Calcium Carbonate + Post-carbonation Slag Product Carbon Footprint Research Report

GREENORE Cleantech(Shanghai) Co., Ltd

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Contents

Abbreviations

Short name	Full name
IPCC	The Intergovernmental Panel on Climate Change
CFP	Carbon Footprint of Product
CO_2e	Carbon Dioxide Equivalent
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
ISO	International Organization for Standardization
GWP	Global Warming Potential
dLUC	direct Land Use Change
ELCD	European Reference Life Cycle Database

Abstract

The purpose of this research is to calculate the carbon footprint value of 1 ton of calcium carbonate (product, including packing) and 1 ton of post-carbonation slag (by-product, excluding packing) produced by Greenore Cleantech (Shanghai) Co., Ltd . according to the life cycle assessment (LCA) method stipulated by International Standards Organization (ISO) and ISO 14067:2018.

In order to meet the needs of carbon footprint and communication with interested parties, the functional units of this research are defined as 1 ton of calcium carbonate (including packing) and 1 ton of post-carbonation slag (excluding packing). The system boundary of the research is defined as "Cradle-to-Gate", which covers the acquisition stage of main raw materials and the site production stage of products. The results indicate that the carbon footprint of 1 ton of calcium carbonate (including packing) is 70.76 kgCO_2e, in which the carbon emission of the raw material acquisition stage is -185.69 kgCO_2e, and that of the production stage is 256.46 kgCO_2e; the carbon footprint of 1 ton of post-carbonation slag (excluding packing) is 85.12 kgCO_2e, in which the carbon emission of the raw material acquisition stage is 42.38 kgCO_2e, and that of the production stage is 42.74 kgCO_2e.

1. Overview

GREENORE Cleantech (Shanghai) Co., Ltd. (hereinafter referred to as "GREENORE" or the "Company") was founded at Columbia University in 2016, and its founding team returned to China and settled in Shanghai Caohejing Development Zone in 2019. Engaged in basic research and development, industrial demonstration and industrial production, the Company is a high-tech company specialized in full life-cycle carbon sinks and unconventional resources.

Based on carbon dioxide mineralization technology, GREENORE's core business is to use calcium and magnesium elements in industrial solid wastes such as steel slag to react with carbon dioxide to generate calcium carbonate, converting steel slag into high value-added industrial products while realizing the utilization and storage of carbon dioxide. High purity calcium carbonate is widely used as filling material in papermaking, plastics, coatings, rubber and other industries, while low purity calcium carbonate can be used in place of limestone and dolomite. GREENORE not only directly consumes carbon dioxide in the production process (0.2 tons to 0.4 tons of carbon dioxide per ton of steel slag), but also achieves considerable indirect carbon dioxide emission reduction in the production process and downstream product application, winning the reputation of a genuine "negative carbon" practitioner (see Figure 1).

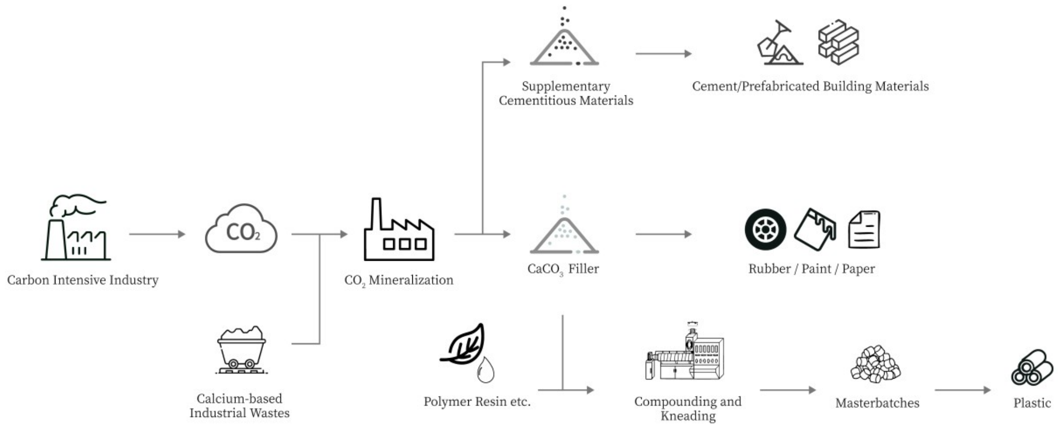


Figure 1

This year, GREENORE and Baotou Steel Group have jointly launched the construction of the world's first industrial demonstration plant with an annual treatment capacity of 100,000 tons of steel slag and 20,000 tons of carbon dioxide. In addition, the Company has carried out diversified research and business cooperation with Baowu Group, SD Steel, Yonggang Group, JCOAL, POSCO, Tata Steel and other institutions. GREENORE has been among the top in the world in the industrialization process of carbon dioxide mineralization based on steel slag. The carbonic acid-based new hydrometallurgical technology derived from the treatment of iron and steel slag has also been developed and applied in the cyclic utilization of other industrial wastes, construction wastes and lithium batteries.

