LIFE CYCLE ASSESSMENT (LCA) OF NATURAL STONE COUNTERTOPS 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 countertops in all life cycle stages, from stone quarrying to processing, fabrication, 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 countertops 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 countertops.

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 NSF's PCR for residential countertops [2].

NSI commissioned Sustainable Minds, an external practitioner, to develop an LCA for three main product categories: stone cladding, stone flooring, and stone countertops, manufactured by its members. This document is focused on countertops. 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 countertops manufactured by participating NSI members.

1.2 Life Cycle Assessment

This report includes the following phases:

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

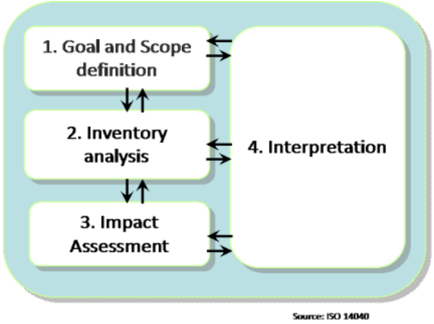

Figure 1. Phases in an LCA

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.

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 1.

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.

Countertops require additional manufacturing operations at fabricators. Fabricator operations data were collected from six NSI member fabricators, each with a single facility as listed in Table 3.

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 methods
- Chapter 5: Assessment and interpretation

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 countertops 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. Results presented in this document 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 Countertops

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.

Countertops refer to a raised, flat, and horizontal surface, built for work mainly in kitchens, bathrooms, and workrooms. This surface is mostly supported by cabinets and is positioned at a suitable height for the user to perform the intended task. Countertops can be constructed of different materials with different attributes of functionality, durability, and aesthetics. Countertops manufactured by NSI are made of natural stone.

As an organization of manufacturers that produce stone countertops, NSI is interested in demonstrating its sustainability leadership. It is also interested in leveraging business value associated with transparent reporting of stone countertops' cradle-to-grave environmental impacts. NSI's stone countertops is made of natural stone and the different stone types included in this study are granite, marble, quartzite, limestone, sandstone, and soapstone. It is used in commercial, residential, and public sector buildings. Based on the data provided by the participating natural stone countertop fabricators, most of the fabricated countertops were made of granite (93.56%), 3.69% were from marble, and 2.75% were from other natural stones (including quartzite and soapstone).

Natural stone extracted from quarries goes to stone processors and then to fabricators where the quarried stone is processed into stone countertops. The participating quarries and their type of stone are listed in Table 1. Participating processors and fabricators are listed in Table 2 and Table 3.

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, Oolitic, 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, Oolitic, 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

Table 3. Participant countertop fabricators with stone types fabricated and plant locations

Company	Stone type	Plant location(s)
Cutting Edge Countertops	Granite Marble Quartzite Soapstone	Perrysburg, OH
Freshwater Stone	Granite Marble Quartzite Soapstone	Orland, ME
Ontra Stone Concepts	Granite Marble Quartzite Soapstone	Bridgeport, CT
Planet Granite, Inc.	Granite Marble Quartzite Soapstone	Colorado Springs, CO
Stone Interiors	Granite Marble Quartzite	Gaston, SC
Valley View Granite	Granite Marble Quartzite Soapstone	West Tremonton, UT

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 natural stone countertops for a service life of 10 years in residential use, inclusive of front edge and backsplash [3].

The natural stone countertop product system is an industry-average product, i.e., the product profile represents the weighted average of NSI's natural stone countertops based on NSI's industry average quarrying for all stone types and also includes industry average production of countertops of all stone types. The product system in this study also includes the ancillary materials used in the installation of the product. NSI members produce only the natural stone component while the installer purchases the ancillary materials separately. Materials required to meet the functional unit have been listed in Table 4.

Table 4. Materials required to meet the functional unit

Product	Functional unit	Materials needed to meet functional unit
Natural Stone Countertops	One square meter (m^2) of product	Natural stone – 92.23 kg per m^2

Associated properties for natural stone countertops are indicated in Table 5 per relevancy, with the appropriate test method. Technical properties are specific to each stone type and a range is provided for each.

Table 5. Technical information table for natural stone countertops

Name	Value	Unit	Test Method
Thickness to achieve Functional unit	28.58 (weighted thickness)	mm	NA
Density	2507 (weighted density)	kg/m^3	NA
Slab Length	1.54	m	NA
Slab Width[1]	0.65	m	NA
Flexural strength	3.45 – 8.27	MPa	ASTM C880
Modulus of Rupture	2.76 – 10.34	MPa	ASTM C99
Compressive Strength	12.41 – 131.00	MPa	ASTM C170
Thermal conductivity (k-value)	1.26 – 5.38	W/mK	
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	$\mu g/m^3$	

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

[1] Kitchen countertop depth varies but a typical depth is 25.5 inches, equivalent to 0.65 m.
[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

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 [3]. 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 countertop included in this LCA study.

Table 6 lists specific inclusions and exclusions for the system boundary.

Table 6. 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 (stone production) • Fabricator operations (countertop fabrication) • Energy production • Outbound transport of stone countertop • Packaging of final stone countertop • 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

