LIFE CYCLE ASSESSMENT (LCA) OF STONE CLADDING BY NATURAL STONE INSTITUTE (NSI)

Status	Final
Client	Natural Stone Institute
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1 INTRODUCTION

1.1 Opportunity

The Natural Stone Institute is a trade association representing every aspect of the natural stone industry including stone quarriers, processors, and fabricators dedicated to ensuring the highest quality stone products and standards. The association offers a wide array of technical and training resources, professional development opportunities, regulatory advocacy, and networking events [1]. In line with their commitment to quality and sustainability, it was important for NSI to conduct an industry wide Life Cycle Assessment (LCA). The LCA will evaluate the environmental impacts of its stone cladding products in all life cycle stages, from stone quarrying to processing and through to the end of life. The goal of creating this industry wide LCA is to discover the full range of environmental impacts the stone cladding products have and to review these impacts along the product specific environmental declarations in order to identify processes and reduce overall impacts. This project is important to NSI's commitment to provide information to the market to assess the environmental impacts associated with stone cladding products.

To understand the total impact of the product through all life cycle stages, NSI has decided to use a cradle-to-grave approach in conducting the LCA. By including all life cycle stages, more information becomes available for understanding how to reduce impacts.

NSI intends to use the results of the LCA to develop a Sustainable Minds Transparency Report™ (TR), a Type III Environmental Declaration that can be used for communication with and amongst other companies, architects and consumers and can be utilized in whole building LCA tools in conjunction with the LCA background report and Life Cycle Inventory (LCI). This study aims at being compliant to the requirements of ISO 14040/14044, ISO 21930 standards as well as UL's product category rules (PCRs) for Building-Related Products and Services Part A: Life Cycle Assessment Calculation Rules and Report Requirements, version 3.2, and Part B: Cladding Product Systems EPD Requirements, version 2.0 [2] [3].

NSI commissioned Sustainable Minds, an external practitioner, to develop an LCA for three main product categories: stone cladding, stone floßoring, and stone countertops, manufactured by its members. This document is focused on cladding. NSI not only wants to communicate environmental information to the market, but its members also want to be able to compare the industry-wide results to their own product-specific results so that they have guidance for future product improvements and contribute to product optimization credit in the Leadership in Energy and Environmental Design (LEED) building rating system.

This LCA report is specific to stone cladding manufactured by participating NSI members.

1.2 Life Cycle Assessment

This report includes the following phases:

- Goal and Scope
- Inventory Analysis
- Impact Assessment
- Interpretation

A critical review of the LCA and an independent verification of the TR are required for Type III Environmental Declarations. Both are included in this project.

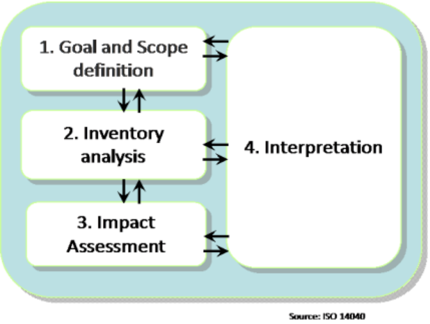

Figure 1. Phases in an LCA

1.3 Status

All information in this report reflects the inputs and outputs provided NSI members at the time it was collected, and best practices were followed by Sustainable Minds and NSI members to transform the inventory into this LCA report.

The data for all stone products were collected from NSI members covering a period of two years, January 2019 to December 2020, unless mentioned otherwise. Data for quarry operations were collected from twelve NSI quarry members covering 36 quarries as listed in Table .

After the stone is extracted from the quarry it goes to a processing facility. Stone processor operations data were collected from six NSI member processors covering 17 facilities as listed in Table 2. Cladding products were produced at all facilities which submitted data but one processor.

NSI resources and other literature data were used to develop estimates or assumptions for other upstream or downstream activities where necessary.

The LCA review and Sustainable Minds Transparency Report / EPD verification was performed by Jack Geibig, President, Ecoform and was determined to be in conformance to ISO 14040/14044 and the aforementioned PCRs.

1.4 Team

This report is based on the work of the project team led by Sarah Gregg on behalf of NSI. Sarah has been assisted by NSI members during the data collection, reporting, and interpretation phases.

Sustainable Minds led the development of the LCA results, report, and TR.

1.5 Structure

The remaining sections of this report are organized as follows:
Chapter 2: Goal and scope
Chapter 3: Inventory analysis
Chapter 4: Impact assessment
Chapter 5: Interpretation
Chapter 6: Sources

This report includes LCA terminology. To assist the reader, special attention has been given to list definitions of important terms used at the end of this report.

2

GOAL AND SCOPE

This chapter explains the goal and scope of the study. The aim of the goal and scope is to define the product under study and the depth and breadth of the analysis.

2.1 Intended Application and Audience

This report intends to describe the application of the LCA methodology to the life cycle of stone cladding manufactured by NSI members. It is intended for both internal and external purposes. The intended audience includes the program operator (Sustainable Minds) and reviewer who will be assessing the LCA for conformance to the PCR, as well as NSIs' internal stakeholders involved in marketing and communications, operations, and design. The information and results presented in this document are intended for business-to-business communication but are not intended to support comparative assertions. The results will be disclosed to the public in a Sustainable Minds Transparency Report / EPD (Type III environmental declaration per ISO 14025).

2.2 Stone Cladding

The Natural Stone Institute is a trade association representing every aspect of the natural stone industry, with history going back to 1894. [1]. NSI members commonly produce stone cladding, stone flooring, and stone countertops.

Stone cladding is applied to a building exterior to separate it from the natural environment and provide an outer layer to the building. It not only provides a control to weather elements but also a durable, aesthetically pleasing building appearance.

As an organization of manufacturers that produce stone cladding, NSI is interested in demonstrating its sustainability leadership. It is also interested in leveraging business value associated with transparent reporting of stone cladding's cradle-to-grave environmental impacts. NSI's stone cladding is made of natural stone and the different stone types included in this study are granite, marble, quartzite, limestone, and sandstone. It is used in commercial, residential, and public sector buildings. Based on the data provided by the participating natural stone processors, limestone and granite represented much of natural stone cladding, 56.72% and 36.18% respectively. Marble cladding covered 0.13% of the market share, while rest (6.97%) were from other natural stones (including quartzite and sandstone).

Natural stone extracted from quarries goes to stone processors where the quarried stone is processed into stone cladding. The participating quarries and their type of stone are listed in Table 1. Participating processors are listed in Table 2.

All processors except Freshwater Stone produced stone cladding.

Table 1. Participant quarries with stone type quarried and quarry locations

Company	Stone type	Quarry location(s)
Coldspring – Milbank Quarry	Granite	Milbank, SD
Coldspring – Mesabi Quarry	Granite	Babbit, MN
Coldspring – Charcoal Quarry	Granite	St. Cloud, MN

Coldspring – Rockville Quarry	Granite	Rockville, MN
Colorado Stone Quarries	Marble	Marble, CO
Delgado Stone Distributors	Quartzite	Sterling, CT
Freshwater Stone	Granite	Frankfort, ME
Independent Limestone Company, LLC	Limestone	Bloomington, IN
Polycor – American Granite Quarries	Granite	American Black Quarry, Elverson, PA; Barre Gray Quarry, Graniteville, VT; Bethel White Quarry, Bethel, VT; Concord Gray Quarry, Concord, NH; Mount Airy Quarry, Mount Airy, NC
Polycor – Canadian Granite Quarries	Granite	Caledonia 4 Quarry, Quebec; Cambrian Black Quarry, Quebec; Kodiak Brown Quarry, Laurentian Rose Quarry, Quebec; Picasso Quarry, Quebec; Saint Henry Black Quarry, Quebec; Saint Sebastien Quarry, Quebec; Stanstead ROA Quarry, Quebec
Polycor – North American Limestone Quarries	Limestone	Adams Quarry, Bloomington, IN; Empire Quarry, Ooloctic, IN; Eureka Quarry, Bedford, IN; Victor Quarry, Bloomington, IN
Polycor – North American Marble Quarries	Marble	Polycor Georgia Marble Quarry, Tate, GA; Saint Clair Quarry, Marble City, OK
Polycor – French Limestone Quarries	Limestone	Massangis Quarry, Massangis, France; Rocherons Quarry, Corgoloin et Comblanchien, France
Quality Stone Corporation	Limestone	Florence, TX
Royal Bedrock Inc.	Dolomite	Ontario, Canada
Russell Stone Products	Sandstone	Grampian, PA
Stony Creek Quarry Corporation	Granite	Branford, CT
Vermont Quarries Corporation	Marble	Danby, VT
Vetter Stone Company	Dolomitic Limestone	Mankato, MN

Table 2. Participant producers/processors with stone type processed and plant locations

Company	Stone type	Plant location(s)
Delgado Stone Distributors	Granite Quartzite	Brookfield, CT
Freshwater Stone	Granite	Orland, ME
Polycor – American Granite Plants	Granite	Mount Airy Plant, Mount Airy, NC; Concord Plant, Concord, NH; Jay White Plant, Jay, ME
Polycor – Canadian Granite Plants	Granite	Beaudoin Plant, Quebec; Precision Plant, Quebec; Rivière-à-Pierre Plant, Quebec; Saint Sebastien Slab Plant, Quebec; Saint Sebastien Tile Plant, Quebec;

Polycor – North American Limestone Plants	Limestone	Empire Plant, Ooloctic, IN; Eureka Plant, Bedford, IN; Victor Plant, Bloomington, IN
Polycor – North American Marble Plant	Marble	Georgia Marble Plant, Tate, GA
Russell Stone Products	Sandstone Limestone	Grampian, PA
Vetter Stone Company	Dolomitic Limestone	Mankato, MN
Continental Cut Stone	Limestone	Florence, TX

2.3 Functional Unit

The results in this report are expressed in terms of a functional unit, as it covers the entire life cycle of the product. Per the PCR, the functional unit is taken as one square meter of installed natural stone cladding for a service life of 75 years [2].

The natural stone cladding product system is an industry-average product, i.e., the product profile represents the weighted average of NSI's natural stone cladding based on NSI's industry average quarrying of stone specific to cladding and also includes industry average production of cladding. The product system in this study also includes the ancillary materials used in the installation of the product – mortar and masonry connectors [3]. NSI members produce only the natural stone component while the installer purchases the mortar and masonry connectors separately. Materials required to meet the functional unit, including the ancillary materials for installation, have been listed in Table 3.

Table 3. Materials required to meet the functional unit

Product	Functional unit	Materials needed to meet functional unit
Natural Stone Cladding	One square meter (m^2) of installed product	Natural stone – 83.28 kg per m^2 Mortar – 4.88 kg per m^2 Masonry connectors – 0.62 kg per m^2 Water [5] – 1 liter per m^2

Associated properties for natural stone cladding are indicated in Table 4 per relevancy, with the appropriate test method. Technical properties are specific to each stone type and a range is provided for each. Please refer to Appendix for technical properties specific to natural stone types.

Table 4. Technical information table for natural stone cladding

Name	Value	Unit	Test Method
Thickness to achieve Functional unit	0.05 (weighted thickness)	m	NA
Density	2507 (weighted density)	kg/m^3	NA
Length[1]	1.52	m	NA
Width	0.66	m	NA

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[1] Dimensions for a typical stone cladding is 5' * 3'

Flexural strength	3.45 – 8.27	MPa	ASTM C880
Modulus of Rupture	2.76 – 13.79	MPa	ASTM C99
Compressive Strength	12.41 – 137.89	MPa	ASTM C170
Thermal conductivity (k-value)	1.26 – 5.38	W/mK	ASTM C518
Thermal resistance (R-value)[2]	0.19 – 0.79	m.K/W	ASTM C518
Liquid water absorption	0.2 – 12.00	% of dry weight	ASTM C97
VOC emissions[3]	0	µg/m3	

2.4 System Boundaries

This section describes the system boundary for the product. The system boundary defines which life cycle stages are included and which are excluded.