The object of this product carbon footprint research is the main product calcium carbonate and the by-product post-carbonation slag. Precipitated calcium carbonate (light calcium carbonate) is a widely used inorganic salt industrial product, which is used as a filler in the production of plastics, paper, coatings and rubber. By-product post-carbonation slag is cement (concrete) admixture with high activity, which can directly replace part of the cement.

The product carbon footprint research of calcium carbonate and post-carbonation slag was carried out in strict accordance with ISO 14040:2006, ISO 14044:2006 and ISO 14067:2018.

2. Research Objective

Based on carbon dioxide mineralization technology, GREENORE uses industrial solid wastes such as steel slag to react with carbon dioxide to generate calcium carbonate, converting such wastes into high value-added industrial products while realizing the utilization and storage of carbon dioxide. This technology not only directly consumes carbon dioxide in the production process, but also achieves considerable indirect carbon dioxide emission reduction in the production process and downstream product application. GREENORE hopes that this ore-based carbon dioxide mineralization technology can contribute to the national and global carbon neutrality goals in 2030 and 2060.

The reasons and decision-making background for the Company to carry out product carbon footprint are as follows: on the one hand, the Company intends to prove advantages in terms of carbon emissions through the comparison of carbon emissions between the new calcium carbonate produced by the Company and traditional products; in addition, to show the reduced total carbon emissions of society through the carbon footprint survey as by-product (tailings) can be used as the cement (concrete) admixture, partially replacing the function of cement. On the other hand, the Company intends to find out through the assessment what can be optimized in terms of carbon emissions.

Research client and other interested parties: the Company voluntarily conducts this product carbon footprint research, and other potential interested parties include customers, government departments, LCA evaluation institutions, etc.

3. Research Scope

3.1. Function, functional unit and benchmark flow

The product object of this research is calcium carbonate, whose basic function is to be used as a filler in the production of plastics, paper, coatings and rubber. In this research, 1 ton of calcium carbonate (product, including packing) and 1 ton of post-carbonation slag (by-product, excluding packing) are directly used as the benchmark flow, and all inventory results and impact assessment results are accounted for using 1 ton of calcium carbonate and 1 ton of post-carbonation slag as the benchmark.

3.2. System boundary

The system boundary of this research is "Cradle-to-Gate”, and the life cycle stage includes from resource exploitation to product delivery, which mainly includes the upstream raw material manufacturing process, upstream raw material transportation process, product on-site production process, generated waste treatment service process, with the main production auxiliary materials and packing included (see Figure 2).

Product use stage (including downstream production process emissions, etc.) and waste stage (including product recycling and waste disposal, etc.) are not included in the system boundary. The Company's cleaning, administration, marketing, research and development, laboratory facilities, employee-related activities (heating, lighting, work clothes, transportation, canteen, toilet facilities), equipment and facilities maintenance are not included in the scope of research. The data researched are merely data of normal operations, and do not include the data of on-off conditions and the data reasonably foreseeable or in emergency.

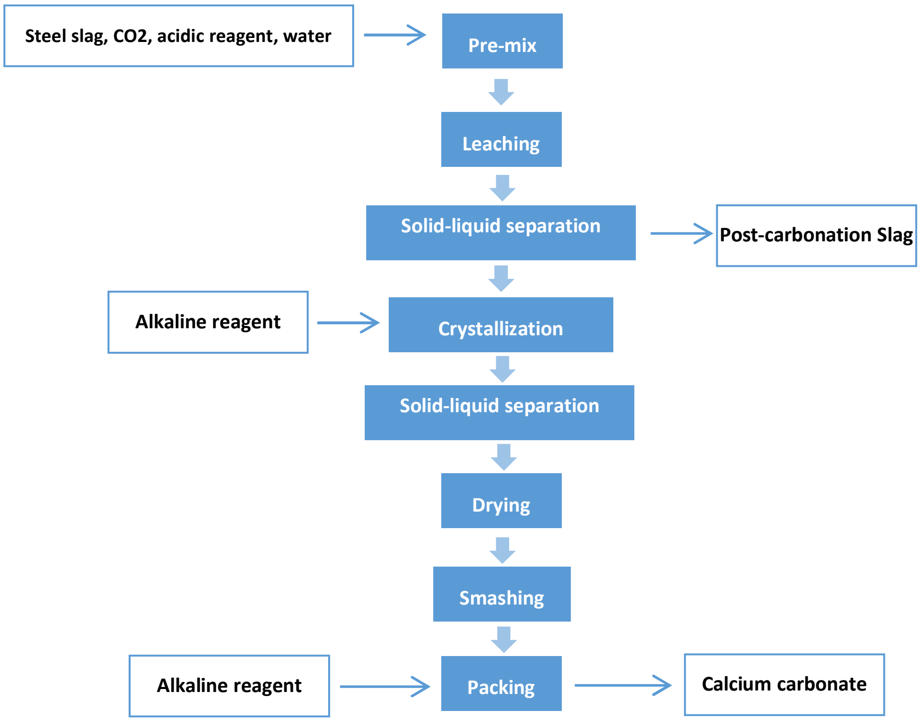


Figure 2 System Boundary Diagram of This Research

3.3. Assumption

The system boundary of this research is "Cradle-to-Gate", which does not include the research of product use and scrap stage, so there is no assumption about the product use and scrap stage on the whole.