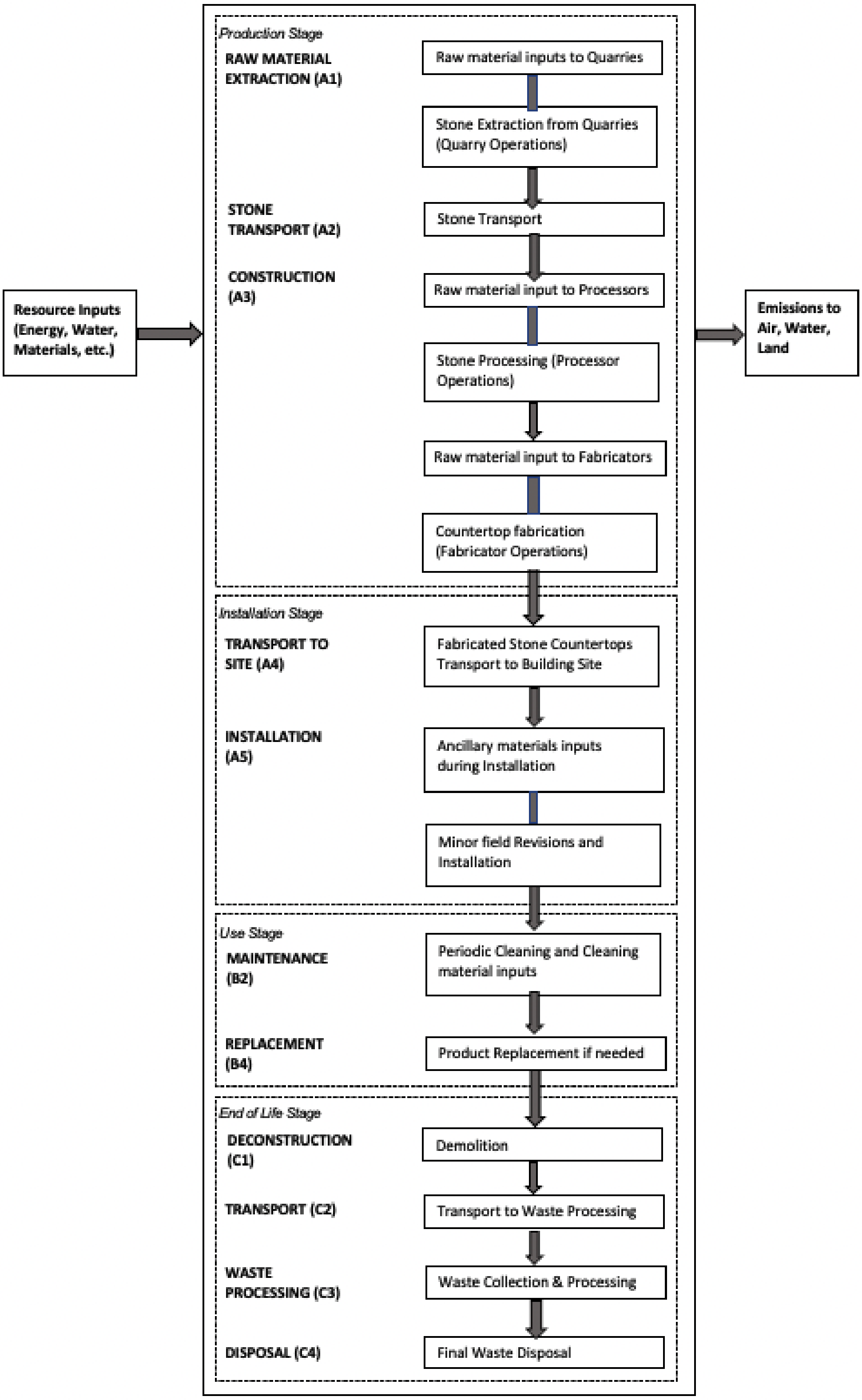

Figure 2. Applied system boundary for natural stone countertop

Since this PCR was developed before the ISO 21930 framework existed, a mapping has been performed as shown in Table 7 between the system boundary defined by ISO 21930 and the PCR for easy understanding of equivalent life cycle stages.

Table 7. Mapping of life cycle stages between residential countertop PCR and ISO 21930

PCR life cycle stages	ISO 21930 life cycle stages
Material acquisition and pre-processing stage (Quarry + transport from quarry)	Raw material acquisition (A1)
	Upstream transport (A2)
Countertop Construction stage (Stone processors + Countertop fabricators)	Construction / Manufacturing (A3)
Installation stage	Transport to building sites (A4)
	Installation (A5)
Use and maintenance stage	Product use (B1)
	Maintenance (B2), Repair (B3), Replacement (B4), and Refurbishment (B5)
	Operational energy use (B6) and water use (B7)
End-of-life stage	Deconstruction (C1) and Transport to waste processing/disposal (C2)
	Waste processing (C3) and Disposal (C4)

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

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)

Construction (A3) Construction stage starts when the natural stone enters the production site and ends with the final countertop product leaving the fabrication site. This stage includes:

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

Energy production is also included for all quarry, processors, and fabricator operations.

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. This stage includes:

- Electricity and ancillary materials specifically required for installation
- Installation waste product and packaging
- Waste transport and treatment as applicable.

2.4.3. B1-B7: Use

The use stage begins when the consumer starts using the product. Stone countertop 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. Based on discussions with NSI members, we assume the countertop requires occasional cleaning with soap and water. In the absence of primary data, we used maintenance quantities from an EPD for natural stone manufactured in Turkey [4].

Repair (B3), Replacement (B4), and Refurbishment (B5) are not relevant to stone countertop. Estimated service life of buildings is 75 years [5]. 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 countertop will last for the lifetime of the building. Since the PCR specifies the service life of countertop to be 10 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 countertop 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 32 kilometers, as prescribed by the PCR [3].

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 [6].

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), countertop fabrication (fabricators), 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 countertop 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 Countertop is produced in several manufacturing steps that involve extraction of stones, its processing, and countertop fabrication. The finished stone countertop is then distributed to construction sites where they are installed, and the packaging is disposed. The service life for stone countertop is 10 years, after which it is removed and disposed.

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

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 9. After that inventory per kg of stone quarrying specific to countertops was developed using the market distribution of countertops by stone type as collected from participant countertop fabricators (93.56% granite, 3.69% marble, and 2.75% other natural stone).

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]. The generation of scrap is embedded in the unit data used. Excess process materials (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 8 to represent 1 kg of natural stone extracted specific to countertop fabrication. Mean, median, and standard deviation observed in the primary quarry data (for different stone type quarrying) is also tabulated. The proportion of stone types represented in the overall quarry data are listed in Table 9.

Table 8. Weighted NSI Inventory to quarry 1 kg of natural stone specific to countertop

Resource category	Inputs & outputs	Unit	NSI Total (Participants)	Inventory specific to countertop	Mean	Median	Standard Deviation
Electricity	Electricity	kWh	3.32E+07	3.84E-02	2.82E-02	1.28E-02	3.83E-02
Fuels	Gasoline	liters	7.47E+05	7.42E-04	5.10E-04	4.94E-04	3.24E-04
	Gasoline E10	liters	9.44E+04	4.64E-05	2.76E-04	0.00E+00	6.17E-04
	Diesel (100% petroleum-based)	liters	1.09E+07	9.24E-03	9.84E-03	7.51E-03	9.78E-03
	Biodiesel 5%	liters	2.51E+05	5.58E-06	8.37E-05	0.00E+00	1.87E-04
	Biodiesel 70%	liters	2.91E+05	6.46E-06	9.69E-05	0.00E+00	2.17E-04
	Propane	liters	2.50E+04	1.47E-05	5.47E-05	6.08E-06	1.15E-04
	Natural gas	MJ	1.04E+05	2.31E-06	3.46E-05	0.00E+00	7.73E-05
	Heating oil	liters	3.99E+02	7.27E-07	1.53E-07	0.00E+00	3.41E-07
	Oil	liters	9.08E+03	2.02E-07	3.02E-06	0.00E+00	6.76E-06
Waste Generation	Total EPM generated	kg	2.35E+09	2.06E+00	1.80E+00	1.64E+00	1.86E+00
	EPM kept onsite	kg	1.89E+09	1.62E+00	1.28E+00	1.40E+00	1.35E+00
	EPM sold	kg	4.23E+08	3.71E-01	5.02E-01	3.33E-01	5.77E-01
	EPM hauled offsite	kg	3.67E+07	6.58E-02	1.61E-02	0.00E+00	2.98E-02
	Solid waste to landfill	kg	7.03E+05	7.89E-04	8.60E-04	1.79E-04	1.35E-03
	Waste to recycling	kg	4.36E+05	6.63E-04	9.62E-04	5.30E-05	1.73E-03
	Hazardous waste to landfill	kg	7.01E+04	3.23E-05	1.93E-04	0.00E+00	4.27E-04
	Hazardous waste to recycling	kg	7.17E+04	3.02E-05	3.50E-05	2.84E-05	3.83E-05
Material inputs	ANFO	kg	5.36E+05	1.26E-04	2.23E-04	1.15E-04	3.16E-04
	Blasting caps	kg	1.14E+03	1.79E-06	1.18E-06	2.03E-07	1.67E-06
	Detonating cord	kg	2.33E+04	2.55E-05	2.92E-05	1.38E-05	4.40E-05
	Stainless steel	kg	1.91E+05	3.15E-04	1.11E-04	2.52E-05	1.41E-04
	Wood products	kg	1.19E+06	5.39E-04	1.47E-03	3.40E-04	2.56E-03
	Hydraulic fluid	kg	1.44E+05	8.60E-05	2.95E-04	1.02E-04	4.82E-04

[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.

