18th August 2021

Life Cycle Assessment of Spheronized Coated and Micronized Graphite Products from the Preliminary Economic Assessment Stage Woxna Graphite Anode Project

---

Authors: Pell, R. Whattoff, P. Lindsay, J.J.

Review: Sprecher. B, Smith, L.

---

1. Our Statement

Information contained in this report has been compiled from and/or computed from sources believed to be credible. Application of the data is strictly at the discretion and the responsibility of the reader. Minviro is not liable for any loss or damage arising from the use of the information in this document.

Life Cycle Assessment (LCA) is an environmental accounting tool with an inherent level of uncertainty, and it should not be seen as having the same level of precision as financial accounting. LCA requires a very large amount of data, particularly to calculate all the inputs and outputs for every step. Databases are often used since it is impractical to collect all the necessary data from original sources (e.g. it is impossible to get data from all the specific electricity plants from which electricity was sourced).

The report does not claim to be exhaustive, nor does it claim to cover all relevant products. While steps have been taken to ensure accuracy, the listing or featuring of a particular product or company does not constitute an endorsement by Minviro. This material is copyrighted. It may be reproduced free of charge, subject to the material being accurate and not used in misleading context. The source of the material must be identified, and the copyright status acknowledged.

Leading Edge Materials Corp. commissioned Minviro Ltd as LCA practitioner in December 2020, to complete a Life Cycle Assessment on the production of coated spherical purified graphite (“CSPG”) and micronized graphite products.

The LCA was conducted using the best available data. The intended application of this LCA study is to assist in project and product development and improvement, demonstrate the environmental benefits versus current supply and in strategic planning for Leading Edge Materials Corp.

Document Details	
Document Title	Life Cycle Assessment of Spheronized Coated and Micronized Graphite Products from the Preliminary Economic Assessment Stage Woxna Graphite Anode Project
Date	18th August 2021
Version	5
Author	Pell, R. Whattoff, P. Lindsay, J.J.
Reviewers	Sprecher. B, Smith, L.
Client Name	Leading Edge Materials Corp

Document History

Version	Revision	Author	Reviewed By	Comments
Draft	1.0	Pell, R. Whattoff, P. Lindsay, J.J.	Tijsseling, L.T.	
Final	2.0	Pell, R. Whattoff, P. Lindsay, J.J.	Leading Edge Materials Corp	
Final	3.0	Pell, R. Whattoff, P. Lindsay, J.J.	Tijsseling, L.T.	
Final	4.0	Pell, R. Whattoff, P. Lindsay, J.J.	Leading Edge Materials Corp	
Final	Final	Pell, R. Whattoff, P. Lindsay, J.J.	Sprecher. B, Smith, L.	

2. Executive Summary

Minviro was appointed by Leading Edge Materials Corp (LEM) to conduct a cradle-to-gate Life Cycle Assessment (LCA) to produce coated spherical purified graphite (CSPG), used as the active anode material in lithium-ion batteries, and micronized graphite (MG) products from natural flake graphite. The life cycle impact of producing 1 kilogram of CSPG from natural flake graphite from natural resources has been evaluated, whilst simultaneously evaluating the life cycle impact of the production of micronized graphite co-products. Economic allocation has been used to split the life cycle impact between the two products.

The project consists of a mine, concentrator and upgrade plant, which are all located in Central Sweden. The impact categories investigated in this LCA study are Global Warming Potential, Acidification Potential, Eutrophication Potential (Freshwater, Terrestrial and Marine environmental compartments), Disease Incidences and Water Use. The results of the LCA study are shown in Table 1.

The project was benchmarked against the production of CSPG via natural and synthetic production routes located in Guangdong and Heilongjiang Provinces, China. The results of the benchmarking exercise are detailed in Table 2 and 3.

Table 1: Overall LCIA Results per Impact Category for the Production of 1 kg of CSPG and Micronized Graphite.

Impact Category	Total Value CSPG	Total Value MG	Units
Global Warming Potential	1.7	0.04	kg CO_2 eq.
Acidification Potential	$8.6E^{-3}$	$1.4E^{-4}$	Mol H^+ eq.
Freshwater Eutrophication Potential	$2.9E^{-3}$	$1.8E^{-4}$	kg P eq.
Terrestrial Eutrophication Potential	$1.8E^{-2}$	$6.5E^{-4}$	Mol N eq.
Marine Eutrophication Potential	$3.5E^{-3}$	$2.1E^{-4}$	kg N eq. per kg
Disease Incidences	$7.9E^{-5}$	$7.3E^{-6}$	disease incidence eq.
Water Use	3.2	0.1	kg Water eq.

Table 2: LCIA Results for Production of Anode Grade Graphite via Natural and Synthetic Routes in China vs LEM Production Route.

	Synthetic CSPG-China	**Natural CSPG - China**	**LEM - CSPG**
Global Warming Potential	16.7	13.2	1.7
Acidification Potential	$7.2E^{-3}$	$8.1E^{-2}$	$8.6E^{-3}$
Freshwater Eutrophication Potential	$3.1E^{-4}$	$2.1E^{-3}$	$2.9E^{-3}$
Terrestrial Eutrophication Potential	$2.0E^{-1}$	$1.6E^{-1}$	$1.8E^{-2}$
Marine Eutrophication Potential	$1.3E^{-3}$	$4.9E^{-3}$	$3.5E^{-3}$
Disease Incidence	$6.6E^{-7}$	$1.9E^{-6}$	$7.9E^{-5}$

Table 3: LCIA Results of Micronized Graphite via Natural Routes in China vs LEM Production Route.

	Natural MG - China	**LEM - MG**
Global Warming Potential	2.53	0.04
Acidification Potential	$3.7E^{-3}$	$1.4E^{-4}$
Freshwater Eutrophication Potential	$1.7E^{-4}$	$1.8E^{-4}$
Terrestrial Eutrophication Potential	$1.0E^{-2}$	$6.5E^{-4}$
Marine Eutrophication Potential	$9.7E^{-4}$	$2.1E^{-4}$
Disease Incidence	$6.0E^{-8}$	$7.3E^{-6}$

Contents

List of Tables

List of Figures

Acronyms and Abbreviations

Acronym	Meaning
ANFO	Ammonium Nitrate Fuel Oil
AP	Acidification Potential
CO_2	Carbon Dioxide
DI	Disease Incidence
EP	Eutrophication Potential
ERF	Emissions Reduction Fund
eq.	equivalent
FEP	Freshwater Eutrophication Potential
GWP	Global Warming Potential
kg	kilograms
L	liters
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEM	Leading Edge Materials
LOM	Life of Mine
LOP	Life of Project
m^3	cubic metres
MEP	Marine Eutrophication Potential
MG	Micronized Graphite
MJ	Megajoules
MIBC	Methyl IsoButyl Carbinol
Mol H^+	Acidification Potential Unit
Mol N	Terrestrial Eutrophication Potential Unit
N	Marine Eutrophication Potential Unit
P	Freshwater Eutrophication Potential Unit
PEA	Preliminary Economic Assessment
PM	Particulate Matter
CSPG	Spheronized Coated Graphite
t	tonnes
TEP	Terrestrial Eutrophication Potential
WU	Water Use

3. Introduction

Leading Edge Materials Corp. owns 100% of Woxna Graphite AB, which owns a graphite mine in Sweden, which was refurbished and brought into production in July 2014. Production of the graphite concentrate product was halted within a year due to low global market prices for that product, and the mine is currently on care and maintenance whilst the production processes for higher value products are being developed. The focus is on producing high purity coated spherical purified graphite (CSPG) and micronized graphite products to supply the materials required in the emerging energy production and storage, thermal insulation and additive manufacturing markets. In this Life Cycle Assessment (LCA) study, the environmental impact of the proposed CSPG and micronized graphite production routes are evaluated and quantified [1].

3.1. Project Description

The Woxna graphite project is located along a 40 km trend in central Sweden with four deposits held under mining leases: Kringelgruvan, Gropabo, Mattsmyra and Mansberg. The LCA only assesses the Kringelgruvan site, where a permitted graphite concentrate processing facility and a tailing's storage dam have already been constructed. Graphite concentrate is then planned to be transported to an upgrade facility in Edsbyn in the Ovanåker Municipality, Gävleborg County, Sweden, where graphite concentrate is upgraded to form CSPG and micronized graphite products. Table 4 details the project production estimates for the Woxna graphite project.

Table 4: Woxna Graphite Project Production Estimates.

Description	Value	Unit
Life of Project	19	years
Graphite Concentrate	15,692	t/year
Spheronized coated graphite	6,519	t/year
Micronized Graphite	8,631	t/year

3.2. Scope of Assessment

The goal of the Life Cycle Assessment was to quantify environmental impacts addressed through different impact categories for the production of CSPG and/or micronized graphite from graphite mineralized material extracted from natural resources. This includes identifying hotspots and mitigating impacts as the project advances. The goal for LEM is to produce CSGP and micronized graphite products to supply to the emerging energy production and storage, thermal insulation and additive manufacturing markets, with minimal environmental impacts [1].

LCA is a tool to assess the environmental impacts associated with all stages of a product, process or activity [2]. An important aspect is that it allows the evaluation of indirect impacts that occur in the development of a product or process system over the entire life cycle, providing information that otherwise may not be considered. A wide range of environmental impacts can be captured into a single integrated framework in a scientific and quantitative way. The holistic approach generates results on how decisions made at one stage of the life cycle might have consequences elsewhere, ensuring that a balance of potential trade-offs can be made and avoiding shifting of the environmental burden [3,4].

3.3. Life Cycle Assessment Methodology

This LCA study has been conducted according to the requirements of the ISO-14040:2006 and ISO-14044:2006 standards [5]. LCA has four fundamental steps that include goal and scope definition, inventory analysis, impact assessment, and interpretation.

The Ecoinvent version 3.7.1 database was used for the assessment stage. This database provides a well-documented process for products supporting the understanding of their environmental impacts. The Ecoinvent database comprises inventory data for most economic activities. The consistency and cohesion of the LCI datasets increase the credibility and acceptance of the results obtained using this database. The baselines of this database are LCI datasets that consider human activities and their interactions with the environment ([6]).

3.3.1. Goal and Scope

This study assesses the life cycle impact of the production of 1 kg of coated spherical purified graphite upgraded from graphite ore and 1 kg of micronized graphite upgraded from graphite ore. This is a cradle-to-gate study, which means the product life cycle is being assessed from the point of extraction from natural resources to the end-gate of the upgrade plant facility. Use phase or end-of-life of CSPG and micronized graphite are outside the scope of this LCA study. The LCA study will cover the impacts associated with the mining, concentrating and upgrading processes. This includes transport of graphite concentrate from the concentrate plant to the upgrade plant. Transport of reagents are not included in this LCA study, due to data not being available.

To evaluate the techno-economic feasibility of this project, a Preliminary Economic Assessment (PEA) was carried out. The material and energy requirements deduced from that study are used as the input for this LCA study. Additional estimates regarding the economic contribution of the different products, intermediate and material transport and location of the facility were provided during the project.

The primary objective for carrying out this study is to quantify the environmental impacts of the proposed production route and identify the environmental ‘hotspots’ for the production of CSPG and micronized graphite. The second objective of this study is to assist in project development and improvement, with a third motivation being to assist with strategic planning and assess the environmental performance of the LEM route versus the current supply chain.

This study has been conducted according to the requirements of the ISO-14040:2006 and ISO-14044:2006, including a third-party review from LCA experts to ensure that the LCA study is scientifically robust. The intended audience for this study includes parties that are interested in the graphite value chain, ranging from project developers to producers to end-users of spheronized coated and/or micronized graphite. The results are intended to be used for comparative assertions to be disclosed to the public.

3.3.2. Functional Unit

LCA uses a functional unit as a reference to evaluate the components within a single system or among multiple systems on a common basis. The **functional unit** is the quantitative reference used for all inventory calculations and impact evaluations.

The **functional unit** for this study is defined as: ***The production of one kilogram of coated spherical purified graphite (CSPG), produced from natural flake graphite originating from Kringelgruvan, Sweden.***

The micronized graphite co-product is being considered as an alternative functional unit in this study as 1 kg of micronized graphite.

3.3.3. System Boundary

The system boundary of the CSPG production and micronized graphite production processes used in this study are shown in Figure 1. For this project, it is assumed that the electricity for the concentrator and upgrade facility is sourced from electricity supplier: Vattenfall [7].

The micronized and CSPG products originate from material that goes through identical routes for the mining and concentrating processes. The system starts with mining of the flake graphite ore using a conventional diesel fueled haulage fleet and ammonium nitrate fuel oil (ANFO) as explosives. The extracted ore undergoes comminution, flotation to produce a graphite concentrate (grading 93% Carbon). Diesel as collector, flocculant and Methyl IsoButyl Carbinol (MIBC) are added as reagents within this stage. The graphite concentrate is then transported to the planned/possible upgrade plant situated in Edsbyn, Sweden, for further processing. It is assumed the concentrate will be transported by lorry/truck (~40 tonnes of graphite concentrate per lorry) to the upgrade plant.

At the upgrade plant, the graphite concentrate is fed into one process, where the material is separated into two processing streams at a later stage to produce the two products. For both routes, initially, the concentrate passes through a micronizer and spheronization step. The rejected material from the spheronizer is filtered from the spheronized graphite and is further micronized using three jet mills, to produce micronized graphite products. The micronized graphite grades 93% carbon and is to be sold as a micronized graphite product. The CSPG is fed to a vacuum furnace and coating stage. Nitrogen, solvent, argon, and pitch are added as reagents. Argon and nitrogen are transported to the upgrade facility as a liquid gas. In the upgrading process, argon is in its gaseous form. The CSPG product produced is at least 99.95% C purity. The water system for the upgrade plant is within a closed system, therefore all the water is recycled within the process and not released into the environment.

The furnace off-gas released from the upgrade plant process is cooled to solidify the vaporized impurities. The off-gas that is released is assumed to be heat only, not containing substances that could harm the environment, thus is not included within the LCA. This should be investigated, however, in future LCA studies (see section 10.2). Solid wastes are discharged from the upgrade facility. The solid waste is included within the LCA.

Table 5 states all assumptions made throughout this Life Cycle Assessment associated with the foreground and background data used within this LCA.

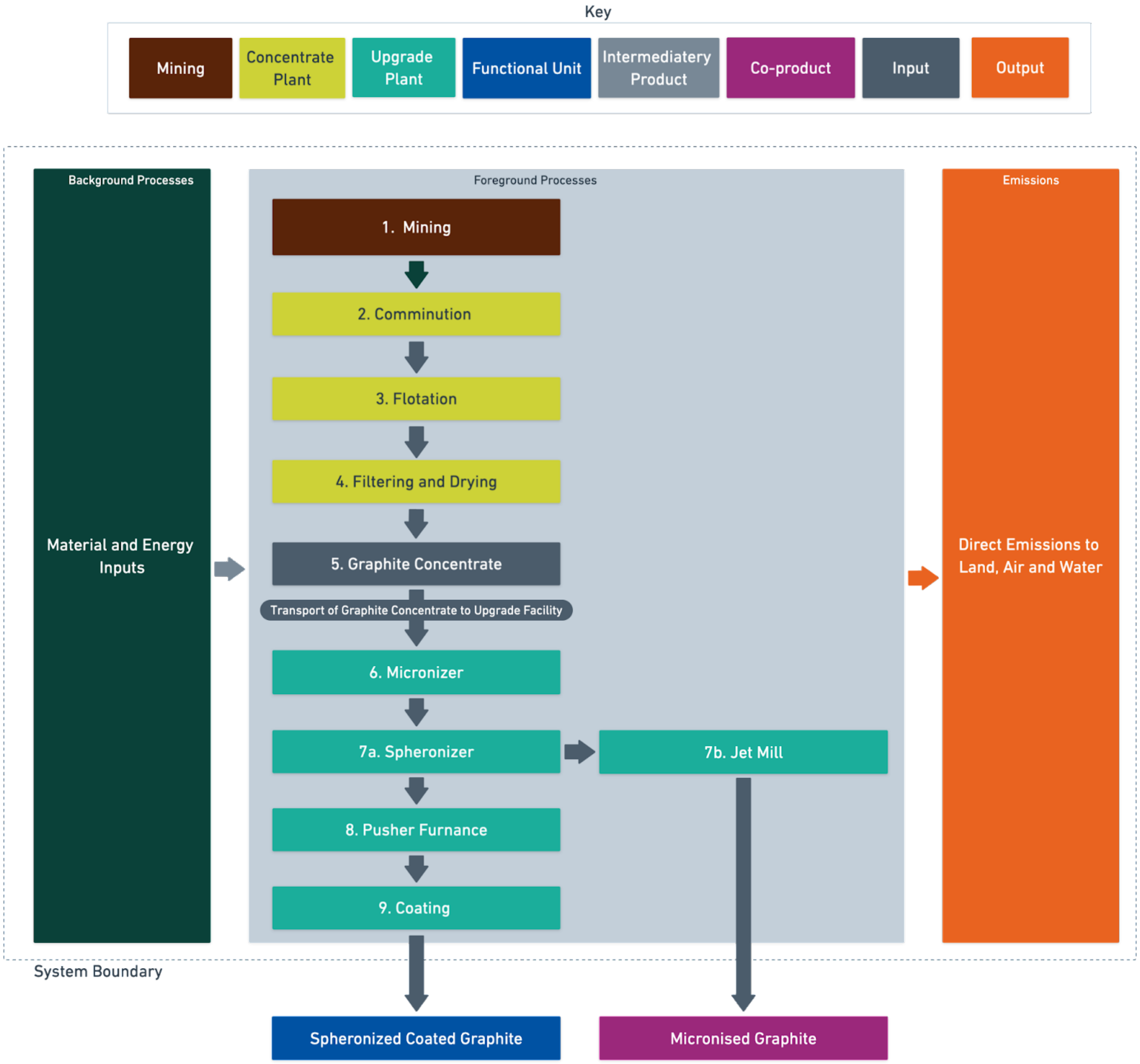


Figure 1: System Boundary Applied to the LCA Study of the Production of Spheronized Coated and Micronized Graphite from Natural Flake Graphite Ore.

Table 5: Assumptions Made Regarding the Foreground and Background Data of the LCI.

Item	Description
Electricity	Electricity for concentrator and upgrade plant is sourced from Vattenfall.
Transport	Graphite concentrate is transported by lorry/truck 40km from mine site to upgrade plant.
Off-gas Heat	Assumed off-gas released is heat only, with no harmful substances being released into the atmosphere.
Nitrogen	Assumed density of 1.25 kg per m^3.
Argon	Assumed density of 1.75 kg per m^3.
Disease Incidence	Particulate matter assumed to be emitted outdoors in a rural area at ground level.
Water Use	Water exits the concentrator through the tailings and is recirculated back into the concentrator, therefore water lost is through evaporation only.
Water Use	Cooling water in the upgrade plant is a closed loop system.
Water Use	Assumed water returned to the local water system is not degraded.
Uncertainty	For mine and concentrator, a standard deviation of 15% was assumed due to being in care and maintenance stage.
Uncertainty	For the upgrade plant, 30% uncertainty was assumed due to being in PEA stage.
Uncertainty	Assumed uncertainty associated with foreground data is high enough, thus covers the uncertainty associated with the background data.
Benchmarking	Electricity for the benchmark routes is sourced from the region's grids, the operations are located in.
Tailings	Assumed to be non-acid generating.
Vattenfall Electricity	No division in the eutrophication potential into the 3 sub-categories, so the eutrophication potential value was assumed to be the same for all three.
Reagents	Average database values are used to present the embodied impact associated with the production of reagents.

3.3.4. Multi-Output Allocation

In Life Cycle Assessments, it is critical to ensure that environmental impacts are divided among the different products of an operation or flowsheet in a way that follows best practice and is scientifically valid. Following the guidance provided in the ISO-14044:2006 standards, it is recommended to avoid allocation where possible. Following that, it is recommended to allocate the impacts following the physical relationship, then allocate impacts following other methodologies, of which one is allocation by economic relationships between different products of the process. In this case, a combination of the physical relationship between the products and the economic contribution towards the project has been used. This is known as economic allocation.

Economic allocation is appropriate because although the production volume of CSPG and micronized co-product are similar, the economic value for CSPG (10,000 USD$/t) holds 86% of the total economic contribution, whereas the micronized co-product holds 14% (1,200 USD$/kg), as seen in Table 6. System expansion was also evaluated as a method to avoid allocation and to discount the micronized graphite. This was not considered appropriate as there are no data points available in literature for the production of micronized graphite.

Economic allocation will allocate a proportion of the environmental impact to the functional unit and the co-products as a result of the difference in both market values and the production volumes.

Table 6: Production Volume, Revenue, and Economic Contribution over Life of Project.

Product	Production Volume (tonne/year)	Economic Value (USD$/tonne)	Revenue (USD$/year)	Economic Contribution	Life of Project (years)
CSPG	6,519	10,000	65,190,000	86%	19
Micronized Graphite	8,631	1,200	10,357,200	14%	19

3.3.5. Life Cycle Inventory

This study was desk-based, meaning that all data was either provided by LEM, collected from public sources or used from public and private databases. A complete Life Cycle Inventory (LCI) for the study is included in appendix A. Background data was used from Ecoinvent 3.7.1. The characterization factor for electricity has been provided by Vattenfall. This was calculated based on their Environmental Product Declaration (EPD) [7]. Nitrogen and argon consumption was provided in cubic metres and converted to mass based, assuming a density of 1.25 kg per m^3 and 1.78 kg per m^3 respectively. Energy input of diesel from haulage was calculated under the assumption of a calorific value of 38.6 MJ per litre. The disease incidence characterization factor is $6.3E^{-5}$ kg PM2.5 intake per kg PM2.5 emitted, assuming each input is outdoors in a rural area at ground level. The average non-agricultural water scarcity characterization factor for the project location was used for the direct water inputs and electricity used. Other material inputs were multiplied by the world average, due to the locations of the reagents being sourced from are unknown. Bags and pallets used for product packaging were excluded from the LCA. This is because packaging is not associated with the functional unit and there is a lack of data for the production of bags and pallets, reducing the robustness of the LCA.

An analysis of the material and energy flows within the system boundary was made and all material and energy flows related to the processing of the flake graphite ore have been included in the Life Cycle Inventory and included in the Life Cycle Impact Assessment (LCIA), including transport of raw materials and materials consumed. Flows related to the production of equipment or infrastructure have been excluded, this includes the mill liners. The reason for excluding these flows is that it will not allow for a like-for-like comparison against published and database values for operational facilities.

3.3.6. Cut-off Criteria

Cut-off criteria is used in LCA practice to decide which inputs are included in the assessment, based on mass, energy and environmental significance. In this study, no cut-off criteria was applied to the flows entering or leaving the system. All flows were considered in the LCA study.

3.3.7. Life Cycle Impact Assessment

The Life Cycle Impact Assessment categories selected for this study included Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (Freshwater, Terrestrial and Marine), Disease Incidence and Water Use (AWARE). The GWP, AP, Eutrophication Potential and Water Use impact categories have been selected as these have been identified as relevant impact categories in the scientific literature for the mining and metal industry [4] and so can accurately highlight areas where insights into the life cycle impact of CSPG and micronized graphite products are required. It must be noted that the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

3.3.7.1. Global Warming Potential

Baseline model of 100 years of the IPCC (based on IPCC 2013)

Climate change can be defined as the change in global temperature caused by the greenhouse effect that the release of “greenhouse gases” by human activity creates. There is now scientific consensus that the increase in these emissions is having a noticeable effect on climate. Climate change is one of the major environmental effects of economic activity, and one of the most difficult to handle because of its broad scale. The Environmental Profile's characterization model is based on factors developed by the UN’s Intergovernmental Panel on Climate Change (IPCC) [8]. Factors are expressed as Global Warming Potential over the time horizon of different years, the most common being 100 years (GWP100), measured in the reference unit, kg CO_2 equivalent.

3.3.7.2. Acidification Potential

Accumulated Exceedance [9,10]

Acidic gases such as sulphur dioxide (SO_2) react with water in the atmosphere to form “acid rain”, a process known as acid deposition. When this rain falls, often a considerable distance from the original source of the gas, it causes ecosystem impairment of varying degree, depending upon the nature of the landscape ecosystems. Gases that cause acid deposition include ammonia (NH_3), nitrogen oxides (NO_x) and sulphur oxides (SO_x).

Acidification potential is expressed using the reference unit, mol H^+ equivalent. The model does not take account of regional differences in terms of which areas are more or less susceptible to acidification. It accounts only for acidification caused by SO_2 and NO_x. This includes acidification due to fertilizer use, according to the method developed by the

Intergovernmental Panel on Climate Change (IPCC). CML has based the characterization factor on the RAINS model developed by the University of Amsterdam [11].

3.3.7.3. Eutrophication Potential

Accumulated Exceedance [9,12]

Eutrophication is the build-up of a concentration of chemical nutrients in an ecosystem which leads to abnormal productivity. This causes excessive plant growth like algae in rivers, which causes severe reductions in water quality and animal populations. Emissions of ammonia, nitrates, nitrogen oxides and phosphorus to air or water all have an impact on eutrophication. Direct and indirect impacts of fertilizers are included in the method. The direct impacts are from production of the fertilizers and the indirect ones are calculated using the IPCC method to estimate emissions to water causing eutrophication. Eutrophication Potential is divided into three subcategories.