3.4. Choice criteria

The choice criteria used in this research are based on the weight or energy ratio of each raw material and energy inputs to the total input of the process, or the weight or energy ratio of outputs to the total output. The specific rules are as follows:

- When the weight of ordinary materials is less than 1% of the weight of products, and when the weight of materials containing rare and expensive or high-purity components and materials being hazardous substances is less than 0.1% of the weight of products, the environmental impact of such materials shall be ignored, provided that the total weight of discarded materials shall not exceed 3% of the total weight of all materials;
- when the energy input or output accounts for less than 1% of the total input or output, it will be discarded, provided that the total discarded energy shall not exceed 3% of the total energy;

- emission data with known environmental impacts are not ignored.

There are no discarded inputs and outputs in this research.

3.5. Principle of distribution

The multifunctional product system is required to distribute the input and output of the whole system by a reasonable distribution method, and then calculate the life cycle assessment results of products and symbiotic products.

According to ISO 14040:2006, ISO 14044:2006 and ISO 14067:2018, the research shall avoid distribution as much as possible when it is possible to avoid distribution, such as by adopting the system amplification method. When it is impossible to avoid distribution, physical distribution method, such as energy use and solid waste data, is preferred, and when physical distribution method is not feasible, other distribution methods such as economic distribution method and cycle number distribution method are adopted.

3.6. Data and data quality requirements

The data for the Company's site material consumption and energy consumption emissions are required to be site-specific data. In case of no site-specific data for emissions related to the production and transportation of raw materials and energy, non-site database data or data from other sources can be used.

In order to meet the data quality requirements, the following aspects are mainly considered in this research:

Data integrity: first of all, the life cycle stages, processes and inputs and outputs within the product boundary system shall be as integral as possible. Afterwards, based on the choice principle, site-specific data shall be obtained as much as possible, and secondary data may be adopted when site-specific data are not available, while ensuring that the data required to be collected within the scope of choice criteria are collected in its entirety.

Time representativeness: It is required that the collected site-specific data can represent the real situation of the product system under research, therefore the collected site-specific data shall be the data from 8th, July, 2024 to 18th,July, 2024 in the mass production period.

Geographical representation: It is required that the collected data shall be local data as much as possible, and when local data are not available, the most representative data shall be obtained in the sequence of regional, national, international and global data.

Technical representativeness: It is required to represent the actual level of the process, including the following aspects:

- Process equipment: 2*150m^3 reaction tanks, filter presses thickener, pumps and bag packing machine

- Production scale: The total output of calcium carbonate is 188.7 tons and the total output of post-carbonation slag is 698.2 tons from 8th, July, 2024 to 18th,July, 2024.
- Main raw materials: steel slag, CO_2, water, acid reagent, alkaline chelating agent, packing bags, etc.
- Main energy consumption: outsourced electricity (used in the whole process), outsourced coke oven gas (used in boilers), while steam used for drying products is produced by boilers.
- Main emission sources: energy consumption emissions in the stages of raw material production, transportation and production.

Consistency: The methods and assumptions adopted shall be consistent.

In order to meet the above requirements and ensure the reliability of the calculation results, the data directly provided by manufacturer is the first choice for initial data in the research process. When the original data are unavailable, the secondary data representing the regional average and specific technical conditions shall be selected as much as possible, with preference to the secondary data sourcing from China, and when secondary data from China are unavailable, selection shall be made with data from databases of European ELCD, Swiss Ecoinvent and Industry Data, which offer data that are strictly examined and widely used in international life cycle assessment. The individual data sets and data quality are described in detail in later sections.

As for the uncertainty of the results, Simapro software tools are used to assess the consumption and emission inventory data in the model from five dimensions: ① reliability, ② time representativeness, ③ regional representativeness, ④ technical representativeness and ⑤ integrity, thus obtaining the uncertainty of LCA data results.

3.7. Database and software tools

The software system, Simapro Life Cycle Assessment, version 9.3.0.2 Analyst, is used in this research. The life cycle models of "carbon footprint of calcium carbonate (product)" and "carbon footprint of post-carbonation slag (by-product)" are established in Simapro, and the results of carbon footprint of products are calculated. In addition, sensitivity analysis, uncertainty analysis, process contribution analysis and various data chart processing can be carried out.

