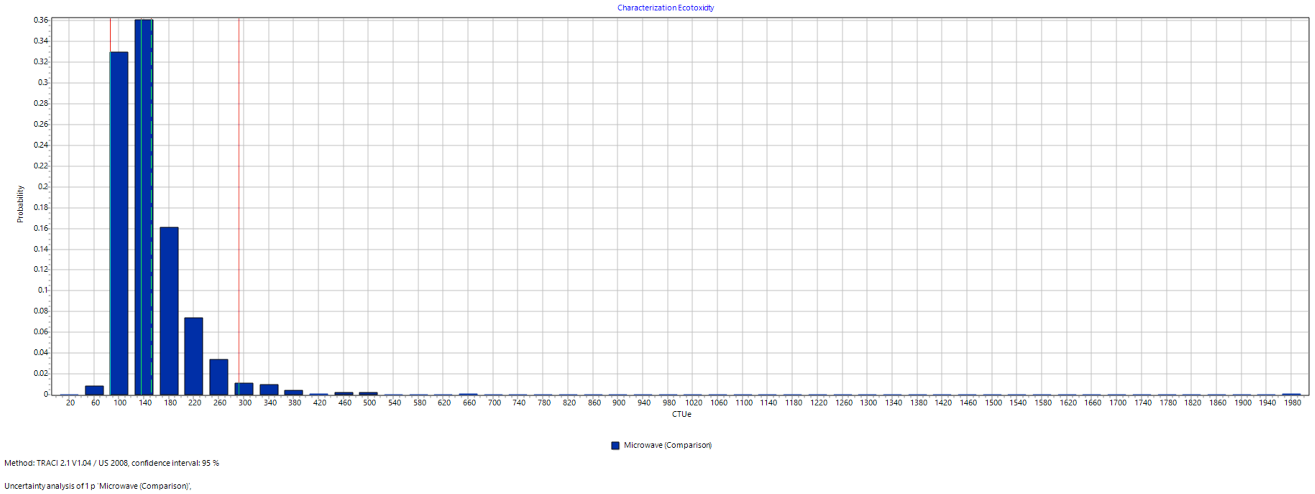


Figure K-4.10. Microwave Reclamation - Exotoxicity Uncertainty

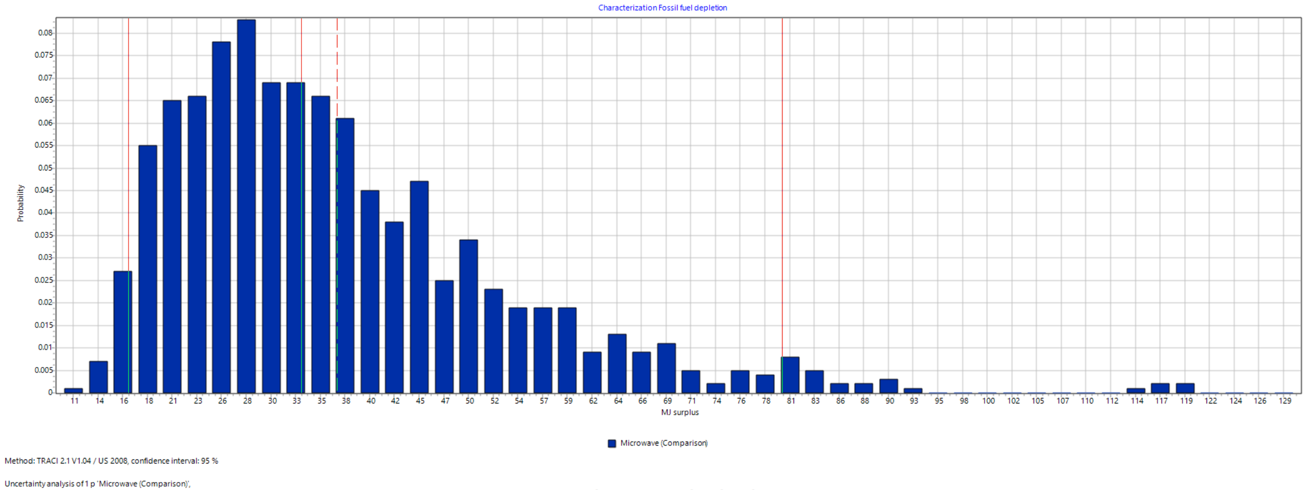


Figure K-4.11. Microwave Reclamation - Fossil Fuel Depletion Uncertainty