3.3.7.3.1 Freshwater Eutrophication

With respect to freshwater eutrophication, phosphorus is the limiting factor, therefore only P-compounds are provided for the assessment of freshwater eutrophication. The reference unit is expressed as kg P equivalent. This category is based on the work of ReCiPe2008.

3.3.7.3.2 Marine Eutrophication

With respect to marine eutrophication, nitrogen is the limiting factor, therefore only N-compounds are included in the characterization of marine eutrophication. The reference unit is expressed as kg N equivalent. This category is based on the work of ReCiPe2008.

3.3.7.3.3 Terrestrial Eutrophication

With respect to terrestrial eutrophication, the concentration of nitrogen is the limiting factor. This category is based on the work of Seppala and Posch. Units of the characterization factor are mol N equivalent.

3.3.7.4. Disease Incidence

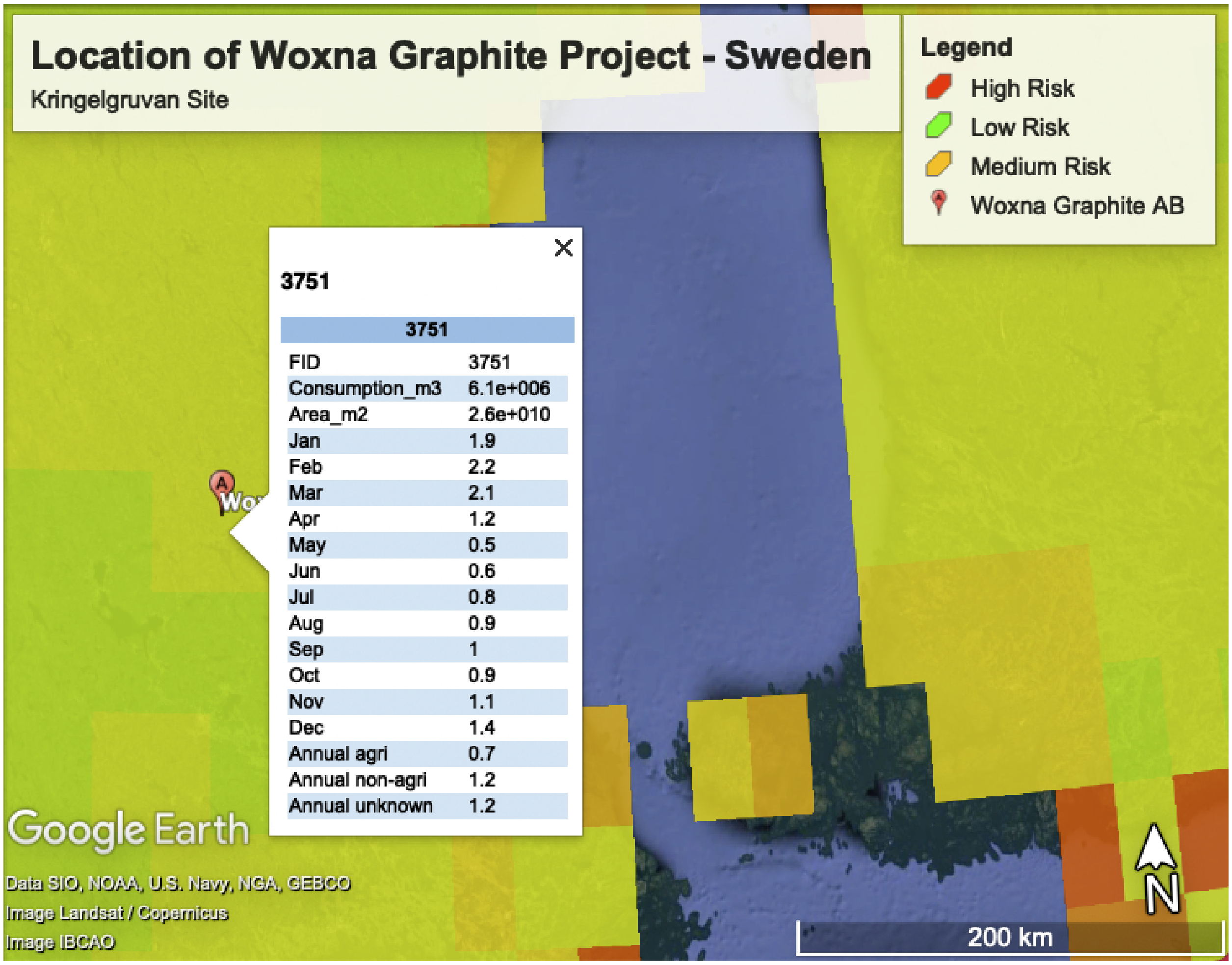
PM model recommended by UNEP [13]

Fine particulate matter (PM2.5) is considered to be one of the most important environmental factors contributing to the global human disease burden [13]. The particulate matter impact category quantifies human health effects associated with exposure to PM2.5. The impact is calculated by calculating the direct emissions of PM2.5 along with data on emission location such as population density and height of PM2.5 release. This data will inform the disease incidences emitted. The same approach is calculated for background PM2.5 emissions. The characterization factors provided by the model for the average Emissions Reduction Fund (ERF) were collected as they are published by model developers and then mapped to the ILCD elementary flow list. The PM2.5 and PM10 characterization factors are from the reference elementary flow of the International Reference Life Cycle Data System (ILCD).

3.3.7.5. Water Scarcity (Aware Methodology)

Available WAter REmaining (AWARE) [14]

Water use is measured using the AWARE method. This approach is based on the available water remaining (AWARE) per unit of surface area in a given watershed relative to the world average after human and aquatic ecosystem demands have been met. The resulting characterization factor (CF) ranges between 0.1 and 100 and can be used to calculate water scarcity footprints as defined in the ISO standard [14]. Units of the characterization factor are dimensionless, expressed in **m^3 world eq./m^3**. Figure 2 provides the AWARE overlay map for the region, highlighting regions with high characterization factors for this impact category. Woxna Graphite mine location is at lower water scarcity risk (green) to surrounding areas (orange and red areas).



3751

3751	
FID	3751
Consumption_m3	6.1e+006
Area_m2	2.6e+010
Jan	1.9
Feb	2.2
Mar	2.1
Apr	1.2
May	0.5
Jun	0.6
Jul	0.8
Aug	0.9
Sep	1
Oct	0.9
Nov	1.1
Dec	1.4
Annual agri	0.7
Annual non-agri	1.2
Annual unknown	1.2

Figure 2: Regional Water Scarcity Impact for Kringelgruvan Mine, Sweden.

3.3.8. Interpretation

The results were interpreted with reference to the goal and scope, comparing the impacts associated with the identified process routes, geographic regions and technology employed. Contribution analysis, sensitivity analysis and uncertainty analysis were carried out to support the interpretation of the LCA.

3.3.9. Data Quality Requirements

The cradle-to-gate data was reviewed at a high level by the technical experts reviewing this LCA study. The key data criteria used to create the LCI for this study were:

- Technological, Time and Geographical Representativeness - Representativeness assesses to what extent the used data matches geographical, temporal and technological aspects of the goal and scope of the study. By utilizing representative data for all foreground processes, the study can be made as representative as possible. When primary data is not available, best-available proxy data can be employed.
- Completeness - Completeness is judged based on completeness of inputs and outputs per unit processes and completeness of the unit processes. The goal is to capture all relevant data in terms of unit processes and associated inputs and outputs.
- Precision - Measured primary data are considered to be of the highest precision, followed by calculated data, data from literature and estimated data. This study is carried out with either measured or calculated data.
- Methodological Appropriateness and Consistency - This refers to choices made in regard to modelling and data sources. The differences should reflect actual differences between the two distinct product systems and not due to inconsistencies in terms of modelling, data sources, etc.

Table 7 details the grading system of the data quality indicators. An evaluation of the data quality with regard to the data quality requirements mentioned below can be found in Chapter 5.

Table 7: Grading Guidelines for Data Quality Assessment as per ISO 14040/44:2006 Standards.

	Very Good	Good	Fair	Poor	Very Poor
Technological representativeness	All Technology aspects of data have been modelled.	From Technology specific to the region.	Generic technology average.	Technology dissimilar to what is used.	Old to dissimilar technology used.
Time representativeness	The data is ≤ 2 years old with respect to the dataset.	The data is ≤ 4 years old with respect to the dataset.	The data ≤ 6 years old with respect to the dataset.	The data ≤ 8 years old with respect to the dataset.	The data > 8 years with respect to the dataset.
Geographical representativeness	Region of interest is fully represented in data.	Country of interest is represented in the data.	Global average is represented in data.	Similar regions are represented in data.	Data represented is from a distinctly dissimilar region of project location.
Completeness	Data representative of the entire target region.	Samples from > 50% of the target region.	Sample is ≤ 50% of the target region.	Sample from small parts of the target region.	Unknown coverage.
Precision	Measured and verified value. Very low uncertainty (< 7%)	Estimates based on measured and prior values.	Estimates based on expert judgment.	Estimates based on calculations, not checked by the reviewer.	Rough estimate with known deficits
Methodological Appropriateness and Consistency	Criterium is met.	Mostly the criteria is met, small improvements required.	Criterium partially met, additional information required.	Does not meet the criteria to a sufficient degree.	Criterium is not met.

3.3.10. Critical Review

A critical review was carried out by independent experts and together cover the required competencies relevant to the critical review. Their findings and suggestions to improve the study have been included in Appendix B.

4. Results

4.1. Global Warming Potential

Kg CO_2 equivalent.

4.1.1 Global Warming Potential

4.1.1.1. Coated Spheronized Purified Graphite

The total Global Warming Potential (GWP) for the Woxna graphite project is 1.7 kg CO_2 eq. per kg CSPG, as shown in Figure 3. The largest contributor to GWP is the upgrade plant, with 1.5 kg CO_2 eq. per kg CSPG, followed by the concentrator and mine, which contribute 0.1 kg CO_2 eq. per kg CSPG each. The relative GWP impact from waste management and transportation are negligible, < 0.1 kg CO_2 eq. per kg CSPG. Waste management and transportation have not been included in the contribution analysis by stage due to their minimal impact to the overall GWP.

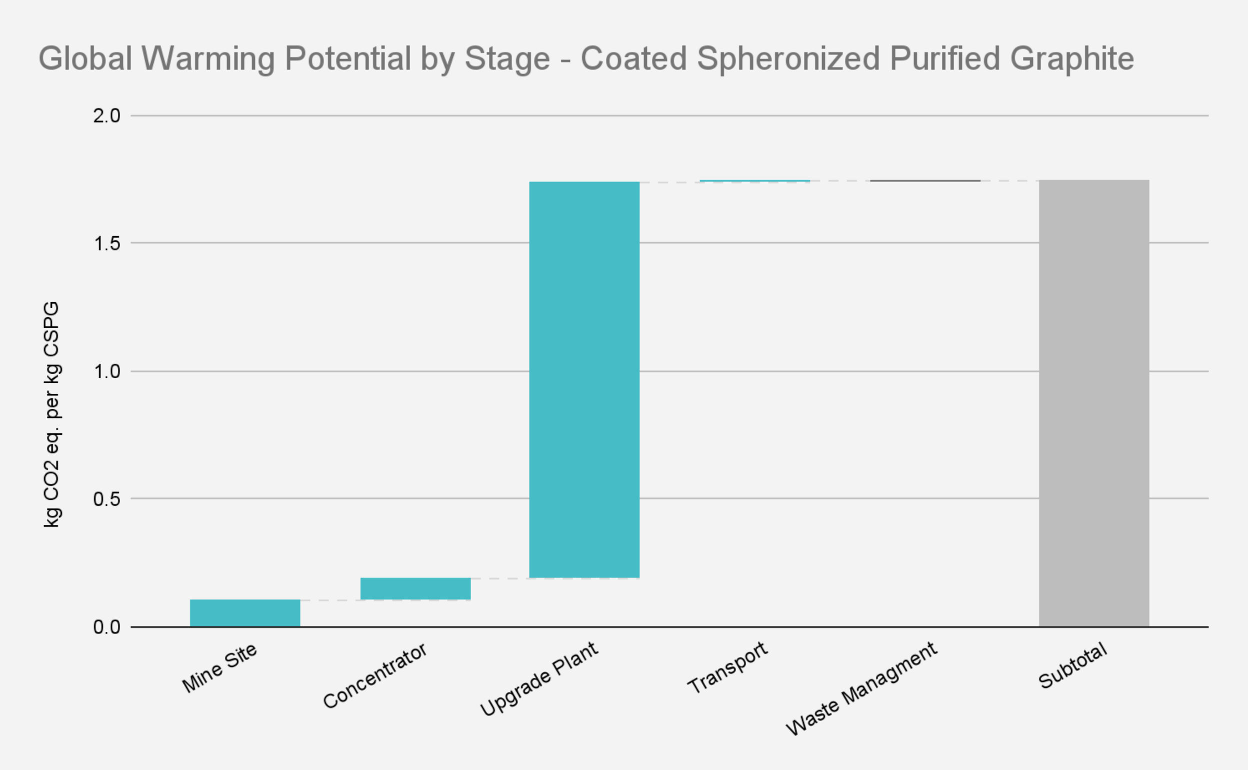


Figure 3: Overall Global Warming Potential by Stage for the Production of Coated Spheronized Purified Graphite.

4.1.1.2. Micronized Graphite

The overall Global Warming Potential (GWP) of the micronized graphite produced from the Woxna graphite project is calculated to be 0.04 kg CO_2 eq. per kg micronized graphite, as shown in Figure 4. The mine, concentrator and upgrade plant each contribute 0.01 kg CO_2 eq. per kg micronized graphite. The relative contributions to the GWP impact from waste management and transportation are negligible, < 0.01 kg CO_2 eq. per kg micronized graphite.

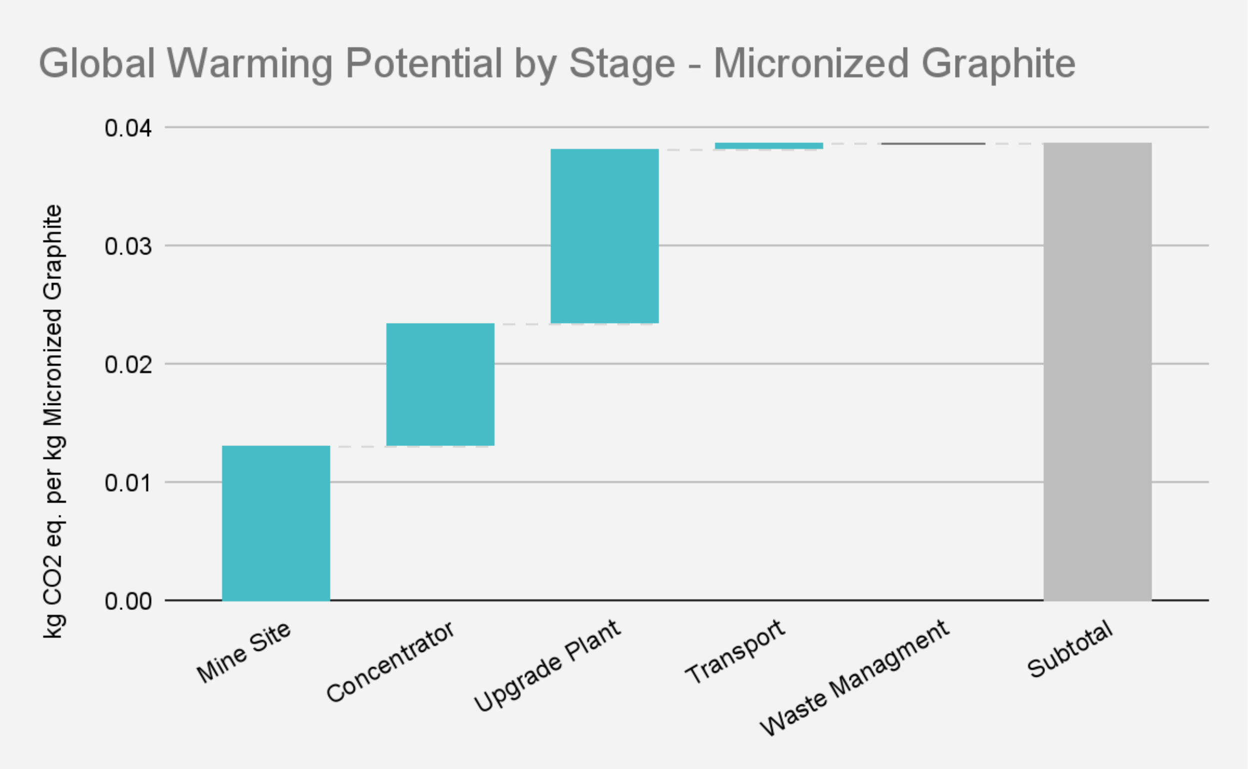


Figure 4: Overall Global Warming Potential by Stage for the Production of Micronized Graphite.

4.1.1 Global Warming Potential by Contribution Analysis

Contribution analysis for the production of CSPG and micronized graphite for the mining, concentrating and upgrade processing is shown in Figure 5 and Figure 6.

4.1.1.1 Mine Site

For CSPG and micronized graphite, the largest contributor to the overall GWP of the mine site is the use of ANFO, with 54.3% of the total. Embodied and direct impacts of the production and combustion of diesel contribute 45.7% to the total GWP of the mine site.

4.1.1.2 Concentrator Plant

For CSPG and micronized graphite, the largest contributor to GWP from the concentrator plant is the use of electricity. This accounts for 61.1% of the total, as shown in Figure 5 and Figure 6. MIBC contributes 23.2% of the GWP impact. Steel mill rods, diesel and ceramic grinding media contribute 10.1%, 2.8% and 2.3%, respectively. Consumption of flocculant and water have a negligible contribution to the GWP of the concentrator for both products.

4.1.1.3 Upgrade Plant

For CSPG, the largest contributor to GWP from the upgrade plant is the use of gaseous argon in the upgrading process. This contributes 54.3% of the total impact, as shown in Figure 5. The consumption of the other reagents: nitrogen, solvent, and pitch contribute 20.6%, 12.1%, and 1.8% of the total impact to product CSPG. Electricity and water consumption contribute 10.7% and 0.5% respectively.

The contribution analysis for the production of micronized graphite is shown in Figure 6. Electricity contributes 93.1% and water consumption contributes 6.9% of the environmental impact.

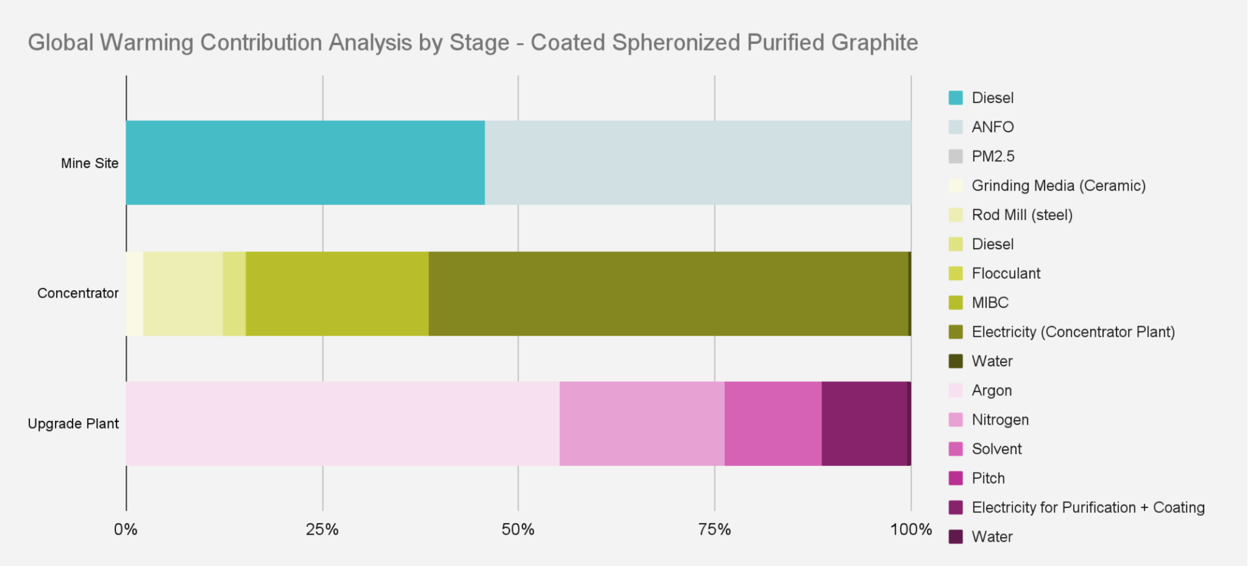


Figure 5: Contribution Analysis for the Global Warming Potential Category of Coated Spheronized Purified Graphite.

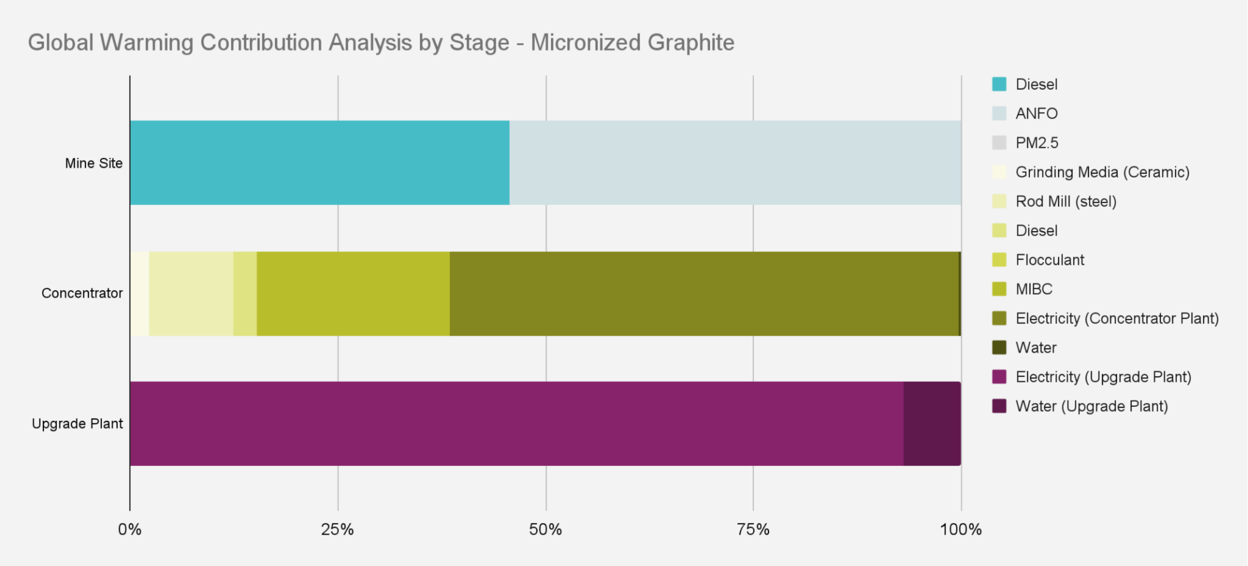


Figure 6: Contribution Analysis of the for the Global Warming Potential Category of Micronized Graphite.

4.2. Acidification Potential (Freshwater and Terrestrial)

Mol H^+ equivalent.

4.2.1. Acidification Potential

4.2.1.1. Coated Spheronized Purified Graphite

The overall Freshwater and Terrestrial Acidification Potential (AP) for the Woxna graphite project is estimated to be approximately $8.6E^{-3}$ mol H^+ eq. per kg CSPG, as shown in Figure 7. The largest contributor to the overall AP is the upgrade plant, which contributes $7.6E^{-3}$ mol H^+ eq. per kg CSPG. The mine site and concentrator plant each contribute $<7.8E^{-4}$ mol H^+ eq. per kg CSPG. Contribution analysis by stage for transport and waste management has not been carried out due to those stages having a negligible impact on the overall AP results.

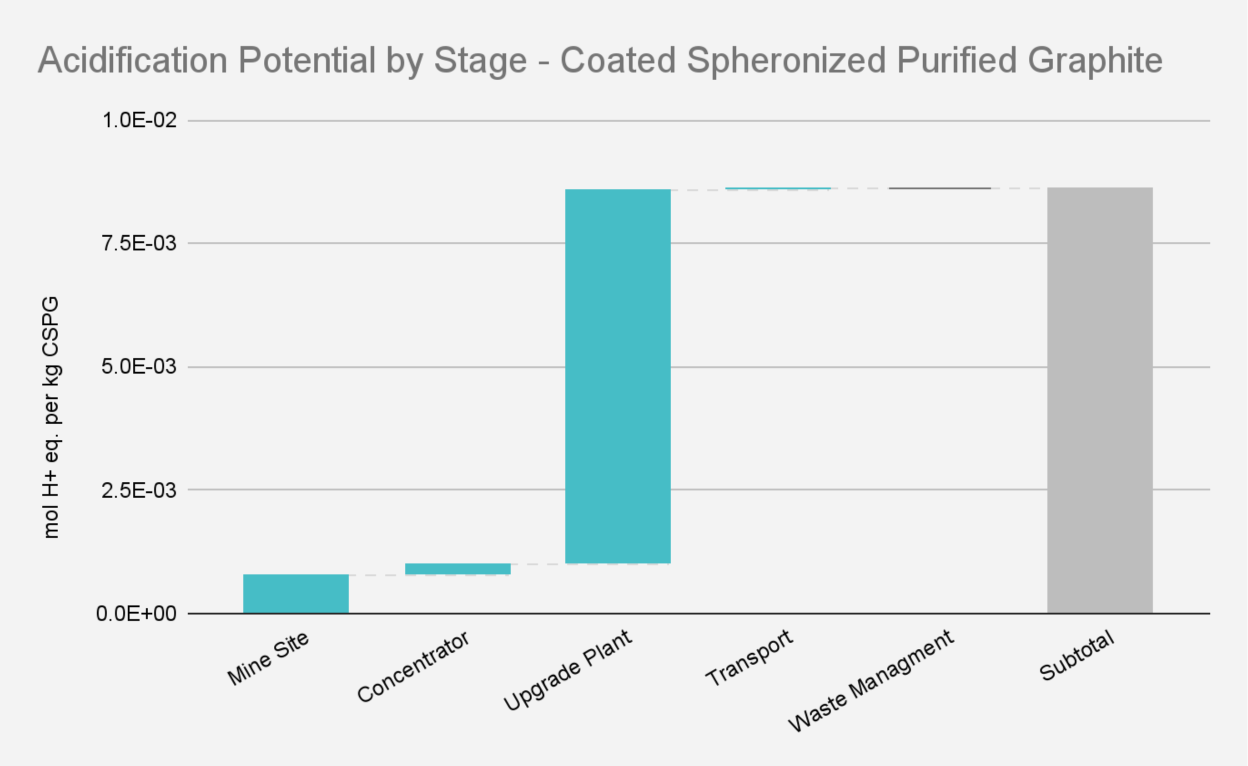


Figure 7: Overall Acidification Potential by Stage for the Production of Coated Spheronized Purified Graphite.