Simapro software system supports the whole life cycle process analysis, and has built-in some basic data of Chinese life cycle, European ELCD database, Swiss Ecoinvent database and Industry Data database, etc. The secondary data used in the research are all from the above databases built into the software.

3.8. Environmental Impact Categories, Category Parameters and Characterization Models

As the environmental impact categories, category parameters and characterization models of this life cycle research have been clearly defined by the Company's customers, this research will be carried out completely according to the requirements of customers. Through comparison, it is found that the impact categories, category parameters and characterization models are completely consistent with the requirements of the

Environmental Footprint Proposal of the European Union, so the results of impact assessment in this research can also cover the requirements of the Environmental Footprint Proposal of the European Union.

Table 1 summarizes the environmental impact categories, category parameters and characterization models used in this research. Characterization coefficients are specified separately in each characterization model.

Table 1. Environmental Impact Categories, Parameters and Models

Impact category	Category parameters	Unit	Recommended default LCIA method	Version
Climate change	Radiation intensity as global warming potential (GWP100)	$kgCO_2e$	IPCC 100-year baseline model (based on IPCC 2021)	1.00

Global warming potential (GWP): the GWP value of the product life cycle is calculated with the method proposed in the sixth evaluation report of IPCC (2021). The IPCC (2021) method covers a variety of characteristic substances, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon tetrafluoride (CF_4), hexafluoroethane (C_2F_6), sulfur hexafluoride (SF6), hydrofluoro carbon (HFC), and halon, etc. The method is based on the relative radiation impact value of other greenhouse gases compared with carbon dioxide in the 100-year time range, namely the eigenfactor, which is used to convert the emissions of other greenhouse gases into CO2e. For example, the influence of 1kg methane on global warming in 100 years is equivalent to that of 27.9 kg CO2 emissions, so based on CO2 equivalent (CO_2e), the eigenfactor of methane is 27.9 kg CO2e.

3.9. Normalization and weighting

In this research, normalization and weighting are not required in the evaluation stage of product carbon footprint research.

3.10. Reporting requirements

In this research, the product carbon footprint research report is prepared in the format specified by ISO 14040: 2006, ISO 14044: 2006 and ISO 14067: 2018. The Company mainly requires reporting the product carbon footprint research results, without specifying the corresponding reporting format.

3.11. Appraisal review

This research will be subject to an appraisal review as required by the customers, which will be carried out upon completion of the product carbon footprint research.

4. Life cycle inventory analysis

The data used in this life cycle study can be divided into two categories:

Site-specific data: production record data collected from the Company, which are "Gate-to-Gate" original data.

Background data: "Cradle-to-Gate" life cycle inventory data from China Products Carbon Footprint Factors Database, Simapro built-in Chinese Data, data from European ELCD, Industry Data and Swiss Ecoinvent) databases.

4.1. Site-specific data

Tables 2-6 show the original production site data provided by the company.

Table 2 Process Inventory Data Sheet-Material Input

Material input	Unit	Functional unit Corresponding amount	Description of sampling procedure
Steel slag	Ton	757.8	Belt weighing
Electric energy for CO_2 capture and liquification	P	13699.95	Feed quantity
Acid Reagent	Ton	2.08	Feed quantity
Alkaline chelating agent	Ton	41.51	Feed quantity
Packing bags (for calcium carbonate only)	Ton	0.4725	On-site consumption
Transportation	P	5183.7	Baidu Map

Table 3 Process Inventory Data Sheet-Energy Input

Energy input	Unit	Functional unit Corresponding amount	Description of sampling procedure	Source
Water (recycled)	Ton	931	Water invoice statistics	Water company
Outsourced coke oven gas	m^3	3679.65	Gas invoice statistics	Gas company
Outsourced electric energy	P	94538.70	Electricity invoice statistics	Electric power company

Table 4 Process Inventory Data Sheet-Material and Product Outputs

Material output (Including products)	Unit	Quantity	Description of sampling procedure	Destination
Calcium carbonate (product)	Ton	188.7	Output from Production	Sold to customers
Post-carbonation slag (by-product)	Ton	695.72	Output from Production	Sold to customers

Table 5. Process Inventory Data - Pollutant Emissions

Pollutant output	Unit	Functional unit Corresponding amount	Proportion (%)	Description of calculation program
CO_2 emissions from coke oven gas combustion	$kgCO_2e$	3679.65	100%	LCA

4.2. Background data

From the perspective of LCA principle, much of the initial data collected by the Company belongs to intermediate flow data rather than basic flow data. Thus, it is necessary to find the life cycle inventory data of these materials or energy sources from the database. However, there are often no materials completely corresponding to the actual materials in the database, which can only be replaced by approximate materials. See Table 6 for the search results. This means that the actual process of product life cycle is substituted by other processes, leading to varying degrees of uncertainty in representativeness.