This LCA's system boundary include the following life cycle stages:

I. **A1-A5**
  - Raw materials acquisition, transportation, and manufacturing
  - Distribution and installation

II. **B1-B7**
  - Use

III. **C1-C4**
  - Disposal/reuse/recycling

This boundary applies to the modeled product and can be referred to as 'cradle-to-grave', which means that it includes all life cycle stages and modules as identified in the PCR [2]. The life cycle includes all industrial processes from raw material acquisition and pre-processing, production, product distribution, use and maintenance, and end-of-life management. Figure 2 represents the life cycle stages for natural stone cladding included in this LCA study.

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[2] Thermal resistance or R-value depends on the thickness of the material. These values have been calculated for a 1" thick dimension stone sample. https://www.naturalstoneinstitute.org/designprofessionals/technical-bulletins/rvalue/

[3] Natural Stone is inherently non-emitting per LEED credit. https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-data-38

Table 5 lists specific inclusions and exclusions for the system boundary.

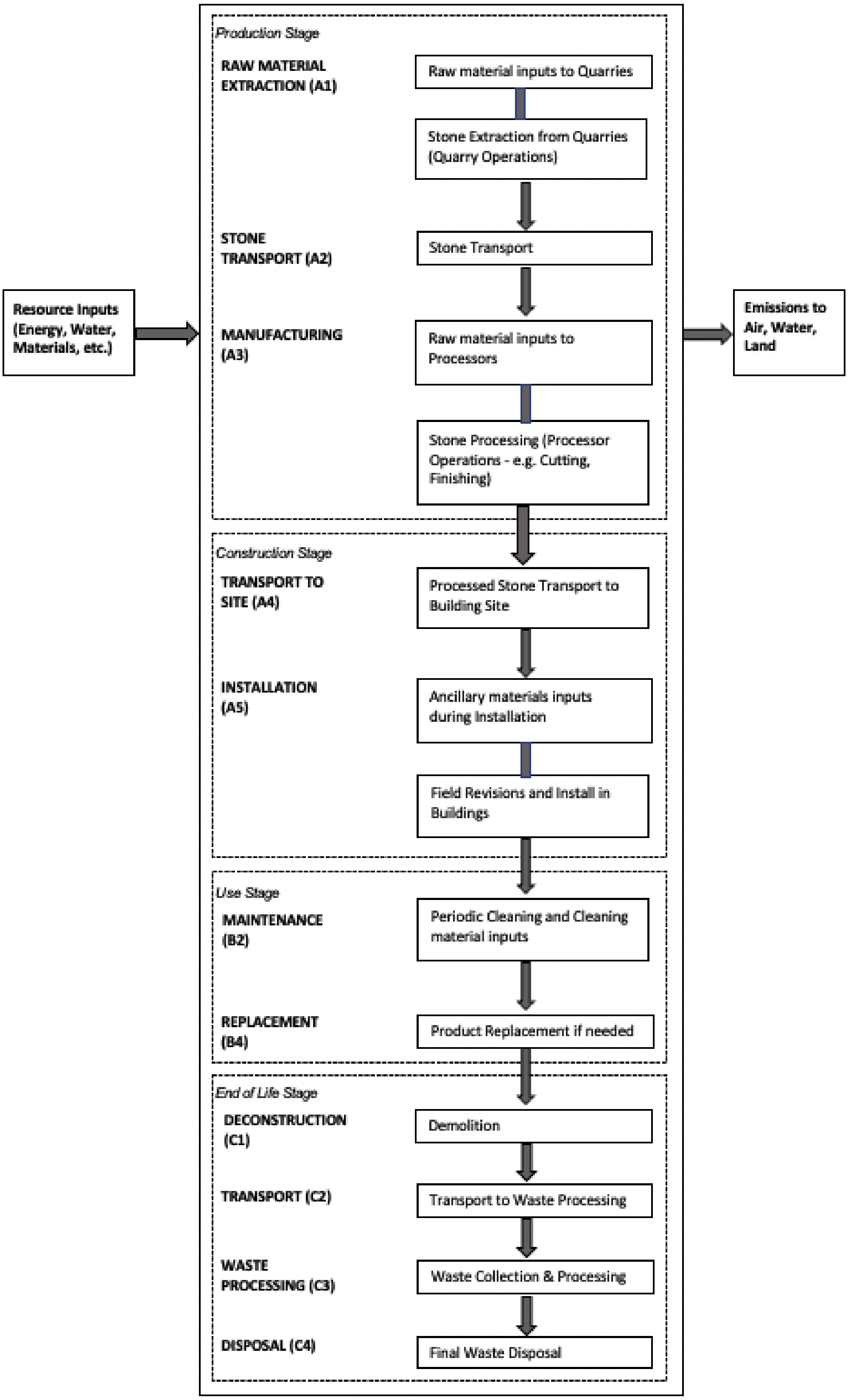

Figure 2. Applied system boundary for natural stone cladding

Table 5. System boundary inclusions and exclusions

Included	Excluded
● Raw material extraction ● Processing of raw materials ● Transport of raw materials ● Stone extraction operations at quarries ● Stone transport from quarries to processors ● Processor operations (cladding production) ● Energy production ● Outbound transportation of stone cladding ● Packaging of final stone cladding ● Installation at building site ● End-of-life, including transportation	● Construction of capital equipment ● Maintenance and operation of support equipment ● Manufacture and transport of packaging materials not associated with final product ● Human labor and employee transport ● Building operational energy and water use not associated with final product ● Overhead energy (e.g., heating, lighting) of manufacturing facility, when separated data were available

2.4.1. A1-A3: Raw materials acquisition, transportation, and manufacturing

Raw materials acquisition and transportation (A1-A2) These stages start when the material is extracted from the nature. This stage includes stone quarrying and ends when the stone reaches the gate of the processor/production facility. A1-A2 stage includes the following processes:

- Extraction and processing of raw material inputs to quarries (A1)
- Transport of raw materials from suppliers to quarries (A1)
- Quarry operations for stone extraction from mines (A1)
- Quarry stone scrap (A1)
- Transport of quarried stone from quarries to stone processors (A2)

Manufacturing (A3) Manufacturing/Production stage starts when the natural stone enter the production site and ends with the final cladding product leaving the production site. This stage includes:

- Extraction and processing of raw material inputs to processing facilities
- All processor operations, manufacturing of stone cladding
- Manufacturing waste (scrap stone and others)

2.4.2. A4-A5: Distribution and installation

Distribution (A4) Product distribution starts with the product leaving the gate of the production facility and ends after the product reaches the customer/building site.

Installation (A5) Product installation occurs after the customer takes possession of the product and before the customer can start using the product. The installation process is considered to be manual (no energy use). This stage includes:

- Any materials specifically required for installation
- Installation waste product and packaging
- Scrap during installation (A default assumption of 5% installation scrap is used)
- Waste transport and treatment as applicable.

2.4.3. B1-B7: Use

The use stage begins when the consumer starts using the product. Stone cladding requires no energy in the Product Use phase (B1).

Maintenance (B2) is related to any activities to maintain the function of the product in its lifetime. Any of the studied stone types is suitable for outdoor cladding and based on discussions with NSI members, we assume the cladding does not require any cleaning during the service period. There is no additional maintenance required specific to any one stone type.

Repair (B3), Replacement (B4), and Refurbishment (B5) are not relevant to stone cladding. Estimated service life of buildings (ESL) is 75 years [2]. A product's RSL depends on the product properties and reference in-use conditions. Due to the nature of natural stone, it is anticipated that stone cladding will last for the lifetime of the building, so the reference service life of the cladding (RSL) is also considered to be 75 years. No replacement will be needed during the entire ESL.

Operational Energy Use (B6) and Operational Water Use (B7) are also not relevant.

2.4.4. C1-C4: Disposal/reuse/recycling

The end-of-life stage begins when the used product is ready for disposal, recycling, reuse, etc. and ends when the product is landfilled, returned to nature, or transformed to be recycled or reused. Processes that occur because of the disposal are also included within the end-of-life stage.

When the stone cladding is done being used it is collected as construction and demolition waste.

The following life cycle stages are used to describe the end-of-life processes.

Deconstruction (C1) This stage includes dismantling/demolition of the product. Since the dismantling is assumed to be manual, there is no energy use during uninstallation.

Transport (C2) This stage includes transport of the product or disassembled product components from building site to final disposition. The waste transport distance is 100 kilometers, as prescribed by the PCR [2].

Waste processing (C3) This stage includes processing required before final disposition.

Disposal (C4) This stage includes final disposition (recycling or reuse). An end-of-life scenario of 31.5% landfilling and 68.5% recycling is considered using US EPA's construction waste disposal scenarios [7].

2.4.5. D: Benefits and loads beyond the system boundary

This study does not account for benefits and loads beyond the system boundary.

3 INVENTORY ANALYSIS

This chapter includes an overview of the obtained data and data quality that has been used in this study. A complete life cycle inventory calculation workbook, which catalogs the flows crossing the system boundary and provides the starting point for life cycle impact assessment, is available to the reviewer but is not appended in this report to protect confidentiality of member companies.

3.1 Data Collection

Data used for this project represents a mix of primary data collected from NSI members on the stone extraction (quarriers), stone processing (processors), and background data from databases available in SimaPro, primarily ecoinvent. Overall, the quality of the data used in this study is considered to be good and representative of the described systems. All appropriate means were employed to obtain the data quality and representativeness as described below.

- **Gate-to-gate:** Data on stone extraction, processing materials, and manufacturing the stone cladding were collected in a consistent manner and level of detail to ensure high quality data. All submitted data were checked for quality multiple times on the plausibility of inputs and outputs. All questions regarding data were resolved with NSI participants. Inventory calculations were developed by an Analyst at Sustainable Minds and subsequently checked by a supporting consultant.

- **Background data:** The model was constructed in SimaPro with consistency in mind. Expert judgment was used in selecting appropriate datasets to model the materials and energy for this study and has been noted in the preceding sections. Detailed database documentation for ecoinvent can be accessed at: https://www.ecoinvent.org/database/database.html.

All primary data were provided by NSI participants and from operations between January 2019 and December 2020 (except Polycor which reported data from January 2020 through December 2021 since data from 2019 was unavailable). Upon receipt, data were cross-checked for completeness and plausibility using mass balance and benchmarking. If gaps, outliers, or other inconsistencies occurred, Sustainable Minds engaged with individual NSI participants to resolve any questions.

3.2 Primary Data

Natural Stone Cladding is produced in several manufacturing steps that involve extraction of stones and its processing. The finished stone cladding is then distributed to construction sites where they are installed, and the packaging is disposed. Stone cladding has a 75-year reference service life which is equal to that of the building. At the end of life, stone cladding is manually removed and disposed.

Data used in this analysis represent the stone cladding production from participating NSI members. Results were then scaled to reflect the functional unit. Primary data was collected from both quarries and processors.

3.2.1. Quarry operations and transport to processors (A1-A2)

This stage includes raw materials inputs to the quarries and the extraction of stone from the quarries which are then transported to processors.

The stones quarried by the participants in this study are granite, marble, quartzite, limestone, sandstone, dolomite, and dolomitic limestone. Stones occur in the form of natural rock masses or layers either on the surface or underground. The process of extraction of suitable stones from those natural rock layers is called quarrying. There are multiple techniques used by participant quarries and those techniques can be divided into two main categories – with and without blasting.