4.2.1.2. Micronized Graphite

The overall Freshwater and Terrestrial Acidification Potential (AP) for the Woxna graphite project is estimated to be 1.4E^{-4} mol H^{+} eq. per kg micronized graphite, as shown in Figure 8. The mine site is the largest contributor to the overall AP, contributing 9.3E^{-5} mol H^{+} eq. per kg micronized graphite. The concentrator contributes 2.7E^{-5} mol H^{+} eq. per kg micronized graphite, with the upgrade plant contributing 1.9E^{-5} mol H^{+} eq. per kg micronized graphite. Transport contributes 4.6E^{-6} mol H^{+} eq. per kg micronized graphite. The contribution of waste management to the overall AP is minimal.

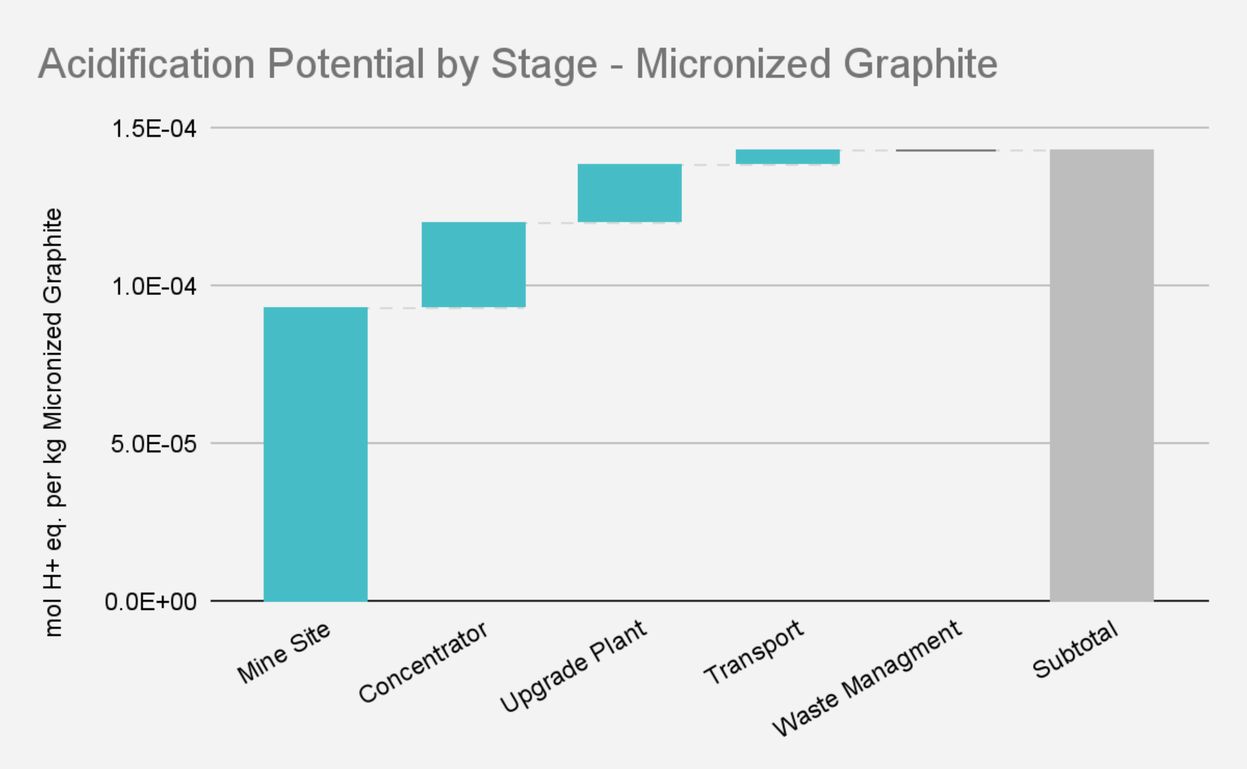


Figure 8: Overall Acidification Potential by Stage for the Production of Micronized Graphite.

4.2.1. Acidification Potential by Contribution Analysis

Figure 9 and Figure 10 show the contribution analysis for the mine, concentrator and upgrade plant for the production of the two graphite products. Contribution analysis has not been conducted for transport and waste management, as the impact is minimal. The tailings are assumed to be non-acid generating according to the PEA study. If this is to change, this will need to be considered (see recommendations 10.2).

4.2.1.1 Mine Site

For CSPG and micronized graphite, the largest contributor to AP from the mine site is the use of ANFO, accounting for 67.7% of the total impact for this impact category. Impacts of the production and combustion of diesel contribute 32.3% to the total AP of the mine site.

4.2.1.2 Concentrator Plant

At the concentrator plant, for CSPG and micronized graphite, the largest contributor to AP is the MIBC consumption. This contributes 43.4% of the total impact for the AP of the concentrator plant. This is as a result of the embodied impact associated with the production of MIBC. Electricity contributes 21.9% and consumption of diesel as flotation reagent contributes 12.6%. The use of steel rod mill and ceramic grinding media contribute 16.7% and 4.5% towards the total AP, respectively, and the contribution from the use of flocculant is negligible.

4.2.1.3 Upgrade Plant

For CSPG, the largest contributor to AP in the upgrade plant is the consumption of argon, which contributes 54.3% to the total, as shown in Figure 9. Argon has the largest contribution as a result of having a large embodied impact. Nitrogen contributes 20.6%. The use of solvent, pitch and water contribute 12.1%, 1.8%, and 0.5% to the total AP, respectively. The consumption of electricity contributes 10.7%. Despite electricity being the largest input, the impact is low due to Vattenfall sourcing their electricity from hydroelectric power.

Figure 10 details the contribution to the total AP for the upgrade plant for producing micronized graphite. Electricity holds 68.8% of the AP impact, compared to water consumption, which contributes 31.2%.

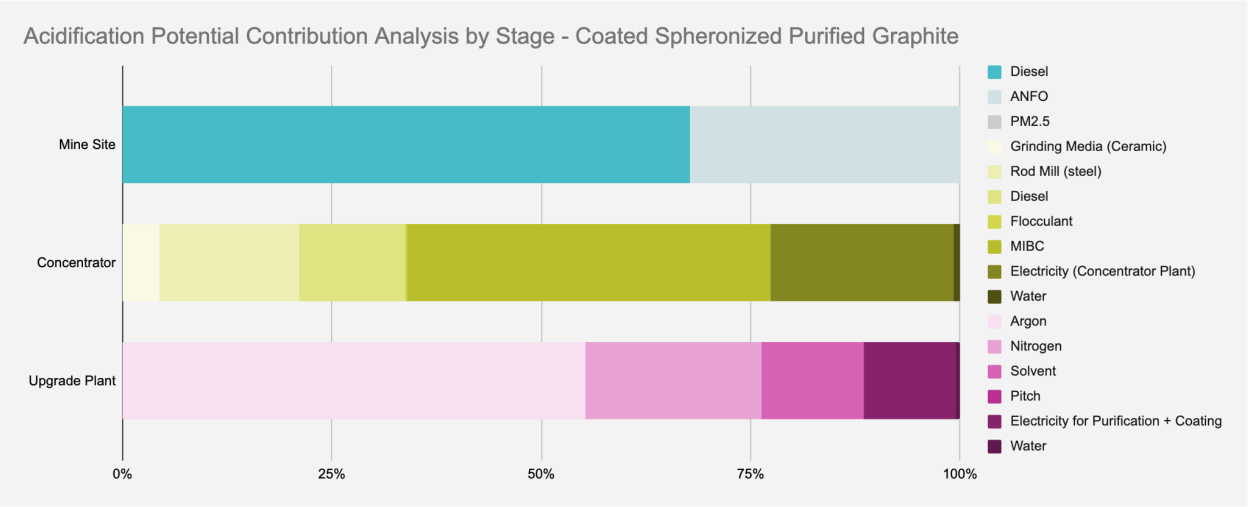


Figure 9: Contribution Analysis of the for the Acidification Potential Category of Coated Spheronized Purified Graphite.

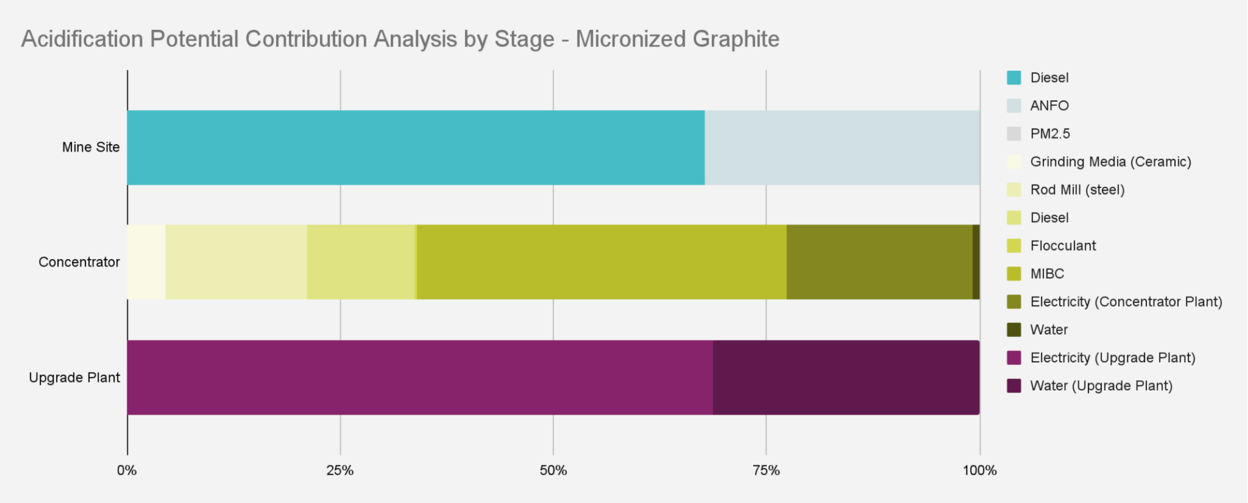


Figure 10: Contribution Analysis for the Acidification Potential Category of Micronized Graphite.

4.3. Eutrophication Potential

Kg P / mol N / kg N equivalent.

4.3.1. Freshwater Eutrophication Potential by Stage

4.3.1.1 Coated Spheronized Purified Graphite

The overall Freshwater Eutrophication Potential (FEP) for the Woxna graphite project is estimated to be 2.9E^{-3} kg P eq. per kg CSPG, as shown in Figure 11. The largest contributor is the upgrade plant, having an impact of 2.4E^{-3} kg P eq. per kg CSPG. The concentrator plant and mine site contribute 4.6E^{-4} and 9.3E^{-6} kg P eq. per kg CSPG, respectively. Contribution analysis by stage for transport and waste management has not been carried out due to their negligible impact on the overall Freshwater Eutrophication results.

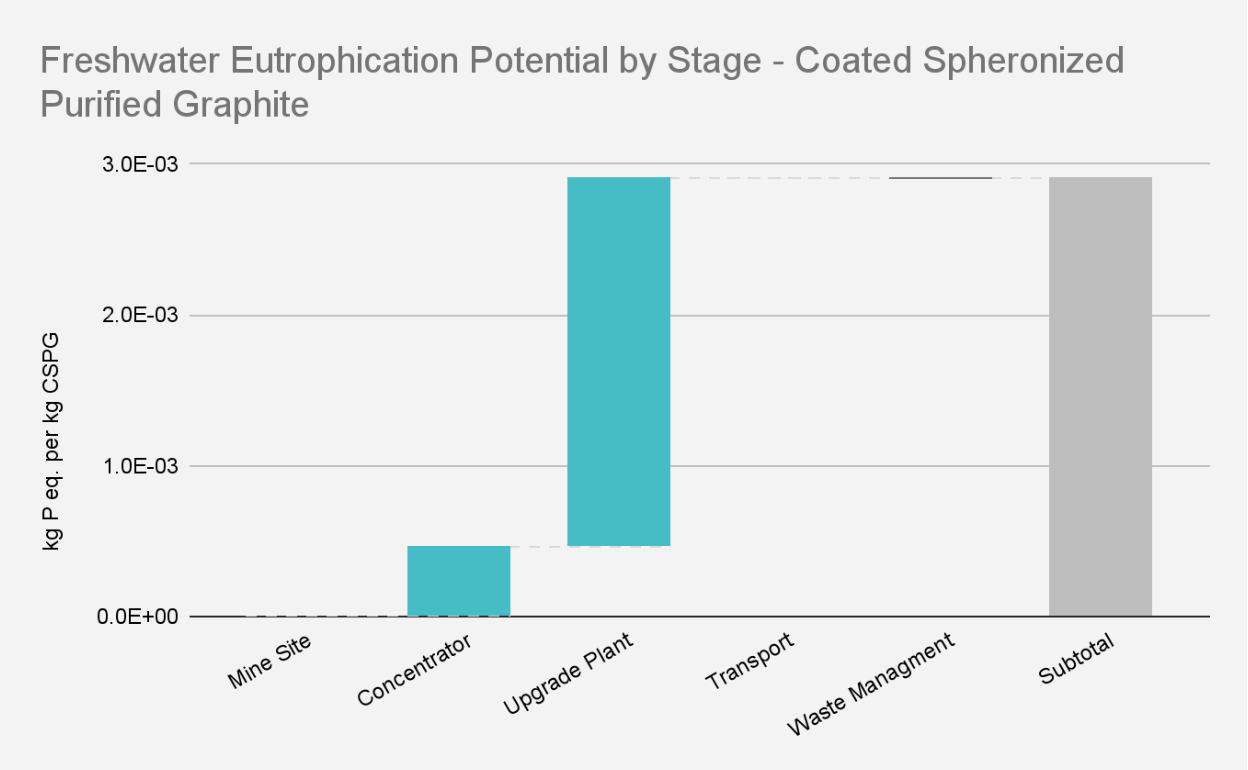


Figure 11: Overall Freshwater Eutrophication Potential by Stage for the Production of Coated Spheronized Purified Graphite.

4.3.1.1.2. Micronized Graphite

The overall Freshwater Eutrophication Potential (FEP) for the Woxna graphite project is estimated to be approximately 1.8E^{-4} kg P eq. per kg micronized graphite, as shown in Figure 12. The largest contributor is the upgrade plant, with an impact of 1.2E^{-4} kg P eq. per kg micronized graphite. The concentrator plant and mine site contribute 5.6E^{-5} and 1.1E^{-6} kg P eq. per kg micronized graphite, respectively. Contribution analysis by stage for transport and waste management has not been carried out due to their negligible impact on the overall FEP results.

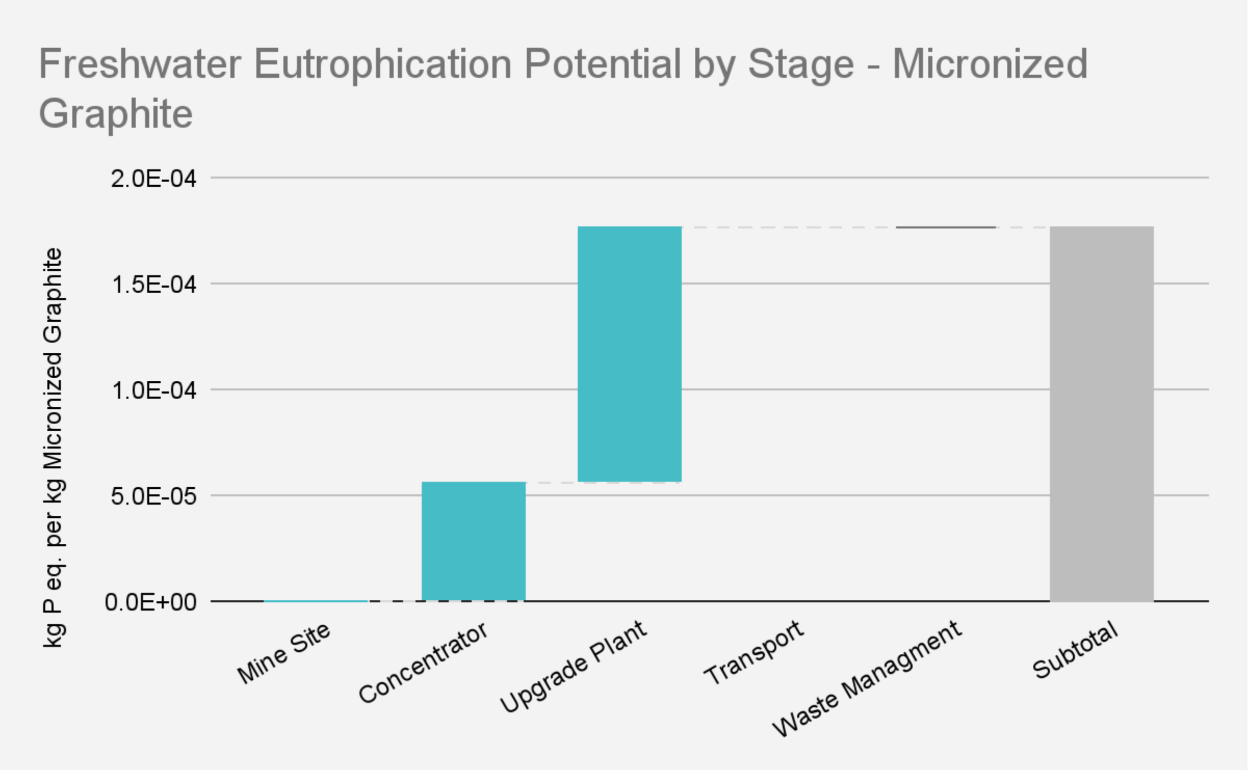


Figure 12: Overall Freshwater Eutrophication Potential by Stage for the Production of Micronized Graphite.

4.3.1. Freshwater Eutrophication Potential by Contribution Analysis

Figure 13 shows the contribution analysis for the three stages for the production of CSPG and micronized graphite.

4.3.1.1 Mine Site

The largest contributor to FEP from the mine site is the use of ANFO, accounting for 80.5% of the total impact in this category. Embodied and direct impacts of the production and combustion of diesel contribute 19.5% to the total FEP of the mine site.

4.3.1.1 Concentrator Plant

For CSPG and micronized graphite, the largest contributor to FEP from the concentrator plant is electricity consumption (98.1%). This is due to electricity being sourced from hydropower, which has a higher FEP, than the Swedish grid. MIBC contributes 0.8% of the FEP impact. The impact of grinding media, flocculant, water, and diesel is negligible.

4.3.1.1 Upgrade Plant

For CSPG, the largest contributor to FEP in the upgrade plant is consumption of electricity for purification, which contributes 59.4% to the total, as shown in Figure 13. This is due to electricity being the largest input to the upgrade plant, which has a large embodied environmental impact to the FEP impact category. Argon, nitrogen, and solvent contribute 33.4%, 5.6%, and 1.3% to the FEP. Water and pitch have a negligible contribution.

Contribution analysis to the FEP impact for the upgrade plant to produce micronized graphite is shown in Figure 14. Electricity contributes the largest (99.4%) to the FEP. Water consumption contributes 0.6%. No reagents are required for the production of micronized graphite.

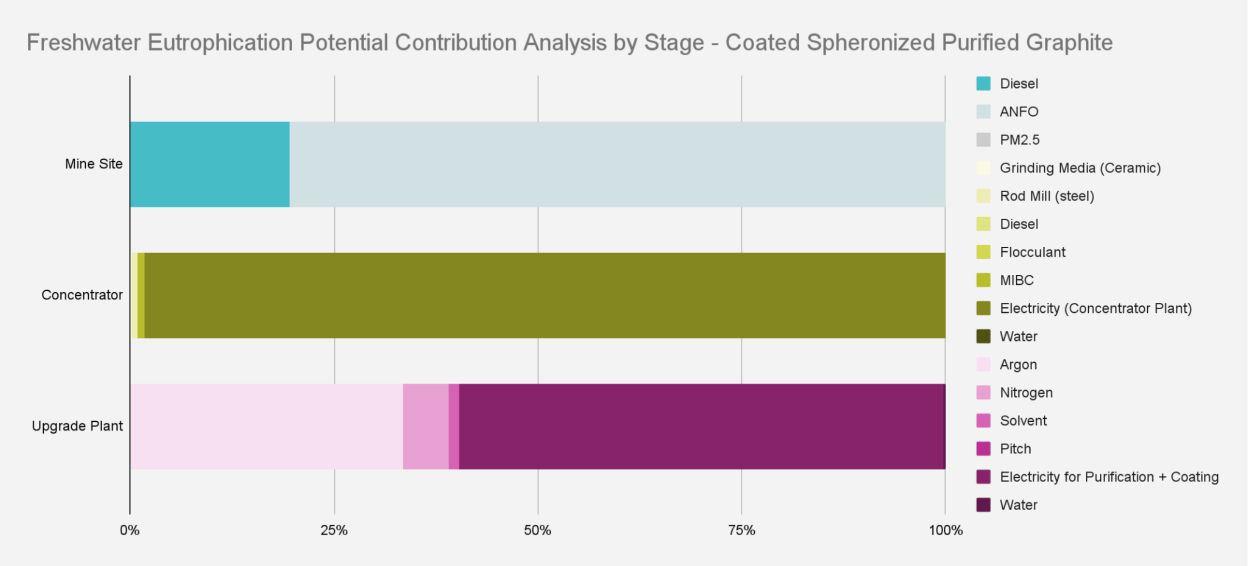


Figure 13: Contribution Analysis for the Freshwater Eutrophication Potential Impact Category for Coated Spheronized Purified Graphite.

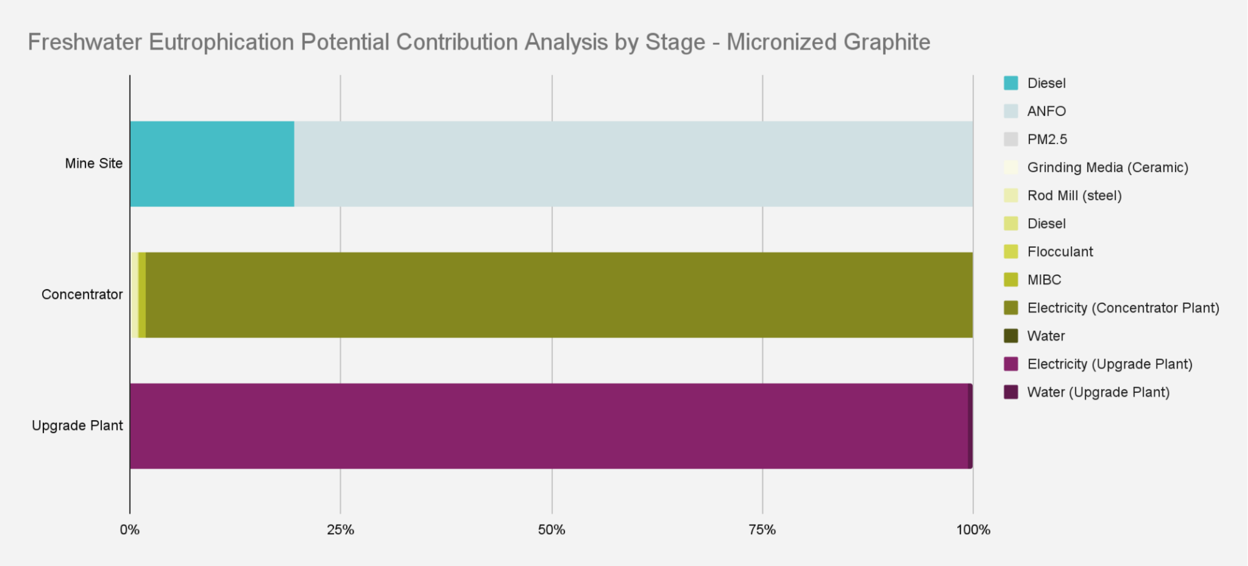


Figure 14: Contribution Analysis for the Freshwater Eutrophication Potential Impact Category for Micronized Graphite.

4.3.2 Terrestrial Eutrophication Potential by Stage

4.3.1.2 Coated Spheronized Purified Graphite

The overall Terrestrial Eutrophication Potential (TEP) for the Woxna graphite project is estimated to be approximately 1.8E^{-2} mol N eq. per kg CSPG, as shown in Figure 15. The largest contributor is the upgrade plant, with 1.4E^{-3} mol N eq. per kg CSPG. The mine and concentrator plants contribute 3.4E^{-3} and 7.7E^{-4} mol N eq. per kg CSPG, respectively. Contribution analysis by stage for transport and waste management has not been carried out due to their negligible impact on the overall Terrestrial Eutrophication results.

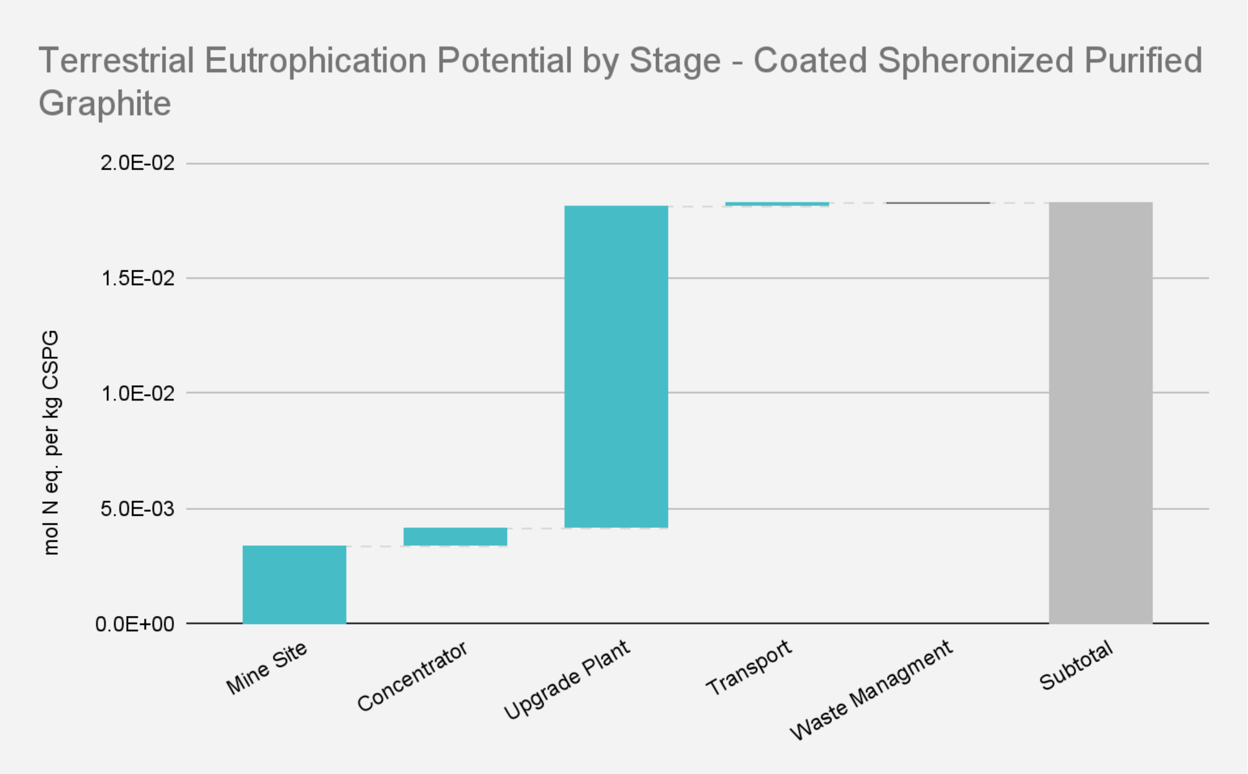


Figure 15: Overall Terrestrial Eutrophication Potential by Stage for the Production of Coated Spheronized Purified Graphite.

4.3.1.2.2. Micronized Graphite

The overall Terrestrial Eutrophication Potential (TEP) for the Woxna graphite project is estimated to be approximately 6.5E^{-4} mol N eq. per kg micronized graphite, as shown in Figure 16. The largest contributor is the upgrade plant, with 1.3E^{-4} mol N eq. per kg micronized graphite. The mine and concentrator plants contribute 4.0E^{-4} and 9.2E^{-5} mol N eq. per kg micronized graphite, respectively. Contribution analysis by stage for transport and waste management has not been carried out due to their negligible impact on the overall Terrestrial Eutrophication results.

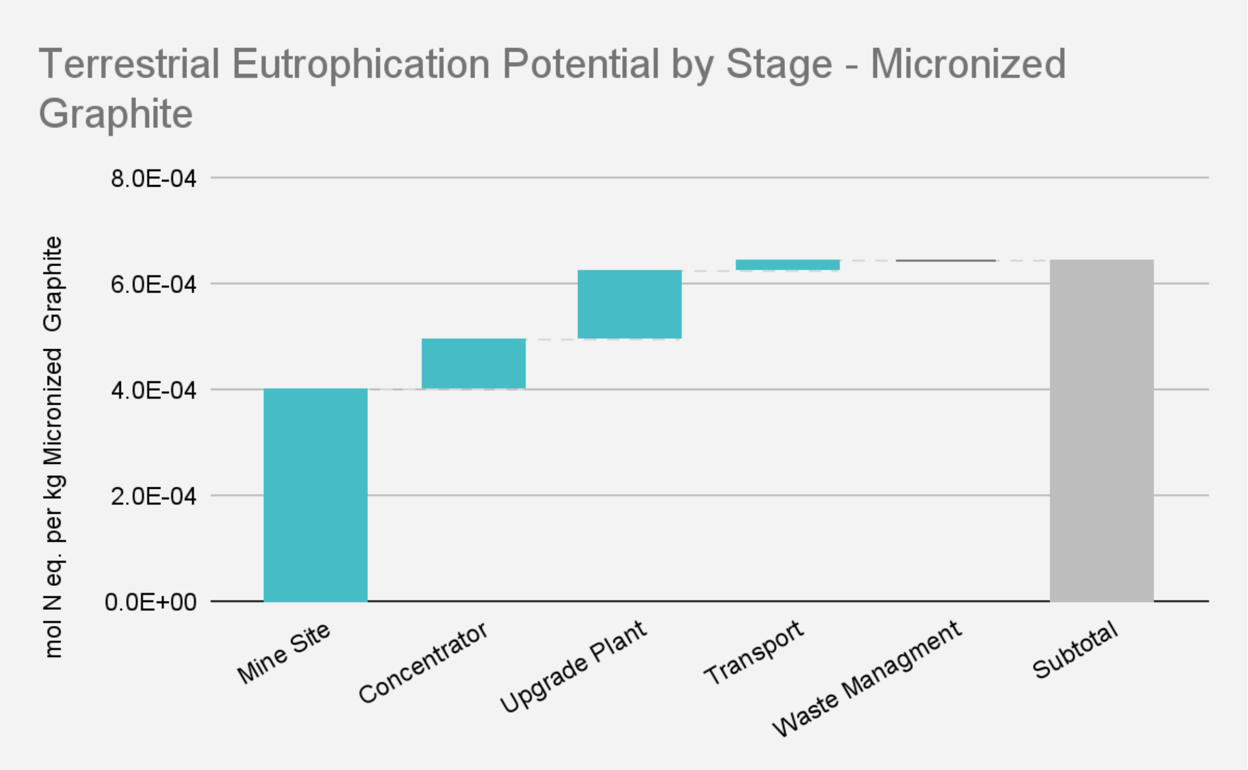


Figure 16: Overall Terrestrial Eutrophication Potential by Stage for the Production of Micronized Graphite.

4.3.2 Terrestrial Eutrophication Potential by Contribution Analysis

Contribution analysis for the production of the two graphite products are shown in Figure 17 and 18. Due to both graphite products being processed by the same stream for the mining and concentrating stages, the contribution analysis is the same for those two stages. The products are separated into two streams within the upgrade plant.

4.3.2.1 Mine Site

For the CSPG and micronized graphite, the largest contributor to TEP from the mine site is the use of diesel, accounting for 75.4% of the total impact in this category. This is due to diesel having a larger embodied impact for the TEP impact category than ANFO. ANFO contributes 24.6% to the total TEP of the mine site.

4.3.2.2 Concentrator Plant

For the CSPG and micronized graphite, the largest contributor to TEP from the concentrator plant is electricity usage, contributing 59.2% to this impact category. MIBC, steel rod mill and diesel contribute 22.4%, 10.1% and 4.8% respectively. The ceramic grinding media contributes 3.0%. The impact associated with the use of flocculant and direct water consumption for the TEP impact category is negligible.

4.3.2.3 Upgrade Plant

For CSPG, the largest contributor to TEP in the upgrade plant is the use of argon, which contributes 53.2% to the total, followed by nitrogen consumption (22.4%). The use of solvent, and pitch contribute 10.2%, and 3.3% to the total TEP respectively. The consumption of electricity for purification and coating contributes 10.3%. Electricity is the largest input consumed, but has the lowest environmental contribution to the TEP due to having a low environmental embodied impact associated with the electricity source. Impact of water consumption is negligible.

For micronized graphite, electricity holds the majority of the impact (91.7%), with water consumption only contributing 8.7% to the TEP for the upgrade plant.

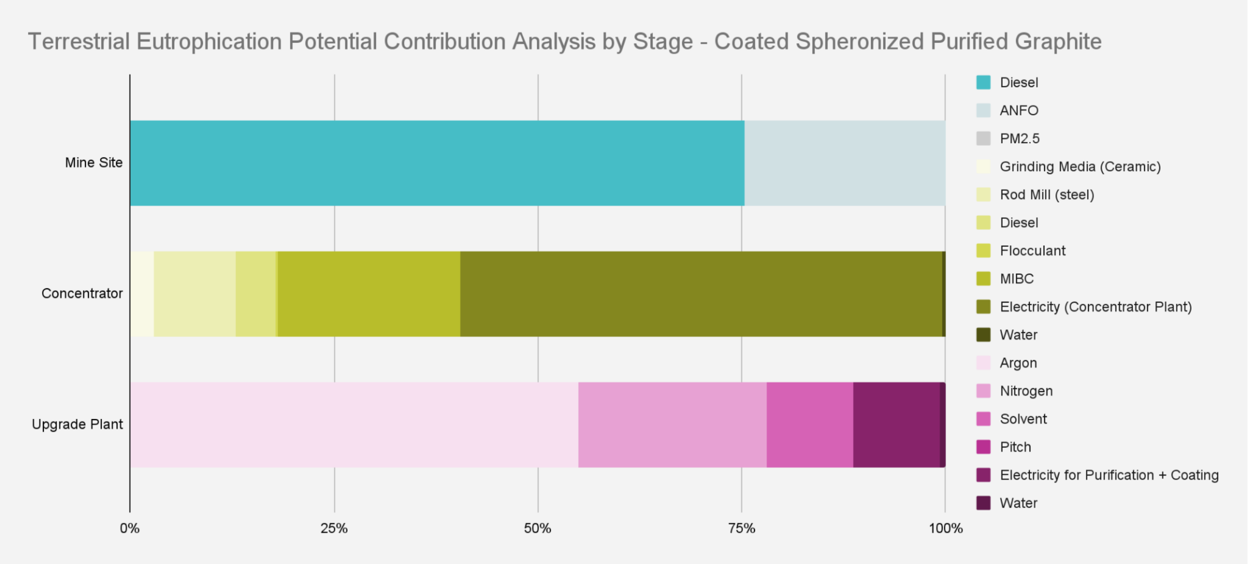


Figure 17: Contribution Analysis for the Terrestrial Eutrophication Potential Impact Category for Coated Spheronized Purified Graphite.

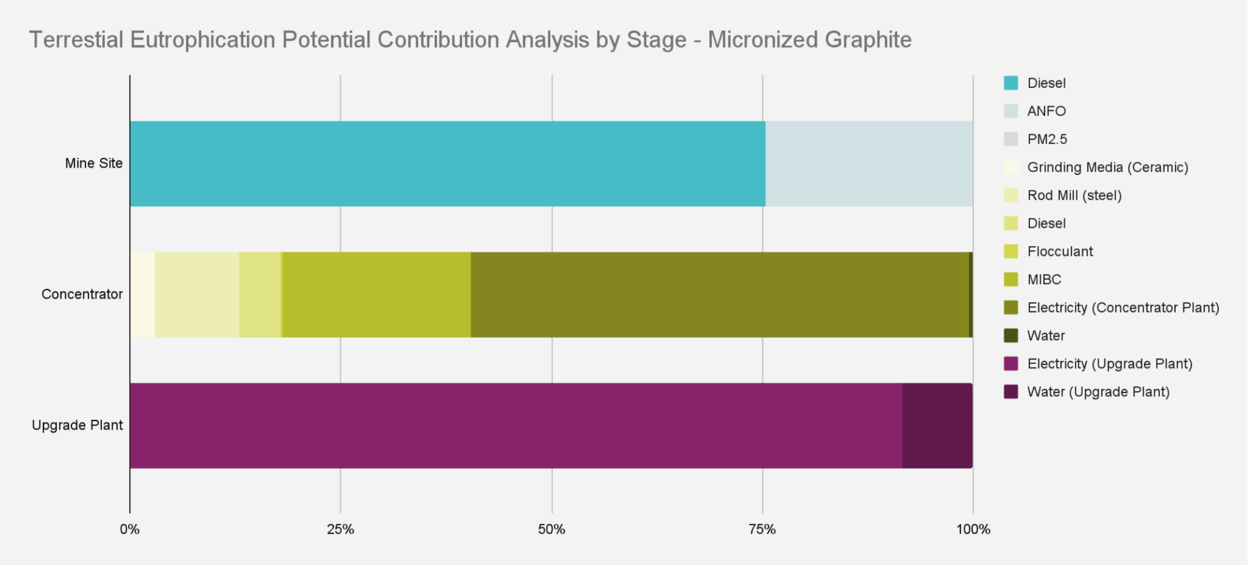


Figure 18: Contribution Analysis for the Terrestrial Eutrophication Potential Impact Category for Micronized Graphite.

4.3.3 Marine Eutrophication Potential by Stage

4.3.3.1 Coated Spheronized Purified Graphite

The overall Marine Eutrophication Potential (MEP) for the Woxna graphite project is estimated to be approximately 3.5E^{-3} kg N eq. per kg CSPG, as shown in Figure 19. The largest contributor is the upgrade plant, with 2.7E^{-3} kg N eq. per kg CSPG. The mine site and concentrator plant contribute 2.7E^{-4} and 4.9E^{-4} kg N eq. per kg CSPG, respectively. Contribution analysis by stage for transport and waste management has not been carried out due to their negligible impact on the overall Marine Eutrophication results.

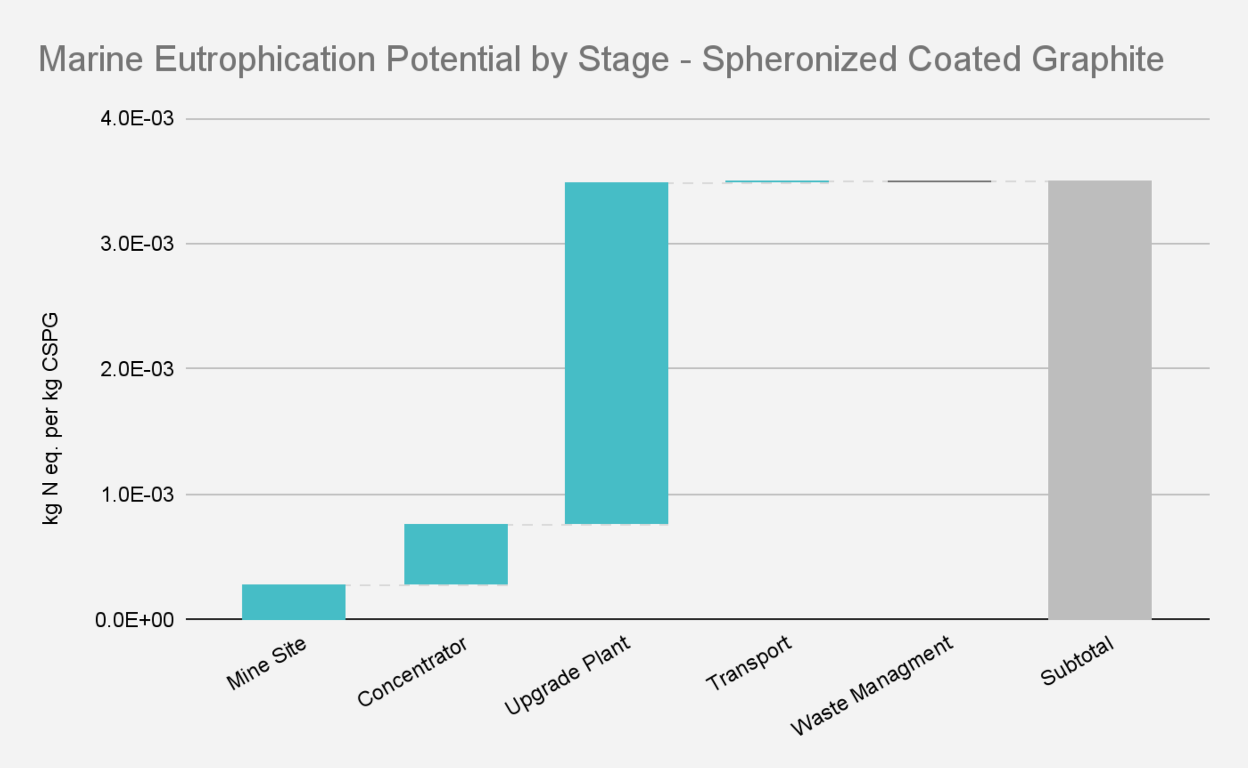


Figure 19: Overall Marine Eutrophication Potential by Stage for the Production of Coated Spheronized Purified Graphite.

4.3.3.2 Micronized Graphite

The overall Marine Eutrophication Potential (MEP) for the Woxna graphite project is estimated to be approximately 2.1E^{-4} kg N eq. per kg micronized graphite, as shown in Figure 20. The largest contributor is the upgrade plant, with 1.2E^{-4} kg N eq. per kg micronized graphite. The mine and concentrator plant contribute 3.3E^{-5} and 5.8E^{-5} kg N eq. per kg micronized graphite, respectively. Contribution analysis by stage for transport and waste management has not been carried out due to their negligible impact on the overall Marine Eutrophication results.

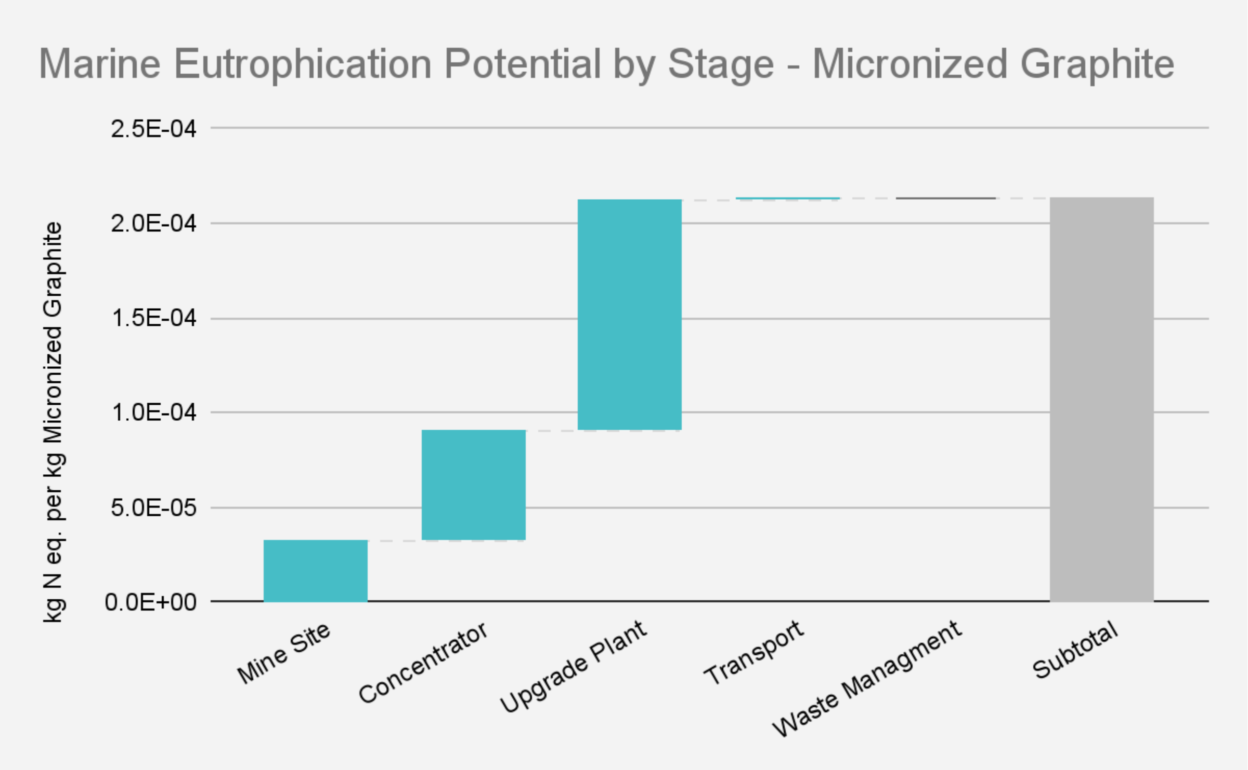


Figure 20: Overall Marine Eutrophication Potential by Stage for the Production of Micronized Graphite.

4.3.3 Marine Eutrophication Potential by Contribution Analysis

Figure 21 and 22 details the contribution analysis for the production of CSPG and micronized graphite products.

4.3.3.1 Mine Site

For CSPG and micronized graphite, the largest contributor to MEP from the mine site is the use of diesel, accounting for 84.6% of the total impact in this category. Impacts of the production and consumption of ANFO contribute 15.4% to the total MEP of the mine site.

4.3.3.2 Concentrator Plant

For CSPG and micronized graphite, the largest contributor to MEP from the concentrator plant is electricity consumption, contributing 93.7% of the impact in this category. The electricity contributes the most due to the electricity source having a large embodied environmental impact for the MEP impact category. MIBC, steel rod mill and diesel contribute 3.3%, 1.8% and 0.7% respectively. The impact of direct water consumption, ceramic media and flocculant is negligible for the MEP impact category.

4.3.3.3 Upgrade Plant

For CSPG, the largest contributor to MEP in the upgrade plant is the consumption of electricity for purification and coating, which contributes 53.0% to the total. Argon contributes 28.9%, due to the embodied impact associated with the production of argon. Nitrogen, solvent, and pitch contributed 11.4%, 4.9%, 1.6% to the MEP. Impact of water consumption is negligible.

For micronized graphite, the MEP for the upgrade plant is shown in Figure 22. Electricity contributes 99.1% to the total MEP. This is as a result of being the largest input consumed and the electricity sourced used having a large embodied impact. Water consumption contributes 0.9%.

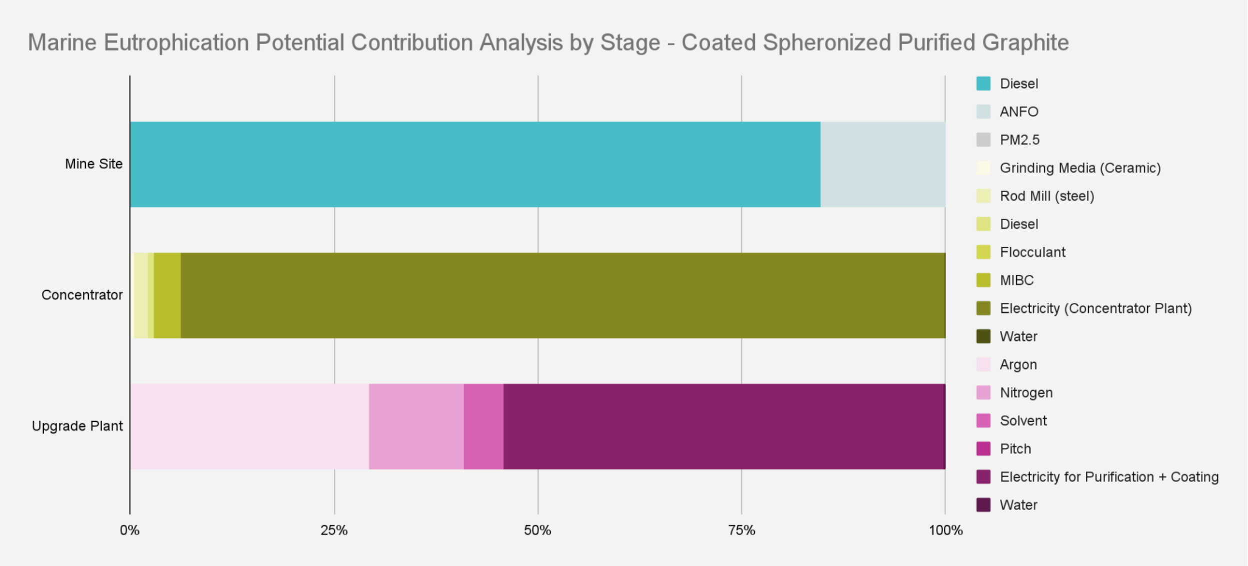


Figure 21: Contribution Analysis for the Marine Eutrophication Potential Impact Category for Coated Spheronized Purified Graphite.

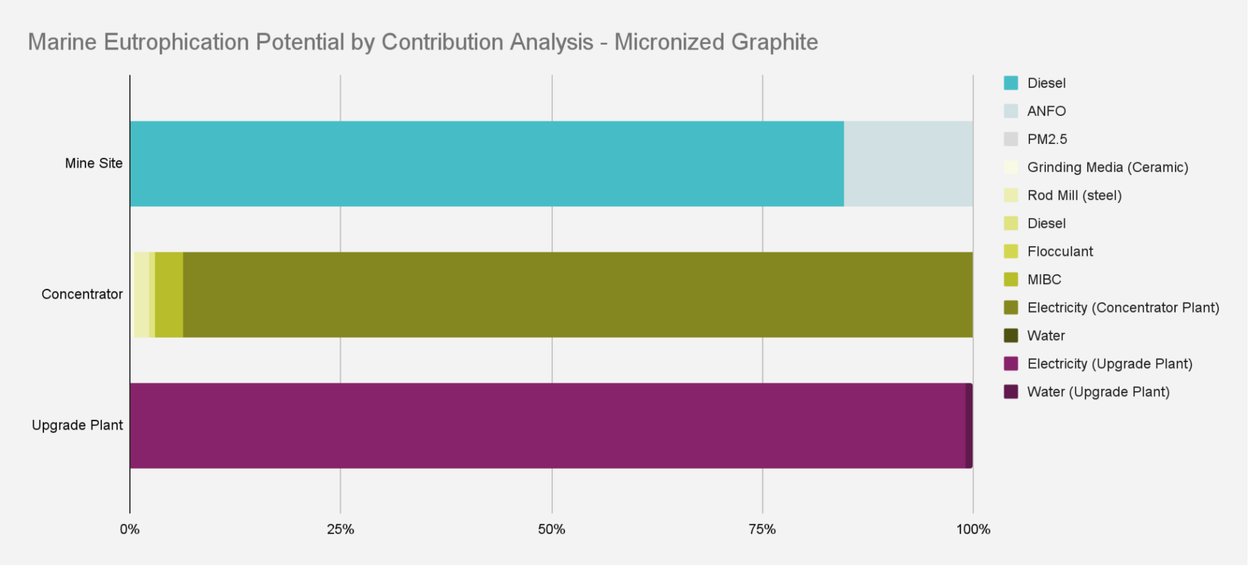


Figure 22: Contribution Analysis for the Marine Eutrophication Impact Category for Micronized Graphite.

4.4. Disease Incidences

Disease Incidences equivalent.

4.4.1. Disease Incidence

4.4.1.1 Coated Spheronized Purified Graphite

The overall impact of Disease Incidence (DI) for the production of spheronized coated graphite is 7.9E^{-5} disease incidences eq. per kg CSPG, as shown in Figure 23. The upgrade plant holds approximately half of the impact of disease incidence, contributing 6.0E^{-5} disease incidences eq. per kg CSPG. The mine and concentrator contribute 1.6E^{-8} and 1.9E^{-5} disease incidences eq. per kg CSPG respectively. The transport and waste management contributions are negligible. No contribution analysis by stage for the transport and waste management has been included for disease impacts due to their minimal impact on the overall results.

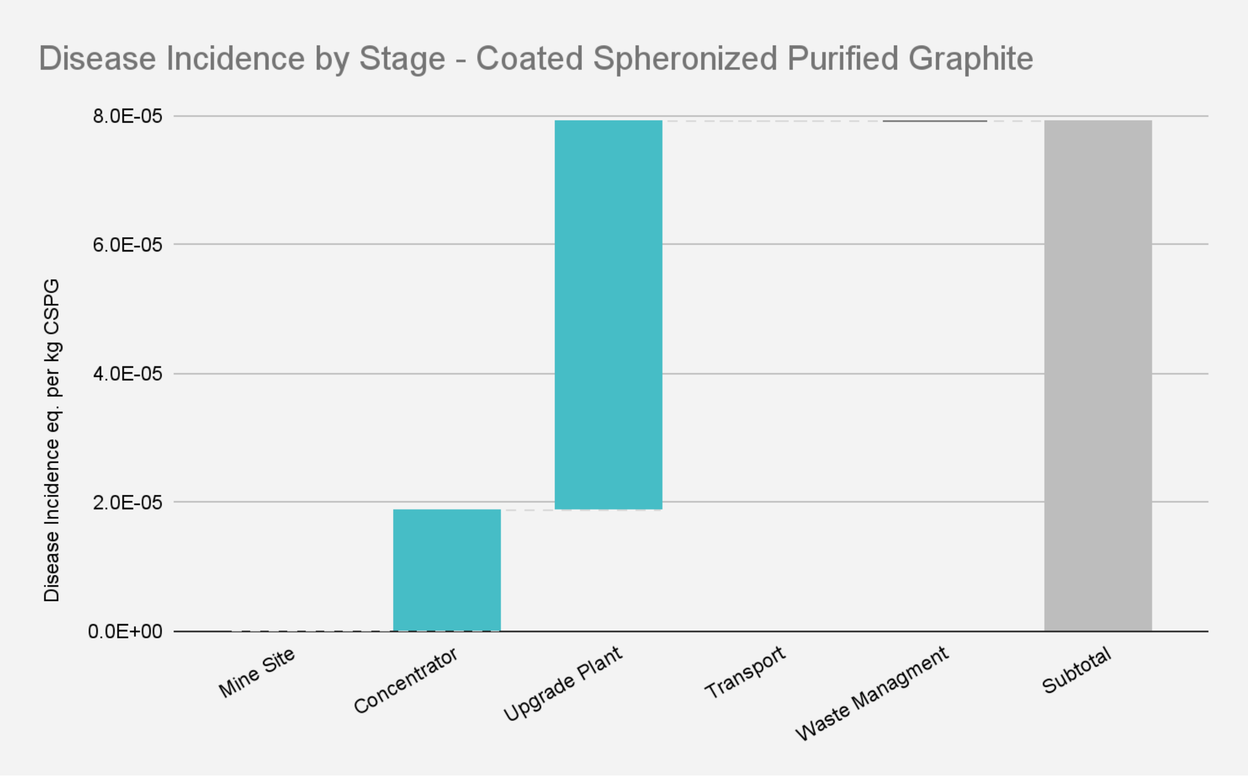


Figure 23: Overall Disease Incidence by Stage for the Production of Coated Spheronized Purified Graphite.

4.4.1.2 Micronized Graphite

The overall Disease Incidences for the Woxna graphite project is estimated to be approximately 7.3E^{-6} disease incidences eq. per kg micronized graphite, as shown in Figure 24. The largest contributor is the upgrade plant, with 5.0E^{-6} disease incidences eq. per kg micronized graphite. The mine and concentrator plants contribute 1.9E^{-9} and 2.3E^{-6} disease incidences eq. per kg micronized graphite, respectively. Contribution analysis by stage for transport and waste management has not been carried out due to their negligible impact on the overall Terrestrial Eutrophication results.

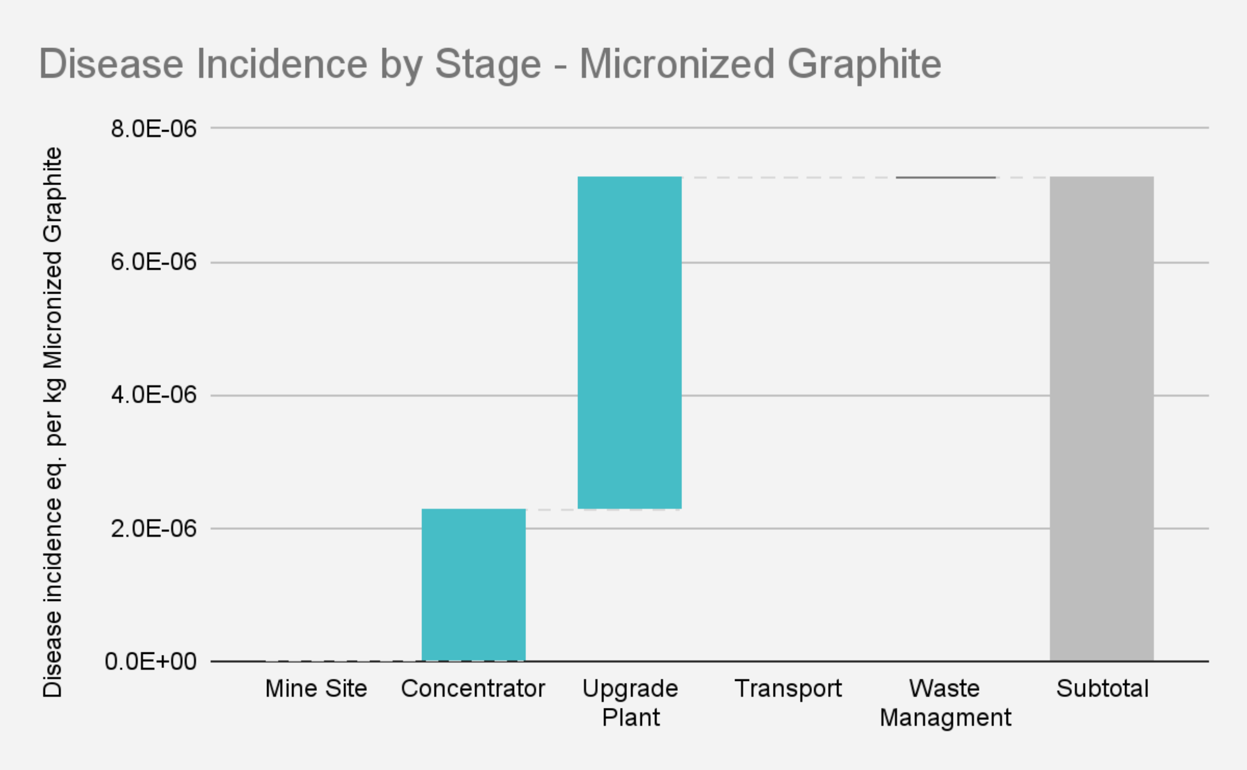


Figure 24: Overall Disease Incidence by Stage for the Production of Micronized Graphite.

4.4.2. Disease Incidence by Contribution Analysis

Contribution analysis for disease incidence for the production of the two graphite products are shown in Figures 25 and 26. The contribution analysis for the mine and concentrator are identical for both graphite products.

4.4.2.1 Mine Site

For CSPG and micronized graphite, the largest contributor to DI from the mine site is the consumption of diesel, accounting for 86.6% of the total impact in this category. The consumption of ANFO contributes 13.4%. The particulate matter emissions from haulage (PM2.5) have no contribution to the disease incidences. This is because there is minimal dust emissions due to the high ground saturation levels and precipitation rates, minimizing dust emissions.

4.4.2.2 Concentrator Plant

For CSPG and micronized graphite, the single contributor to DI from the concentrator plant is the electricity consumption. This contributes 100% to the DI, due to being the largest input and electricity source, having a large embodied environmental impact. The embodied impact of the electricity is largely associated with the deforestation of land and building of the infrastructure (reservoir dam for hydropower). The emissions are produced from the production of metals used within the core infrastructure, as well as the combustion of fuels from equipment used in the building process.

4.4.2.3 Upgrade Plant

The material inputs have a negligible input to the total DI. For CSPG, the largest contributor to DI from the upgrade plant is the consumption of electricity for purification and coating (99.9%), as shown in Figure 25. The reagents consumed in the upgrade process and water consumed contribute <0.1% to the DI impact category.

For micronized graphite, electricity consumption holds 100% of the DI impact, as shown in Figure 26. Water use does not contribute to the DI impact category for the upgrade plant.

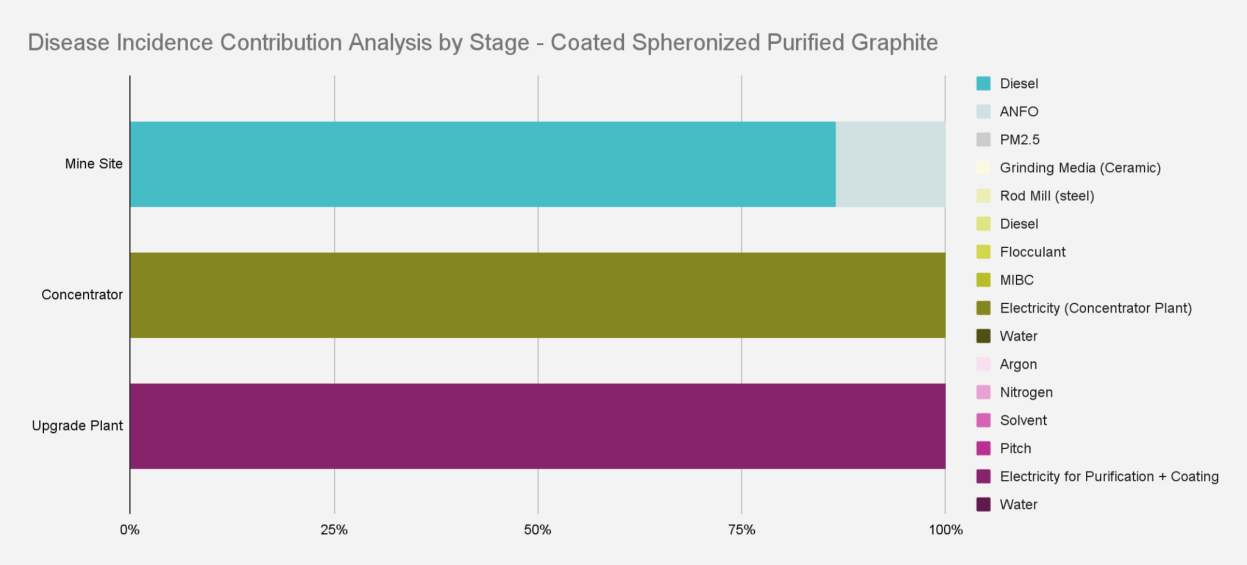


Figure 25: Contribution Analysis for the Disease Incidence Impact Category for Coated Spheronized Purified Graphite.

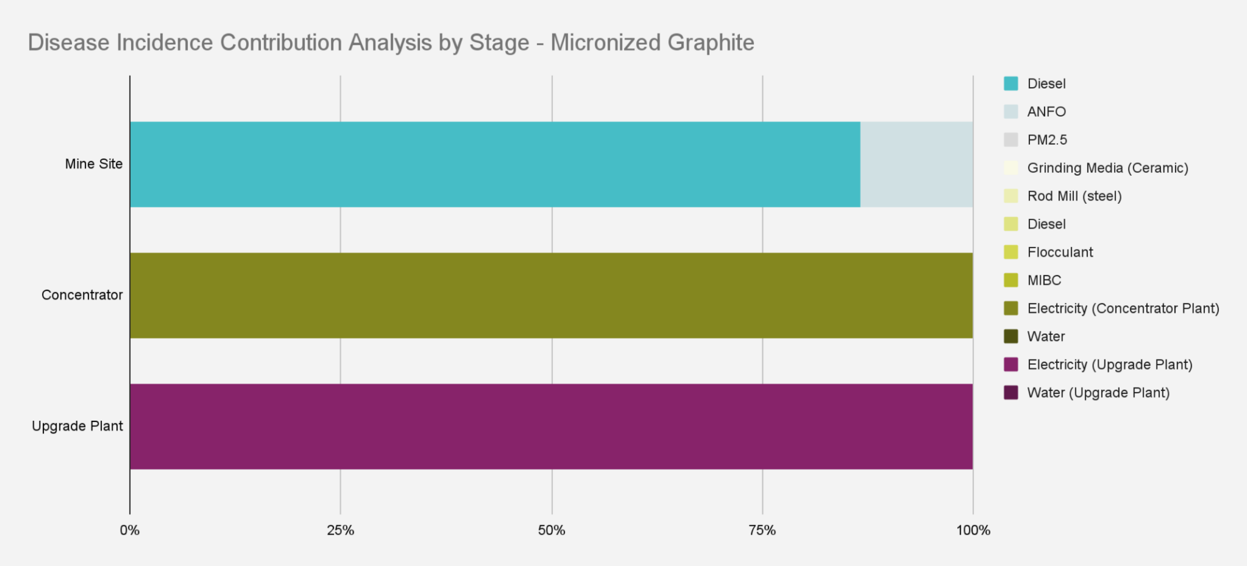


Figure 26: Contribution Analysis for the Disease Incidence Impact Category for Micronized Graphite.

4.5. Water Use (AWARE method)

Kg water equivalent.

4.5.1. Water Use

4.5.1.1 Coated Spheronized Purified Graphite

The water impact associated with the production of LEM CSPG product is shown in Figure 27. In total, the regionalized water impact of the process is 3.0 kg water eq. per kg CSPG. The upgrade plant is the largest contributor to this: 2.1 kg water eq. per kg CSPG.

The concentrator plant contributes 0.9 kg water eq. per kg CSPG. This assumes water exits the concentrator through the tailings and is re-circulated back into the concentrator. Only water lost through evaporation is accounted for. The upgrade plant contributes 2.1 kg water eq. per kg CSPG. The upgrade plant has minimal water consumption, as it is assumed that the cooling water of the CSPG stage is a closed loop system. Once water enters the upgrade plant, it is recycled throughout the graphite production process and not released back into the environment.

It must be noted that the water impact is based on two parameters: the raw water intake as stated in the PEA study and the regionalized water scarcity index as defined in section 3.3.7.5. Using the AWARE method, the direct water use is multiplied by the dimensionless water scarcity factor of 1.2. Due to the study being at PEA stage, it is assumed that water consumed is recycle through the tailings and back into the concentrator, thus only water lost through evaporation is calculated. It is assumed the water used is not returned to the local water table in degraded form. If water degradation did take place, the Water Use impact would be higher. As the study progresses and higher resolution data becomes available, the water lost and degraded should be taken into account for. Contribution analysis for the transport and waste management have not been included within this report due to having a negligible contribution to the water use impact category.

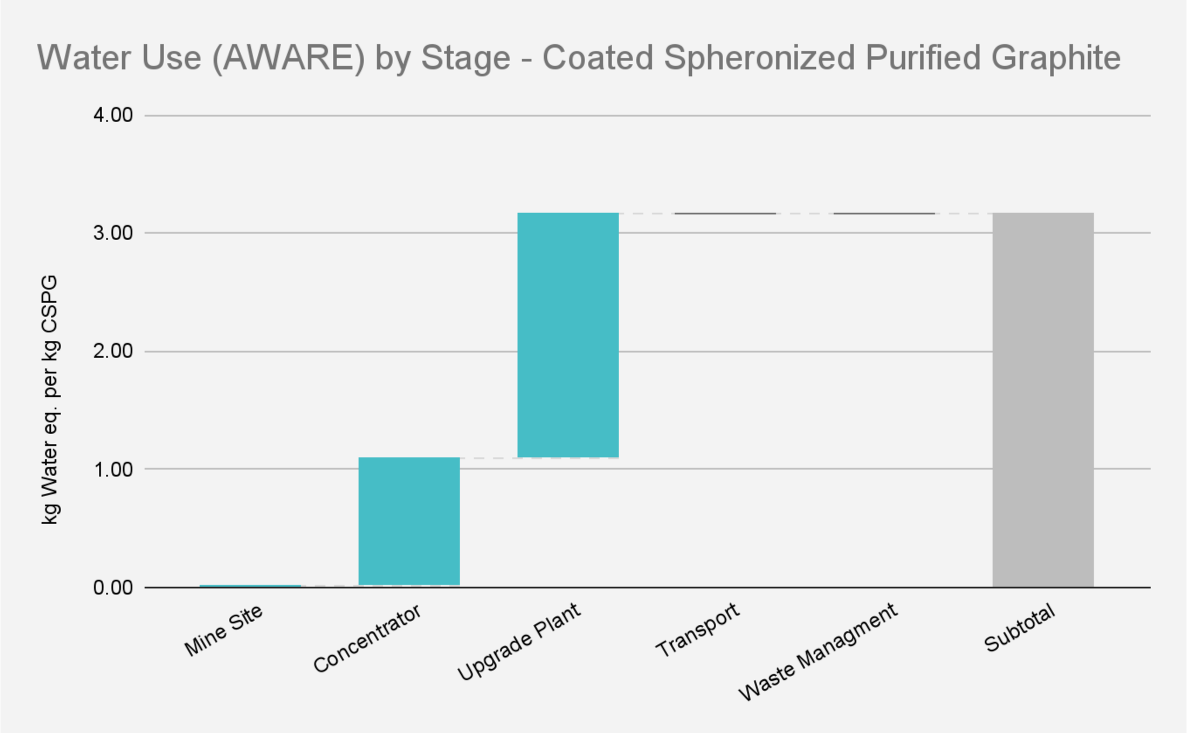


Figure 27: Overall Water Use (AWARE) by Stage for the Production of Coated Spheronized Purified Graphite.

4.5.1.2 Micronized Graphite

The total water use of Leading Edge's micronized graphite product is 0.1 kg water eq. per kg micronized graphite as shown in Figure 28. The concentrator plant contributes 0.1 kg water eq. per kg micronized graphite. The mine site and upgrade plant contribute <0.1 kg water eq. per kg micronized graphite. The cooling water required in the upgrade plant is recycled, thus having a very low contribution to the overall water use.

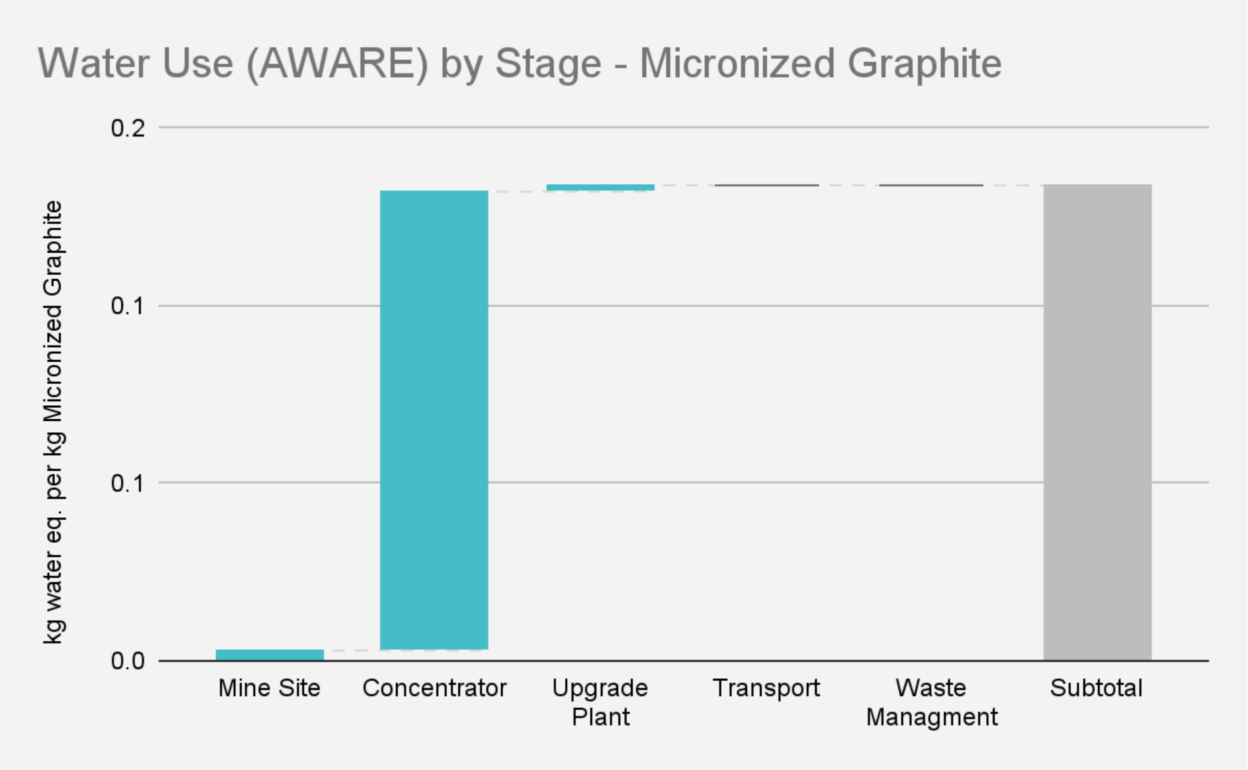


Figure 28: Overall Water Use (AWARE) by Stage for the Production of Micronized Graphite.

4.5.2. Water Use by Contribution Analysis

Water Use by contribution analysis for spheronized coated graphite and micronized graphite is shown in Figures 29 and 30.

4.5.2.1 Mine Site

The largest contributor to Water Use (WU) from the mine site is the embodied water impact of ANFO, accounting for 92.9% of the total impact in this category. Embodied impacts of the production and combustion of diesel contribute 7.1% to the total WU of the mine site.

4.5.2.2 Concentrator Plant

For spheronized coated graphite and micronized graphite, the regional impact of direct water consumption of the concentrator plant contributes 98.0% to the WU for the concentrator plant. This considers the direct water consumed on site and the regionalized water scarcity impact. The electricity and reagents consumed have a minimal impact on the total water usage for the concentrator.

4.5.2.3 Upgrade Plant

For spheronized coated graphite, the largest contributor to WU from the upgrade plant is the consumption of argon (80.6%). This is as a result of the embodied water impact associated with the production of argon being larger than the other consumables. The consumption of nitrogen, solvent, and pitch each contribute 15.7%, 2.5%, 5.2%, and 0.3% respectively. Electricity for purification and coating contributes 0.6%. The impact of direct water consumption is negligible due to water consumption being within a closed system, thus is being recycled within the upgrade plant process.

The WU impact for the upgrade plant for producing micronized graphite is shown in Figure 30. Overall, the Water Use for the production of the micronized graphite for the upgrade plant is minimal. Electricity contributes just over half (52.6%) of the Water Use due to the embodied impact associated with the production of the electricity used. The direct water consumption contributes 47.4% of the Water Use impact category.

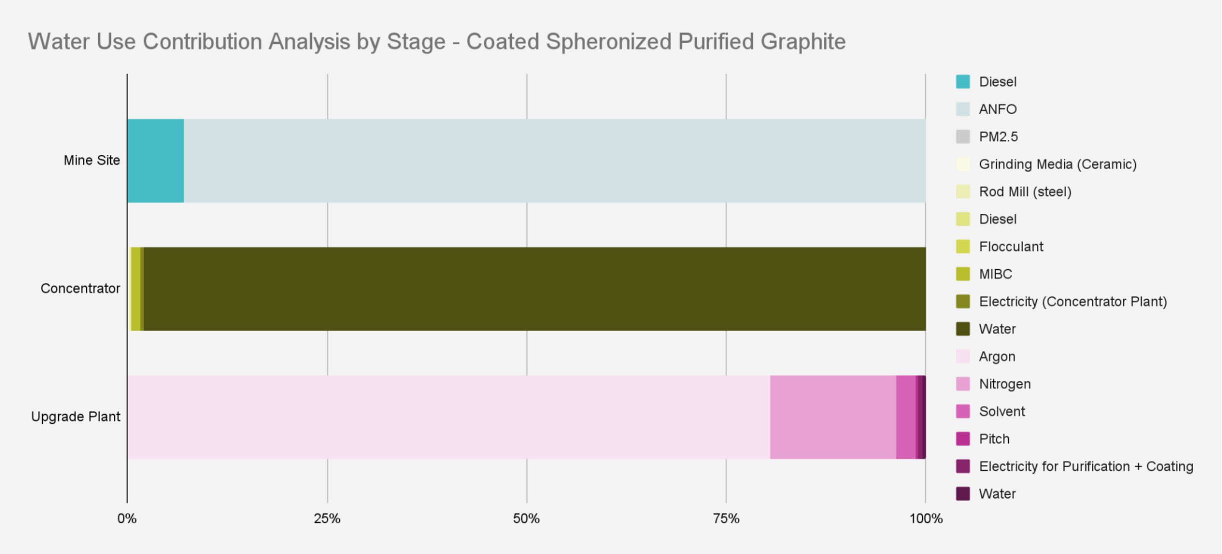


Figure 29: Contribution Analysis for the Water Use Impact Category for Coated Spheronized Purified Graphite.

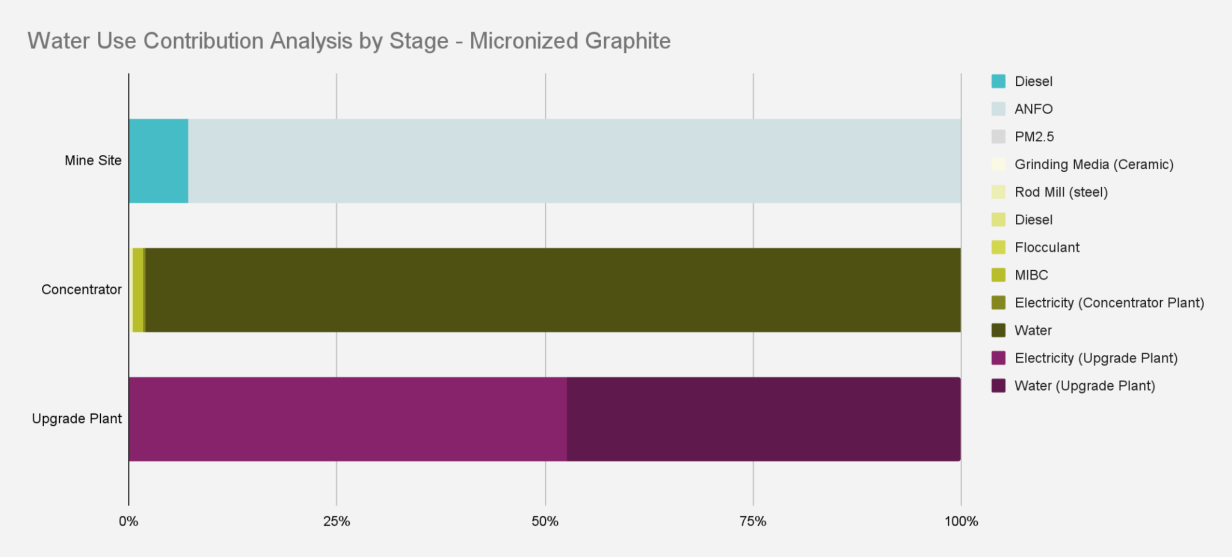


Figure 30: Contribution Analysis for the Water Use Impact Category for Micronized Graphite.

5. Data Quality Assessment

The foreground and background data of the Life Cycle Inventory was judged on technological and time representativeness, geographical coverage, completeness, precision and consistency. Foreground data used in this study was generated from data provided by Leading Edge Materials Corp. The background data used within this LCA was from Ecoinvent 3.7.1 [15].

The foreground data used for the mine and concentrator plant in the PEA is based on operational data, with an uncertainty of 15% associated with it. The upgrade plant data in the PEA has a lower definition of data, thus is associated with an uncertainty of 30%. As more effort is put into defining the upgrade plant and the associated process, the quality of the available information increases, which will determine the level of accuracy of the production and cost estimates and thus directly the associated LCA study inputs.

- Technological Representativeness: The PEA documents for the study, provided by Leading Edge Materials Corp, were checked for completeness of the Life Cycle Inventory, whilst modelling specifically for the technology relevant for this study. Proxy data was used for the silt content (% by weight) and number of days rain was above 0.25 mm for the PM2.5 calculation. Proxy data was calculated for ANFO (60% ammonium nitrate and 40% fuel oil). This includes direct emissions. All background data sources were sourced from Ecoinvent 3.7.1. No data points were left out during this study. The technological representativeness is considered to be good.
- Time Representativeness: All foreground data was collected, including proxy data required to calculate PM2.5 emissions, for the reference year 2020-2021 (data provided by Leading Edge Materials Corp). All background data was sourced from Ecoinvent 3.7.1. The time representativeness was considered very good.
- Geographical Coverage: country specific data was selected for the foreground and background processes where possible. All background data sources were sourced from Ecoinvent 3.7.1. The geographical representativeness is considered to be very good.

- Completeness: foreground processes were checked for mass balance and completeness of the emission inventory. No data points were left out during this study. The completeness of the foreground data is good. Proxy data was required for the PM2.5 calculations. All background data sources were sourced from Ecoinvent 3.7.1 of which the completeness was documented. The completeness was considered good.
- Precision: all data associated with this study was based on primary information sources provided by Leading Edge Materials Corp. The precision of the data was considered to be very good. All background data sources were sourced from Ecoinvent 3.7.1 of which the precision was documented.
- Methodological Appropriateness and Consistency: the primary data required for the foreground processes was provided by Leading Edge Materials Corp. All background data points were sourced from Ecoinvent 3.7.1. The methodology appropriateness is good and aligns with recent academic research [16]. By using the Life Cycle Inventory provided in Appendix A, the modelling methodology outlined in the report and the guidance provided about the background dataset choices, the study should be able to be reproduced by an external party.

6. Sensitivity Analysis

6.1 Sensitivity Analysis - Coated Spheronized Purified Graphite

Sensitivity analysis was carried out to explore the effects of the variations in reagent, material and energy consumption in relation to the final product life cycle impact assessment categories results for CSPG. The effect of changes in consumption of five main impact drivers were evaluated, being: nitrogen, solvent, argon, electricity for purification + coating and pitch. The results of this are shown in Figure 31 for the Global Warming Potential (GWP) impact category, in kg CO_2 eq. per kg CSPG. The results for the sensitivity analysis carried out for the other impact categories are available upon request.

If the consumption of argon is reduced by 20%, the GWP decreases from 1.7 kg CO_2 eq. per kg CSPG to 1.6 kg CO_2 eq. per kg CSPG. Alternatively, if the consumption of argon increases by 20%, the overall GWP increases to 1.9 kg CO_2 eq. per kg CSPG each. Additionally, if the embodied impacts associated with the production of argon change by ±20%, this will also increase or decrease the GWP.

If the consumption of nitrogen, solvent or electricity were to decrease by 20%, the overall GWP would decrease by < 0.04 kg CO_2 eq. per kg CSPG. On the other hand, if the consumption of these three inputs were to increase by 20%, the increase in GWP is < 0.03 kg CO_2 eq. per kg CSPG.

There is minimal change in the overall GWP if the consumption of pitch is to increase or decrease by 20%.

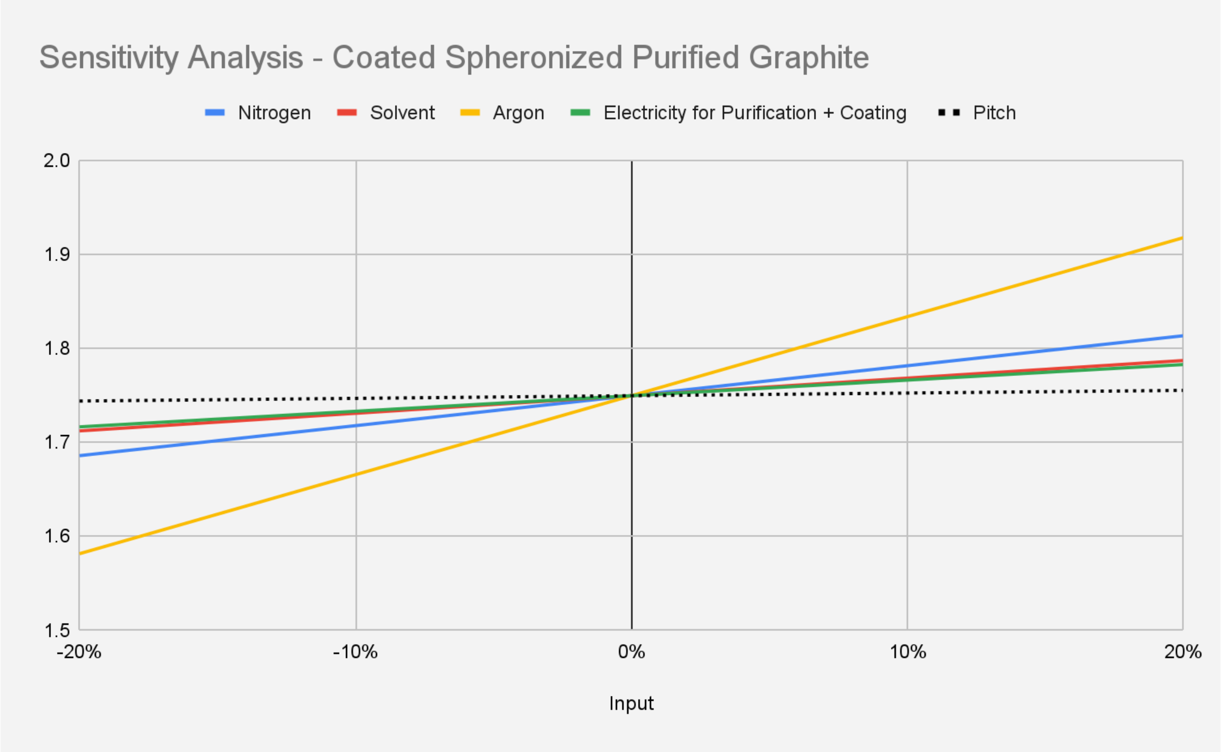


Figure 31: Sensitivity Analysis for the Global Warming Potential for the Production of Coated Spheronized Purified Graphite.

6.2 Sensitivity Analysis - Micronized Graphite

Sensitivity analysis was carried out to explore the effects of the variations in reagent, material and energy consumption in relation to the final product life cycle impact assessment categories results for micronized graphite. The effect of changes in consumption of five main impact drivers were evaluated, being: electricity used for the concentrator plant, diesel for haulage, ANFO, electricity used for the upgrade plant and water used for the concentrator plant. The results of this are shown in Figure 32 for the Global Warming Potential (GWP) impact category, in kg CO_2 eq. per kg micronized graphite. The results for the sensitivity analysis carried out for the other impact categories and co-product are available upon request.

Overall, there is minimal change in all the consumables chosen, with the maximum change in GWP being < 0.01 kg CO_2 eq. per kg micronized graphite. The electricity consumed at the upgrade plant has the greatest impact on the GWP, with the overall GWP increasing or decreasing by 0.003 kg CO_2 eq. per kg micronized graphite, if the consumption of electricity were to increase or decrease by 20%.

The diesel for haulage, ANFO, and electricity and water consumed at the concentrator plant have a minimal change in GWP if the consumption is increased or decreased by 20%. For each of those consumables, the GWP remains 0.04 kg CO_2 eq. per kg micronized graphite.

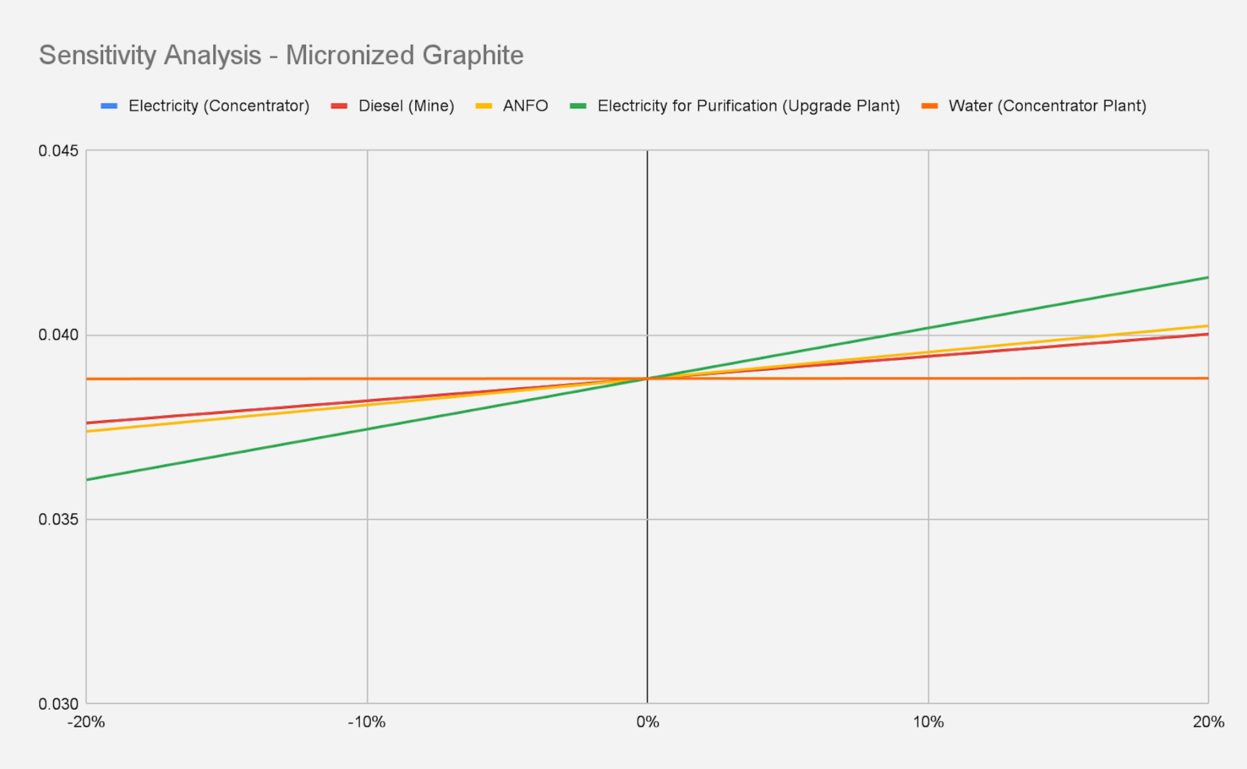


Figure 32: Sensitivity Analysis for the Global Warming Potential for the Production of Micronized Graphite.

7. Monte Carlo Simulations

The uncertainty related to the data quality of the LCI and the background data quality has been explored in relation to the environmental impacts using Monte Carlo simulations. This will allow for the assessment of the possible range of the calculated impacts associated with the LCI and background data uncertainty. These results assist with understanding the risk and uncertainty associated with this prospective LCA.

Different uncertainties are associated with the individual flows within the system. For the mine and concentrator, due to being within its care and maintenance stage, a standard deviation uncertainty of 15% was assumed for the energy and material inputs and associated direct emissions. The upgrade plant is at PEA stage, thus a 30% uncertainty was assumed for the consumables and associated direct emissions within this stage.[17]

The model is built in such a way that an increase in direct emissions cannot take place without an increase in the process parameter that is responsible for that. At this time, no uncertainty associated with the background data was included. It is assumed that the uncertainties associated with the foreground data, is high enough so that it also covers the uncertainty of the background data. The uncertainty of the background data will become of a larger importance when the project becomes more defined.

7.1 Monte Carlo Simulation - Coated Spheronized Purified Graphite

The results of the Monte Carlo simulations of the Global Warming Potential for the functional unit are shown in Figure 33. A wide range of values has been obtained, ranging from 0.9 to 2.8 kg CO_2 eq. per kg CSPG, as shown in Table 8. The mean value of the 1,000 iterations is 1.7 kg CO_2 eq. per kg CSPG. This is a similar value as the value obtained by the LCA model (section 4.1). The results for the Monte Carlo Simulations carried out for the other impact categories and co-product are available upon request.

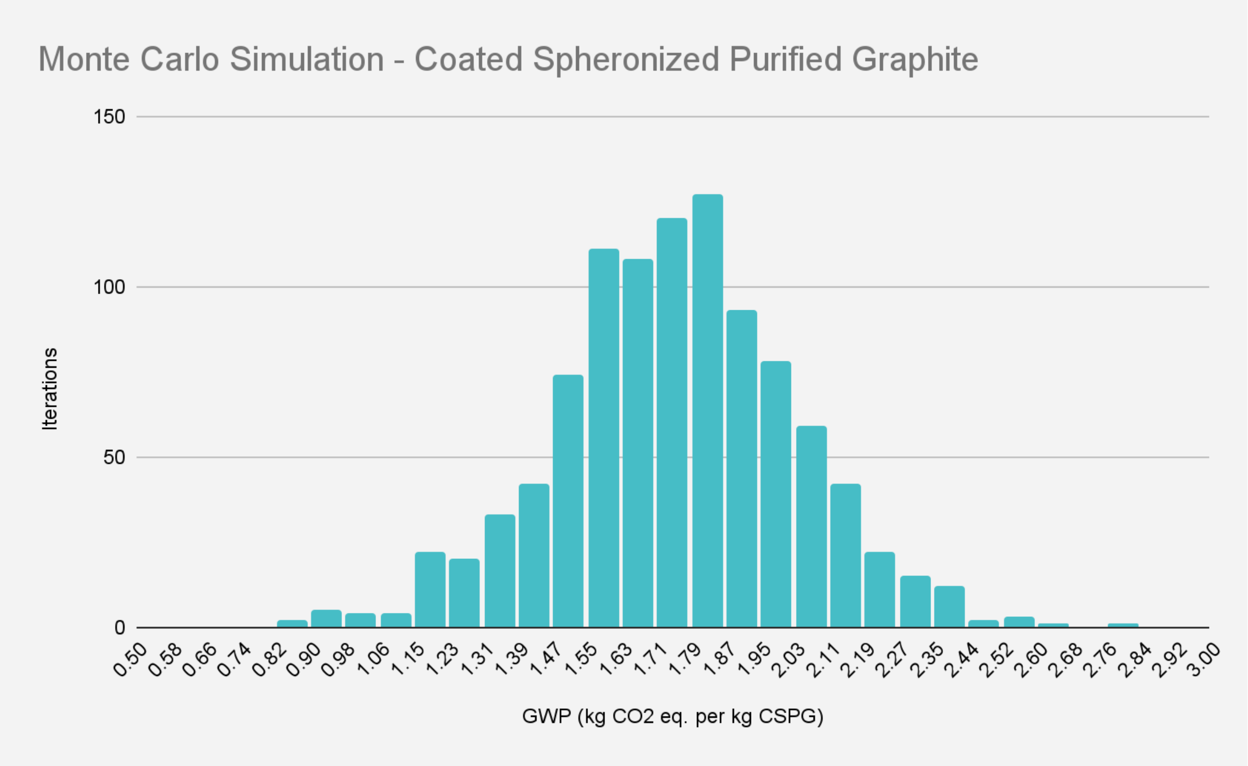


Figure 33: Results of Monte Carlo simulations for Global Warming Potential of Coated Spheronized Purified Graphite.

Table 8: Statistics Describing Results for the Global Warming Potential as a Result of the Monte Carlo Simulations.

Descriptor	Global Warming Potential (kg CO_2 eq. per kg CSPG)
LCA Study	1.7
Mean	1.8
Minimum	0.9
Maximum	2.8
Standard Deviation	0.3

7.1 Monte Carlo Simulation - Micronized Graphite

The results of the Monte Carlo simulations of the Global Warming Potential for the functional unit are shown in Figure 34. Values obtained range from 0.02 to 0.05 kg CO_2 eq. per kg micronized graphite, as shown in Table 9. The mean value of the 1,000 iterations is 0.04 kg CO_2 eq. per kg micronized graphite. This is the same as the value obtained by the LCA model (section 4.1). There are no significant differences between the value calculated in the LCA study and the average value obtained through the Monte Carlo simulations. The results for the Monte Carlo Simulations carried out for the other impact categories and co-product are available upon request.

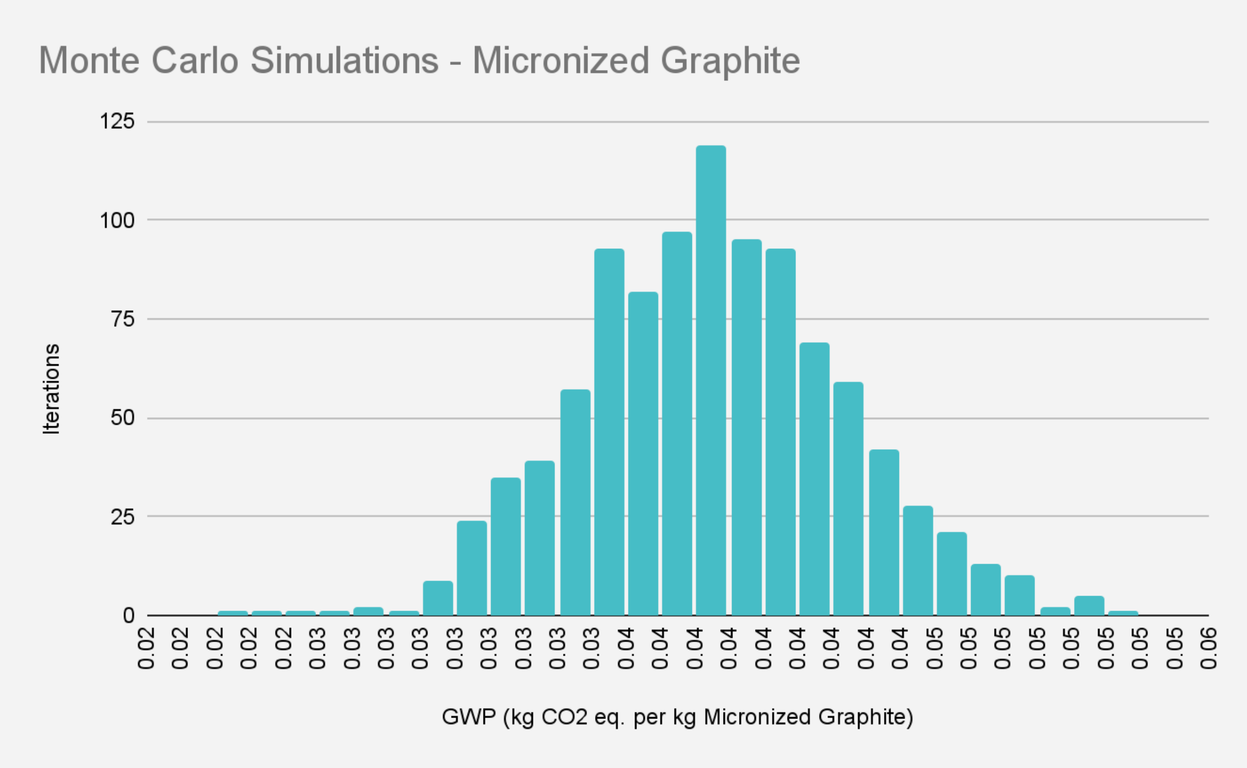


Figure 34: Results of Monte Carlo simulations for Global Warming Potential of Micronized Graphite.

Table 9: Statistics Describing Results for the Global Warming Potential as a Result of the Monte Carlo Simulations.

Descriptor	**Global Warming Potential (kg CO_2 eq. per kg micronized graphite)**
LCA Study	0.04
Mean	0.04
Minimum	0.02
Maximum	0.05
Standard Deviation	0.004

8. Benchmarking Against Operational Facilities

The final objective of this LCA is to compare the results of LEMs CSPG and MG products against CSPG and MG products produced via natural and synthetic production routes in China. The comparison of the assessed impact categories against operational routes for producing CSPG and micronized graphite in China can be found in Table 11. The natural graphite route was based on anode grade natural graphite production by Aoxing New Materials Co. Ltd in Luobei, Heilongjiang. The synthetic graphite route was based on anode grade synthetic graphite production by Futan New Material Technology Co. Ltd in Jinjiang, Fuijan. In this comparison, the following points need to be considered:

- The data collected for the benchmark studies assessed are derived from public sources.[18–20]
- The background databases used for the benchmarking studies are Ecoinvent 3.7.1 and ILCD 2011 Direct Air Emissions database.
- Transport data of consumables and waste management have not been collected for the Chinese processing facilities. Transport and waste management impact data has been excluded from the benchmarking results for Leading Edge Materials (LEM) to allow for a direct comparison.
- Proxy data has been collected to fill data gaps in the purification stage of the coated spheronized graphite by Aoxing New Materials Co. Ltd. A higher uncertainty is associated with this. It is assumed that LEM and Aoxing New Materials Co. Ltd have the same purification route.
- Proxy data for the upgrade stage of producing micronized graphite benchmark has been used due to the lack of public data. The data was collected from Minviro's internal database.
- A comparison could not be made for the Water Use impact category due to the lack of data available on the water lost and degraded for the LEM process and the natural and synthetic graphite benchmark routes to allow for a fair comparison.
- 15-30% uncertainty range is associated with LEM routes (see Chapter 7). There is an uncertainty margin of 10% with the benchmark route, with 45% uncertainty

assigned to proxy data used.[17] The 10% uncertainty is assigned to operations due to the data being collected or measured from the operation specifically, which lowers the uncertainty overall. In comparison, the data for projects in development are assigned a higher uncertainty due to the data being produced from modelling.

8.1 Impact of Producing Anode Grade Graphite - Natural vs Synthetic Graphite

A comparison of the LEM process for producing anode grade graphite against the Aoxing New materials Co. Ltd process and Futan New Material Technology Co. Ltd process, based in China, is shown in Table 10. It must be noted, electricity for the Chinese routes (natural and synthetic) are assumed to be sourced from the regional grids, where the companies are located.

The environmental impact for LEM's route is lower than the Chinese routes (natural and synthetic) for three impact categories selected. For GWP, the impact of LEM's CSPG is 1.7 kg CO_2 eq. per kg CSPG. The GWP calculated for Aoxing New materials Co. Ltd is 13.2 kg CO_2 eq. per kg CSPG. For synthetic graphite, the equivalent product to CSPG is anode grade graphite, thus this is used as the functional unit for synthetic graphite. The GWP for synthetic graphite production at Futan New Material Technology Co. Ltd is 16.7 kg CO_2 eq. per kg anode grade graphite. The GWP is considerably higher than LEM's, due to the higher electricity consumption and environmental impact associated with the electricity grid mix used in China, compared to the electricity source used by Leading Edge Materials, giving LEM a clear advantage when producing CSPG in Sweden.

Table 10: Overall Results for Comparing the Production of Anode Grade Graphite via Natural and Synthetic Routes.

	Synthetic CSPG - China	Natural CSPG - China	LEM - CSPG
Global Warming Potential	16.7	13.2	1.7
Acidification Potential	0.01	0.1	$8.6E^{-3}$
Freshwater Eutrophication Potential	$3.1E^{-4}$	$2.1E^{-3}$	$2.9E^{-3}$
Terrestrial Eutrophication Potential	$2.0E^{-1}$	$1.6E^{-1}$	$1.8E^{-2}$
Marine Eutrophication Potential	$1.3E^{-3}$	$4.9E^{-3}$	$3.5E^{-3}$
Disease Incidence	$6.6E^{-7}$	$1.9E^{-6}$	$7.9E^{-5}$

Monte Carlo simulations were run on each scenario with different uncertainties associated with each production route to produce the anode grade graphite material. The results of the Monte Carlo simulation can be found in Figure 35. It is clear that even with the uncertainty, the maximum GWP for the LEM route to produce spheronized coated graphite is lower than the minimum GWP for producing spheronized coated graphite in China. The production of anode grade graphite via the synthetic route has the highest GWP, but there is considerable overlap with the natural graphite production route in China. This indicates that CSPG via natural graphite production can have a higher GWP impact than synthetic.

Nonetheless, Chinese coal power generation is one of the largest single sources of emissions within the life cycle context, with reducing these emissions by replacing the older power plants with newer, more thermal efficient plants, alongside air polluting control devices, being a priority for the Chinese government over the last 10 years.[21] It should be noted that if the Chinese benchmark route were to use hydropower instead of the average grid mix of the regions where the operations take place, the overall environmental impact of producing CSPG will decrease significantly. Despite China's decarbonizing strategies, the majority of natural and synthetic graphite produced in China, and more specifically Inner Mongolia, is producing using electricity currently sourced from coal.

Overall, the results of the Monte Carlo simulations indicate that the spheronized coated graphite product of the Woxna project is likely to have a lower GWP impact compared to the two routes from China.

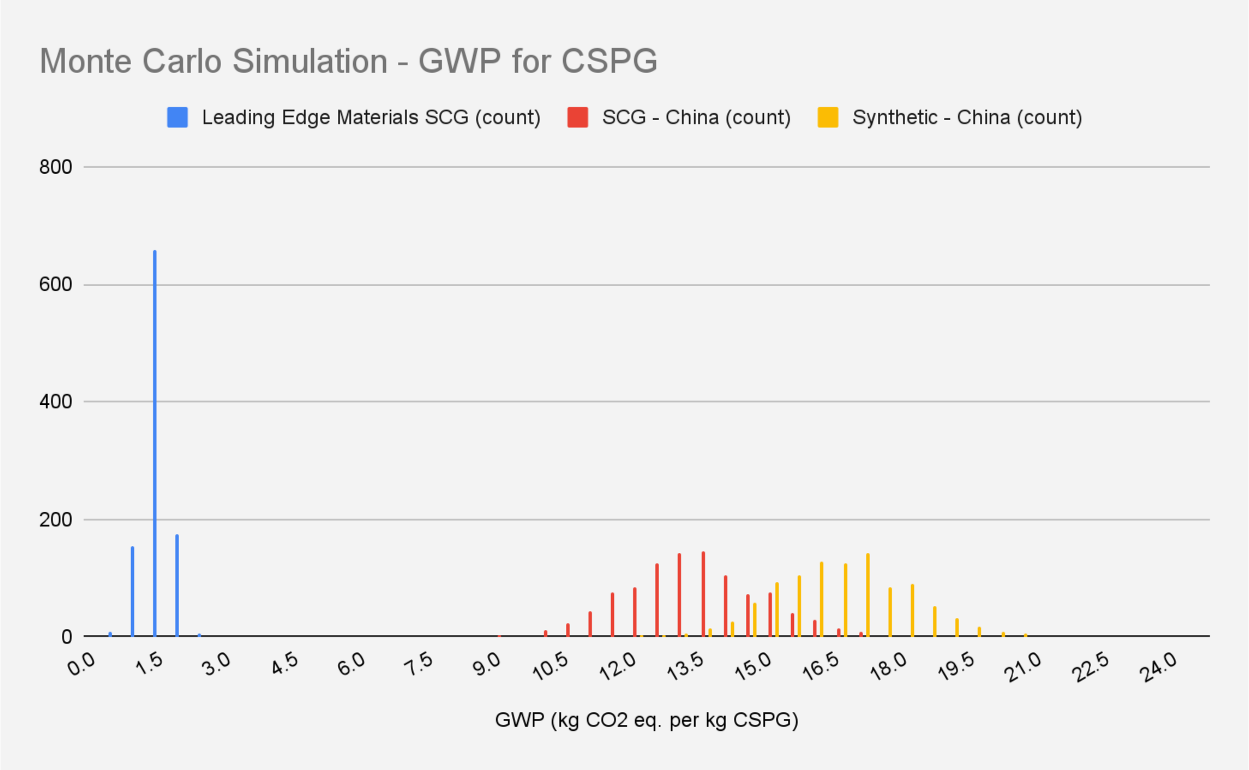


Figure 35: Results of Monte Carlo simulations for Global Warming Potential of Three Production Routes of Anode Grade Graphite.

The LEM route has a higher environmental impact for FEP (2.9E^{-3} kg P eq. per kg CSPG) than synthetic route (3.1E^{-4} eq. per kg anode grade graphite), and natural CSPG production route in China (2.1E^{-3} kg P eq. per kg CSPG). Additionally, for the Disease Incidence impact category, LEM has the higher impact of 7.9E^{-5} disease incidence eq. per kg CSPG, compared to its Chinese competitors. The natural graphite benchmark route in China has an impact of 1.9E^{-6} disease incidence eq. per kg CSPG. Synthetic graphite production impact has a disease incidence of 6.6E^{-7} disease incidence per kg anode grade graphite. The primary reason for this is due to the higher environmental impact associated with these two impact categories with the Vattenfall hydropower source than the grid electricity produced in China. The Vattenfall hydropower has larger embodied emissions associated with the deforestation and building of infrastructure for the hydropower facility, in comparison to the Chinese grid. As a result of this, the overall impact for FEP and Disease Incidence is higher for the LEM route than the Chinese benchmarking routes.

8.2 Impact of Producing Micronized Natural Graphite vs Leading Edge Micronized Graphite

A comparison of the LEM micronized graphite production against the production of micronized graphite in China is shown in Table 11. There is currently no public data for the production of micronized graphite available, therefore proxy data has been used, with the energy inputs being characterized to the Chinese grid mix. The grid mix chosen, is the same region as the Aoxing New materials Co. Ltd process, due to being the region which produces the largest amount of natural graphite products. As a result of the lack of data, the natural micronized graphite production route was assigned higher uncertainty of 45%.

LEM's micronized graphite product has a lower environmental impact in four of the five impact categories calculated, in comparison to the production of micronized based in China. The GWP of micronized graphite via the LEM route is 0.04 kg CO_2 eq. per kg micronized graphite. The GWP of producing micronized graphite based in China, is estimated to be 2.5 kg CO_2 eq. per kg micronized graphite. LEM's location for its CSPG production is at a considerable advantage, regarding the GWP. The main advantage is from the electricity grid mix. The Chinese grid is predominantly coal-powered, thus having a significantly higher environmental impact than electricity sourced from Vattenfall.

Table 11: Overall Results for Comparing the Production of Micronized Graphite at LEM vs Chinese Production Route.

	Natural MG	**Leading Edge MG**
Global Warming Potential	2.5	0.04
Acidification Potential	$3.7E^{-3}$	$1.4E^{-4}$
Freshwater Eutrophication Potential	$1.7E^{-4}$	$1.8E^{-4}$
Terrestrial Eutrophication Potential	$1.0E^{-2}$	$6.5E^{-4}$
Marine Eutrophication Potential	$9.7E^{-4}$	$2.1E^{-4}$
Disease Incidence	$6.0E^{-8}$	$7.3E^{-6}$

Monte Carlo simulations were conducted to show the range in GWP dependent on the uncertainty associated with each production route. The results are shown in Figure 36. It is clear that the maximum GWP for LEM production route for producing micronized graphite is lower than the minimum GWP for producing micronized graphite in China. This is mainly due to the lower environmental impact associated with the electricity source in Sweden, than the grid mix in China.

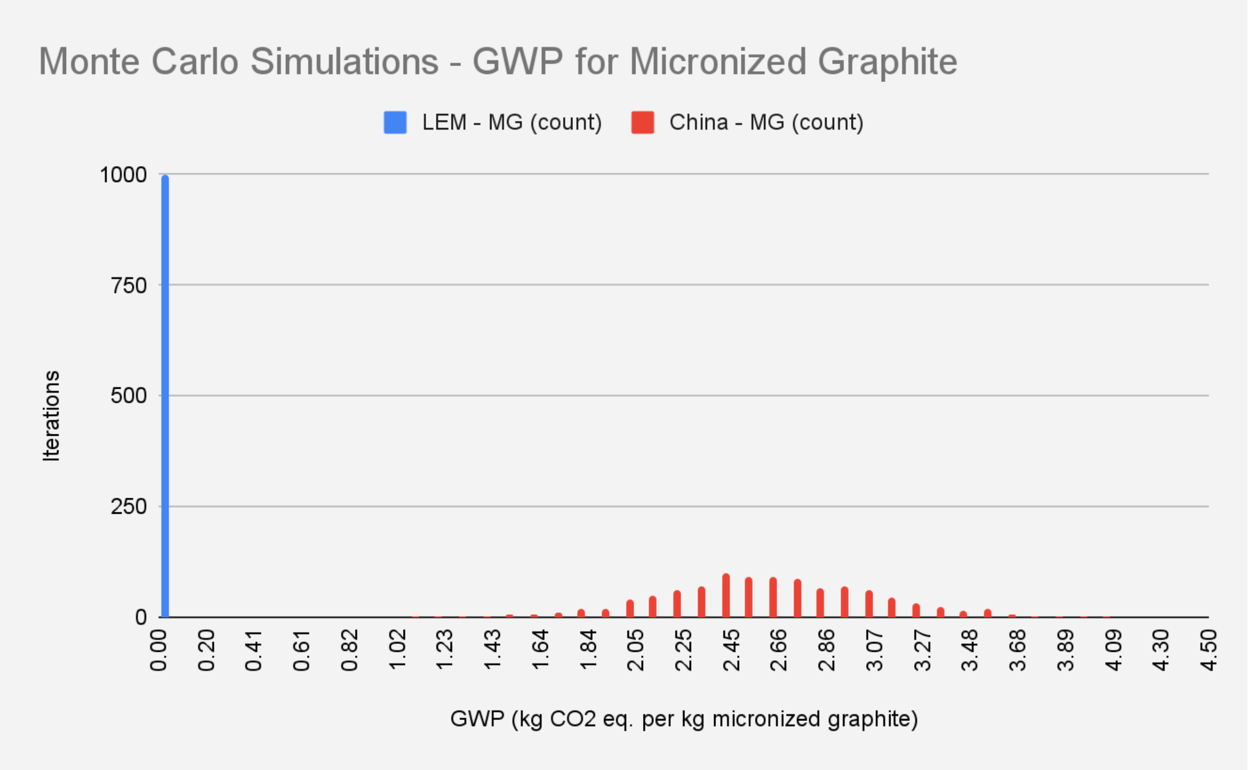


Figure 36: Results of Monte Carlo simulations for Global Warming Potential of Three Production Routes of Micronized Graphite.

For two of the three subcategories of the EP (freshwater, terrestrial and marine), LEM production route has a lower impact than that of the Chinese production process. This is likely due to the higher embodied impact associated with the Chinese electricity grid mix. For FEP, LEM has a marginally higher environmental impact of 1.8E^{-4} kg P eq. per kg micronized graphite, in comparison to micronized graphite being produced in China (1.7E^{-4} kg P eq. per kg micronized graphite). This also applies to the Disease Incidence impact category. As mentioned above, this is due to the embodied impact associated with the building and infrastructure used to produce the hydropower at Vattenfall hydropower facility.

9. Mitigation Strategies

This chapter assesses impact mitigation strategies that should be considered to further reduce the environmental impact for the production of CSPG and micronized graphite products.

- The largest contributions to the overall environmental impacts are produced from the consumption of argon and nitrogen, mainly due to the large embodied impact associated with producing these reagents. It is recommended to investigate suppliers e.g., Air Liquide claims to produce these reagents with a lower environmental impact and have type II environmental declarations for the environmental impact calculated. It is recommended that consistent ISO-compliant Life Cycle Assessments are carried out to quantify the impact of producing these reagents.
- ANFO has a large quantity of direct air emissions as well as upstream scope 3 emissions associated with its production. It is recommended to change the ANFO source with lower direct and embodied emissions. For example, Hypex have produced a NOx-free bio hydrogen peroxide emulsion to be used for mine explosives.[22]
- To minimize the environmental impact from haulage, it is advised to electrify the mining feet. This will reduce the direct emissions on site. Alternatively, an investigation into the use of a trolley assist system or in-pit crushing combined with a conveyor belt system could also be a method to reduce the environmental impact of the haulage fleet.

10. Conclusions and Recommendations

10.1. Conclusions

A life cycle assessment was carried out to quantify the environmental impact associated with the production of spheronized coated graphite and micronized graphite for the Woxna graphite project. To allocate the impacts associated with the different products, economic allocation has been used. One kg of spheronized coated graphite was used as the functional unit, as the product contributes to 86.3% of the project's economic value.

The Global Warming Potential for the functional unit was calculated to be 1.7 kg CO_2 eq. per kg CSPG. The main drivers of the GWP impact category are the consumption of argon, as well as electricity consumption (concentrator + upgrade plant), nitrogen, and solvent. The micronized graphite co-product has a GWP of 0.04 kg CO_2 eq. per kg micronized graphite.

For the acidification potential impact category, the results for one kg of CSPG is $8.6E^{-3}$ mol H^+ per kg CSPG. For the FEP impact category, the result for the functional unit was $2.9E^{-3}$ kg P eq. per kg CSPG. The overall result for TEP is $1.8E^{-2}$ mol N eq. per kg CSPG. The MEP impact category, the overall result is $3.5E^{-3}$ kg N eq. per kg CSPG. Disease Incidence per kg CSPG was calculated to be $7.9E^{-5}$ disease incidence eq. per kg CSPG. Water Use per kg of the functional unit was identified to be 3.2 kg water per kg CSPG. This takes into account the direct water consumed on site and lost through evaporation, mainly driven by the water requirements of the concentrator, and the regionalized water scarcity impact.

For the micronized graphite products, the results for the other impact categories follow an identical trend as for the Global Warming Potential impact category, as the same input and output flows were considered for all products together with the same allocation methodology.

10.2. Study Recommendations

The major recommendations for further work to address the limitations of this LCA study are listed below.

- This LCA currently uses PEA data to assess the environmental impact of the project, which is data generated with a relatively low level of definition. The LCA study should be updated at a later date using pre-feasibility and feasibility study-level data to provide more accurate LCA results associated with the life cycle impact of the graphite products.
- Through personal communication, it has been assumed the off-gas data is assumed to consist of thermal energy released without any harmful components. As the project moves forward, and more high-resolution data is available, it is recommended to investigate the composition of the off-gas stream and how it can impact the future LCA results.
- The PEA study assumes the tailings are non-acid generating. If this is to change as the study develops, this will need to be considered when calculating the environmental impact of the waste streams.
- Proxy data from similar projects in similar locations is used for the silt content and number of days rainfall is above 0.25 mm for the PM2.5 calculation. It is recommended to repeat the calculation at higher resolution with the correct data sourced from the Woxna Graphite project.
- The electricity is sourced from Vattenfall, with the characterization factor (CF) being provided by their personal Environmental Product Declaration. Thus, there was no division within the Eutrophication Potential into the three subcategories, meaning the same value was assumed for the freshwater, terrestrial and marine eutrophication impacts. It is recommended to repeat the LCA, using a CF calculated from their LCI. This would enable a more accurate Eutrophication Potential impact to be calculated.
- Argon consumed was calculated under the impression that there is 1.78 kg/m^3, at 0°C and standard atmospheric pressure. Consumption of nitrogen was calculated

assuming there is 1.25 kg/m^3, at 0℃ and standard atmospheric pressure. If these reagents consumed during the upgrade facility are produced under different conditions, this will need to be taken into account when future LCA model updates are made.

- In this model, it is assumed that the water intake for the concentrator is extracted from the local water table and is recycled, thus the only water lost is through evaporation. It is recommended to include a more detailed water balance for a future study so that it is possible to separate water use and water returned to the water table in its degraded form. If water degradation did take place, the Water Use impact would be higher.
- It is recommended to update the results when there is clarity from where the reagents will be sourced. This could alter the embodied impacts associated with certain reagents, as for this study, database average values are assumed. Additionally, the location of the reagents will influence the impact associated with the transport of the reagents and will allow for a more accurate representation of total water footprint as it will be possible to integrate regional water scarcity for the reagents as well.
- It is recommended to complete a temporally explicit LCA for the Woxna Graphite project to determine how the environmental impact is affected over the life of mine (LOM). This will provide a more accurate insight into the overall environmental impact of the project.
- If the electricity supplier is to change, it is recommended to update the LCA study, using the grid mix or LCA completed for the new supplier as currently a CF is being used specific to Vattenfall only.
- For the benchmarking exercise, public data was collected, and proxy data from Minviro's internal database was used to fill in data gaps. It is recommended to repeat the benchmarking exercise using data collected directly from operation facilities to minimize the uncertainty when comparing between LEM projects and the operations in China.
- The infrastructure and equipment utilized within the upgrade plant has not been taken into account in this LCA. On average, over a LOM of 10 years, 0.05-0.5 kg CO_2

eq. is consumed for the production and utilization of the equipment. For future LCA's, this should be considered.

- The benchmark routes are operators; thus the Monte Carlo simulation has a low uncertainty of 10% associated with the model inputs. It should be noted that the structural uncertainty associated with inadequacies in the LCA modelling process have not been accounted for, and it is recommended to include this in future comparative LCA work.
- A mass and energy balance were not yet created for the project at this stage. It is recommended to repeat the LCA once a mass and energy balance is completed to increase the accuracy of the LCA, confirming all emissions to air, land and water are included within the LCA.

11. References

1. Leading Edge Materials. *Leading Edge Materials Corp* https://leadingedgematerials.com/.
2. Finkbeiner, M., Tan, R. & Reginald, M. Life cycle assessment (ISO 14040/44) as basis for environmental declarations and carbon footprint of products. in *ISO Technical Committee 207 Workshop, Norway* (2011).
3. Horne, R. E., Grant, T. & Verghese, K. *Life Cycle Assessment: Principles, Practice and Prospects*. (Csiro Publishing, 2009).
4. Santero, N. & Hendry, J. Harmonization of LCA methodologies for the metal and mining industry. *Int. J. Life Cycle Assess.* **21**, 1543–1553 (2016).
5. Klöpffer, W. The critical review of life cycle assessment studies according to ISO 14040 and 14044. *Int. J. Life Cycle Assess.* **17**, 1087–1093 (2012).
6. Weidema, B. P. *et al.* Overview and methodology: Data quality guideline for the ecoinvent database version 3. (2013).
7. Nordic, B. U. H. *EPD of Electricity from Vattenfall's Nordic Hydropower*. https://portal.environdec.com/api/api/v1/EPDLibrary/Files/fc28fbf0-21fa-47fc-ab0b-08d8c11ab8a5/Data (2021).
8. Hiraishi, T. *et al.* 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. *IPCC, Switzerland* (2014).
9. Seppälä, J., Posch, M., Johansson, M. & Hettelingh, J.-P. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator (14 pp). *Int. J. Life Cycle Assess.* **11**, 403–416 (2006).

10. Posch, M. & Reinds, G. J. A very simple dynamic soil acidification model for scenario analyses and target load calculations. *Environmental Modelling & Software* **24**, 329–340 (2009).
11. Alcamo, J., Shaw, R. W. & Hordijk, L. The RAINS Model of Acidification: Science and Strategies in Europe. 30 (1991).
12. Posch, M. *et al.* The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. *Int. J. Life Cycle Assess.* **13**, 477 (2008).
13. Jolliet, O. *et al.* Global guidance on environmental life cycle impact assessment indicators: impacts of climate change, fine particulate matter formation, water consumption and land use. *Int. J. Life Cycle Assess.* **23**, 2189–2207 (2018).
14. Boulay, A.-M. *et al.* The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *Int. J. Life Cycle Assess.* **23**, 368–378 (2018).
15. Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).
16. Simulation-based life cycle assessment for hydrometallurgical recycling of mixed LIB and NiMH waste. *Resour. Conserv. Recycl.* **170**, 105586 (2021).
17. Nethery, B. The role of feasibility studies in mining ventures. in *Conference Board of Canada, Structuring More Effective Mining Ventures, AMEC Mining and Metals, Vancouver* (yomgedid.kenanaonline.com, 2003).
18. *High-end specialty graphite research and development and industrialization projects*. (2019).

19. *Sichuan Linghang Graphite Products Co., Ltd. Pinghe Graphite Mining and Deep Processing Project Phase I Environmental Impact Report*. (2017).
20. *Graphite Industry Development and Park Construction in Heilongjiang Province overall plan Environmental Impact Report*. (2020).
21. Henriksson, P. J. G., Zhang, W. & Guinée, J. B. Updated unit process data for coal-based energy in China including parameters for overall dispersions. *Int. J. Life Cycle Assess.* **20**, 185–195 (2015).
22. NOx-free Hypex Bio hydrogen peroxide emulsion mining explosives launched by new Swedish company Hytech - International Mining. https://im-mining.com/2021/05/13/nox-free-hypex-bio-hydrogen-peroxide-emulsion-mining-explosives-launched-new-swedish-company-hytech/ (2021).

Appendix A - Life Cycle Inventory for CSPG and Micronized Graphite Products

The data quality and availability was generally high for this study. Regionally specific and technologically representative data was obtained for the primary contributors to the different impact categories.

Table 12: The Full Life Cycle Inventory for the Production of Coated Spheronized Purified Graphite and Micronized Graphite.

Energy and Material Inputs	Flow Type	Value	Unit	Reference Unit
Area 100 - Mining				
Diesel	Input	107,309	L	per annum
ANFO	Input	167	tonnes	per annum
Area 200 - Concentrator				
Plant throughput	Input	14,523	tonnes	per annum
Concentrate Production	Output	15,692	tonnes	per annum
Liners - 1 m^3 Regrind Mill	Input	9	set	per annum
Liners - 3 m^3 Regrind Mill	Input	1	set	per annum
Media - 1 m^3 Regrind	Input	13.5	tonnes	per annum
Media - 3 m^3 Regrind	Input	4.5	tonnes	per annum
Rod Mill	Input	32	tonnes	per annum
Diesel	Input	32	tonnes	per annum
Flocculant	Input	0.2	tonnes	per annum
MIBC	Input	32	tonnes	per annum
Electricity	Input	27,509,923	kWh	per annum
Water	Input	760	kg	per hour
Area 300 - Upgrade Plant				
Spherical Graphite Produced	Output	6,519	tonnes	per annum
Micronized Graphite Produced	Output	8,631	tonnes	per annum
Argon	Input	2,049,840	sm3	per annum
Solvent	Input	510,000	kg	per annum
Nitrogen	Input	3,750,000	sm^3	per annum
Pitch	Input	445,709	kg	per annum

Total Electricity	Input	83,847,686	kWh	per annum
Furnace off-gas	Output	8,700,000	sm^3	per annum
Cooling Water	Input	3,521,520	tonnes	per annum
Area 400 - Product Handling / Transport				
Concentrate Transport		454,500	km * tonne	per annum
Product Bulk Bags		15,150	bags	per annum
Product Pallets		15,150	pallets	per annum
Area 500 - Waste Management / Tailings Facility				
Solids	Output	142,791	tonnes	per annum
Water	Output	511,564	tonnes	per annum

Appendix B - Reviewers Feedback

CRITICAL REVIEW REPORT RESULTS TABLE

Initials	Index	Page number	Paragraph/ Figure /Table	Type of comment	Reviewer comments	Reviewer recommendation	Practitioner response
LS	1	5	Table 2	ED	The headings of Table 2 are quite confusing as the "Synthetic – China" and "Natural – China" headings do not specify the material as with the others i.e. "LEM – CSPG".	Re-word the "Synthetic – China" and "Natural – China" headings to include the type of material.	Corrected.
BS		5	Table 2	ED	In addition to the above, LEM and Leading Edge is not consistent between tables 2 and 3	Choose either LEM or Leading Edge	Corrected - LEM chosen.
LS	2	14	3.3	ED	Typo – "ISO-104040:2006".	Address typo – "ISO-14040:2006".	Corrected.
LS	3	15	3.3.1	TE	ISO14044:2006 requires the limitations of the system boundary to be outlined. Section 3.3.1 states: "Transport of reagents are not included in this LCA study". The report should state why this limitation has been implemented.	Provide an explanation as to why the transportation of the reagents was not included.	Explanation provided - data not available.
BS	4	16	3.3.2	TE	The alternative functional unit is also 1kg, but that is not stated here.	Change the sentence so it mentions 1 kg of micronized graphite.	Sentence has been changed.
LS	5	19	3.3.5	TE	ISO14044:2006 requires the assumptions of the system boundary to be outlined. The first paragraph on page 19 (and throughout other sections) provides information about the assumptions made. This information could be simplified in a table.	Consider providing a table to outline all of the assumptions made in this study.	A table of assumptions associated with the foreground and background data associated with this LCA has been added below the system boundary.

LS	6	23	Fig. 2	ED	It is not clear exactly what Figure 2 is showing. Is the data more important than the colour-coding? Or vice-versa? The colour-coding is not very clear.	Consider making Figure 2 clearer depending on the intended aim.	Colours have been amplified on image to show the different regional water scarcities in mine location.
LS	7	36	4.3.1.1	ED	Unfinished sentence: "MIBC contributes".	Finish this sentence by outlining the MIBC contribution.	Corrected.
BS	8	48	4.4.2.1	ED	The first two sentences of 4.4.2.1 should probably be directly below 4.4.2, as was done at 4.3.2.	Check opening paragraphs of all the 4.3.x sections for consistency.	Results edited so all impact categories follow same layout structure.
LS	9	29 33 37 41 45 49 54	Fig. 5 and 6 Fig. 9 and 10 Fig. 13 and 14 Fig. 17 and 18 Fig. 21 and 22 Fig. 25 and 26 Fig. 29 and 30	ED	The contribution analysis charts can be confusing when different colours are attributed to the same input between the CSPG and MG. This is particularly prevalent for the "big-hitters" such as electricity and water. The charts would be easier to interpret if each input had its own colour and this was used for all of the charts.	Consider standardizing the colours used for each input in the contribution analysis charts to make them easier to interpret.	Colours have been altered so are consistent for the MCSPG and MG products. E.g. water consumed for the upgrade plant for CSPG and MG are now the same colour.
LS	10	52	4.5.1.2	ED	This paragraph is the first time the abbreviation "WU" is used.	Please provide the full terminology in this section and then continue to use the abbreviation.	Abbreviation has been provided.
LS	11	60	Fig. 32	TE	The y-axis does not clearly indicate the results of the sensitivity analysis.	Alter the scale on the y-axis to provide additional information for the reader.	This has been corrected.

BS	12	61	Reference 16	ED	Reference 16 is not readable without a subscription to a platform	Reference to the actual document instead of a website that hosts it in a non-accessible manner.	This has been corrected.
LS	13	65	8	GE	The report states: "**The data collected for the benchmark studies assessed are derived from public sources**", without providing reference.	Please provide references for the benchmark studies.	References have been added.
BS	14	65	8	TE	The Chinese benchmark routes are not described well enough (also goes to the above comment by LS).	Make clearer what you are actually modelling with the benchmark routes.	More clear objective to what is being benchmark has been added. Benchmarking has been carried out to compare the impact of producing CSPG and MG by operators in China compared to Leading Edge's CSPG and MG products.
BS	15	65	8	TE	'there is an uncertainty margin of 10% with the benchmark route'. This seems rather low. What is it based on? More general comment: there is parametric uncertainty and structural uncertainty. With Monte carlo simulation as done here you can estimate the uncertainty of your input values, but you don't estimate inadequacies in the modelling	Justify the 10%	Justify 10% - added to the limitations of the study the structural uncertainty has not been accounted for and is

					of the process itself. Which is not necessarily a problem, but the report does not really go into detail how the benchmark Chinese route is modelled (see above comment) hence structural uncertainty should not be discounted.		recommended to include in future studies. Reference to 10% uncertainty has been included for model inputs. An explanation is given to where the 10% has come from - the 10% is from the data used is data that has been collected or measured from the operation specifically in comparison to projects in development which have a higher uncertainty due to the data being produced from modelling.
BS	16	68	8.1	TE	It seems that the higher impact of the Chinese routes is mostly based on the combination of higher energy use, and dirtier energy used. For the latter it is relevant that the standard ecoinvent Chinese electricity mix assumes a 'dirtier' mix than is probably true. And	Add a comment on the fact that the Chinese benchmark route could perform better if it was also based on hydropower. Or better, switch the Chinese mix for	A small paragraph has been added addressing China's decarbonising strategies and

					on top of that, the Chinese grid is decarbonising. I don't know what exact Chinese mix you used here, but there should be some comment that if the Chinese benchmark route were to use hydropower instead of an average mix, the difference would be less dramatic. (see e.g. Henriksson, P.J.G., Zhang, W. & Guinée, J.B. Updated unit process data for coal-based energy in China including parameters for overall dispersions. *Int J Life Cycle Assess* **20,** 185–195 (2015))	Chinese hydro and see what happens.	the reduction in impact if hydropower was utilized. Additionally, a comment was added to reason why the dirtier mix was used - due to the majority of natural and synthetic graphite being produced is from Inner Mongolia where the electricity is sourced from combusting coal.
BS	17	67	8.1	ED	The word 'confirm' is too strong (in 'the monte carlo simulations confirm that') considering the rather large uncertainties (see above comments).	Use 'indicate' rather than confirm.	Corrected.
BS	18	69	8.2	ED	'the natural micronized graphite production route has a higher uncertainty of 45%'. Inaccurate language, you don't know the actual uncertainty.	Replace 'has' with 'we assign'.	Corrected.
BS	19	71	9	GE	What about finding another floatation reagent than diesel as a suggestion? (this might not be technically possible, I don't know)	Consider an additional mitigation strategy round the used reagents.	Diesel has a minimal impact overall as it is not combusted in this case when

							used as flotation reagent and the two main reagents that contribute to the impact have been addressed within the mitigation strategies.
LS	20	Excel	LCI H10	TE	Cell states 604,196,000 kg/yr Email correspondence tab states waste rock is 599,172 t/a.	Check and confirm the correct value.	Corrected.
LS	11	Excel	LCI H18	TE	Cell states 15,692,000 kg/yr Email correspondence tab states waste rock is 14,523 t/a.	Check and confirm the correct value.	Updated to 14,523 t/a.
LS	22	Excel	LCI	TE	The values for electricity in the LCI tab do not match those provided in the Email Correspondence tab.	Please provide details of how the electricity data in the LCI tab was calculated.	Final power requirements are sourced from email correspondence tab cell B112 and B116
LS	33	Excel	LCI H59	TE	There is a value of 445,709 in LCI H59, there is no corresponding inventory item in column C.	Please confirm this inventory item.	Previous mistake that wasn’t removed - has now been removed.
LS	44	Excel	Area 5	TE	The “bags” and “pallets”, listed in the LCI tab, have not been included in the Area LCIA 5 tab.	Please indicate in the report why these inputs have not been accounted for.	A comment in LCI has been added reasoning why packaging (bags and pallets) have not

							been included. There are not included due to not being related to the functional unit and therefore not relevant in this LCA/part of the system boundary.

“type of comment”: the type may be referring to “general” (ge), “editorial” (ed) or “technical” (te)

Self-declaration of reviewer independence and competencies

I, the signatory, hereby declare that:

☒ I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study (external reviewers only)

☒ I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study at hand, i.e. I have not been part of the commissioner's or practitioner's project team(s)

☒ I do not have vested financial, political or other interests in the outcome of the study

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

☒ ISO 14040 and ISO 14044

☒ LCA methodology and practice, particularly in the context of LCI, (including data set generation and data set review, if applicable)

☒ critical review practice

☒ the scientific disciplines relevant to the important impact categories of the study

☒ environmental, technical and other relevant performance aspects of the product system(s) assessed

☒ language used for the study

I attach a curriculum vitae and a list of relevant references.

I declare that the above statements are truthful and complete. I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: 31/08/2021

Name (print): Benjamin Sprecher

Signature:

Curriculum vitae

Family name:	Sprecher
First name:	Benjamin
Date of birth:	26 July 1985
Place of birth:	The Hague, Netherlands
Nationality:	Dutch
Languages:	Dutch (C2), English (C2), German (B2) Spanish (B1)

Work experience

April 2017 – current	**Assistant Professor at the Institute of Environmental Sciences (CML), Leiden University**
Feb. 2009 – now	**Freelance journalist and Columnist** Regular column in the Leiden university newspaper Mare and freelance journalism.
Mar 2016 – Mar 2017	**Postdoctoral researcher at the Yale University School of Forestry and Environmental sciences** Working with professor Thomas Graedel on issues related to critical materials.
May 2015 – Jun 2015	**Consultancy for UNEP and Royal Government of Bhutan** Environmental impacts of paper use and recommendations for improvement.
2014 – 2018	**Volunteer for the ‘Stichting Duurzame Horeca Leiden’**
2012 – 2014	**Secretary of the interuniversity organisation of environmental science departments**

Education

Mar 2011 – Jun 2016	**PhD researcher at M2i / Institute for Environmental Sciences (CML), Leiden University** In the area of resource scarcity, with a focus on critical materials and related environmental / societal impacts. Dissertation title: “When materials become critical: lessons from the 2010 rare earth crisis”.
Apr 2014 – Sep 2014	**Guest researcher at Tokyo University, Department of Materials Engineering** Focus on data collection, collaborative paper writing.
Sep 2013 – Dec 2013	**Guest researcher at Delft Technical University, Faculty of Technology, Policy and Management** Focus on learning dynamic and agent-based modelling.
2011 – 2013	**Management trainee** Training focussed on project management and personal development at the biggest waste management company of the Netherlands.
2008 – 2010	**Master Industrial Ecology** Master’s thesis: decision modelling of investment opportunities (CML & Van Gansewinkel). *Faculty of Science, Leiden University*

Sep 2007 –
Jan 2008
Combined bachelor thesis for SMST & psychology in Guayaquil, Ecuador
The influence of industrial wastewater on a large mangrove forest located next to Guayaquil, with a focus on combining environmental sciences and psychology to gain a more complete understanding of the problems surrounding this beautiful nature area.
ESPOL, Ecuador

2004 – 2008
Bachelor Psychology
Specialization: Social & Organisational psychology (note: missing one piece of paperwork).
Faculty of Social Sciences, Leiden University

2003 – 2008
Bachelor Sustainable Molecular Science & Technology (SMST)
Faculty of Sciences, Leiden University

References

Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. B Sprecher, Y Xiao, A Walton, J Speight, R Harris, R Kleijn, G Visser, ...
Environmental science & technology 48 (7), 3951-3958

Trade-offs between social and environmental Sustainable Development Goals.
L Scherer, P Behrens, A de Koning, R Heijungs, B Sprecher, A Tukker
Environmental science & policy 90, 65-72

A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO2 versus MEA-Based Postcombustion Capture.
C van der Giesen, CJ Meinrenken, R Kleijn, B Sprecher, KS Lackner, ...
Environmental science & technology 51 (2), 1024-1034

Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite. G Bailey, PJ Joyce, D Schrijvers, R Schulze, AM Sylvestre, B Sprecher, ...
Resources, Conservation and Recycling 155, 104675

Self-declaration of reviewer independence and competencies

I, the signatory, hereby declare that:

☑I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study (external reviewers only)

☑ I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study at hand, i.e. I have not been part of the commissioner's or practitioner's project team(s)

☑ I do not have vested financial, political or other interests in the outcome of the study

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

☑ ISO 14040 and ISO 14044

☑ LCA methodology and practice, particularly in the context of LCI, (including data set generation and data set review, if applicable)

☑ critical review practice

☐ the scientific disciplines relevant to the important impact categories of the study

☑ environmental, technical and other relevant performance aspects of the product system(s) assessed

☐ language used for the study

I attach a curriculum vitae and a list of relevant references.

I declare that the above statements are truthful and complete. I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: 01/09/2021

Name (print): Lucy Smith

Signature:

Dr Lucy Smith

CURRICULUM VITAE

Dr Lucy Smith

Materials Processing Institute
Eston Rd
Middlesbrough
TS6 6US

Education and Qualifications

The University of Sheffield
PhD Materials Science and Engineering and the Sheffield University Management School
May 2016 - June 2019

‘The comparative hybrid life cycle assessments and sustainability of functional devices and related materials’

Loughborough University
BEng Materials Engineering **1st Class Hons**
September 2008 - July 20131

Associate Member of the Institute of Environmental Management and Assessment- **AIEMA**

Professional Experience

Principal Researcher – Circular Economy
Materials Processing Institute

- Project management of core Circular Economy Group strategy projects and support across the Institute’s project portfolio.
- Identification, development, and delivery of both commercially and government grant funded proposals.
- Generation of collaborative partnerships with businesses, manufacturers, research organisations, and technology developers in the foundation industries and the circular economy field.
- Application of life cycle thinking throughout the Institute’s research portfolio.
- “Year-In-Industry” and Summer Student Supervision.

The University of Sheffield, Sheffield, UK
EPSRC Post-Doctoral Prize Fellow: Material Sustainability

Academic challenge, innovation and novelty:

- The application of the Chemical Element Sustainability Index (CESI) and other sustainability assessment methodologies (e.g. BS 8905) to an established industrial supply chain (steel manufacturing) in a comparative manner.
- The development of the CESI to address sustainability across the whole supply chain.
- Establish the “Material Sustainability Network”- a network of industry, academic, policymaking and non-governmental organisation professionals to promote the development and implementation of sustainability within supply chains.
- Development of the CESI website to provide an annual update of the results of the CESI and to act as a conduit for blog posts and other relevant communications.
- Development of a future Fellowship proposal(s).

Dr Lucy Smith

- Grant proposal writing.
- Deployment of research impact through the Material Sustainability Network, website, conferences and journal publications.

The University of Sheffield, Sheffield, UK
Post-Doctoral Research Associate: TransEnergy - Road to Rail energy Exchange (R2REE)

Academic challenge, innovation and novelty:

- Interdisciplinary research between Advanced Resource Efficiency Centre and the Energy Institute focusing on the life cycle assessment (LCA) of battery technologies.
- Publication of high quality research in high quality journals.
- Grant proposal and industrial research proposal writing.
- Workshop organisation.
- LCA and Supply Chain Environmental Analysis Tool training for internal academic and external industrial collaborators.

The University of Sheffield, Materials Science and Engineering
Research Student- Designing Alloys for Resource Efficiency (DARE)
January 2018- December 2019

The University of Sheffield, Sheffield, UK
Research Associate
September 2018- April 2019

Tarmac, Tunstead, UK
Environmental Coordinator
April 2014- May 2016

Bridon International Ltd, Doncaster, UK
Health, Safety and Environmental Coordinator- Europe, Middle East and Africa
August 2011- April 2014

Research

As an interdisciplinary researcher, my research interests fall within the areas of sustainability, circular economy and resource efficiency, with particular emphasis on material usage within supply chains. My research impacts the whole life cycle of a material or product, from cradle to grave/cradle, and addresses the interconnected nature of the three pillars of sustainability and how the pillars relate to material production, use and recovery.

I have developed the Chemical Element Sustainability Index (CESI), the first, novel composite indicator to quantify the sustainability of a chemical using four individual, publically available data sets. The CESI is now being applied within the steel industry and I am expanding the methodology using the Delphi technique to determine the sustainability of a material throughout its life cycle. I am leading interdisciplinary, industry-informed research between the Management School and the School of Clinical Dentistry to determine the environmental impacts of dental restorative materials and establishing the future environmental impacts of battery technologies using machine learning techniques.

I have designed and developed the Supply Chain Environmental Analysis Tool- Augmented Reality game, a game to teach children about sustainability in a city-scape using augmented reality to visualise their built environment. The game addresses the social, environmental and economic issues associated with building a city and encourages the player to adopt sustainable practices over a 10-year period.

I am keen to make an impact through further exploration of material sustainability using both quantitative and qualitative measures to determine the individual effects of the environment, society and economy. I believe that direct impact can be achieved through the application of these measures in industrial environments to enable supply chains to increase their sustainability credentials.

Publications

Refereed Journals - in print - Original articles

Martin. N, **Smith. L**, Mulligan. S, "Sustainable oral healthcare and the environment: mitigation strategies", Dental Update, **2021**, 48 (7), 524-531.

Mulligan. S, **Smith. L**, Martin. N, "Sustainable oral healthcare and the environment: challenges", Dental Update, **2021**, 48 (6), 493-501.

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, "A Chemical Element Sustainability Index", Resources, Conservation and Recycling, **2021**, 166, 105317.

Smith L, Ibn-Mohammed T, Astudillo D, Brown S, Reaney I. M., Koh, S. C. L, "The Role of Cycle Life on the Environmental Impact of Li6.4La3Zr1.4Ta0.6O12 based Solid-State Batteries", Advanced Sustainable Systems, **2021**, 5 (2), 2000241.

Smith. L, Ibn-Mohammed. T, Yang. F, Reaney. I. M, Sinclair. D. C, Koh. S. C. L, "Comparative Environmental Profile Assessments of Commercial and Novel Material Structures for Solid Oxide Fuel Cells", Applied Energy, **2019**, 235, 1300-1313.

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, "Life cycle assessment and environmental profile evaluations of high volumetric efficiency capacitors", Applied Energy, **2018**, 220, 496-513.

Ibn-Mohammed. T, Reaney. I. M, Koh. S. C. L, Acquaye. A, Sinclair. D. C, Randall. C. A, Abubakar. F. H, **Smith. L**, Schileo. G, Ozawa-Meida. L, "Life cycle assessment and environmental profile evaluation of lead-free piezoelectrics in comparison with lead zirconate titanate", Journal of the European Ceramic Society, **2018**, 38(15), 4922-4938.

Refereed Journals - in print- Reviews

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, "Life cycle assessment of functional materials and devices: opportunities, challenges and current and future trends", Journal of the American Ceramic Society, 2019 102(12), 7037-7064.

Research under review

Koh. S. C. **L, Smith**. L, Miah. J, Astudillo. D, Gladwin. D, Brown. S, Stone. D, "Life Extension: Enhancing the Eco-Efficiency of Battery Energy Storage using Techno-Hybridisation". Under review- Renewable and Sustainable Energy Reviews

Conference Presentations

Smith. L, Tijsseling. L, “Life Cycle Sustainability Assessment for a Circular Resource Economy – Comparing primary production of neodymium against recycling using an LCA approach”, 9th Scientific Seminar of the PROMETIA Association, 31st August 2021

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, “A Material Sustainability Index: A tool to assess the sustainability of materials for resource efficiency”, Centre for Dielectrics and Piezoelectrics Studies Spring 2019 Meeting, The University of Sheffield, UK, May 2019

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, ““Green” Materials- Are they sustainable?”, Sustainable Functional Materials (SGM) 2018, Weston-Super-Mare, UK, May 2018

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, “Sustainable Functional Materials: The role of hybrid life cycle assessment”, Centre for Dielectrics and Piezoelectrics Studies Spring 2018 Meeting, Penn State University, USA, April 2018

Smith. L, Yang. F, Ibn-Mohammed. T, Reaney. I. M, Sinclair. D. C, Koh. S. C. L, “Comparative life cycle assessment and environmental profile evaluations of high and intermediate temperature solid oxide fuel cells”, 2nd Global Conference on Theory and Applications of OR/OM for Sustainability (GCTAOS): “Moving forward the world climate change and sustainability agenda”, Beijing, China, September 2017

Conference Poster Presentations

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, “A Material Sustainability Index”, Centre for Dielectrics and Piezoelectrics Studies Spring 2019 Meeting, The University of Sheffield, UK, May 2019

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, “A Review of the Application of Life Cycle Assessment of Functional Materials and Devices”, Centre for Dielectrics and Piezoelectrics Studies Spring 2018 Meeting, Penn State University, USA, April 2018

Smith. L, Ibn-Mohammed. T, Koh. S. C. L, Reaney. I. M, “Life cycle assessment and environmental profile evaluations of high volumetric efficiency capacitors”, Centre for Dielectrics and Piezoelectrics Studies Spring 2018 Meeting, Penn State University, USA, April 2017

Teaching and Administration

The University of Sheffield, Faculty of Engineering
GEC and EYH Facilitator
January 2017, 2018 and 2019

The University of Sheffield, Materials Science and Engineering
Seminar Tutor: 'Cradle to ?: Materials and the Environment'
May 2018, 2019 and 2020

The University of Sheffield, Faculty of Engineering
Seminar Tutor: Social Science of Energy Storage
May 2018

Lancaster University, Material Social Futures CDP
Seminar Tutor: “Sustainability of Materials”
July 2019

The University of Sheffield, Faculty of Engineering
Seminar Tutor: MEC6401, Sustainability in the Industrial Environment- “Sustainability of Materials”

Dr Lucy Smith
October 2019

Grants and Awards

EPSRC Doctoral Prize Fellowship January 2020 – December 2020

- £55,957- 12-month Fellowship to develop innovative research within EPSRC priority areas

Armourers & Brasiers Gauntlet Trust April 2017

- £900 towards travel expenses and conference costs for the 2nd Global Conference on Theory and Applications of OR/OM for Sustainability (GCTAOS): "Moving forward the world climate change and sustainability agenda", Beijing, China, September 2017

Sheffield University Management School Engagement and Impact Stimulation Fund July 2016

- £375 to contribute towards the SCEnAT Augmented Reality Game, user engagement event

Training and Development

The University of Sheffield

- 'The Researcher as Manager induction and CDP', March 2020
- 'Demystifying the EPSRC Peer Review', February 2020
- EPSRC: 'Early Career Researcher Workshop', November 2019
- 'Working in Partnership Workshop', April 2019
- Online course: 'Academic career planning', January 2019
- 'CHANGE Online Leadership', March 2018
- 'Springboard for Women', Semester 1 2017
- 'Pathways to Impact', November 2017
- 'Public Engagement Masterclass', February 2017

Industry

- Cranfield University: 'Women as Leaders', January 2016
- Institute of Environmental Management and Assessment: 'Diploma in Sustainable Business Practice', 2015
- Institute of Environmental Management and Assessment: 'Associate Certificate in Environmental Management', 2014

References

Professor Ian Reaney, BSc MSc PhD FIMM FRMS
Professor in Ceramics
Dyson Chair in Ceramics
Department of Materials Science and Engineering
University of Sheffield
Sir Robert Hadfield Building
Sheffield
S1 3JD
0114 222 5471
i.m.reaney@sheffield.ac.uk

Andrew Buchanan
Group Manager – Circular Economy
Materials Processing Institute
Eston Rd

Dr Lucy Smith
Middlesbrough
TS6 6US
01642 382053
andrew.buchanan@mpiuk.com