Table 6. Background Data / Secondary Data Sources

Original data name	Data set	Data set source
Steel products	Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S *According to http://baojia.steelcn.cn/, the average price of steel is RMB 4,500/ton, and the purchase price of steel slag is RMB 50/ton. Based on the principle of economic value distribution, the carbon footprint of steel products is 2.26 tCO2e/t, so the carbon footprint of steel slag is calculated to be 0.025 tCO2e/t.	Ecoinvent3
Liquid carbon dioxide	Electricity, low voltage {CN}| market group for | Cut-off, S * According to the supplier Shenhua Baotou Branch, originally, the high-concentration carbon dioxide (of 99.5% concentration) eluted by methanol in the coal-to-olefin process was directly discharged into the air. Shenhua exhaust outlet produces carbon dioxide into liquid carbon dioxide by compression (to 18Bar), and then transports it to GREENORE Baotou Steel Project by tanker. Each ton of liquid carbon dioxide requires 160-170 kWh of electricity for compression (depending on winter and summer).	Ecoinvent3
Water	Tap water {GLO}| market group for | Cut-off, S	Ecoinvent3

Acid Reagent	[redacted]	Ecoinvent3
Alkaline chelating agent	[redacted]	Ecoinvent3
Packaging bag	China Products Carbon Footprint Factors Database	Jiang Kejuan, Wei Xun, Wu Qi. Searching for Carbon Footprint Hidden in Consumer Goods [N]. China Economic Herald, 2010-01-05 (B03).
Coke oven gas production	China Products Carbon Footprint Factors Database	[1] Hou Ping, Wang Hongtao, Zhang Hao, Fan Cidong, Huang Na. GreenHouse Gas Emission Factors of Chinese Power Grids for Organization and Product Carbon Footprint [J]. China Environmental Science, 2012, 32 (06): 961-967; [2] Bai Zongqing, Bai Jin, Li Wen. Comprehensive Utilization of Coke Oven Gas and Analysis of CO_2 Emission Reduction Potential [J]. Clean Coal Technology, 2016, 22 (01): 90-94; [3] General Office of the National Development and Reform Commission. Accounting Methods and Reporting Guidelines for Greenhouse Gas Emissions of Chinese Coal Production Enterprises. 2014
Coke oven gas combustion	China Products Carbon Footprint Factors Database	
Electricity	Electricity, low voltage {CN}| market group for | Cut-off, S	Ecoinvent3
Transport of raw materials	Transport, freight, lorry, unspecified {RoW}| market for transport, freight, lorry, unspecified | Cut-off, S	Ecoinvent3

4.3. Distribution

The multifunctional product system is required to distribute the input and output of the whole system by a reasonable distribution method, and then calculate the life cycle assessment results of products and symbiotic products.

According to ISO 14040:2006, ISO 14044:2006 and ISO 14067:2018, the research shall avoid distribution as much as possible when it is possible to avoid distribution, such as by adopting the system amplification method. When it is impossible to avoid distribution, physical distribution method, such as energy use and solid waste data, is preferred, and when physical distribution method is not feasible, other distribution methods such as economic distribution method and cycle number distribution method are adopted.

In this research, there are two product systems with different functions: calcium carbonate (product) and post-carbonation slag (by-product). Given the quite different economic value of the two products, it is obviously reasonable to adopt the economic value distribution method, thus there is no need for sensitivity analysis on different distribution methods.

In this research, the economic value distribution method is adopted for the two product systems with different functions of calcium carbonate and post-carbonation slag, i.e., according to the price of RMB 1,200/ton of calcium carbonate, and the price of RMB 200/ton of post-carbonation slag, the distribution ratio of all unit processes (except packing) is calculated to be 6:1.

The original data collected by the Company are the total data of material energy consumption and emission during the period from 8th, July, 2024 to 18th,July, 2024, and the distribution of input and output data is based on the economic value ratio of products in this period, as the emissions of various materials and energy consumption are mainly related to the economic value of products in different process stages.

5. Life cycle impact assessment

5.1. LCIA results (product carbon footprint results)

Modeling on Simapro and using the environmental impact categories, category parameters and characterization models specified in Scope of Research 3.8, the product carbon footprint research results of 1 ton of calcium carbonate and 1 ton of post-carbonation slag are calculated as shown in Table 7 and Table 8.

Table 7. Product Carbon Footprint Results per 1 Ton of Calcium Carbonate

Environmental impact type	Unit	1 ton of calcium carbonate Product carbon footprint
Climate change	$kgCO_2e$	70.76

Table 8. Product Carbon Footprint Results per 1 Ton of Post-carbonation slag

Environmental impact type	Unit	1 ton of post-carbonation slag Product carbon footprint
Climate change	$kgCO_2e$	85.12

5.2. Process contribution analysis

Process contribution refers to the cumulative value of the direct contribution of the process and the contributions of all upstream processes.

Table 9 and Table 10 show the product carbon footprint in each stage of the life cycle.