	Lubricant	kg	1.27E+05	1.20E-04	7.08E-05	9.42E-05	4.94E-05
	Motor oil	kg	1.84E+05	1.34E-04	8.14E-04	1.32E-04	1.59E-03
	Tires	kg	1.92E+05	1.82E-04	1.83E-04	1.41E-04	2.03E-04
	Antifreeze	kg	5.54E+05	9.88E-04	2.78E-04	1.80E-05	4.45E-04
	Diamond belts/wires/blades	kg	6.66E+04	4.95E-05	1.48E-04	7.06E-06	3.12E-04
	Carbide tooling on chains	kg	1.06E+03	3.32E-08	4.07E-07	0.00E+00	7.54E-07
Waste transport	Diesel powered truck	tkm	2.06E+05	2.44E-04	3.30E-04	2.31E-04	3.34E-04

Table 9. 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. Construction (A3) – Processor operations

Natural stone processing plants process the quarried stone as needed for end product applications, including countertop fabrication, cladding, flooring, and others. 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. For countertops, the stone blocks are first cut into slabs using high-speed gang saws fitted with several blades that make simultaneous parallel cuts. The slabs are then sent through a polishing machine that puts the desired finish on the piece. During this stage, slab is also calibrated, working down to a relatively uniform thickness across the length of the material. 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 [7]. 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 area production share of each stone type. After that, inventory per m^2 of stone processing specific to countertops was developed, using the market distribution of countertops by stone type as collected from participant countertop fabricators (93.56% granite, 3.69% marble, and 2.75% other natural stone). It was suggested by participant processors that although cladding and flooring stone go through additional processing steps after cutting and polishing, because of the heavy polishing countertop stone goes through, countertop actually use more energy (~10%) than other products. This estimate has been used to scale the inventory for processing stone specific to countertop manufacturing, as represented in Table 10. Mean, median, and standard deviation observed in the primary processor data is also tabulated.

Table 10. Weighted NSI inventory to process 1 m^2 of end natural stone specific to countertop

Resource category	Inputs & output	Unit	NSI Total (Participants)	Inventory specific to countertop	Mean	Median	Standard Deviation
Electricity	Electricity	kWh	3.94E+07	5.16E+01	2.91E+01	2.98E+01	2.03E+01
Fuels	Gasoline	liters	9.33E+04	1.27E-01	1.38E-01	6.51E-02	1.92E-01
	Diesel	liters	1.20E+06	9.37E-01	4.52E-01	4.60E-01	3.86E-01
	Propane	liters	1.54E+06	4.80E+00	1.30E+00	2.85E-01	2.21E+00
	Natural gas	MJ	2.39E+07	1.01E+00	7.50E+00	5.16E+00	9.35E+00
	Heating oil	liters	4.49E+04	2.07E-01	5.00E-02	0.00E+00	1.00E-01
	Oil	liters	2.75E+03	2.19E-03	6.59E-04	2.78E-04	9.83E-04
Material inputs	Wood products	kg	4.52E+06	6.35E+00	3.03E+00	2.64E+00	2.16E+00
	Steel banding	kg	2.92E+04	2.35E-02	6.23E-03	1.30E-03	1.08E-02
	Plastic banding	kg	9.96E+04	1.24E-01	1.22E-01	5.33E-02	1.81E-01
	polyurethane	kg	8.25E+01	1.09E-06	1.95E-04	1.18E-06	3.88E-04
	Packaging material	kg	8.97E+02	2.98E-04	3.42E-04	2.95E-04	3.22E-04
	Diamond blades/wires	kg	9.67E+04	1.51E-01	3.88E-02	4.82E-03	7.07E-02
	Diamond tooling	kg	2.05E+03	3.37E-05	4.55E-04	3.91E-04	5.32E-04
	Carbide tooling	kg	2.19E+02	2.90E-06	2.13E-04	3.72E-05	3.77E-04

[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.

	Steel with less than 1 year life	kg	5.25E+04	1.91E-02	4.70E-03	4.85E-04	8.76E-03
	Cardboard	kg	4.77E+03	3.52E-03	1.03E-03	3.89E-04	1.58E-03
	Foam packaging	kg	6.40E+03	8.50E-05	8.48E-04	0.00E+00	1.70E-03
Waste Generation	Waste to landfill	kg	1.15E+06	3.42E-04	2.56E+00	6.16E-01	4.25E+00
	Recycling	kg	1.09E+05	3.88E-02	5.37E-02	4.92E-02	6.24E-02
	Hazardous (to recycler)	kg	6.22E+04	3.49E-02	4.38E-02	2.47E-02	5.64E-02
	Hazardous (to landfill)	kg	9.07E+02	3.88E-03	1.20E-04	0.00E+00	2.40E-04
Waste transport	Diesel powered truck	tkm	2.13E+05	4.55E-04	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 11.

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 12 lists the stone mass per m^2 and weighted density calculation of stone produced from processors for different stone types. The generation of scrap is embedded in the unit data used. The difference between the input stone and produced stone mass per m^2 of stone processed represents the scrap stone generated during countertop fabrication. Weighted average thickness of stone produced from processors was 51.066 mm (2.010 inches).

Table 11. 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 12. Processed stone mass per m^2 and final density

Stone category	Stone input share	Input stone kg per m^2 stone processed	Stone production share	Produced stone kg per m^2 of processed stone	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*

3.2.3. Construction (A3) – Fabricator operations

Countertop goes through additional manufacturing steps at fabricator facilities. Stone is offloaded at fabricators with fork trucks. Someone from fabrication team is sent to the job site to take the measurements for templating purpose. Based on the template, the stone is cut to size, and the edges are polished, and finished countertop is then strapped onto an A-frame on a delivery truck and sent to the job site. Figure 3 represents the manufacturing operations, inputs, and outputs at fabricator facilities.

Primary data was provided by the participant fabricators for the consumable materials, electricity, fuels, and packaging materials used during the time period of January 2019 to December 2020. Data was also collected on stone waste, non-stone solid waste, hazardous waste, and recycled waste. Production data on both mass and area units, and number of fabrication jobs for each fabricator were also collected.