Appendix K-5: Process Uncertainty Comparisons

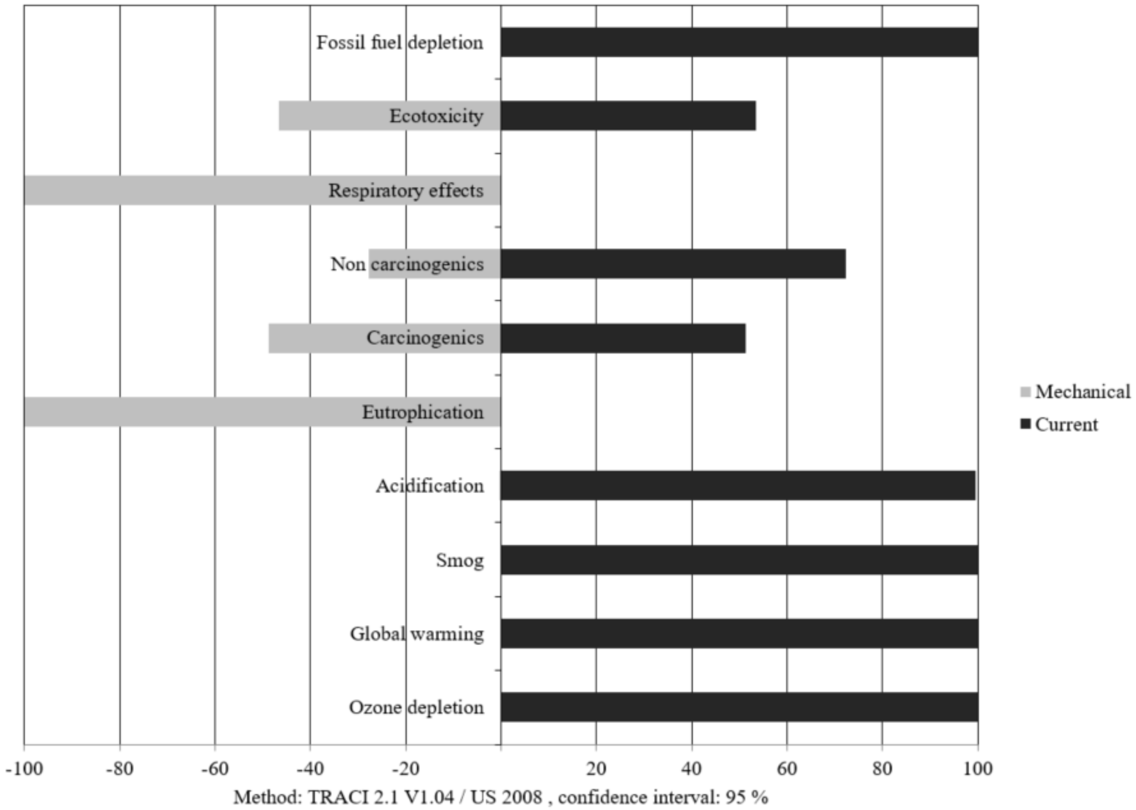


Figure K-5.1. Process Uncertainty Comparison - Mechanical Reclamation vs. Current Process

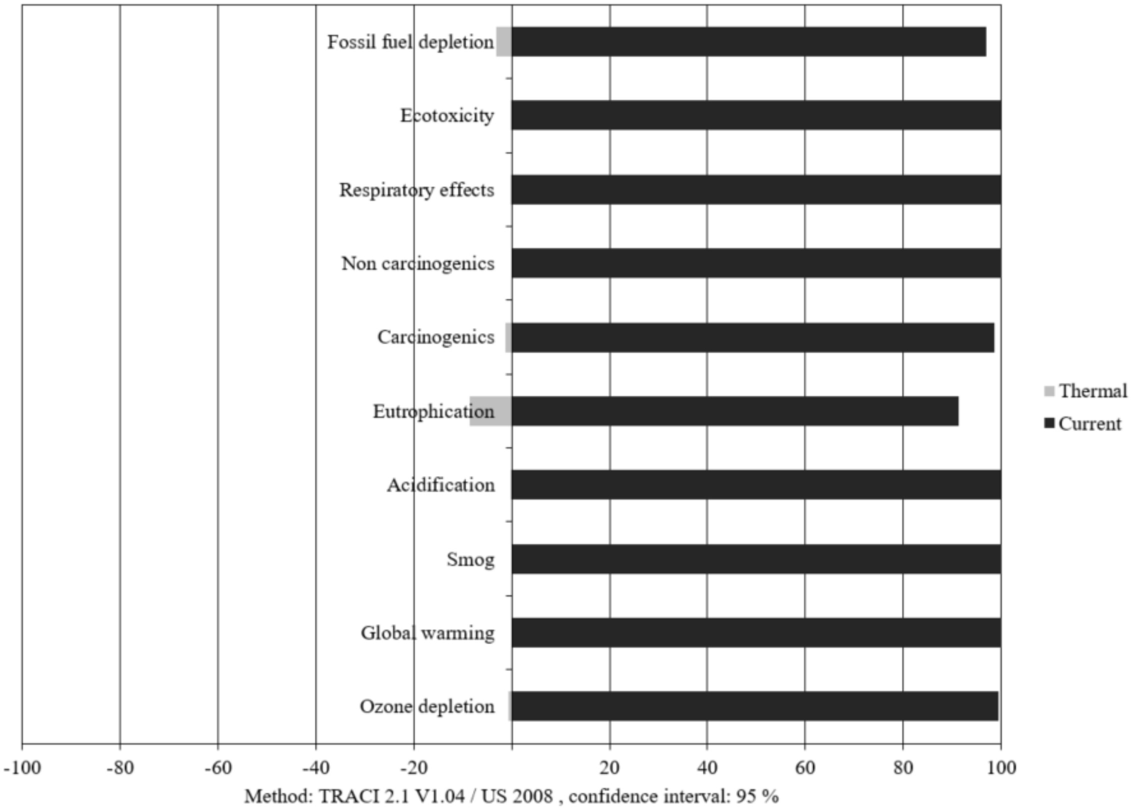


Figure K-5.2. Process Uncertainty Comparison - Thermal Reclamation vs. Current Process

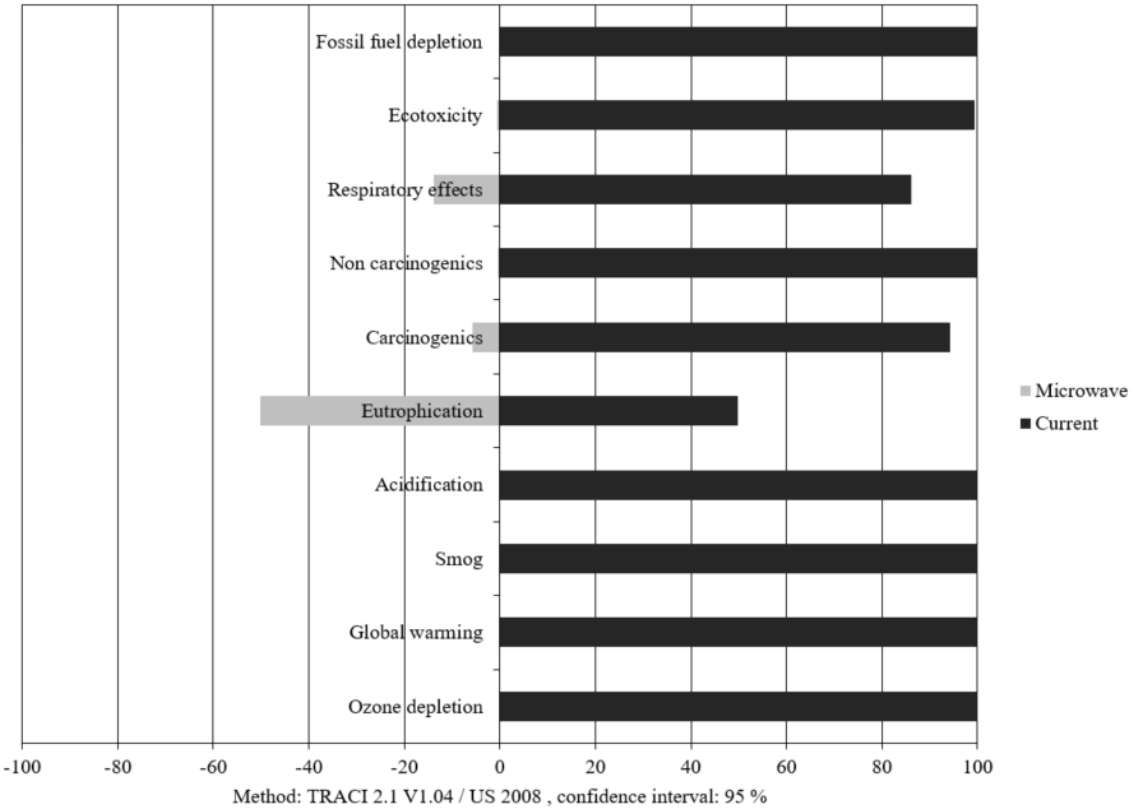


Figure K-5.3. Process Uncertainty Comparison - Microwave Reclamation vs. Current Process

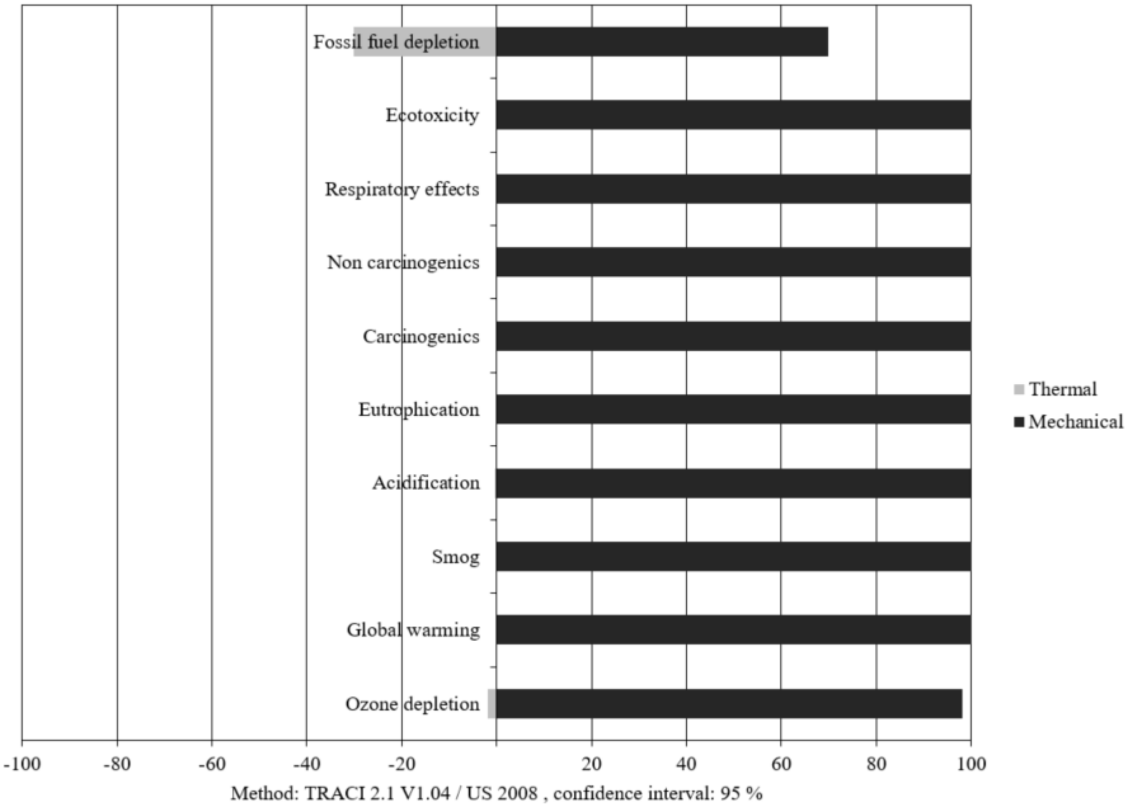


Figure K-5.4. Process Uncertainty Comparison - Thermal Reclamation vs. Mechanical Reclamation

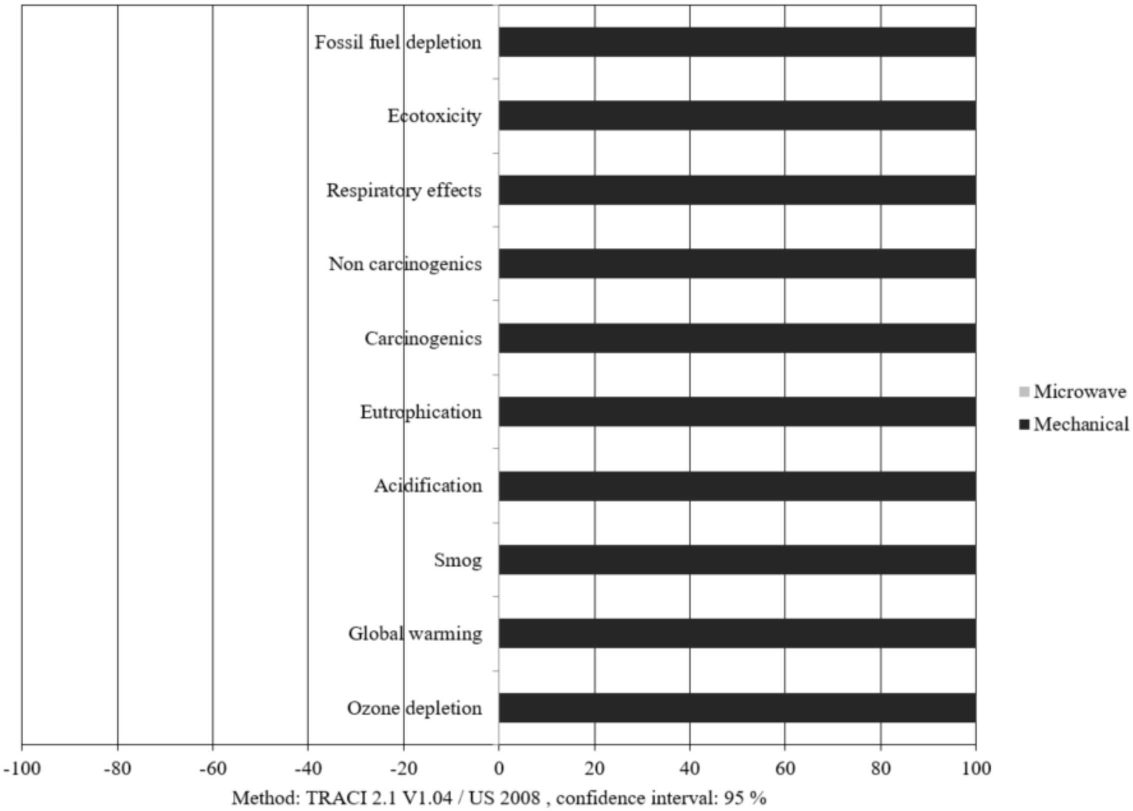


Figure K-5.5. Process Uncertainty Comparison - Microwave Reclamation vs. Mechanical Reclamation

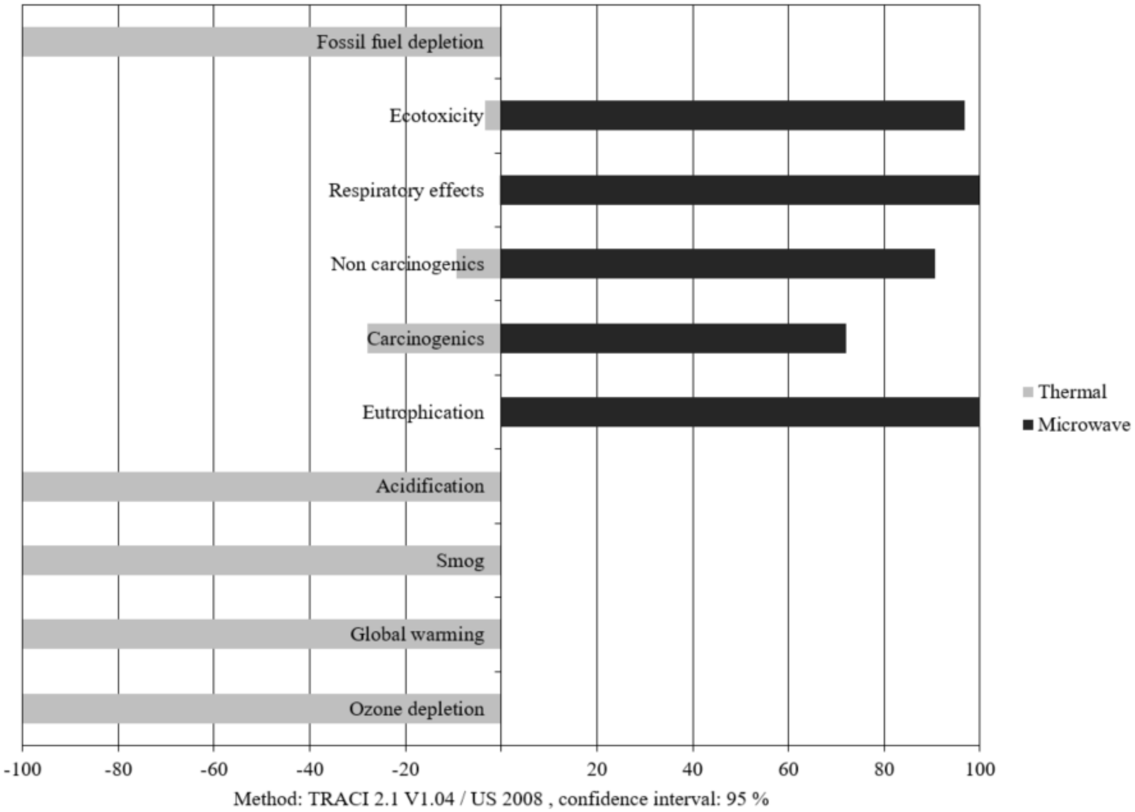


Figure K-5.6. Process Uncertainty Comparison - Thermal Reclamation vs. Microwave Reclamation