Table 10. Carbon Footprint Contribution of Products at Different Life Cycle Stages (Calcium Carbonate)

Life cycle stage	Carbon footprint (kgCO_2e)	Contribution
Raw material stage	-185.69	-262.42%
Production stage	256.46	362.42%
Total	70.76	11%

Specific GHG emissions and removals	Carbon footprint (kgCO_2e)	Contribution
GHG net emissions and removals from fossil fuel	70.86	100.14%
GHG emissions and removals from biomass	1.38	1.95%
GHG emissions and removals from dLUC	0.05	0.07%
GHG emissions from aircraft transportation	-1.53	-2.16%

Table 11. Carbon Footprint Contribution of Products at Different Life Cycle Stages (Post-carbonation slag)

Life cycle stage	Carbon footprint (kgCO_2e)	Contribution
Raw material stage	42.38	49.47%
Production stage	42.74	40.53%
Total	85.12	100%

Specific GHG emissions and removals	Carbon footprint(kgCO_2e)	Contribution
GHG net emissions and removals from fossil fuel	85.14	100.02%
GHG emissions and removals from biomass	0.23	0.27%
GHG emissions and removals from dLUC	0.01	0.01%
GHG emissions from aircraft transportation	-0.25	-0.29%

The raw materials or processes that contribute a lot are mainly raw materials or energy such as alkaline chelating agent production and electricity consumption in the production stage, and their contribution to the environment exceeds 70-75% of the total.

5.3. Sensitivity analysis of life cycle assessment results

As defined in ISO 14044, “sensitivity analysis” is a systematic procedure for estimating the impact of selected methods and data on research results. In this research, the sensitivity of different LCIA methods is analyzed.

Impact category	Unit	IPCC 2021 GWP 100a V1.00	IPCC 2021 GWP 500a V1.00	Difference
Climate change of calcium carbonate	kgCO_2e	70.86	60.01	15.18%

Impact category	Unit	IPCC 2021 GWP 100a V1.00	IPCC 2021 GWP 500a V1.00	Difference
Climate change of post-carbonation slag	kgCO_2e	85.12	83.34	2.10%

It can be seen that when IPCC 2021 GWP 500a V1.00 is selected as LCIA method, the product carbon footprint of calcium carbonate calculated is 10.75 $kgCO_2e$ less than that of this research, and the product carbon footprint of post-carbonation slag calculated is 1.78 $kgCO_2e$ less than that of this research.

6. Life cycle interpretation

Pursuant to the requirements of ISO 14040:2006, ISO 14044:2006 and ISO 14067:2018 for life cycle interpretation, this stage mainly covers: identifying major problems, checking integrity, sensitivity and consistency, and finally drawing conclusions, illustrating limitations and proposing suggestions.

6.1. Identification of major problems

From each stage of the product life cycle, the largest contribution of the product carbon footprint is attributed to the outsourced electricity in the production stage, followed by the consumption of raw material alkaline chelating agent.

6.2. Inspection of integrity, sensitivity and consistency

6.2.1. Inspection of integrity

The upstream production data in the life cycle data model is sufficiently integral to support the research conclusion without supplement. The data of energy consumption and emission of various resources in the site production process are collected completely. Input and output are chosen strictly according to the prescribed choice criteria, and 100% of the data in the criteria are collected and retained.

6.2.2. Inspection of sensitivity

The purpose of the sensitivity check is to determine the reliability of the final results and conclusions by determining the uncertainty calculated with the data, distribution method and type parameter results. The output of sensitivity check determines whether more extensive and accurate sensitivity analysis is required.

The sensitivity analysis carried out according to the actual research conditions in this research is sufficient and reasonable.

6.2.3. Inspection of consistency

According to the requirements of ISO 14040:2006, ISO 14044:2006 and ISO 14067:2018, consistency check should be done from the following aspects:

a) Is the difference in data quality in the life cycle of the same product system and among different product systems consistent with the purpose and scope of the study?

✓ Consistent, see data quality accounting for details.

b) Are regional and (or) time differences (if any) applied consistently?

✓ It can be seen from the selection of background data sets that the data sets are basically consistent in terms of geographical representativeness and time representativeness. However, there are cases where there is no local data available and other geographical data have to be used.

c) Are consistent distribution rules and system boundaries used by all the production systems?

✓ This research includes two product systems of calcium carbonate and post-carbonation slag with different functions, and the input and output of all unit processes adopt consistent distribution rules, i.e., the economic value-based distribution method.

d) Are the accounting elements of life cycle assessment applied consistent?

✓ In this research, the choice of accounting methods of life cycle assessment mainly takes into account the scientific nature of the methods, the availability of characteristic coefficients and the applicability of the methods, all of which are consistent.