Quarrying of stones with blasting
This method uses explosives to break stones from hard rocks of granites, quartzites, sandstones etc. A small quantity of explosive material (ANFOs - ammonium nitrate/fuel oil) is exploded at a calculated depth within the rocks so as to create cracks and loosen large stone blocks. There are a series of operations including drilling of blast holes, charging of blast holes with explosives, and then firing the shots. Blast holes can be driven either manually or mechanically. The loading or charging of blast holes with explosives needs to be done with great caution. For firing the shots, detonators are used.

Quarrying without blasting
This method does not use any explosive material; blocks of rocks are broken loose from their natural layers using hand tools or special purpose machineries. Quarrying is either done following a wedge method or channeling method. In the wedge method, holes are dug on the rock using manual chisels, hammers, or hammer drills. Steel wedge is inserted in the holes which are struck with the hammer to generate cracks. In the channeling method, channelizers are used which have reciprocating cutting tools and are power driven.

Most of the participant quarries use blasting. They use explosives and power drills. Some quarries use channelizers like power saws and diamond belts. Prior to data collection, Sustainable Minds conducted interviews with participating quarry personnel to identify the relevant raw material inputs, water inputs, energy sources, waste practices and total stone production tracking methods used at the quarries. Based on this Sustainable Minds developed a custom data collection form to collect primary data from each participating quarry. An average inventory per kg of stone quarried for each stone category (granite, limestone, marble, and other natural stone) was developed and later a weighted inventory per kg of stone quarried was generated using the production share of each stone type as shown in Table 7. After that inventory per kg of stone quarrying specific to stone cladding was developed using the market distribution of natural stone cladding by stone type as collected from participant stone processing facilities (56.72% limestone, 36.18% granite, 0.13% marble, and 6.97% other natural stone).

Stone cladding does not contain substances that are identified as hazardous according to standards or regulations of the Resource Conservation and Recovery Act (RCRA), Subtitle C, though the equipment used in quarrying stones generate waste oil, which is considered to be a hazardous waste and is either sent to recycling centers or landfilled according to regulations.

Electricity and fuels used for office activities have been excluded in most cases. Some quarries were not able to separate this data, and, in those cases, it was included in the total. In most quarries, extract blocks and stone that do not meet specifications are crushed and sold as aggregate material. Background energy datasets used for in modeling have been included in section 3.5.1. Fuels used for this crushing has also been excluded from the inventory. The inventory includes transport of waste and hazardous waste to either the landfill centers or recycling centers, which are assumed to be transported 161 km via diesel powered trucks [8]. Excess process material (EPM) is generated in all the quarries in the form of waste blocks, cut-off stones, grouts, fragments, trimmings, and others. These stone pieces are predominantly either kept onsite to fill in older sections of the quarry or sold to others.

The participant quarries extracted about 1.2 million tons of stone during the reporting time frame (2 years), 89% of which was from quarries in the US. The U.S Geological Survey (USGS) estimated that approximately 2.6 million tons of dimension stone was sold or used by US producers in 2020[4]. Using this annual estimate, it can be effectively assumed that the US stone quarries included in this study represent about 21% of the dimension stone produced in US. No data was found for Canada and France. A weighted inventory table was developed as depicted in Table 6 to represent 1 kg of natural stone extracted specific to stone cladding production. Mean, median, and standard deviation observed in the primary quarry data is also tabulated. The proportion of stone types represented in the data are listed in Table 7.

Table 6. Weighted NSI Inventory to quarry 1 kg of natural stone specific to cladding

Resource category	Inputs & outputs	Unit	NSI Total (Participants)	Inventory specific to cladding	Mean	Median	Standard Deviation
Electricity	Electricity	kWh	3.32E+07	2.26E-02	2.82E-02	1.28E-02	3.83E-02
Fuels	Gasoline	liters	7.47E+05	5.93E-04	5.10E-04	4.94E-04	3.24E-04
	Gasoline E10	liters	9.44E+04	7.19E-06	2.76E-04	0.00E+00	6.17E-04
	Diesel (100% petroleum-based)	liters	1.09E+07	8.05E-03	9.84E-03	7.51E-03	9.78E-03
	Biodiesel 5%	liters	2.51E+05	2.52E-04	8.37E-05	0.00E+00	1.87E-04
	Biodiesel 70%	liters	2.91E+05	2.91E-04	9.69E-05	0.00E+00	2.17E-04
	Propane	liters	2.50E+04	7.74E-06	5.47E-05	6.08E-06	1.15E-04
	Natural gas	MJ	1.04E+05	1.04E-04	3.46E-05	0.00E+00	7.73E-05
	Heating oil	liters	3.99E+02	2.99E-07	1.53E-07	0.00E+00	3.41E-07
	Oil	liters	9.08E+03	9.09E-06	3.02E-06	0.00E+00	6.76E-06
Waste Generation	Total EPM generated	kg	2.35E+09	1.78E+00	1.80E+00	1.64E+00	1.86E+00
	EPM kept onsite	kg	1.89E+09	1.47E+00	1.28E+00	1.40E+00	1.35E+00
	EPM sold	kg	4.23E+08	2.81E-01	5.02E-01	3.33E-01	5.77E-01
	EPM hauled offsite	kg	3.67E+07	2.69E-02	1.61E-02	0.00E+00	2.98E-02
	Solid waste to landfill	kg	7.03E+05	4.03E-04	8.60E-04	1.79E-04	1.35E-03
	Waste to recycling	kg	4.36E+05	3.03E-04	9.62E-04	5.30E-05	1.73E-03
	Hazardous waste to landfill	kg	7.01E+04	9.52E-06	1.93E-04	0.00E+00	4.27E-04
	Hazardous waste to recycling	kg	7.17E+04	6.43E-05	3.50E-05	2.84E-05	3.83E-05
Material inputs	ANFO	kg	5.36E+05	5.08E-04	2.23E-04	1.15E-04	3.16E-04
	Blasting caps	kg	1.14E+03	8.59E-07	1.18E-06	2.03E-07	1.67E-06

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[4] USGS surveys ~250 US dimension stone quarries each year, around 40% respond, representing 40-50% of the annual tonnage; remaining tonnage is estimated based on prior years and /or data provided by the Mine Safety and Health Administration.

	Detonating cord	kg	2.33E+04	1.88E-05	2.92E-05	1.38E-05	4.40E-05
	Stainless steel	kg	1.91E+05	1.44E-04	1.11E-04	2.52E-05	1.41E-04
	Wood products	kg	1.19E+06	7.65E-04	1.47E-03	3.40E-04	2.56E-03
	Hydraulic fluid	kg	1.44E+05	1.15E-04	2.95E-04	1.02E-04	4.82E-04
	Lubricant	kg	1.27E+05	1.04E-04	7.08E-05	9.42E-05	4.94E-05
	Motor oil	kg	1.84E+05	1.21E-04	8.14E-04	1.32E-04	1.59E-03
	Tires	kg	1.92E+05	1.59E-04	1.83E-04	1.41E-04	2.03E-04
	Antifreeze	kg	5.54E+05	4.14E-04	2.78E-04	1.80E-05	4.45E-04
	Diamond belts/wires/blades	kg	6.66E+04	1.85E-05	1.48E-04	7.06E-06	3.12E-04
	Carbide tooling on chains	kg	1.06E+03	1.05E-06	4.07E-07	0.00E+00	7.54E-07
Waste transport	Diesel powered truck	tkm	2.06E+05	1.26E-04	3.30E-04	2.31E-04	3.34E-04

Table 7. Production mass share of quarried stone

Stone category	Quarry production share (by mass)
Limestone	49.0%
Granite	42.6%
Marble	5.6%
Quartzite	2.0%
Sandstone	0.8%

Stone blocks extracted from quarries are then transported to the processing plants. Some companies have quarries and processing plants located next to each other, which will require insignificant stone transport distance, while for some the plants are located farther from each other. Some participant quarries have provided primary data on this stone transport, and the weighted transport distance was 65 km. For the quarries who had no primary information, we have taken a conservative stone transport distance of 100 km via truck & trailer.

3.2.2. Manufacturing (A3) – Processor operations

Natural stone processing plants process the quarried stone as needed for end product applications, including countertop fabrication, cladding, flooring, and others. For cladding production, stone blocks go through a series of block saws and saw slabs, and later to bridge saws to complete cut-to-size pieces and profiling. All products are checked for quality control and then stacked on pallets. Stone pallets are stored in a yard until shipped to the building site.

The processors use various energy sources to power the operations. Diesel fuel is used to power the front-end loaders, portable generators, haul trucks, skid steers, and sawing equipment. Gasoline is used mainly for pickup trucks and cars. The plant is powered via grid electricity and uses various fuels. Major consumable materials used in the plants include saw blades, diamond-tipped cutting tools, lumber for pallets, and banding. Packaging materials used include wooden pallets, styrofoam, banding, and shrink-wrap.

EPM is generated in all the processors in the form of waste blocks, cut-off stones, grouts, fragments, trimmings, and others. Much of the generated EPM is reclaimed or recycled. Methods for recycling include filling on premises and processing/crushing into aggregate.

The inventory also includes transport of waste and hazardous waste generated in processors to either the landfill centers or recycling centers, which is assumed to be 161 km via diesel powered trucks [8]. Electricity and fuels used for office activities; fuels used from crushing of coproducts in the processor plants have been excluded when separated data were available.

The participant processors processed about 1.1 million tons of stone during the reporting time frame (2 years), 94% of which was processed in the US, and the rest in Canada. U.S Geological Survey (USGS) estimated that approximately 2.6 million tons of dimension stone was sold or used by US producers in 2020[5]. Using this annual estimate, it can be effectively assumed that the US stone processors included in this study represent about 20% of the dimension stone produced in US. No data was found for Canada.

An average inventory per m^2 of stone processed for each stone category (granite, limestone, marble, and other natural stone) was developed and later a weighted inventory per m^2 of stone processed was generated using the production share of each stone type as shown in Table 7. After that, inventory per m^2 of stone processing specific to cladding was developed was developed using the market distribution of natural stone cladding by stone type as collected from participant stone processing facilities (56.72% limestone, 36.18% granite, 0.13% marble, and 6.97% other natural stone). It was suggested by participant processors that the energy consumed for processing cladding stone is similar to the average energy consumed to process various stone products. Primary data were collected from the participating NSI processors for the defined time frame and a weighted inventory to produce 1 m^2 of cladding stone was developed as represented in Table 8. Mean, median, and standard deviation observed in the primary processor data is also tabulated.

Table 8. Weighted NSI inventory to process 1 m^2 of end stone specific to cladding

Resource category	Inputs & outputs	Unit	NSI Total (Participants)	Inventory specific to cladding	Mean	Median	Standard Deviation
Electricity	Electricity	kWh	3.94E+07	5.23E-02	2.91E+01	2.98E+01	2.03E+01
Fuels	Gasoline	liters	9.33E+04	7.11E-01	1.38E-01	6.51E-02	1.92E-01
	Diesel	liters	1.20E+06	1.84E+00	4.52E-01	4.60E-01	3.86E-01
	Propane	liters	1.54E+06	1.20E+01	1.30E+00	2.85E-01	2.21E+00
	Natural gas	MJ	2.39E+07	7.37E-02	7.50E+00	5.16E+00	9.35E+00
	Heating oil	liters	4.49E+04	1.15E-03	5.00E-02	0.00E+00	1.00E-01
	Oil	liters	2.75E+03	3.53E+00	6.59E-04	2.78E-04	9.83E-04
Material inputs	Wood products	kg	4.52E+06	1.00E-02	3.03E+00	2.64E+00	2.16E+00
	steel banding	kg	2.92E+04	4.20E-02	6.23E-03	1.30E-03	1.08E-02
	plastic banding	kg	9.96E+04	3.88E-06	1.22E-01	5.33E-02	1.81E-01
	polyurethane	kg	8.25E+01	3.06E-04	1.95E-04	1.18E-06	3.88E-04
	Packaging material	kg	8.97E+02	5.81E-02	3.42E-04	2.95E-04	3.22E-04
	Diamond blades/wires	kg	9.67E+04	5.23E-02	3.88E-02	4.82E-03	7.07E-02
	Diamond tooling	kg	2.05E+03	6.53E-04	4.55E-04	3.91E-04	5.32E-04

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[5] USGS surveys ~250 US dimension stone quarries each year, around 40% respond, representing 40-50% of the annual tonnage; remaining tonnage is estimated based on prior years and /or data provided by the Mine Safety and Health Administration.

	Carbide tooling	kg	2.19E+02	4.90E-05	2.13E-04	3.72E-05	3.77E-04
	Steel with less than 1 year life	kg	5.25E+04	8.18E-03	4.70E-03	4.85E-04	8.76E-03
	Cardboard	kg	4.77E+03	1.36E-03	1.03E-03	3.89E-04	1.58E-03
	Foam packaging	kg	6.40E+03	2.12E-03	8.48E-04	0.00E+00	1.70E-03
Waste Generation	Waste to landfill	kg	1.15E+06	4.00E-01	2.56E+00	6.16E-01	4.25E+00
	Recycling	kg	1.09E+05	4.56E-02	5.37E-02	4.92E-02	6.24E-02
	Hazardous (to recycler)	kg	6.22E+04	5.65E-02	4.38E-02	2.47E-02	5.64E-02
	Hazardous (to landfill)	kg	9.07E+02	3.01E-04	1.20E-04	0.00E+00	2.40E-04
Waste transport	Diesel powered truck	tkm	2.13E+05	8.08E-02	4.28E-01	1.19E-01	6.89E-01

Prior to data collection, Sustainable Minds interviewed participating stone processing facilities to identify relevant materials, energy sources, water sources, waste practices, and production tracking and developed a custom data collection form for stone processors to report data. Net production units of each stone type including the percentage of each stone type going to end stone applications (cladding, flooring, countertops, slabs, blanks, and others) was collected. This information is shown in Table 9.

Thickness breakdown information was provided by facilities representing 67% of production. Thickness data were not by tracked by other producers. For those producers without thickness data, average thickness of stone production was calculated using their stone production volume (primary data collected) and stone production area (primary data collected on production mass and kg per m^2 for stone type used). Table 10 lists the stone mass per m^2 and weighted density calculation of stone produced from processors for different stone types. The difference between the input stone and produced stone mass per m^2 of stone processed represents the scrap stone generated during cladding manufacturing. Weighted average thickness of stone produced was 51.066 mm (2.010 inches).

Table 9. Share of end applications for produced stone

End stone application	Produced stone share
Cladding	43.1%
Flooring	26.9%
Countertops	4.2%
Others	25.8%

Table 10. Stone mass per m^2 and final density

Stone category	Stone input share	Input stone kg per m^2 of cladding	Stone production share	Produced stone kg per m^2 of cladding	Weighted Density (kg/m^3)
Limestone	44.6%	133	42.6%	82	2,339
Granite	48.2%	181	50.8%	124	2,653
Marble	2.0%	190	2.1%	130	2,699
Quartzite	2.0%	139	1.9%	83	2,339
Sandstone	3.3%	182	2.7%	96	2,403
Weighted avg. (NSI)		*159*		*104*	*2,508*

Weighted avg. (Cladding)		*151*		*83*	

3.2.3. Distribution (A4)

Distribution refers to the transport of the produced stone from the processing plants to the building sites for installation. Partial primary data on final shipping distance were provided by the processors which was scaled to represent all production units for each processor. Finally, weighted transport parameter was calculated to represent the NSI industry. This information is listed in table below.

Table 11. Distribution parameters for natural stone cladding, per functional unit

Name	Value	Unit
Fuel type	Diesel	
Liters of fuel[6]	0.36	l/100km
Vehicle type	Lorry, 16-32 ton	
Transport distance	301	km (weighted avg)
Capacity utilization (including empty runs, mass based)	100	%
Gross density of products transported	2,508	kg/m^3 (weighted avg)
Capacity utilization volume factor	1	

3.3 Secondary Data

For life cycle stages after the distribution of natural stone cladding, in the absence of primary data, secondary data sources are used to develop assumptions and generate the results.

3.3.1. Installation (A5)

Installation refers to the installation of stone cladding in the buildings. Even though cladding fabrication (cutting and finishing to required size) is done at the processing plants and is typically delivered to the job site ready for installation, minor changes may be necessary to accommodate design revisions. Based on discussion with NSI participants, the PCR-suggested scrap rate of 5% during cladding installation was used.

The amount of ancillary materials depend largely on the building design, but most stone cladding installations incorporate anchors and mortar, used either as a masonry bed or to fill veneer cavities. In the absence of primary data, the amount of ancillary materials (mortar and masonry connectors) required per m^2 of stone cladding installation were taken from a published Natural Stone Cladding EPD [4]. Installation of 1 m^2 of stone cladding using cement mortar will also require 1 liter of water [5]. Installation is considered to be manual. Waste generated in this stage includes stone scrap and stone packaging waste. For stone scrap, US EPA's end of life scenarios for construction waste is used (31.5% landfilled) and for packaging waste, a landfilling rate of 37% is used based on US EPA's data for containers and packaging [9]. Regardless of disposal

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[6] Total liters of diesel consumed per tkm was calculated from the ecoinvent dataset, which was later scaled to meet the functional unit

scenarios, waste transport distance for both stone scrap and packaging waste is taken to be 100 km.

Table 12 provides the ancillaries and energy use required for the installation of natural stone cladding.

Table 12. Information during the installation of natural stone cladding, per functional unit

Name	Value	Unit
Installation scrap rate assumed	5	%
Ancillary materials Mortar Masonry connectors	 4.88 0.62	 kg kg
Net freshwater consumption	0.001	m^3
Electricity consumption	Not necessary	
Product loss per functional unit (scrap)	4.16	kg
Waste materials at the construction site before waste processing, generated by product installation (both stone scrap and packaging waste)	6.17	kg
Output materials resulting from on-site waste processing	0	kg
Mass of packaging waste specified by type Plastic packaging Cardboard Wood	 0.003 0.002 2.005	kg
Biogenic carbon contained in packaging	3.68	kg CO_2
Direct emissions to ambient air, soil, and water	0	kg
VOC emissions[7]	0	μg/m^3

3.3.2. Use (B1-B7)

This stage is related to any activities to ensure the functionality of stone cladding in its lifetime. Estimated service life for building is 75 years and due to the nature of natural stone, it is anticipated that the stone cladding products will last for the lifetime of the building. Reference service life (RSL) thus meets ESL of 75 years and cladding will need no replacements during its service life.

With suggestions from NSI team, it was assumed that under normal operating conditions, stone cladding will not require any cleaning. Stone cladding also does not require any repair, replacement, or refurbishment during its entire service life. It also does not consume energy during its operation. Table 13 provides an overview of use phase scenarios and parameters for natural stone cladding.

Table 13. Information on maintenance of natural stone cladding

Name	Value	Unit
Reference service life (RSL)	75	years
Estimated service life (ESL)	75	years
Maintenance process information	None	-
Maintenance cycle	None	Cycles/RSL
Energy input during maintenance	Not necessary	

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[7] Natural stone cladding is inherently non-emitting.

3.3.3. Deconstruction (C1)

Per PCR, manual deconstruction is considered for the stone cladding. There will be no operational energy use and thus, no impacts associated with the deconstruction work after the service life ends.

3.3.4. End of Life Transport (C2)

Deconstructed stone cladding is then shipped to the end-of-life disposal centers. We assumed that the transport for final cladding disposal is 100 km as prescribed by the PCR [2]

3.3.5. Waste Processing (C3)

We assume that no waste processing is required before either the landfill or the recycling process.

3.3.6. Final Disposal (C4)

Based on US EPA's data on construction end waste disposal scenarios, it was assumed that 31.5% of stone cladding will be landfilled for inert disposal, while the rest will be recycled for various purposes [7].

Table 14 provides an overview of the end-of-life scenarios and parameters for natural stone cladding from NSI.

Table 14. Information on end-of-life scenarios for natural stone cladding

Name		Value	Unit
Collection process	Collected separately	0	kg
	Collected with mixed construction waste	88.78	kg
Recovery	Reuse	0	kg
	Recycling (68.5%)	60.82	kg
	Landfill (31.5%)	27.97	kg
Waste transport		100	km
Final Disposal		27.97	kg
Removal of biogenic carbon (excluding packaging)		0	kg CO_2

3.4 Data selection and quality

Data requirements provide guidelines for data quality in the LCA and are important to ensure data quality is consistently tracked. Data quality considerations include precision, completeness, and representativeness.

Precision describes the variability of the inventory data. This study applies a combination of primary data, estimates and assumptions for some inventory inputs. We apply secondary data for non-stone consumable and ancillary materials. Since the inputs/outputs for both quarries and producers were directly measured by the NSI participants, we consider inventory data to have good precision.

Completeness is a measure of the flows (mass, energy, emissions) that are included in the study in relation to the total flows covered in the scope of the product life cycle. We developed separate data collection forms for quarries and producers and worked extensively with the individual participants to obtain a comprehensive set of primary data associated with the manufacturing processes. We considered the dataset complete based on our understanding of the manufacturing site and a review with key stakeholders on the NSI team. Even though we observe cut-off criteria consistent with those prescribed in the PCR, no known flows are deliberately excluded from this analysis other than those defined to be outside the system boundary as stated in

Table 5.

Representativeness describes the ability of the data to reflect the system in question. We measure representativeness with the time, technology, and geographic coverage of the data. An evaluation of the data quality about these requirements is provided in the interpretation chapter of this report.

Time coverage. Time coverage describes the age of the inventory data, and the period of time over which data is collected. All of the participants provided primary data for a time period of January, 2019 to December, 2020 except for Polycor, which provided data for January, 2020 to December, 2021 because of data unavailability for 2019. This time period of 2 years will be able to represent typical operations of quarry and producers. Background data for upstream and downstream processes (i.e., raw materials, energy resources, transportation, and ancillary materials) were obtained from the ecoinvent database and U.S. ecoinvent (US-EI) database.

Technology coverage. Data were collected for participant NSI quarries and producers in covering a range of technologies as described earlier in this document. Incorporation of this range provides a representative depiction of the industry average.

Geographical coverage. Data were collected from participant quarries and producers mainly operating in North America (mainly the US and Canada). Quarries in France are responsible for 3% of the total quarried stone included in this study. As such, the geographical coverage for this study is based on North American conditions. Whenever geographically relevant background data were not readily available, other geographies were used as proxies. Following production, stone cladding is shipped for use within North America. Installation, use and end-of-life impact were modeled using background data that represents average conditions.

3.5 Background data

This section details background datasets used in modeling for stone cladding. Each table lists dataset purpose, name, source, reference year, and location. All datasets used are market datasets representing unit processes. Market based datasets already include the transportation of the material from average producers to average consumers.

3.5.1. Fuels and energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from databases in SimaPro. For fuels, specific US based datasets for specific fuels were used if available. In cases where fuel mixes were specified (e.g., fossil and biofuel mixes), manual datasets were created to reflect the fuel ratios. Manual electricity datasets were developed to represent average NSI quarry and NSI producer based on the production share of participants. For quarries within US, specific e-GRID regions were identified. Table 15 shows the most relevant LCI datasets used in modeling the product systems.

Table 15. Key energy datasets used in inventory analysis

Energy source	Dataset used	Primary source	Reference year	Geography
Electricity - Quarry	Manual dataset based on production share: - e-grid datasets for US based quarries, - Canadian average electricity dataset for Canada based quarries*, - France average electricity dataset for France based quarries*	US -EI 2.2, Ecoinvent v3 (for Canada & France)	2018	US (includes different e-grid regions), Canada, France
Electricity – Producer	Manual dataset based on production share: - e-grid datasets for US based quarries, - Canadian average electricity dataset for Canada based quarries*	US -EI 2.2, Ecoinvent v3 (for Canada)	2018	US (includes different e-grid regions), Canada
Gasoline	Gasoline, combusted in equipment NREL	US -EI 2.2	2018	US
Diesel (100% petroleum based)	Diesel, combusted in industrial equipment NREL	US -EI 2.2	2018	US
Propane	LPG combustion, at industrial furnace	US -EI 2.2	2018	US
Natural Gas	Natural gas, combusted in industrial equipment NREL	US -EI 2.2	2018	North America
Heating Oil	Heat, light fuel oil, at industrial furnace	US -EI 2.2	2018	US
Oil	Heat, heavy fuel oil, at industrial furnace	US -EI 2.2	2018	US
Gasoline E10	Manual dataset with 90% petroleum + 10% corn ethanol*	US -EI 2.2	2018	US
Gasoline E85	Manual dataset with 15% petroleum + 85% corn ethanol*	US -EI 2.2	2018	US
Biodiesel 5%	Manual dataset with 95% diesel + 5% soybean biodiesel*	US -EI 2.2	2018	US
Biodiesel 70%	Manual dataset with 30% diesel + 70% soybean biodiesel*	US -EI 2.2	2018	US

*represents proxy datasets used.

3.5.2. Raw materials extraction and transport

Datasets for all upstream and downstream raw materials were obtained from the ecoinvent v3.8 database. Table 16 shows the LCI datasets used in modeling the main raw materials used in either of quarries, producers or during installation/use phase.

Table 16. Material datasets used in inventory analysis

Materials and water	Dataset used	Primary source	Reference year	Geography
Ammonium nitrate (95.5% in ANFO)	Ammonium nitrate*	Ecoinvent v3	2020	North America
Blasting caps	Explosive, tovex*	Ecoinvent v3	2021	Global
Detonating cord	70% explosive tovex* + 30% plastic tube (polyethylene)	Ecoinvent v3	2021	Global
Stainless steel Razor blades	Steel, chromium steel 18/8	Ecoinvent v3	2020	Global
Wood products	Wood pellet	Ecoinvent v3	2020	Rest of World (non-Europe)
Rubber Caulk	Synthetic rubber	Ecoinvent v3	2021	Global

Hydraulic fluid	White mineral oil	US-EI 2.2	2018	US
Lubricant Motor oil	Lubricating oil	Ecoinvent v3	2021	Global
Antifreeze	Ethylene glycol	Ecoinvent v3	2021	Global
Polyurethane Foam packaging	Polyurethane, flexible foam	Ecoinvent v3	2021	Rest of World (non-Europe)
Diamond	Boron carbide*	Ecoinvent v3	2021	Global
Carbide tooling	Silicon carbide*	Ecoinvent v3	2021	Global
Plastic Tape	Polypropylene, granulate	Ecoinvent v3	2021	Global
Epoxy & resin	Epoxy resin, liquid	Ecoinvent v3	2021	Rest of World (non-Europe)
Cardboard	Corrugated board box	Ecoinvent v3	2018	Rest of World (non-Europe)
Adhesive	Polyurethane adhesive	Ecoinvent v3	2020	Global
Fiber glass rodding	Glass fiber reinforced plastic, polyester resin	Ecoinvent v3	2021	Global
Sandpaper Garnet	Sodium silicate, solid	Ecoinvent v3	2021	Europe
Paper rag	Kraft paper*	Ecoinvent v3	2020	Rest of World (non-Europe)
Cloth rag	Fibre, cotton	Ecoinvent v3	2021	Global
Lacquer thinner	White Spirit*	Ecoinvent v3	2021	Global
Masonry connectors	Steel hot-deep galvanized coil	Industry data 2.0	2019	Global
Denatured alcohol	Ethanol from ethylene*	Ecoinvent v3	2021	Rest of World (non-Europe)
Acrylics	Acrylic binder	US-EI 2.2	2018	US
Flocculant (water purifier)	Aluminium sulphate, powder*	US-EI 2.2	2018	US
Well water	Well water	Input from nature	N/A	US
Municipal water	Tap water, at user	Ecoinvent v3	2018	US
Surface water	River water	Input from nature	N/A	US
Mortar	Manual dataset	TCNA's Industry wide EPD for Mortar [10]	2016	North America

*represents proxy datasets used.

3.5.3. Transportation

The following data sets were used to represent typical transport modes.

Table 17. Transportation datasets used in inventory analysis

Transportation	**Dataset name**	**Source**	**Year of publication**	**Geography**
Transport of stone from quarriers to producers and then to building sites	Transport, lorry, lorry, >32 metric ton, EURO5	US -EI 2.2	2018	US
Transport of waste/scrap to end of life scenarios	Transport, lorry, lorry 16-32 metric ton, EURO5	US -EI 2.2	2018	US

3.5.4. Disposal

Disposal processes were also obtained from ecoinvent database to represent disposal scenarios in US. Table 18 presents the relevant disposal datasets used in the model.

Table 18. Disposal datasets used in inventory analysis

Material & Disposition	**Dataset name**	**Source**	**Year of publication**	**Geography**

Septic water output	Sewage to wastewater treatment	US EI-2.2	2019	US
Solid waste to landfill	Disposal, inert waste to inert materials landfill	US EI-2.2	2019	US
Hazardous waste to landfill	Disposal, hazardous waste, for underground deposit	US EI-2.2	2019	US

3.5.5. Emissions to air, water, and soil

NSI participants reported no direct emissions to air, water, or soil.

3.6 Limitations

A life cycle assessment of a product system is broad and complex, and inherently requires assumptions and simplifications. The following limitations of the study should be recognized:

- This study is based on the weighted average values, so as to effectively represent the industry-wide operations but data of each of the quarries and producers vary.
- Some of the quarry participants have provided partial primary data on materials consumed. For gaps in materials data, an average from other facilities was assumed. Total material consumed across all participants was normalized with the total production mass to generate material consumption per production mass of stone (no distinction made between stone types). This was later scaled with the total stone quarried to complete material inputs for participant quarries with partial data.
- As it was very difficult to collect primary transportation data for purchased materials for each participant, market-based datasets are used, which inherently includes the average transport distance from suppliers to consumers. Actual transport data will vary based on supplier location for each participant and for each material.
- Quarrying data has been grouped together based on stone types. All natural stone other than granite, limestone, and marble have been grouped together as other natural stone despite differences in the quarrying techniques.
- Quarrying and processing inventory specific to cladding are generated using the production share of cladding by stone types among participant processors.
- For the quarries with no primary data on stone transport to processors, we have taken a conservative stone transport distance of 100 km via truck & trailer, higher than the weighted transport distance from the primary data. The actual distance varies a lot.
- Energy consumed for cladding stone processing is assumed to be similar to the average energy consumed for stone processing of all stone products. A sensitivity analysis is included in this study to see the robustness of this assumption.
- Generic data sets used for material inputs, transport, and waste processing are considered good quality, but actual impacts from material suppliers, transport carriers, and local waste processing may vary.
- The impact assessment methodology categories do not represent all possible environmental impact categories.

- Characterization factors used within the impact assessment methodology may contain varying levels of uncertainty.
- LCA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

3.7 Criteria for the exclusion of inputs and outputs

All energy and material flow data available were included in the model and comply with the PCR cut-off criteria. No known flows were excluded from the analysis.

- The cut-off criteria on a unit process level can be summarized as follows: All inputs and outputs to a (unit) process shall be included in the calculation of the pre-set parameters results, for which data are available. Data gaps shall be filled by conservative assumptions with average, generic or proxy data. Any assumptions for such choices shall be documented.

- Particular care should be taken to include material and energy flows that are known or suspected to release substances into the air, water or soil in quantities that contribute significantly to any of the pre-set indicators of this document. In cases of insufficient input data or data gaps for a unit process, the cut-off criteria shall be 1 % of renewable primary resource (energy), 1 % nonrenewable primary resource (energy) usage, 1 % of the total mass input of that unit process and 1 % of environmental impacts. The total of neglected input flows per module shall be a maximum of 5 % of energy usage, mass and environmental impacts. When assumptions are used in combination with plausibility considerations and expert judgment to demonstrate compliance with these criteria, the assumptions shall be conservative.

- All substances with hazardous and toxic properties that can be of concern for human health and/or the environment shall be identified and declared according to normative requirements in standards or regulation applicable in the market for which the EPD is valid, even though the given process unit is under the cut-off criterion of 1 % of the total mass.

In this report, no known flows are deliberately excluded; therefore, these criteria have been met.

3.8 Allocation

Whenever a system boundary is crossed, environmental inputs and outputs must be assigned to the different products. Where multi-inputs or multi-outputs are considered, the same applies. The PCR prescribes where and how allocation occurs in the modeling of the LCA.

In this LCA, quarries provided data needed to quarry stone, producers provided data needed to produce stone, and based on the share of produced stone used in stone flooring, an inventory specific to stone cladding was developed.

No co-product allocation was necessary in the quarry operations since each quarry produces a single stone type. The quarry inputs and outputs were divided evenly among the quarried stone by mass.

Different stone products go through slightly different processing steps. Processor inputs and outputs were evenly distributed between the stone products (cladding, countertops, and flooring) based on their production area share as shown in Table 9. Countertop stones receive more polishing than other product types and therefore more resources were allocated (10% more than the average, based on the best judgement of industry experts) to the countertop production. However, since the share of countertop was small (<5%), the increase in resource allocation to other stone products (cladding and flooring) was insignificant (<1%) and the resource allocation for these products were not adjusted.

3.9 Software and database

The LCA model was created using SimaPro Developer 9.4. Ecoinvent and other databases listed in section 3.4 provide the life cycle inventory data of the raw materials and processes for modeling the products.

3.10 Critical review

This is a supporting LCA report for NSI Stone Cladding Transparency Report which will be evaluated for conformance to the PCRs according to ISO 14025 [10] and the ISO 14040/14044 standards [11].

4 IMPACT ASSESSMENT METHODS

4.1 Impact assessment

The environmental indicators as required by the PCR are included as well as other indicators required to derive the SM2013 single score [12] (see Table 19). The impact indicators are derived using the 100-year time horizon[8] factors, where relevant, as defined by TRACI 2.1 classification and characterization [13]. Long-term emissions (> 100 years) are not taken into consideration in the impact estimate. USEtox indicators[9] are used to evaluate toxicity.

Table 19. Selected impact categories and units

Impact category	Unit	Description
Acidification	kg SO_2 eq (sulphur dioxide)	Acidification processes increase the acidity of water and soil systems and causes damage to lakes, streams, rivers and various plants and animals as well as building materials, paints and other human-built structures.
Ecotoxicity	CTUe	Ecotoxicity causes negative impacts to ecological receptors and, indirectly, to human receptors through the impacts to the ecosystem.
Eutrophication	kg N eq (nitrogen)	Eutrophication is the enrichment of an aquatic ecosystem with nutrients (nitrates and phosphates) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass.
Global warming	kg CO_2 eq (carbon dioxide)	Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere.
Ozone depletion	kg CFC-11 eq	Ozone depletion is the reduction of ozone in the stratosphere caused by the release of ozone depleting chemicals.
Carcinogenics	CTUh	Carcinogens have the potential to form cancers in humans.
Non-carcinogenics	CTUh	Non-Carcinogens have the potential to causes non-cancerous adverse impacts to human health.
Respiratory effects	kg $PM_{2.5}$ eq (fine particulates)	Particulate matter concentrations have a strong influence on chronic and acute respiratory symptoms and mortality rates.
Smog	kg O_3 eq (ozone)	Smog formation (photochemical oxidant formation) is the formation of ozone molecules in the troposphere by complex chemical reactions.
Fossil fuel depletion	MJ surplus	Fossil fuel depletion is the surplus energy to extract minerals and fossil fuels.

With respect to global warming potential, biogenic carbon is included in impact category calculations and also reported separately. Carbon emissions during carbonation and calcination are also considered in this study. No carbonation occurs during any of the life cycle stages of natural stone cladding, but calcination occurs during installation stage due to the use of mortar. Mortar

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[8] The 100-year period relates to the period in which the environmental impacts are modeled. This is different from the time period of the functional unit. The two periods are related as follows: all environmental impacts that are created in the period of the functional unit are modeled through life cycle impact assessment using a 100-year time horizon to understand the impacts that take place.

[9] USEtox is available in TRACI and at http://www.usetox.org/

includes cement and calcium carbonate as ingredients. Calcination CO_2 emissions for cement are calculated and reported separately using a carbon intensity factor of 886 CO_2 per ton of cement [14]. Calcium carbonate is not calcined during the production of mortar.

Some emissions occur during blasting as explosives (ANFO, PETN) are used in quarrying. The emissions from the detonation of these explosives have been estimated using the emission factors from National Pollutant Inventory and added to the TRACI results [15].

It shall be noted that the above impact categories represent impact potentials. They are approximations of environmental impacts that could occur if the emitted substances would follow the underlying impact pathway and meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures the environmental load that corresponds to the chosen functional unit.

The results from the impact assessment indicate potential environmental effects and do not predict actual impacts on category endpoints, the exceedance of thresholds, or safety margins or risks.

4.2 Normalization and weighting

To arrive to a single score indicator, normalization [16] and weighting [17] as shown in Table 20 conforming to the SM 2013 Methodology were applied.

Table 20. Normalization and weighting factors

Impact category	Normalization	Weighting (%)
Acidification	90.9	3.6
Ecotoxicity	11000	8.4
Eutrophication	21.6	7.2
Global warming	24200	34.9
Ozone depletion	0.161	2.4
Carcinogenics	5.07E-05	9.6
Non carcinogenics	1.05E-03	6.0
Respiratory effects	24.3	10.8
Smog	1390	4.8
Fossil fuel depletion	17300	12.1

5 ASSESSMENT AND INTERPRETATION

This chapter includes the results from the LCA for the products studied. It details the results per product per functional unit and concludes with recommendations. The results are presented per functional unit (per m^2 of installed natural stone cladding).

5.1 Resource use and waste flows

Resource use indicators, output flows and waste category indicators, and carbon emissions and removals are presented in this section. LCI flows were calculated with the help of the American Center for Life Cycle Assessment guidance to the ISO 21930:2017 metrics [18].

Resource use indicators represent the amount of materials consumed to produce not only the product itself, but the raw materials, electricity, etc. that go into the product’s life cycle.

Primary energy is an energy form found in nature that has not been subjected to any conversion or transformation process and is expressed in energy demand from renewable and non-renewable resources. Efficiencies in energy conversion are considered when calculating primary energy demand from process energy consumption. Water use represents total water used over the entire life cycle. No renewable energy was used in production beyond that accounted for in the electricity grid mixes used, and no energy was recovered.

Table 21 shows resource use, output and waste flows, and carbon emissions and removals per functional unit for natural stone cladding.

Table 21. Resource use, output and waste flows, and carbon emissions and removals per functional unit

		Quarry Operations	Quarry to Processor Transport	Processor Operations	Transport to Building site	Installation	End of Life Transport	Final Disposal
	Unit	**A1**	**A2**	**A3**	**A4**	**A5**	**C2**	**C4**
Resource use indicators								
Renewable primary energy used as energy carrier (fuel) (RPRE)	MJ, LHV	3.46E+00	3.43E-02	6.98E+01	9.21E-02	1.96E+00	2.53E-02	1.98E-03
Renewable primary resources with energy content used as material (RPRM)	MJ, LHV	1.97E+00	0	3.66E+00	0	0	0	0
Total use of renewable primary resources with energy content (RPRT)	MJ, LHV	5.43E+00	3.43E-02	7.35E+01	9.21E-02	1.96E+00	2.53E-02	1.98E-03
Non-renewable primary resources used as an energy carrier (fuel) (NRPRE)	MJ, LHV	1.02E+02	2.21E+01	2.24E+02	5.93E+01	4.16E+01	1.63E+01	9.64E-01
Non-renewable primary resources with energy content used as material (NRPRM)	MJ, LHV	5.61E-01	0	0.00E+00	0	0	0	0
Total use of non-renewable primary resources with energy content (NRPRT)	MJ, LHV	1.03E+02	2.21E+01	2.24E+02	5.93E+01	4.16E+01	1.63E+01	9.64E-01
Secondary materials (SM)	kg	0	0	0	0	0	0	0
Renewable secondary fuels (RSF)	MJ, LHV	0	0	0	0	0	0	0
Non-renewable secondary fuels (NRSF)	MJ, LHV	0	0	0	0	0	0	0
Recovered energy (RE)	MJ, LHV	0	0	0	0	0	0	0
Use of net freshwater resources (FW)	m^3	1.52E+02	3.74E-03	1.02E+01	1.00E-02	3.10E+00	2.76E-03	1.69E-04
Output flows and waste category indicators								
Hazardous waste disposed (HWD)	kg	1.51E-03	0	3.16E-04	0	0	0	0
Non-hazardous waste disposed (NHWD)	kg	6.40E-02	0	4.19E-01	0	2.06E+00	0	2.80E+01
High-level radioactive waste, conditioned, to final repository (HLRW)	kg	5.05E-03	1.80E-06	5.77E-02	4.82E-06	3.16E-04	1.33E-06	1.03E-07
Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW)	kg	3.54E-06	1.88E-08	1.16E-05	5.06E-08	6.48E-07	1.39E-08	1.09E-09
Components for re-use (CRU)	kg	0	0	0	0	0	0	0
Materials for recycling (MR)	kg	2.78E+02	0	2.24E+01	0	4.12E+00	0	6.08E+01
Materials for energy recovery (MER)	kg	0	0	0	0	0	0	0
Exported energy (EE)	MJ, LHV	0	0	0	0	0	0	0
Carbon emissions and removals								
Biogenic Carbon Removal from Product (BCRP)	kg CO_2	0	0	0	0	0	0	0
Biogenic Carbon Emission from Product (NCEP)	kg CO_2	0	0	0	0	0	0	0
Biogenic Carbon Removal from Packaging (BCRK)	kg CO_2	0	0	3.68E+00	0	1.84E-01	0	0
Biogenic Carbon Emission from Packaging (BCEK)	kg CO_2	0	0	0	0	2.79E+00	0	0
Biogenic Carbon Emission from Combustion of Waste from Renewable Sources Used in Production Processes (BCEW)	kg CO_2	0	0	0	0	0	0	0
Calcination Carbon Emissions (CCE)	kg CO_2	0	0	0	0	1.21E+00	0	0
Carbonation Carbon Removals (CCR)	kg CO_2	0	0	0	0	0	0	0
Carbon Emissions from Combustion of Waste from Non-Renewable Sources used in Production Processes (CWNR)	kg CO_2	0	0	0	0	0	0	0

5.2 Life cycle impact assessment (LCIA)

It shall be reiterated at this point that the reported impact categories represent impact potentials; they are approximations of environmental impacts that could occur if the emitted substances would follow the underlying impact pathway and meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Life cycle impact assessment (LCIA) results are shown for natural stone cladding manufactured by NSI members. Unlike life cycle inventories, which only report sums for individual inventory flows, the LCIA includes a classification of individual emissions with regard to the impacts they are associated with and subsequently a characterization of the emissions by a factor expressing their respective contribution to the impact category indicator. The end result is a single metric for quantifying each potential impact, such as ‘global warming potential.’

The impact assessment results are calculated using characterization factors published by the United States Environmental Protection Agency. The TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.1) methodology is the most widely applied impact assessment method for U.S. LCA studies [14]. USEtox indicators are used to evaluate human toxicity and ecotoxicity, results will be reported only as a contribution analysis. The SM 2013 Methodology is also applied to come up with single score results for the sole purpose of representing total impacts per life cycle phase to explain where in the product life cycle greatest impacts are occurring and what is contributing to the impacts [13].

TRACI impact categories are globally deemed mature enough to be included in Type III environmental declarations. Other categories are being developed and defined and LCA should continue making advances in their development; however, the EPD users shall not use additional measures for comparative purposes. All impact categories from TRACI are used to calculate single score millipoints using the SM2013 Methodology, but it should be noted that there are known limitations related to these impact categories due to their high degree of uncertainty.

5.2.1. Impact Assessment Results

The impact results have been calculated per functional unit of natural stone cladding and have been tabulated per life cycle stage in Table 22.

For natural stone cladding, the cradle to gate stages (A1-A3) dominates the results for all the impact categories. Impacts generated at quarries (A1) and processors (A3) are mainly because of the use of grid electricity and fuels in those stages. Material inputs in those stages generate little impacts on comparison to electricity and fuel consumed. Cement mortar is used during the installation (A5) of natural stone cladding, which also generates significant environmental impacts. Cladding delivery to construction sites (A5) and stone transport from quarry to processor (A2) impacts are dependent of transport distance between the quarries to processors and processors to the sites respectively, and these stages also makes considerable impacts in numerous impact categories.

Table 22. Potential impact results per functional unit for natural stone cladding

Impact category	**Unit**	**Quarry Operations**	**Quarry to Processor Transport**	**Processor Operations**	**Transport to Building site**	**Installation**	**End of Life Transport**	**Final Disposal**
		A1	**A2**	**A3**	**A4**	**A5**	**C2**	**C4**
Ozone depletion (ODP)	kg CFC-11 eq	1.74E-07	3.28E-07	6.21E-07	8.81E-07	1.16E-07	2.42E-07	1.17E-08
Global warming	kg CO_2 eq	6.85E+00	1.65E+00	1.29E+01	4.42E+00	4.47E+00	1.22E+00	6.87E-02
Smog (SFP)	kg O_3 eq	2.06E+00	1.36E-01	1.47E+00	3.64E-01	2.44E-01	1.00E-01	2.00E-02
Acidification (AP)	kg SO_2 eq	6.96E-02	5.16E-03	6.39E-02	1.38E-02	1.68E-02	3.81E-03	6.64E-04
Eutrophication (EP)	kg N eq	6.75E-03	6.94E-04	9.05E-03	1.86E-03	9.16E-04	5.12E-04	6.49E-05
Carcinogenics	CTUh	2.09E-07	6.85E-10	4.56E-07	1.84E-09	2.67E-08	5.05E-10	2.01E-11
Non-carcinogenics	CTUh	8.11E-07	6.19E-08	1.06E-06	1.66E-07	3.22E-07	4.57E-08	7.97E-10
Respiratory effects	kg $PM_{2.5}$ eq	6.19E-03	3.24E-04	1.64E-02	8.69E-04	1.47E-03	2.39E-04	8.61E-05
Ecotoxicity	CTUe	43.8%	2.7%	41.4%	7.3%	2.8%	2.0%	<<1%
Fossil fuel depletion (ADP_{fossil})	MJ, LHV	1.23E+01	3.36E+00	1.72E+01	9.00E+00	2.93E+00	2.48E+00	1.46E-01

Single score results

The SM 2013 Methodology single figure millipoint (mPts) score by life cycle phase for this product is presented below in Table 23. The scores are consistent with the trends in the results using the impact assessment results before normalization and weighting. The processor operation stage (A3) dominates the results (~52%) followed by the quarry operation (A1) stage (~31%). Transport of cladding to installation sites (A4) and the installation of the cladding (A5) make significant and equivalent contribution to the single score results.

Table 23. SM 2013 scores for natural stone cladding by life cycle stage per functional unit

Impact category	**Unit**	**Quarry Operations**	**Quarry to Processor Transport**	**Processor Operations**	**Transport to Building site**	**Installation**	**End of Life Transport**	**Final Disposal**
		A1	**A2**	**A3**	**A4**	**A5**	**C2**	**C4**
SM single figure score	mPts	8.86E-01	6.94E-02	1.51E+00	1.86E-01	1.86E-01	5.12E-02	3.70E-03

5.2.2. Contribution Analysis

Table 24 and Figure 3 show the contributions of each stage of the life cycle for natural stone cladding to the environmental impact categories.

Table 24. Percent contributions of each stage to each impact category

Impact category	**A1**	**A2**	**A3**	**A4**	**A5**	**C2**	**C4**
Ozone depletion	7.3%	13.8%	26.2%	37.1%	4.9%	10.2%	<1%
Global warming	21.7%	5.2%	40.8%	14.0%	14.2%	3.9%	<1%
Smog	46.9%	3.1%	33.4%	8.3%	5.6%	2.3%	<1%
Acidification	40.0%	3.0%	36.8%	8.0%	9.7%	2.2%	<1%
Eutrophication	34.0%	3.5%	45.6%	9.4%	4.6%	2.6%	<1%
Carcinogenics	30.1%	<1%	65.6%	<1%	3.8%	<1%	<<1%
Non-carcinogenics	32.9%	2.5%	42.9%	6.7%	13.1%	1.9%	<<1%

Respiratory effects	24.2%	1.3%	64.1%	3.4%	5.7%	<1%	<1%
Ecotoxicity	43.8%	2.7%	41.4%	7.3%	2.8%	2.0%	<<1%
Fossil fuel depletion	26.0%	7.1%	36.3%	19.0%	6.2%	5.2%	<1%

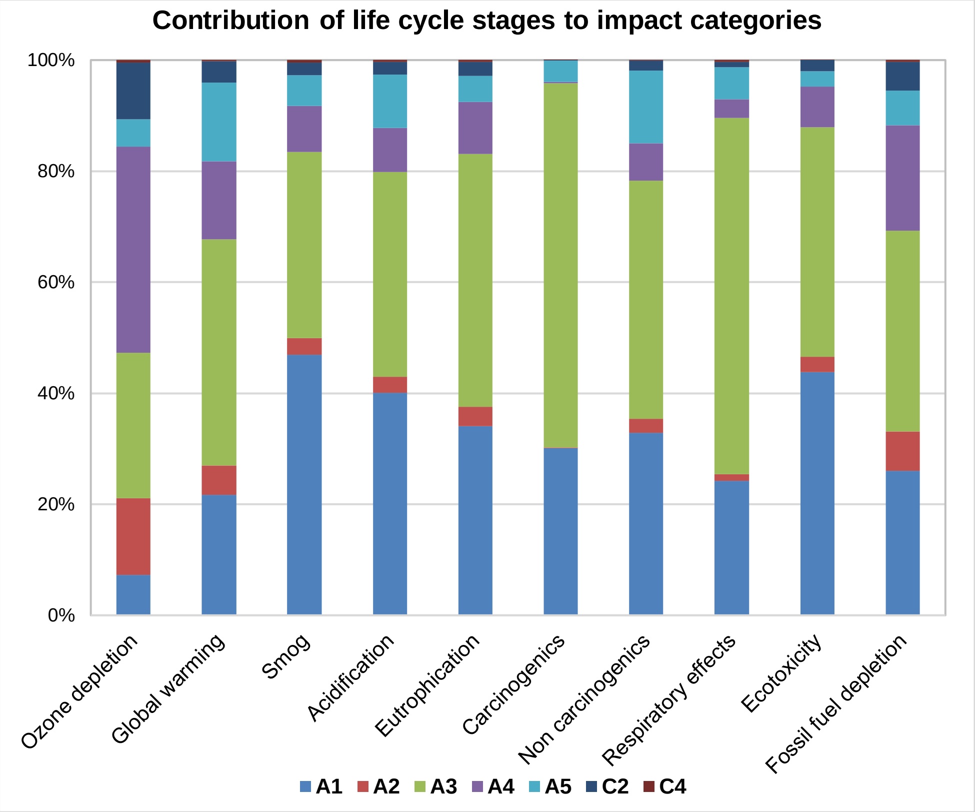

Figure 3. Contribution of each life cycle stages of natural stone cladding to each impact category

Processor operations (A3) stage is the highest contributor to most of the impact categories followed by the quarry operations (A1). In some of the impact categories, A1 makes the highest contribution, followed by A3 stage. Cradle to gate stages (A1-A3) contribute to ~65% of the total impacts in all the impact categories but ozone depletion.

A detailed study has been performed for global warming potential and fossil fuel depletion categories, since these are deemed most relevant and of interest to NSI members. Breakdown for potential CO_2 equivalent emissions is represented by Figure 4. Processor operations (A3) stage is responsible for ~41% of total CO_2 emissions while quarry operations make up ~22% of total CO_2 emissions. Within A3, fuels (mainly diesel, propane, and natural gas) used for various purposes contributes to ~43%, and grid electricity contributes to ~53% of the total emissions generated from processors. Electricity and fuels used also share most of the A1 emissions; electricity makes up ~24% of total A1 emissions while combustion/use of fuels contributes to ~68%.

A5 stage makes ~14% of total CO_2 emissions and use of cement mortar is responsible for ~61% of the CO_2 emissions in this stage. A2 stage contributes to ~5% of total emissions while at the end of life, transportation of discarded waste to either landfilling centers or recycling centers also generates significant CO_2 emissions, ~4% of total.

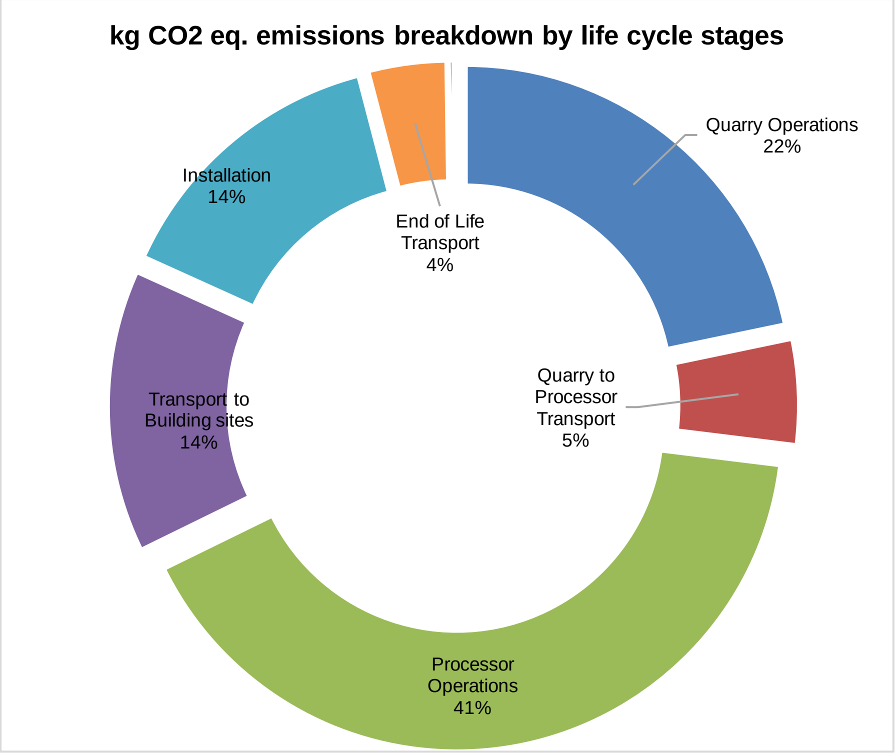

Figure 4. Breakdown of kg CO_2 eq emissions by life cycle stages

Similar breakdown study for potential fossil fuel depletion is represented in Figure 5. Processor operations (A3) stage contributes to ~36% in this category while quarry operations make up ~26%. Fuels (mainly natural gas, gasoline, and LPG) used for various purposes contributes to ~43%, and grid electricity contributes to ~49% of the total fossil fuel depletion impacts generated in A3 stage. Electricity and fuels used also share most of the A1 fossil fuel depletion impacts; electricity makes up ~13% of total A1 emissions while combustion/use of fuels contributes to ~76%. Installation of cladding makes ~6% of total emissions, with ~74% emissions coming from the use of cement mortar. Stone transport from quarries to processors (A2) and cladding transport to building sites (A4) make significant share in the total fossil fuel depletion impacts with a combined share of ~26%, with three quarters of that coming from A4 stage.

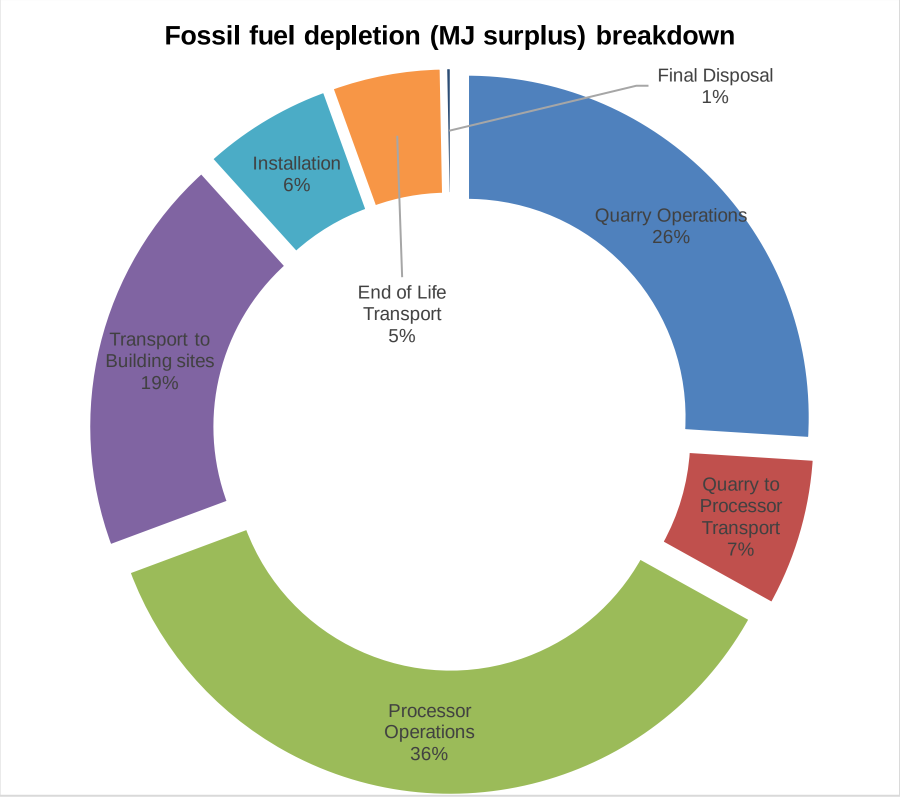

Figure 5. Breakdown of fossil fuel depletion by life cycle stages

For other required impact categories per PCR, unit processes that contribute to more than 10% of the overall life cycle impacts have been identified and tabulated in Table 25.

Table 25. Drivers of life cycle impacts

Impact categories	Major flows (impacts > 10%)	Actual contribution
Ozone depletion	Transport of cladding to building sites (A4)	37.1%
	Electricity for stone processing (A3)	21.2%
	Transport of quarried stone from quarries to processing sites (A2)	13.8%
	End of life transport (C2)	10.20%
Smog	Diesel combusted during stone quarrying (A1)	40.3%
	Diesel combusted during stone processing (A3)	23.4%
Acidification	Diesel combusted during stone quarrying (A1)	31.2%
	Diesel combusted during stone processing (A3)	18.4%
	Electricity for stone processing (A3)	12.9%
Eutrophication	Electricity for stone processing (A3)	30.1%
	Diesel combusted during stone quarrying (A1)	17.3%
	Diesel combusted during stone processing (A3)	10.0%

5.2.3. Variation Analysis

A variation analysis was performed to study the environmental impacts variation between natural stone cladding from different stone types. Results were generated for both quarry operations and processor operations specific to various stone types. One of the major parameters that influences the results is the amount of stone that needs to be quarried to produce 1 m^2 of stone cladding, which varies per stone type.

The minimum and maximum results presented in Table 26 represent the stone types with the lowest (best) and highest (worst) impacts, respectively. Minimum and maximum stone types for both quarry and processor operations are determined for each impact category separately and thus the total life cycle impact result for each impact category is generated. The mean and median also take production volumes for each stone type across facilities into account (i.e., data point is created for each stone type). The weighted average results presented in Table 21 through Table 24 also include the production share of each stone types in the final production.

Table 26. Statistical distribution of LCIA results, per functional unit

Impact category	**Unit**	**Min. values (Cradle to Grave)**	**Max. values (Cradle to Grave)**	**Max/ Min Ratio**	**Mean**	**Median**	**Weighted average values**	**Min/ Weighted %**	**Max/ Weighted %**
Ozone depletion (ODP)	kg CFC-11 eq	1.95E-06	3.59E-06	1.84	2.73E-06	2.78E-06	2.37E-06	82%	151%
Global warming	kg CO$_2$ eq	2.33E+01	6.59E+01	2.83	3.98E+01	4.00E+01	3.15E+01	74%	209%
Smog (SFP)	kg O$_3$ eq	3.23E+00	1.12E+01	3.46	5.95E+00	5.30E+00	4.39E+00	74%	255%
Acidification (AP)	kg SO$_2$ eq	1.43E-01	4.20E-01	2.94	2.33E-01	2.14E-01	1.74E-01	82%	242%
Eutrophication (EP)	kg N eq	1.52E-02	4.48E-02	2.95	2.64E-02	2.50E-02	1.99E-02	77%	226%
Carcinogenics	CTUh	2.15E-07	2.13E-06	9.92	9.46E-07	9.80E-07	6.95E-07	31%	307%
Non-carcinogenics	CTUh	1.78E-06	6.05E-06	3.39	3.31E-06	3.25E-06	2.46E-06	72%	245%
Respiratory effects	kg PM$_{2.5}$ eq	1.39E-02	6.74E-02	4.86	3.79E-02	3.78E-02	2.56E-02	54%	263%
Ecotoxicity	CTUe	2.19E+01	8.94E+01	4.08	4.53E+01	4.43E+01	3.30E+01	66%	271%
Fossil fuel depletion (ADP$_{fossil}$)	MJ, LHV	3.95E+01	9.49E+01	2.41	6.09E+01	5.73E+01	4.75E+01	83%	200%

As shown in Table 26, there is a large variation between the weighted average, minimum, and maximum LCIA results. This all comes down to varying quarry and processor operations used by different quarries and processors.

5.2.4. Sensitivity Analysis

Based on the recommendation provided by NSI processors, impacts for processor operations specific to a m^2 of cladding was assumed to match the average stone processing for 1 m^2 of stone, although different stone products go through variety of processing operations.

A sensitivity analysis was performed to check the robustness of the results when the energy consumed is +-20% of the estimate used in this study. As shown in Table 27, a ~20% variation in the A3 stage is observed in both potential CO$_2$ equivalent emissions and fossil fuel depletion. But the variation in total life cycle impacts is less than 10%; ~8% is observed in potential CO$_2$ equivalent emissions and ~6% is observed in fossil fuel depletion impact category. Other impact categories also follow the similar trend.

Table 27. Sensitivity analysis of the LCIA results, per functional unit

Stone processing scenarios for stone cladding	**A3 stage impacts**				**Total life cycle impacts**			
	kg CO$_2$ eq emissions	**% change from base**	**Fossil fuel depletion (MJ surplus)**	**% change from base**	**kg CO$_2$ eq emissions**	**% change from base**	**Fossil fuel depletion (MJ surplus)**	**% change from base**
Base stone processing	12.869		17.212		31.573		54.512	

Stone processing with 20% more energy	15.443	120%	20.654	120%	34.147	108%	57.955	106%
Stone processing with 20% less energy	10.295	80%	13.769	80%	29.000	92%	51.070	94%

5.3 Overview of relevant findings

This study assessed a multitude of inventory and environmental indicators. The primary finding, across the environmental indicators and for the products considered, was that cradle to gate impacts (A1-A3) contribute the most impacts to most categories, which is mostly driven by use of grid electricity and fuels in quarries and processor plants. Within A1-A3, processor operations (A3) contribute the most to the total impacts, followed closely by quarry operations (A1). Transport of quarried stone from quarries to processor plants (A2) also has significant contribution to the total impacts.

A1-A3 stage covers the large portion of overall impacts, which is followed by A4 and A5 stages. Installation impacts are driven by cement mortar, while maintenance stage is not a contributor as it is assumed that stone cladding does not require any maintenance and repair to achieve its reference service life, which is modeled as being equal to that of the building. No replacements are necessary; therefore, results represent the impacts associated with one square meter of installed natural stone cladding.

At the end of life, stone cladding is removed from the building with a portion being landfilled, and the rest recycled. End of life contributes little to the overall impacts.

5.4 Discussion on data quality

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source), and representativeness (geographical, temporal, and technological). Primary data has been used, when available, for all unit processes.

Precision and completeness

- *Precision*: As the relevant foreground data is primary data or modeled based on primary information sources of the owner of the technology, precision is considered to be high. Background data are from ecoinvent databases with documented precision to the extent available.

- *Completeness*: All relevant process steps for the product system were considered and modeled. The process chain is considered sufficiently complete with regards to the goal and scope of this study. The product system was checked for mass balance and completeness of the inventory. Capital equipment was excluded as required by the PCR. Otherwise, no data were knowingly omitted.

Consistency and reproducibility

- *Consistency*: Assumption, methods, and data were found to be consistent with the study's goal and scope. Primary data were collected with a similar level of detail, while background data were sourced primarily from the ecoinvent database, while other databases were used if data were not available in ecoinvent or the data set was judged to be more representative. Other methodological choices were made consistently throughout the model. System boundaries, allocation rules, and impact assessment methods have also been applied uniformly.

- *Reproducibility*: Reproducibility is warranted as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, a knowledgeable third party should be able to approximate the results of this study using the same data and modeling approaches.

Representativeness

- *Temporal*: Primary data were determined to be representative of typical operations. Secondary data were obtained from the ecoinvent databases and are typically representative of the recent years. Temporal representativeness is considered to be good.
- *Geographical*: Primary data are representative of participant quarries and processors. Most of them are from North America (US and Canada), a few quarries were from France. When possible, secondary data were selected to represent US conditions. Global datasets have been used for most of the materials. Electricity datasets have been created manually based on the production share to represent all the participants, and fuels for US conditions have been selected as most production occurs in US. Geographical representativeness is considered to be fair.
- *Technological*: All primary and secondary data were modeled to be specific to the technologies under study. Technological representativeness is considered to be good.

5.5 Conclusions and recommendations

The goal of this study was to conduct a cradle-to grave LCA on NSI's natural stone cladding to develop an industry-wide SM Transparency Report / EPD. The creation of these Transparency Reports will allow consumers in the building and construction industry to make better informed decisions about the environmental impacts associated with the products they choose. Overall, the study found that environmental performance is driven primarily by cradle-to-gate activities. Operations at quarries to quarry the natural stone and operations at processors to process quarried stone into final stone cladding drive environmental performance. Use of cement mortar for the installation of cladding also result into significant impacts. The end-of-life stages account for minimal contribution to life cycle performance.

The major potential source of impact reduction is in cradle to gate stages. Within this stage, there are several opportunities, including both quarries and processor plants. This is an important area for the NSI quarriers and NSI processors to focus their efforts, since they can directly influence their own operations. Most of the impacts in both quarries and processors are coming from the use of grid electricity and fuels. NSI members can reduce their operations impacts by decreasing the use of electricity and fuels. They can achieve this by either using latest and more effective technologies/equipment or incorporate green energy sources to reduce the dependence on grid electricity. Waste stone is generated in both quarries and processors, this issue should be periodically revisited to incorporate new technology considerations for further improvement mainly to reduce the stone scrap. NSI members can directly influence these areas so are good candidates for prioritizing reduction activity.

Another opportunity for reduction of environmental impact is in the installation stage, though it is often outside of NSI members' control. Cement mortar used during installation contributes largely to impact categories so NSI should consider investigating more environment friendly adhesives. There is also an opportunity to reduce the installation waste. This will also significantly reduce the overall impacts.

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ACRONYMS

ISO	International Standardization Organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact analysis
NSI	Natural Stone Institute
PCR	Product Category Rule document
TR	Transparency Report / EPD™
IPCC	Intergovernmental Panel on Climate Change
USLCI	US Life Cycle Inventory

GLOSSARY

For the purposes of this report, the terms and definitions given in ISO 14020, ISO 14025, the ISO 14040 series, and ISO 21930 apply. The most important ones are included here:

Allocation	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems
Close loop & open loop	A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.
Cradle to grave	Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of life
Cradle to gate	Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of the production process (“gate of the factory”). It may also include transportation until use phase
Declared unit	Quantity of a product for use as a reference unit in an EPD based on one or more information modules
Functional unit	Quantified performance of a product system for use as a reference unit
Life cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal
Life cycle assessment - LCA	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle
Life cycle impact assessment - LCIA	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product
Life cycle inventory - LCI	phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle
Life cycle interpretation	Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations

APPENDIX

- Technical information table for major natural stone types

Technical properties			Natural stone			
Parameter	**Unit**	**Test Method**	**Limestone**	**Granite**	**Marble**	**Quartzite**
Flexural strength	MPa	ASTM C880	3.45	8.27	6.89	NA
Modulus of Rupture	MPa	ASTM C99	2.76	10.34	6.89	13.79
Compressive Strength	MPa	ASTM C170	12.41	131.00	51.71	137.89
Thermal conductivity (k-value)	W/mK	ASTM C518	1.26	1.73	2.07	5.38
Thermal resistance (R-value)[10]	m.K/W	ASTM C518	0.79	0.56	0.49	0.19
Liquid water absorption	% of dry weight	ASTM C97	12.00	0.40	0.2	1.00

- Compilation of data from NSI participants and LCI development workbook

NSI Inventory Calcs_Final.xlsx

- NSI Stone Cladding LCA results workbook

NSI_Stone Cladding LCA

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[10] Thermal resistance or R-value depends on the thickness of the material. These values have been calculated for a 1" thick dimension stone sample. https://www.naturalstoneinstitute.org/designprofessionals/technical-bulletins/rvalue/