Prior to data collection, Sustainable Minds interviewed participating countertop fabricator facilities to identify relevant materials, energy sources, water sources, waste practices, and production tracking and developed a custom data collection form for countertop fabricators to report data.

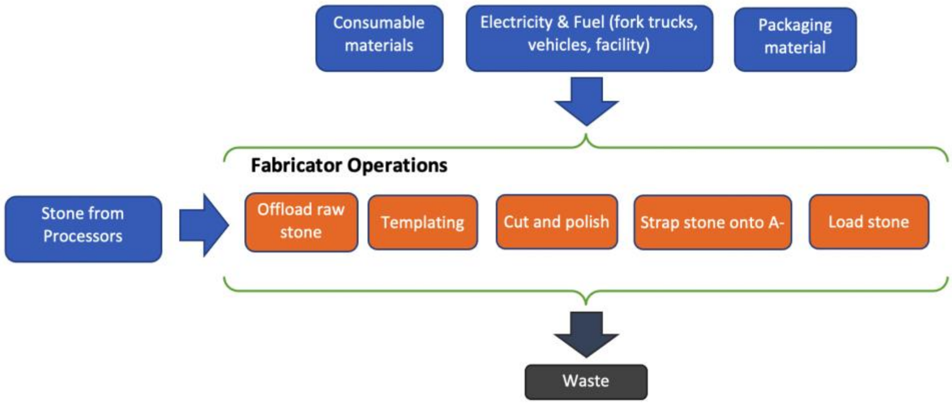

Figure 3. Countertop fabrication steps at fabricator facilities

All but one participant fabricator provided thickness breakdown information, representing 79% of production. This thickness breakdown was considered to accurately represent the NSI countertops. Table 13 lists the stone mass per m^2 and weighted density calculation of countertop fabricated for different stone types. The generation of scrap is embedded in the unit data used. The difference between the input stone and produced stone mass per m^2 of countertops represents the scrap stone generated during countertop fabrication. Weighted average thickness of countertops fabricated was 28.577 mm (1.125 inches).

Table 13. Fabricated countertops mass per m^2

Stone category	Stone input share	Input stone kg per m^2 of countertop	Stone production share	Produced stone kg per m^2 of countertop
Granite	94.1%	157.0	93.6%	95.6
Marble	3.2%	137.2	3.7%	82.7
Other stone	2.7%	142.3	2.8%	89.0
Countertop Weighted avg.		*149.5*		*92.2*

3.2.4. Distribution (A4)

Distribution refers to the transport of the produced countertops from the fabricator facilities to the building sites for installation. Distribution includes two legs of transportation to the end user site. First one is an initial visit to measure the room dimensions via passenger vehicle. Second leg is for the delivery of the countertop, for which primary data on the amount of fuels consumed for countertops shipping were provided by the fabricators. This data on fuel is used to calculate an estimate for an initial site visit, which was 80 km.

3.2.5. Installation (A5)

Installation refers to the installation of stone countertop in the buildings. Even though countertop fabrication (cutting and finishing to required size) is done at the fabricator 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 fabricators, the scrap generated is insignificant and will be recycled if generated, so an installation scrap rate of 0% is assumed.

Primary data was collected on the ancillary materials required for installation of countertop and a weighted average inventory for 1 m^2 of countertop was developed. Major ancillary materials used are adhesives (0.017 kg), resins (0.089 kg), acrylics (0.0005 kg), sealers (0.009 kg), silicones (0.078 kg) etc. Drills and grinders used for installation use 12 Amps, which at 115 Volts equals to 1.38 kW of power. In the absence of primary data, electricity consumed for each job site per functional unit was calculated with an assumption that teams typically use a drill/grinder for 15 minutes on each job site. Waste generated in this stage includes packaging waste, waste transport distance is taken to be 32 km per PCR.

3.3 Secondary Data

For life cycle stages after the installation of countertops, secondary data sources are used to develop assumptions and generate the results.

3.3.1. Use (B1-B7)

This stage is related to any activities to ensure the functionality of stone countertop in its lifetime. Reference service life (RSL) for residential countertops is 10 years. Due to the nature of natural stone, it will last longer than 10 years and will need no replacements during the service life. Natural stone countertops routinely perform their desired function and will mostly require no additional sealing or grouting in the service life. The quality of sealer significantly influences the frequency of sealing, and some sealer manufacturers recommend doing it every 5 years. Although people rarely re-seal their countertops, we have taken a conservative assumption that non-granite stone countertops will be resealed every 5 years with the use of 0.165 kg silicone-based sealing[6]. For the reference service life, only one cycle of sealing will be needed.

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[6] https://www.naturalstonetiles.com.au/2016/09/23/guide-sealing-natural-stone-tiles/
Assumed 1 liter of sealant coat used for 5-10 square meters of non-granite stone countertops (same amount as stone tiles).

Under normal operating conditions, stone countertop also requires periodic cleaning and the cleaning agent used is water with soap. We assumed a weekly cleaning schedule using detergent and rinsing with tap water – 5 grams of detergent with 0.1 liter of water is consumed during each cycle of cleaning per m^2 of stone countertop [4].

Other than this maintenance, stone countertop requires no repair, replacement, or refurbishment during its entire service life. It also does not consume energy during its operation.

3.3.2. Deconstruction (C1)

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

3.3.3. End of Life Transport (C2)

Deconstructed stone countertop is then shipped to the end-of-life disposal centers. We assumed that the transport for final countertop disposal is 32 km.

3.3.4. Waste Processing (C3)

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

3.3.5. Final Disposal (C4)

Based on US EPA's data on construction end waste disposal scenarios, it was assumed that 31.5% of stone countertop will be landfilled for inert disposal, while the rest will be recycled for various purposes [6].

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, producers, and fabricators 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, producers, and fabricators, 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 6.

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 members 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, producers, and fabricators 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 countertop 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 countertop. 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 14 shows the most relevant LCI datasets used in modeling the product systems.

Table 14. 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
Electricity - Fabricator	Manual dataset based on production share Manual dataset based on production share: - e-grid datasets for US based quarries,	US -EI 2.2	2018	US (includes different e-grid regions)
Electricity - Installation	Electricity, medium voltage (US)	Ecoinvent v3	2021	US
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. Quarry, Processor, Fabricator operations, and Installation

Datasets for all upstream and downstream raw materials were obtained from the ecoinvent v3.8 database. Table 15 shows the LCI datasets used in modeling the main raw materials used in either of quarries, producers, fabricators or during installation/use phase.

Table 15. 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
Detergent for cleaning	Soap	US-EI 2.2	2018	US
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

*represents proxy datasets used.

3.5.3. Transportation

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

Table 16. Transportation datasets used in inventory analysis

Transportation	Dataset name	Source	Year of publication	Geography
Transport for initial site visit for measurements	Transport, passenger car, petrol, fleet average	US -EI 2.2	2018	US

Transport of stone between facilities and then to building sites for installation	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 17 presents the relevant disposal datasets used in the model.

Table 17. 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, producers, and fabricators 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 and marble have been grouped together as other natural stone despite differences in the quarrying techniques.

- Quarrying and processing inventory specific to countertop are generated using the production share of countertops by stone types among participant countertop fabricators.
- 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.
- Countertop processing in processors is limited to cutting the quarried stone into slabs and polishing to be shipped to fabricators. Although other stone products like cladding and flooring go through additional manufacturing steps, because of the heavy polishing, it is assumed that countertop processing requires 10% more energy than other products. A sensitivity analysis is included in this study to see the robustness of this estimate.
- 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 11. 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.

No co-product allocation was necessary in countertop fabricator operations; inputs and outputs were divided evenly among the fabricated countertops by area.

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 Countertops Transparency Report which will be evaluated for conformance to the PCRs according to ISO 14025 [8] and the ISO 14040/14044 standards [9].

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 [10] (see Table 18). The impact indicators are derived using the 100-year time horizon[7] factors, where relevant, as defined by TRACI 2.1 classification and characterization [11]. Long-term emissions (> 100 years) are not taken into consideration in the impact estimate. USEtox indicators[8] are used to evaluate toxicity. Global warming potential (GWP) based on AR6 methodology developed by the Intergovernmental Panel on Climate Change (IPCC) 2021 was also calculated in addition to the GWP from TRACI methodology [12]. This GWP includes fossil-based, biogenic, CO_2 uptake, and land transformation CO_2 with a timeframe of 100 years.

Table 18. 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.

[7] 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.

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

With respect to global warming potential, biogenic carbon is included in impact category calculations and also reported separately. 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 [13].

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 [14] and weighting [15] conforming to the SM 2013 Methodology were applied.

Table 19. 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 natural stone countertops).

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 [16].

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 20 shows resource use, output and waste flows, and carbon emissions and removals per functional unit for natural stone countertops.

Table 20. Resource use, output and waste flows, and carbon emissions and removals per functional unit

	Unit	Material acquisition and pre-processing		Countertop Construction	Installation stage		Use & maintenance	End of life	
		Quarry Operations	Quarry to Processor Transport	Construction	Transport to Building site	Installation	Use	End of Life Transport	Final Disposal
		A1	A2	A3	A4	A5	B2	C2	C4
Energy consumption, energy type, and material resources									
Renewable fuels	MJ, LHV	6.57E+00	3.08E-02	1.60E+02	6.18E+00	2.41E+00	1.14E+02	8.42E-03	2.06E-03
Virgin renewable resources	MJ, LHV	1.85E+00	0	3.53E+00	0	4.81E-01	0	0	0
Fossil fuels	MJ, LHV	1.15E+02	1.97E+01	4.86E+02	2.44E+02	7.64E+01	3.04E+01	5.39E+00	9.93E-01
Nuclear fuels	MJ, LHV	1.87E+01	1.23E-01	2.04E+02	3.22E+00	2.26E+00	4.40E+00	3.38E-02	8.26E-03
Miscellaneous fuels	MJ, LHV	9.49E-04	4.82E-06	2.00E-02	5.01E-05	1.55E-03	1.10E+01	1.32E-06	2.47E-07
Virgin non-renewable resources	MJ, LHV	5.27E-01	0	1.59E-01	0	2.18E+00	0	0	0
Recycled resources	kg	0	0	0	0	0	0	0	0
Renewable secondary fuels	MJ, LHV	0	0	0	0	0	0	0	0
Non-renewable secondary fuels	MJ, LHV	0	0	0	0	0	0	0	0
Recovered energy	MJ, LHV	0	0	0	0	0	0	0	0
Use of net freshwater resources	m^3	8.90E+01	3.35E-03	1.57E+01	3.97E-01	1.86E+00	1.81E-01	9.18E-04	1.76E-04
Primary energy demand	MJ	1.43E+02	1.98E+01	8.53E+02	2.54E+02	8.15E+01	1.59E+02	5.43E+00	1.00E+00
Primary energy demand (fossil, nuclear)	MJ	1.34E+02	1.98E+01	6.90E+02	2.48E+02	7.86E+01	3.48E+01	5.42E+00	1.00E+00
Renewable (solar, wind, hydro, biomass)	MJ	8.42E+00	3.08E-02	1.63E+02	6.18E+00	2.90E+00	1.14E+02	8.42E-03	2.06E-03
Emissions to air									
Sulphur oxides (SO_x)	kg	1.11E-02	1.18E-03	6.41E-02	4.93E-03	7.07E-03	5.46E-03	3.21E-04	1.03E-04
Nitrogen oxides (NO_x)	kg	8.06E-02	4.89E-04	1.16E-01	1.37E-02	6.38E-02	8.57E-03	1.34E-03	8.4E-04
Carbon dioxide (CO_2)	Kg	6.17E+00	1.42E+00	4.62E+01	4.63E+00	4.61E+00	4.30E+00	3.88E-01	7.04E-02
Methane (CH_4)	kg	1.04E-02	1.44E-03	1.13E-01	4.58E-03	1.36E-02	1.31E-02	3.96E-04	4.30E-05
Nitrous oxide (N_2O)	kg	1.34E-04	5.84E-05	1.17E-06	2.18E-04	1.19E-04	1.57E-03	1.60E-05	1.90E-06
Carbon monoxide (CO)	kg	5.66E-02	2.65E-04	9.09E-02	2.22E-02	1.79E-02	6.23E-02	7.30E-05	2.16E-04
Water usage and emissions to water									
Phosphates, nitrates, dioxin, and heavy metals	kg	1.31E-03	5.33E-06	2.07E-02	2.04E-05	5.81E-05	3.58E-02	1.44E-06	2.60E-07
Consumption (total water input)	m^3	1.11E+02	3.78E-03	2.69E+01	7.84E-01	4.75E+00	2.52E-01	1.03E-03	2.03E-04
Output flows and waste category indicators									
Hazardous waste disposed	kg	1.51E-03	0	1.96E-03	0	0	0	0	0
Non-hazardous waste disposed	kg	6.41E-02	0	2.41E+01	0	9.45E-05	0	0	2.91E+01
High-level radioactive waste, conditioned, to final repository	kg	4.75E-03	1.73E-06	5.50E-02	4.37E-05	1.00E-06	1.84E-04	5.62E-07	1.08E-07
Intermediate- and low-level radioactive waste, conditioned, to final repository	kg	3.33E-06	6.13E-07	1.10E-05	4.08E-07	1.30E-10	3.19E-08	5.90E-07	4.62E-09
Components for re-use	kg	0	0	0	0	0	0	0	0
Landfill avoidance / materials for recycling	kg	2.79E+02	0	6.53E+01	0	2.80E-02	0	0	6.32E+01
Incineration with energy recovery	kg	0	0	0	0	0	0	0	0
Incineration without energy recovery	kg	0	0	0	0	0	0	0	0
Exported energy	MJ, LHV	0	0	0	0	0	0	0	0
Carbon emissions and removals									
Biogenic Carbon Removal from Product	kg CO_2	0	0	0	0	0	0	0	0
Biogenic Carbon Emission from Product	kg CO_2	0	0	0	0	0	0	0	0
Biogenic Carbon Removal from Packaging	kg CO_2	0	0	7.63E-02	0	3.81E-03	0	0	0
Biogenic Carbon Emission from Packaging	kg CO_2	0	0	0	0	1.12E-02	0	0	0
Biogenic Carbon Emission from Combustion of Waste from Renewable Sources Used in Production Processes	kg CO_2	0	0	0	0	0	0	0	0
Calcination Carbon Emissions	kg CO_2	0	0	0	0	0	0	0	0
Carbonation Carbon Removals	kg CO_2	0	0	0	0	0	0	0	0
Carbon Emissions from Combustion of Waste from Non-Renewable Sources used in Production Processes	kg CO_2	0	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 countertops 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 [11]. 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 [10].

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.

Global warming potential (GWP) based on AR6 methodology developed by the Intergovernmental Panel on Climate Change (IPCC) 2021 was also calculated and reported [12]. This GWP includes fossil-based, biogenic, CO_2 uptake, and land transformation CO_2 with a timeframe of 100 years.

5.2.1. Impact Assessment Results

The impact results have been calculated per functional unit of natural stone countertops and have been tabulated per life cycle stage in Table 21.

For natural stone countertops, the cradle to gate stages (A1-A3) dominates the results for all the impact categories. Impacts generated at quarries (A1), and during construction stage (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. Use of soap for periodic cleaning also generates impacts during the service life of natural stone countertops. Other than this, there is no other activity creating the impacts during the service life. Countertops delivery to construction sites

(A5) impacts are dependent of transport distance between the fabricator plants to the sites, and this also makes considerable impacts in numerous impact categories.

Table 21. Potential impact results per functional unit for natural stone countertops

Impact category	Unit	Material acquisition and pre-processing stage		Countertop Construction stage	Installation stage		Use & maintenance stage	End of life stage	
		Quarry Operations	Quarry to Processor Transport	Construction	Transport to Building site	Installation	Use	End of Life Transport	Final Disposal
		A1	A2	A3	A4	A5	B2	C2	C4
Ozone depletion (ODP)	kg CFC-11 eq	2.46E-07	2.94E-07	2.12E-06	9.09E-07	2.67E-07	1.83E-07	8.06E-08	1.22E-08
Global warming Potential, IPCC	kg CO_2 eq	8.58E+00	1.48E+00	3.67E+01	4.83E+00	4.97E+00	7.61E-02	4.06E-01	7.15E-02
Smog (SFP)	kg O_3 eq	2.27E+00	1.21E-01	2.90E+00	3.47E-01	1.60E+00	2.56E-01	3.33E-02	2.08E-02
Acidification (AP)	kg SO_2 eq	7.74E-02	4.62E-03	1.51E-01	1.53E-02	5.21E-02	1.93E-02	1.27E-03	6.89E-04
Eutrophication (EP)	kg N eq	6.80E-03	6.22E-04	3.04E-02	2.07E-03	3.75E-03	1.46E-02	1.70E-04	6.74E-05
Carcinogenics	CTUh	3.80E-07	6.13E-10	1.28E-06	3.37E-09	1.26E-07	2.09E-08	1.68E-10	2.09E-11
Non-carcinogenics	CTUh	1.02E-06	5.54E-08	3.19E-06	1.26E-07	7.12E-07	2.22E-07	1.52E-08	8.28E-10
Respiratory effects	kg $PM_{2.5}$ eq	9.81E-03	2.90E-04	5.32E-02	1.18E-03	1.70E-03	7.59E-03	7.94E-05	8.94E-05
Ecotoxicity	CTUe	1.77E+01	8.04E-01	3.25E+01	1.17E+00	1.31E+01	3.61E+00	2.20E-01	6.79E-03
Fossil fuel depletion (ADP_{fossil})	MJ, LHV	1.50E+01	3.01E+00	5.55E+01	9.81E+00	1.11E+01	4.13E+00	8.23E-01	1.51E-01
Global warming potential (TRACI)	kg CO_2 eq	8.60E+00	1.48E+00	4.39E+01	4.81E+00	4.95E+00	5.09E-02	4.04E-01	7.14E-02

Single score results

The SM 2013 Methodology single figure millipoint (mPts) score by life cycle phase for this product is presented below in Table 22. The scores are consistent with the trends in the results using the impact assessment results before normalization and weighting. Construction stage (A3) dominates the results (~64%) followed by the quarry operation (A1) stage (~19%), and the installation (A5) of countertops (~9%). Periodic maintenance of the countertops (B2) and the transport of countertops to the building sites (A4) also have significant contributions to the overall life cycle impacts.

Table 22. SM 2013 scores for natural stone countertops by life cycle stage per functional unit

Impact category	Unit	Material acquisition and pre-processing stage		Countertop Construction stage	Installation stage		Use & maintenance stage	End of life stage	
		Quarry Operations	Quarry to Processor Transport	Construction	Transport to Building site	Installation	Use	End of Life Transport	Final Disposal
		A1	A2	A3	A4	A5	B2	C2	C4
SM single figure score	mPts	1.32E+00	6.22E-02	4.38E+00	1.91E-01	6.24E-01	2.08E-01	1.70E-02	3.84E-03

5.2.2. Contribution Analysis

Table 23 and Figure 4 show the contributions of each stage of the life cycle for natural stone countertops to the environmental impact categories.

Table 23. Percent contributions of each stage to each impact category

Impact category	A1	A2	A3	A4	A5	B2	C2	C4
Ozone depletion	6.0%	7.2%	51.5%	22.1%	6.5%	4.5%	2.0%	<1%
Global warming, IPCC	15.0%	2.6%	64.3%	8.4%	8.7%	<1%	<1%	<1%
Smog	30.0%	1.6%	38.4%	4.6%	21.2%	3.4%	<1%	<1%
Acidification	24.1%	1.4%	46.9%	4.8%	16.2%	6.0%	<1%	<1%
Eutrophication	11.6%	1.1%	52.0%	3.5%	6.4%	25.0%	<1%	<1%
Carcinogenics	21.0%	<<1%	70.7%	<1%	6.9%	1.2%	<<1%	<<1%
Non-carcinogenics	19.0%	1.0%	59.8%	2.4%	13.3%	4.2%	<1%	<<1%
Respiratory effects	13.3%	<1%	72.0%	1.6%	2.3%	10.3%	<1%	<1%
Ecotoxicity	25.6%	1.2%	47.0%	1.7%	18.9%	5.2%	<1%	<<1%
Fossil fuel depletion	15.1%	3.0%	55.8%	9.9%	11.2%	4.1%	<1%	<1%

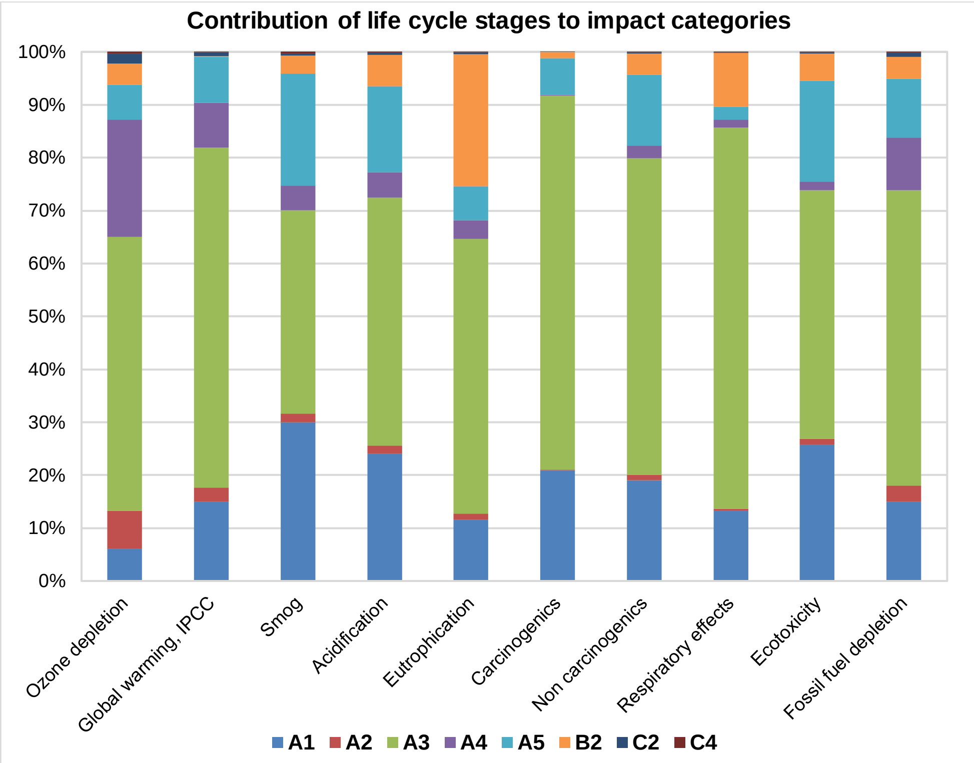

Figure 4. Contribution of life cycle stages of natural stone countertops to impact categories

Construction stage (A3) is the highest contributor to all impact categories, followed by either quarry operations (A1) in all categories but ozone depletion. Countertop transport to building sites (A4) stage follows construction stage ozone depletion impacts. Cradle to gate stages (A1-A3) contribute to more than 65% of the total impacts in all the impact categories. Impacts from quarry operations is followed by the impacts from stone transport (A2), and installation (A5) stage in most of the impact categories.

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 5. Construction operations (A3) stage is responsible for ~64% of total CO_2 emissions while quarry operations make up ~15% of total CO_2 emissions. Within A3, 48% of the emissions come from processor operations, while 52% come from the fabricator operations. Fuels (mainly natural gas, gasoline, and LPG) used for various purposes contributes to ~38%, and grid electricity contributes to ~52% of the total emissions generated from fabricators. In case of processors as well, fuels and grid electricity contribute to almost all of the total emissions, electricity contributing to ~56% of the emissions, while other fuels making ~39% of the emissions. Electricity and fuels used also share most of the A1 emissions; electricity makes up ~25% of total A1 emissions while combustion/use of fuels contributes to ~66%. Installation of countertop makes ~8% of total emissions, with ~95% emissions coming from energy consumed during installation and the rest coming from ancillary materials used during installation.

Periodic cleaning, resealing, and end of life scenarios generate insignificant emissions in global warming potential category.

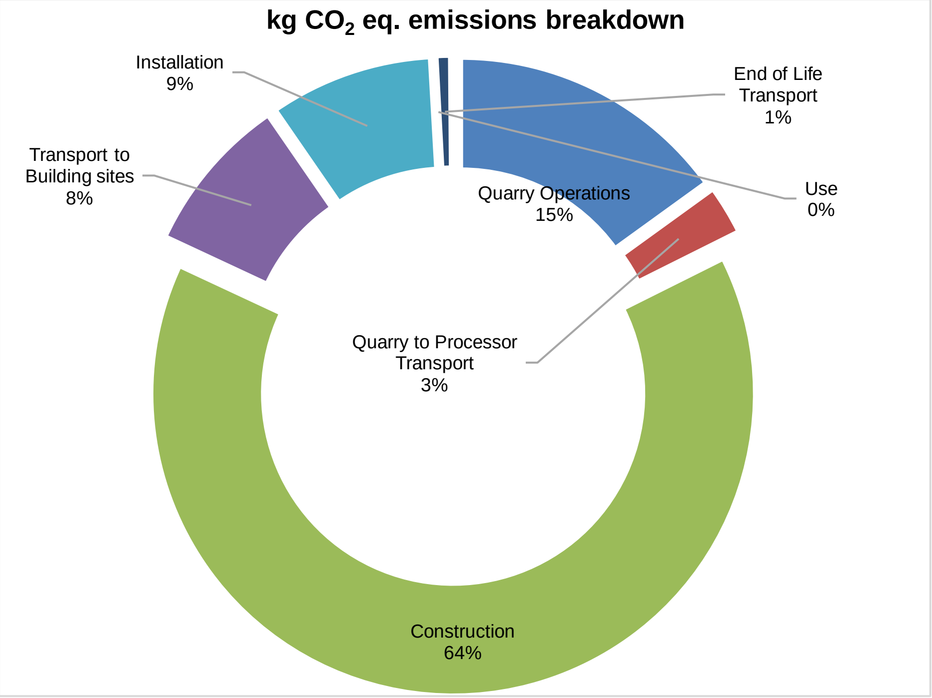

Figure 5. Breakdown of life cycle kg CO_2 eq emissions

Similar breakdown study for potential fossil fuel depletion is represented by Figure 6. Construction operations (A3) stage contributes to ~56% in this category while quarry operations make up ~15%. Within A3, 52% of the emissions come from processor operations, while 48% come from the fabricator operations. Fuels (mainly natural gas, gasoline, and LPG) used for various purposes contributes to ~55%, and grid electricity contributes to ~35% of the total fossil fuel depletion impacts generated from fabricators. In case of processors as well, fuels and grid electricity contribute to almost all of the total fossil fuel depletion impacts, electricity contributing to ~59% of the impacts, while other fuels making ~29% of the emissions. Electricity and fuels used also share most of the A1 fossil fuel depletion impacts; electricity makes up ~18% of total A1 emissions while combustion/use of fuels contributes to ~69%. Installation of countertop makes ~11% of total emissions, with ~82% emissions coming from energy consumed during installation and the rest coming from ancillary materials used during installation. Stone transport from quarries to processors (A2) and countertop transport to building sites (A4) also make significant share in the total fossil fuel depletion impacts with a combined share of ~13%.

Use of soap during cleaning makes ~4% of the fossil depletion impacts and end of life scenarios generate insignificant emissions in this category.

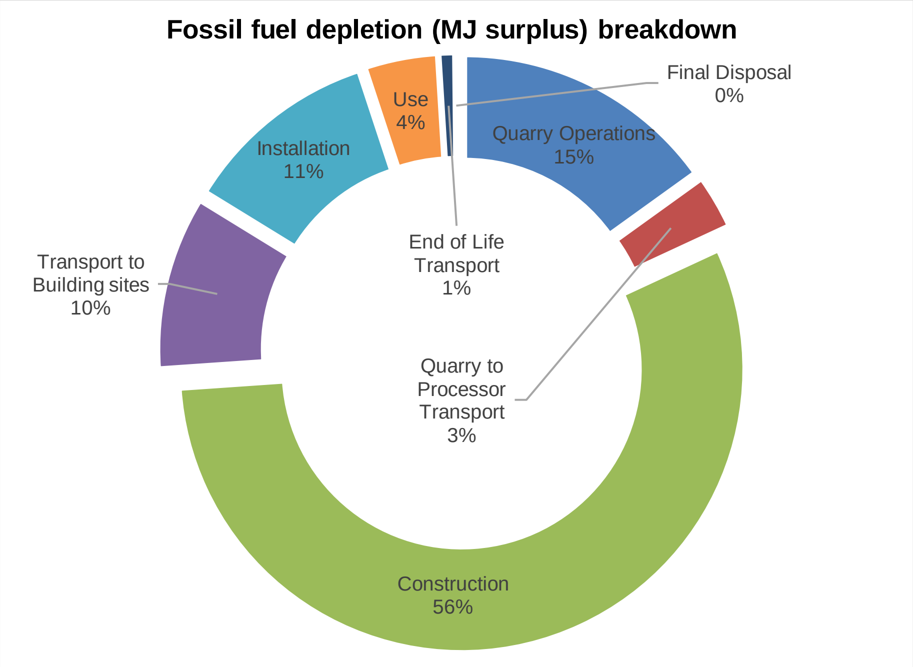

Figure 6. Breakdown of lifecycle fossil fuel depletion (MJ surplus)

For other impact categories, unit processes that contribute to more than 10% of the overall life cycle impacts have been identified and tabulated in Table 24.

Table 24. Drivers of life cycle impacts

Impact categories	Major flows greater than 10%	Actual contribution
Ozone depletion	Electricity for stone processing (A3 processor operations)	26.8%
	Transport of countertop from fabricator to building site (A4)	22.1%
	Electricity for countertop fabrication (A3 fabricator operations)	14.6%
Smog	Diesel combusted for stone quarrying (A1)	26.9%
	Electricity for stone processing (A3 processor operations)	17.1%
	Gasoline used during installation (A5)	13.6%
Acidification	Diesel combusted for stone quarrying (A1)	37.7%
	Electricity for stone processing (A3)	14.0%
	Diesel combusted for stone processing (A3 processor operations)	12.4%
	Gasoline used during installation (A5)	10.0%
Eutrophication	Electricity for stone processing (A3 processor operations)	20.7%
	Electricity for countertop fabrication (A3 fabricator operations)	10.7%

5.2.3. Variation Analysis

A variation analysis was performed to study the environmental impacts variation between natural stone countertops from different stone types. Results were generated for both quarry operations and construction stage specific to various stone. 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 countertops, which varies per stone type.

The minimum and maximum results presented in Table 25 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 20 through Table 23 also include the production share of each stone types in the final production.

Table 25. 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	3.26E-06	4.50E-06	1.38	3.75E-06	3.71E-06	4.11E-06	79%	109%
Global warming (GWP), IPCC	kg CO_2 eq	4.56E+01	7.35E+01	1.61	5.85E+01	5.68E+01	5.71E+01	80%	129%
Smog (SFP)	kg O_3 eq	5.91E+00	1.29E+01	2.19	7.99E+00	7.13E+00	7.54E+00	78%	171%
Acidification (AP)	kg SO_2 eq	2.65E-01	5.00E-01	1.89	3.26E-01	2.98E-01	3.21E-01	82%	155%
Eutrophication (EP)	kg N eq	4.93E-02	7.37E-02	1.50	5.68E-02	5.43E-02	5.85E-02	84%	126%
Carcinogenics	CTUh	7.70E-07	2.40E-06	3.12	1.40E-06	1.28E-06	1.81E-06	42%	132%
Non-carcinogenics	CTUh	4.14E-06	7.54E-06	1.82	5.07E-06	4.81E-06	5.34E-06	78%	141%
Respiratory effects	kg $PM_{2.5}$ eq	5.19E-02	9.24E-02	1.78	6.67E-02	6.37E-02	7.40E-02	70%	125%
Ecotoxicity	CTUe	4.88E+01	1.08E+02	2.21	6.76E+01	6.35E+01	6.92E+01	71%	156%
Fossil fuel depletion (ADP_{fossil})	MJ, LHV	8.35E+01	1.29E+02	1.55	9.81E+01	9.24E+01	9.95E+01	84%	130%

As shown in Table 25, there exists some variation between the weighted average, minimum, and maximum LCIA results. This all comes down to varying quarry and construction 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 countertops was calculated to be 10% more than the average stone processing for m^2 of other products as they go through heavy polishing than other stone products and consume 10% more energy.

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 26, a ~10% variation in the A3 stage is observed in both potential CO2 equivalent emissions and fossil fuel depletion. But the variation in total life cycle impacts is less than 10%; ~6% is observed in both impact categories. Other impact categories also follow the similar trend.

Table 26. Sensitivity analysis of the LCIA results, per functional unit

	A3 stage impacts	Total life cycle impacts

Stone processing scenarios for countertop	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	36.731		55.522		57.141		99.532	
Stone processing with 20% more energy	40.276	110%	61.250	110%	60.686	106%	105.260	106%
Stone processing with 20% less energy	33.186	90%	49.794	90%	53.596	94%	93.803	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 quarrying and construction stage. Within A1-A3, construction stage (A3) contributes 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 the use of fuels and electricity during installation. Additionally, it is assumed that stone countertop does not require any maintenance and repair other than periodic cleaning and resealing to achieve its reference service life, which is modeled as 10 years. No replacements are necessary; therefore, results represent the impacts associated with one square meter of natural stone countertops.

At the end of life, stone countertops 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 other than cleaning, for which secondary sources have been used, as suggested by NSI.

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, processors, and countertop fabricators. 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 countertops 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 and fabricators to process quarried stone into final stone countertops drive environmental performance. Delivery of countertops to the building sites, and the installation also result into significant impacts. Periodic maintenance of countertops and 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 quarry facilities, processor plants, and countertop fabricator sites. This is an important area for the NSI members to focus their efforts, since they can directly influence their own operations. Most of the impacts in all facilities 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. Scrap stone is generated in both quarries and construction facilities, 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. Energy consumed during installation has a significant contribution to impact categories so NSI should consider investigating more environment friendly energy options.

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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

- Compilation of data from NSI participants and LCI development workbook
- NSI Stone Countertops LCA results workbook