6.2.4. Uncertainty analysis

In the report, the uncertainty analysis of the model inventory data is completed systematically by adopting Simapro built-in quality assessment method, namely EF 3.0 Method (adapted) V1.01/EF 3.0 normalization and weight reconstruction, with a confidence interval of 95%, and based on the data quality indicators identified by the Company during data collection. In this research, Monte Carlo method is used, and the data quality assessment results obtained by 1,000 times are shown in Table 12 and Table 13.

Table 12. Results of Uncertainty Analysis (Calcium Carbonate)

Impact category	Unit	Average	Median	SD	CV	2.5%	97.5%	SEM
GWP100 - biogenic	kg CO2-eq	0.196	0.196	0.000711	0.363 %	0.194	0.197	2.25E-5
GWP100 - fossil	kg CO2-eq	497	497	1.31	0.263 %	495	500	0.0413
GWP100 - land transforma	kg CO2-eq	0.174	0.174	0.000604	0.346 %	0.173	0.176	1.91E-5

Table 13. Results of Uncertainty Analysis (Post-carbonation slag)

Impact category	Unit	Average	Median	SD	CV	2.5%	97.5%	SEM
GWP100 - biogenic	kg CO2-eq	0.0237	0.0236	8.85E-5	0.374 %	0.0235	0.0238	2.8E-6
GWP100 - fossil	kg CO2-eq	56.4	56.4	0.167	0.296 %	56.1	56.8	0.00529
GWP100 - land transforma	kg CO2-eq	0.0211	0.0211	7.56E-5	0.358 %	0.0209	0.0212	2.39E-6

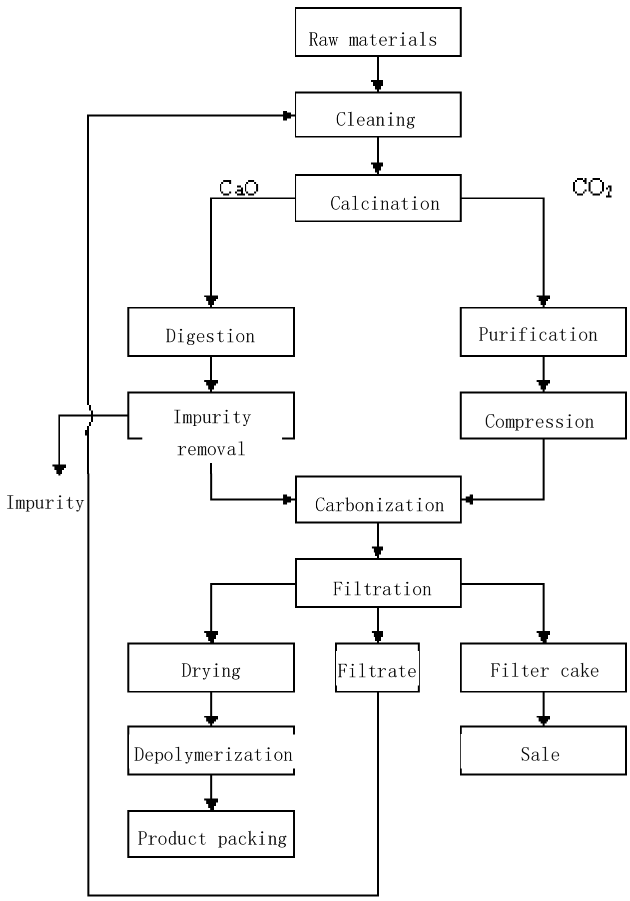
In addition to the above-mentioned data uncertainty, it is generally required to take into account the uncertainty and non-integrity of the model. There are no major defects in these two aspects in this research.

6.3. Comparison with traditional process products

Traditional industrial precipitation of calcium carbonate and production of light calcium carbonate from limestone includes calcination, digestion, carbonization, sorting, drying, crushing and other processes (see Figure 4). Raw limestone shall contain more than 96% calcium carbonate, approximately 1% magnesium salt and less than 0.5% iron and aluminum oxides. Therefore, limestone shall be selected before use and broken to

50 ~ 150mm.The anthracite is mixed with limestone in a ratio of 1:10 ~ 1:12, and then added into a lime kiln, and calcined into lime at 900 ~ 1100℃.Carbon dioxide generated by decomposition reaction is sent to carbonization process after dust removal, washing, drying and compression. Lime is added to the lime pool and digested into lime milk (raw pulp) with water. After filtration for removal of impurities, it is placed in a raw slurry storage tank, then stirred and delivered to a carbonization tower, which is a vertical gas bubbling reactor. The refined carbon dioxide gas is compressed and introduced from the bottom of the carbonization tower and enters the tower through the gas distributor, where the carbonization reaction occurs in contact with the lime milk. The carbonization temperature is 60 ~ 70℃, the carbonization pressure is approximately 0.08 MPa, and the carbonization reaction time varies with the concentration of carbon dioxide, the flow rate and the volume of feed liquid. The end point of carbonization can be determined by the measurement of pH value, and the end point is when the pH is approximately 7.

The carbonized calcium carbonate slurry is cooked slurry, which is put in a cooked slurry pool and then dehydrated by a centrifuge. The dehydrated calcium carbonate contains water between 32% and 42%, which is called wet powder. The wet powder is continuously fed into the rotary drying furnace for drying, and the water content of the material discharged from the drying furnace is less than 0.3%. After cooling, crushing and sieving, the finished product is obtained.



(1) Lime firing: $CaCO_3 \xrightarrow{\Delta} CaO + CO_2 \uparrow - Q$

(2) Digestive reaction: $CaO + H_2O \rightarrow Ca(OH)_2 + Q_2$

(3) Carbonization reaction: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \downarrow + Q_3$

Figure 4 Flow Chart of Calcium Carbonate Production in Traditional Process

The biggest difference in calcium carbonate production between GREENORE's new process and traditional process is that one uses industrial solid waste (steel slag) and carbon dioxide as raw materials, while the other uses high-quality limestone ore as raw materials, and a large amount of carbon dioxide will be emitted in the process of calcining limestone into lime.

According to the following EcoInvent3 data, the carbon footprint per 1 ton of calcium carbonate in the traditional process is 1,720 kgCO_2e (see Figure 5), while the carbon footprint per 1 ton of calcium carbonate in this research project is 70.86 kgCO_2e, which reduces the carbon emission by 1,649.14 kgCO_2e (i.e. 95.88%) compared with the traditional process.

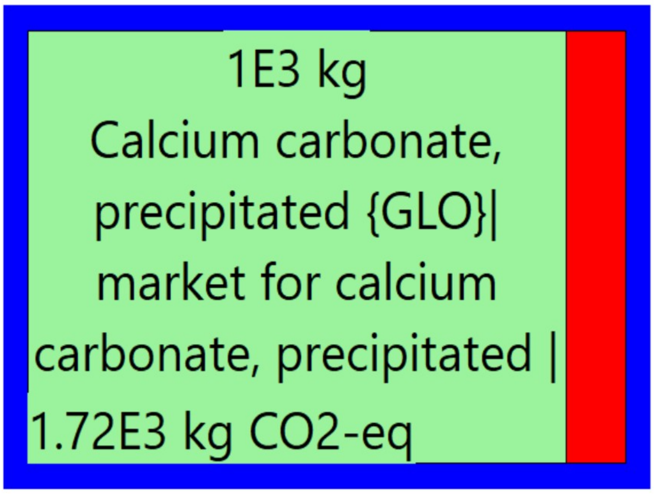


Figure 5 Carbon Footprint Data of Calcium Carbonate in Traditional Process source from Ecoinvent3

With regard to the produced by-product post-carbonation slag, according to the inspection report of mineralized steel slag powder prepared by Shanghai Research Institute of Building Science Co., Ltd. on February 24, 2022 as engaged by the Company (Report No.: CL12F-2200030), the product meets the standard of GB/T 20491-2017 Steel slag powder used for cement and concrete. According to the standard requirements, the test sample is made by mixing steel slag powder and reference cement at the mass ratio of 3: 7, which realizes the same function as 100% cement. According to the calculation, 1 ton of cement mixed with 30% steel slag powder (i.e., post-carbonation slag, the carbon footprint data of post-carbonation slag in this research project is 85.12 kgCO_2e/t) reduces the carbon emissions by 209.36 kgCO_2e/t (i.e., 26.74%) compared with the product carbon footprint of 100% cement (see Figure 6).

Figure 6 Product Carbon Footprint Data of Cement source from Ecoinvent3

6.4. Conclusions and Suggestions

6.4.1. Conclusions and Suggestions

Based upon the provisions of the research purpose, the main purpose of this research is to obtain the product life cycle environmental impact results data, so as to complete the report contents specified by customers, which have been fully satisfied in this regard.

Through this research, it can be seen that the carbon footprint of the Company's products in their life cycle mainly comes from the production of raw material alkaline chelating agent and the electricity consumption in the production stage.

Therefore, it is suggested that the Company give priority to reducing the consumption of outsourced electricity and alkaline chelating agent, improving use efficiency of materials and energy, or purchasing green electricity or using clean energy (such as photovoltaic power) for production.

6.4.2. Limitations

The data provided in this calculation are the data from 8^{th}, July, 2024 to 18^{th},July, 2024 in the mass production period.

The system boundary defined in this research is "Cradle-to-Gate", so the waste cyclic utilization at the use stage and the end of the product life is ignored.

In addition, the performance of product carbon footprint research must rely on LCA software and basic database. At present, there are still certain inadequacies, such as lack of domestic data, mismatch of foreign data, or even no corresponding data at all, which need to be improved in the databases.

7. References

1) ISO 14040:2006 Environmental management - Life cycle assessment-Principles and framework
2) ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines
3) ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification