LIFE CYCLE ASSESSMENT (LCA) OF GRANITE, LIMESTONE, AND MARBLE STONE CLADDING BY POLYCOR

Status: Public report

Client: Polycor

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Contents

1 INTRODUCTION

1.1 Opportunity

Polycor is the world's leading natural stone quarrier and processor [1]. In line with their commitment to sustainability, it was important for Polycor to conduct their own company-specific Life Cycle Assessment (LCA) in parallel with their participation in the Natural Stone Institute's (NSI's) industry-wide LCA. The LCA will evaluate the environmental impacts of Polycor's stone cladding products in all life cycle stages, from stone quarrying to processing and through to the end of life. The goal of creating this LCA is to discover the full range of environmental impacts the stone cladding products have and to review these impacts along the product specific environmental declarations in order to identify processes and reduce overall impacts. This project is important to Polycor's commitment to provide information to the market to assess the environmental impacts associated with stone cladding products.

To understand the total impact of the product through all life cycle stages, Polycor 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.

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

Polycor commissioned Sustainable Minds, an external practitioner, to develop an LCA for three main product categories: stone cladding, stone flooring, and stone countertops. This document is focused on cladding. Polycor wants to communicate environmental information to the market as well as compare the industry-wide results to their own product-specific results so that they have guidance for future product improvements and can contribute towards satisfying credits in the Leadership in Energy and Environmental Design (LEED®) building rating system.

This LCA report is specific to stone cladding fabricated by Polycor. Results are presented separately for granite, marble, and limestone cladding.

1.2 Life Cycle Assessment

This report includes the following phases:

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

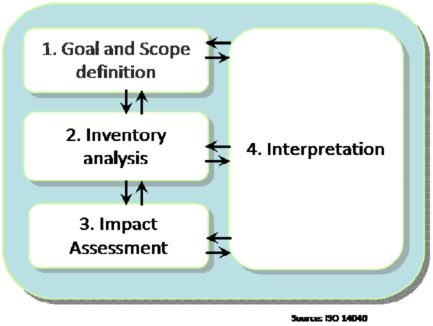

Figure 1. Phases in an LCA

A critical review of the LCA and an independent verification of the TRs 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 Polycor at the time it was collected, and best practices were followed by Sustainable Minds and Polycor to transform the inventory into this LCA report.

The data for all stone products were collected from Polycor covering a period of two years, January 2020 to December 2021. Data for quarry operations were collected from several facilities across eight US states; Quebec, Canada; and France. Data were provided in five consolidated groups as listed in Table .

After the stone is extracted from the quarry it goes to a processing facility. Stone processor operations data were collected from facilities in five US states and Quebec, Canada. Polycor processor data were provided in four consolidated groups as listed in Table 2. Cladding products were produced at all facility groups which submitted data.

Polycor resources and other literature data were used to develop estimates or assumptions for other upstream or downstream activities where necessary. Where relevant, this LCA uses the same assumptions as the NSI industry-wide LCA for consistency.

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 Jasmin Randlett and Ralph Morgan on behalf of Polycor. Jasmin and Ralph were assisted by Polycor staff during the data collection, reporting, and interpretation phases.

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

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: Results 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 cladding processed and fabricated by Polycor. 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 Polycor's 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), which is intended for business-to-business and business-to-consumer communications.

2.2 Stone Cladding

Polycor is the world's leading natural stone quarrier and processor [1]. Polycor produces various natural stone products.

Polycor is interested in demonstrating its sustainability leadership. It is also interested in leveraging business value associated with transparent reporting of natural stone cladding's cradle-to-grave environmental impacts. Polycor's natural stone cladding is made of natural stone and the different types included in this study are granite, limestone, and marble. It is used in commercial, residential, and public sector buildings.

Natural stone extracted from quarries goes to processing facilities where the quarried material is processed into cladding. The quarries and their type of stone are listed in Table 1. Processing facilities are listed in Table 2.

All processing facilities produced natural stone cladding.

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

Polycor data group	Stone type	Quarry location(s)
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
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
North American Limestone Quarries	Limestone	Adams Quarry, Bloomington, IN; Empire Quarry, Oolitic, IN; Eureka Quarry, Bedford, IN; Victor Quarry, Bloomington, IN
North American Marble Quarries	Marble	Polycor Georgia Marble Quarry, Tate, GA; Saint Clair Quarry, Marble City, OK
French Limestone Quarries	Limestone	Massangis Quarry, Massangis, France; Rocherons Quarry, Corgoloin et Comblanchien, France

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

Polycor data group	Stone type	Plant location(s)
American Granite Plants	Granite	Mount Airy Plant, Mount Airy, NC; Concord Plant, Concord, NH; Jay White Plant, Jay, ME
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;
North American Limestone Plants	Limestone	Empire Plant, Oolitic, IN; Eureka Plant, Bedford, IN; Victor Plant, Bloomington, IN
North American Marble Plant	Marble	Georgia Marble Plant, Tate, GA

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 vertical covering [3].

The natural stone cladding product systems for granite, limestone, and marble are weighted average of Polycor's stone-specific quarries and production facilities. The product system in this study also includes the ancillary materials used in the installation of the product – mortar and masonry connectors [4]. Polycor produces only the natural stone component while the installer purchases the ancillary materials separately. Materials required to meet the functional unit, including the ancillary materials for installation, have been listed in Table 3.

Table 3. Materials required to meet the functional unit

<table>
<tr><th>Product</th><th>Functional unit</th><th>Stone mass per functional unit</th><th>Materials needed to meet functional unit</th></tr>
<tr><td>Granite Cladding</td><td rowspan="3">One square meter (m^2) of installed product</td><td>89.77 kg per m^2</td><td rowspan="3">Mortar – 4.88 kg per m^2
Masonry connectors – 0.62 kg per m^2
Water – 1 liter per m^2 [5]</td></tr>
<tr><td>Limestone Cladding</td><td>81.35 kg per m^2</td></tr>
<tr><td>Marble Cladding</td><td>129.94 kg per m^2</td></tr>
</table>

Associated properties for natural stone cladding are indicated in Table 4 per relevancy, with the appropriate test method. Technical properties are specific to each stone type.

Table 4. Technical information table for natural stone cladding

Name	Natural stone			Unit	Test method
	Granite	Limestone	Marble		
Thickness to achieve Functional unit	42.11	56.77	48.16	mm	NA
Product weight	89.77	81.35	129.94	kg/m^2	NA
Density	[redacted]	[redacted]	[redacted]	kg/m^3	NA
Length[1]	1.52	1.52	1.52	m	NA
Width	0.66	0.66	0.66	m	NA
Flexural strength	8.27	3.45	6.89	MPa	ASTM C880
Modulus of Rupture	10.34	2.76	6.89	MPa	ASTM C99
Compressive Strength	131.00	12.41	51.71	MPa	ASTM C170
Thermal conductivity (k-value)	1.73	1.26	2.07	W/mK	ASTM C518
Thermal resistance (R-value)[2]	0.56	0.79	0.49	m.K/W	ASTM C518
Liquid water absorption	0.1-1.0	10-15	0.1-1.0	% of dry weight	ASTM C97
VOC emissions[3]	0	0	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, processing, and fabrication
- Distribution and installation

II. **B1-B7**
- Use

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

This boundary applies to the modeled product and can be referred to as 'cradle-to-grave', which means that it includes all life cycle stages and modules as identified in the PCR [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 cladding included in this LCA study. Table 5 lists specific inclusions and exclusions for the system boundary.

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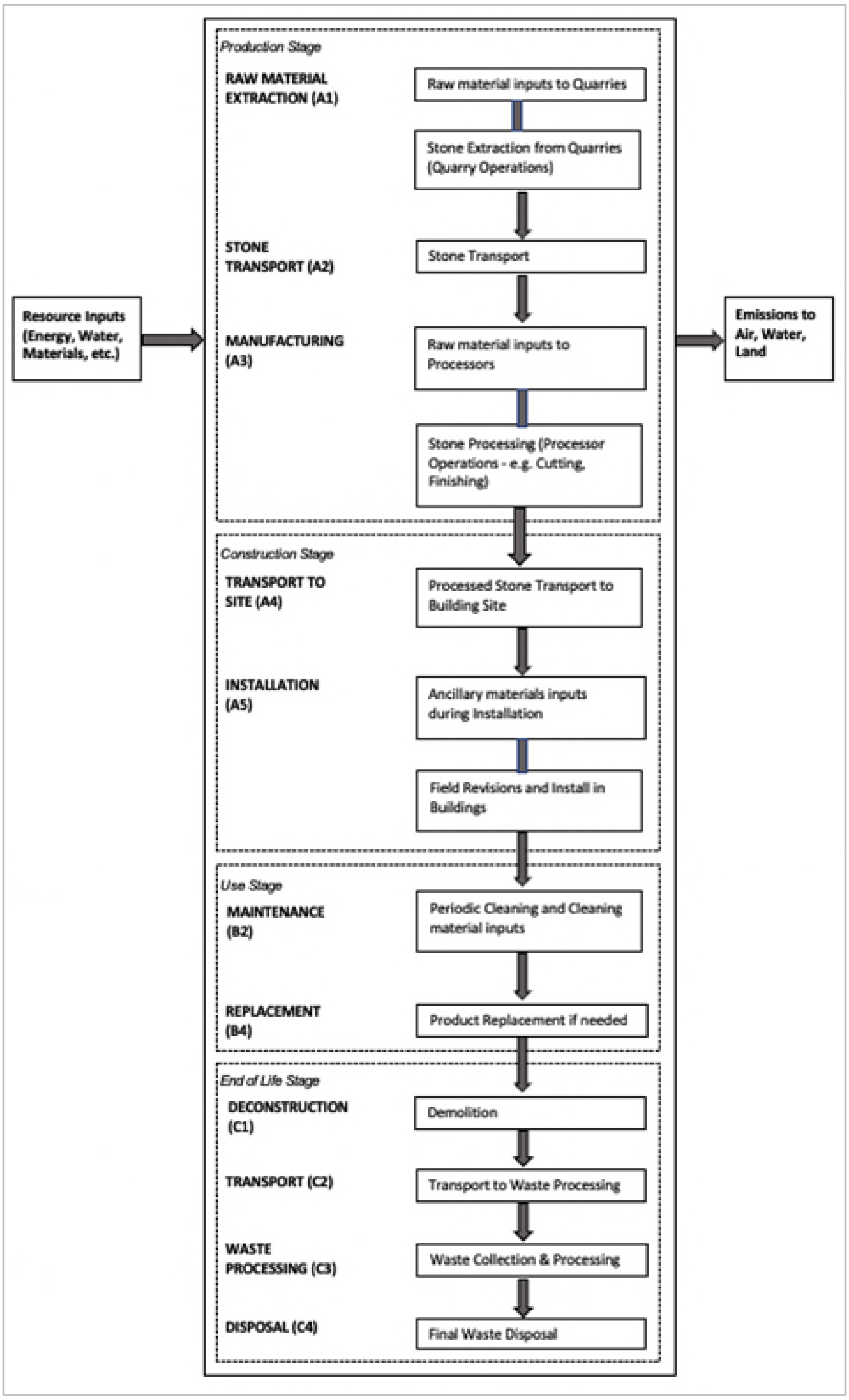
[1] Dimensions for a typical stone cladding is 5' * 3'

[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



*B1, B3, B5, B6, & B7 stages have no associated activities and are not shown in this flow diagram

Figure 2. Applied system boundary for natural stone cladding

Table 5. System boundary inclusions and exclusions

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

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

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

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

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

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

Energy production is also included for all quarry and processor 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. The installation process is considered to be manual (no energy use). This stage includes:

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

2.4.3. B1-B7: Use

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

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

Repair (B3), Replacement (B4), and Refurbishment (B5) are not relevant to stone flooring. Estimated service life of buildings (ESL) is 75 years [3]. A product's RSL depends on the product properties and reference in-use conditions. Due to the nature of natural stone, it is anticipated that stone cladding will last for the lifetime of the building, so the reference service life of the cladding (RSL) is also considered to be 75 years. No replacement will be needed during the entire ESL.

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

2.4.4. C1-C4: Disposal/reuse/recycling

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

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

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

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

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

3.1 Data Collection

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

- **Gate-to-gate:** Data on stone extraction, processing materials, and fabricating the stone cladding were collected in a consistent manner and level of detail to ensure high quality data. All submitted data were checked for quality multiple times on the plausibility of inputs and outputs. All questions regarding data were resolved with Polycor. 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 Polycor from operations between January 2020 and December 2021. 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 Polycor to resolve any questions.

3.2 Primary Data

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

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

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

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

The stones quarried by Polycor in this study are granite, limestone, and marble. 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 Polycor 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 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.

Polycor uses various quarry techniques depending on the stone deposit and development of the quarry. Polycor provided quarry data as part of the parallel industry-wide LCA, including relevant raw material inputs, water inputs, energy sources, waste practices and total stone production. That primary data provided by Polycor was used to develop the inventory for this study. Data from multiple sites, as listed in Table 1, was aggregated to develop a weighted average inventory per kg of stone quarried for each stone type (granite, limestone, and marble).

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

Electricity and fuels used for office activities have been excluded. In most quarries, extracted blocks and stone that do not meet specifications are crushed and sold as aggregate material. 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 [7]. 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 quarries extracted [redacted] stone during the reporting time frame (2 years). A weighted inventory table was developed as depicted in Table 6 to represent 1 kg of natural stone extracted, each for granite, limestone, and marble.

Table 6. Polycor inventory to quarry 1 kg of natural stone

Resource category	Inputs & outputs	Unit	Granite	Limestone	Marble
Electricity	Electricity	kWh	[redacted]	[redacted]	[redacted]
Fuels	Gasoline	liters	[redacted]	[redacted]	[redacted]
	Gasoline E10	liters	[redacted]	[redacted]	[redacted]
	Diesel (100% petroleum-based)	liters	[redacted]	[redacted]	[redacted]
	Biodiesel 70%	liters	[redacted]	[redacted]	[redacted]
	Propane	liters	[redacted]	[redacted]	[redacted]
	Heating oil	liters	[redacted]	[redacted]	[redacted]
Waste Generation	Total EPM generated	kg	3.10E+00	1.51E+00	8.94E+00
	EPM kept onsite	kg	2.65E+00	1.11E+00	4.56E+00
	EPM sold	kg	4.58E-01	3.96E-01	4.38E+00
	Solid waste to landfill	kg	9.86E-04	2.50E-04	9.36E-03
	Waste to recycling	kg	1.22E-03	2.51E-05	1.57E-04
	Hazardous waste to recycling	kg	5.30E-05	1.36E-04	1.62E-04
Material inputs	ANFO	kg	[redacted]	[redacted]	[redacted]
	Detonating cord	kg	[redacted]	[redacted]	[redacted]
	Stainless steel	kg	[redacted]	[redacted]	[redacted]
	Wood products	kg	[redacted]	[redacted]	[redacted]
	Hydraulic fluid	kg	[redacted]	[redacted]	[redacted]
	Lubricant	kg	[redacted]	[redacted]	[redacted]
	Motor oil	kg	[redacted]	[redacted]	[redacted]
	Tires	kg	[redacted]	[redacted]	[redacted]
	Antifreeze	kg	[redacted]	[redacted]	[redacted]
	Diamond belts/ wires/blades	kg	[redacted]	[redacted]	[redacted]
Waste transport	Diesel powered truck	tkm	3.64E-04	6.62E-05	1.56E-03

Stone blocks extracted from quarries are then transported to the processing plants. Some quarries and processing plants are located next to each other, which require insignificant stone transport distance, while some plants are located farther from the quarries. Polycor provided primary data on this stone transport. In some cases, stone was picked up by customers and no distance information was available. The transport distance varies and the weighted transport distances for granite, limestone, and marble are 83 km, 36 km, and 157 km respectively. In the cases with no primary distance available, we assumed a conservative stone transport distance of 100 km via truck & trailer.

3.2.2. Manufacturing (A3) – Processor operations

At the processing facilities, stone blocks go through a series of block saws and saw slabs, and later to bridge saws to complete cut-to-size pieces and profiling. All products are checked for quality control and then stacked on pallets. Stone pallets are stored in a yard until shipped to the building site.

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

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. Recycling methods include filling on premises and processing 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.

Polycor processors processed [redacted] stone during the reporting time frame (2 years). A weighted average inventory per m^2 of stone processed for each stone type (granite, limestone, and marble) was developed as represented in Table 7. Consistent with the NSI industry-wide LCA, this study also assumes that the energy consumed for processing cladding stone is similar to the average energy consumed to process various stone products.

Table 7. Polycor inventory to process 1 m^2 of stone cladding

Resource category	Inputs & output	Unit	Granite	Limestone	Marble
Electricity	Electricity	kWh	[redacted]	[redacted]	[redacted]
Fuels	Gasoline	liters	[redacted]	[redacted]	[redacted]
	Diesel	liters	[redacted]	[redacted]	[redacted]
	Propane	liters	[redacted]	[redacted]	[redacted]
	Natural gas	MJ	[redacted]	[redacted]	[redacted]
	Heating oil	liters	[redacted]	[redacted]	[redacted]
Material inputs	Wood products	kg	[redacted]	[redacted]	[redacted]
	steel banding	kg	[redacted]	[redacted]	[redacted]
	plastic banding	kg	[redacted]	[redacted]	[redacted]
	Diamond blades/wires	kg	[redacted]	[redacted]	[redacted]
	Cardboard	kg	[redacted]	[redacted]	[redacted]
Waste Generation	Waste to landfill	kg	3.74E-01	7.07E-02	8.91E+00
	Recycling	kg	1.80E-01	0	9.83E-02
	Hazardous (to recycler)	kg	6.74E-02	5.16E-03	3.36E-02
Waste transport	Diesel powered truck	tkm	1.00E-01	1.22E-02	1.46E+00

Polycor provided primary data as part of the corresponding industry-wide LCA, including energy, water, waste, and production. 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 8.

Thickness breakdown information was provided by all Polycor facilities. Table 9 lists the stone mass per m^2 and weighted density calculation of stone produced from processors for different stone types.

Table 8. Share of end applications for produced stone

End stone application	Granite stone share	Marble stone share	Limestone stone share
Cladding	[redacted]	[redacted]	[redacted]
Flooring	[redacted]	[redacted]	[redacted]
Countertops	[redacted]	[redacted]	[redacted]
Others	[redacted]	[redacted]	[redacted]

Table 9. Stone mass per m^2 of cladding and final density

Stone category	Input stone kg per m^2 of cladding	Produced stone kg per m^2 of cladding	Weighted Density (kg/m^3)
Granite	[redacted]	[redacted]	[redacted]
Limestone	[redacted]	[redacted]	[redacted]
Marble	[redacted]	[redacted]	[redacted]

3.2.3. Distribution (A4)

Distribution refers to the transport of the produced stone cladding from the processing plants to the building sites for installation. Partial primary data on final shipping distance were provided by the facilities. Gaps were filled by assuming a transport distance of 100 km. Distribution information is listed in the table below.

Table 10. Distribution parameters for natural stone cladding, per functional unit

Name	Granite	Limestone	Marble	Unit
Fuel type	Diesel			
Liters of fuel[4]	0.41			l/100km
Vehicle type	Lorry, 16-32 ton			
Transport distance	199.5	100	100	km
Capacity utilization (including empty runs, mass based)	100			%
Gross density of products transported	2,654	2,307	2,699	kg/m^3
Capacity utilization volume factor	1			

3.3 Secondary Data

For life cycle stages after the transport of stone cladding to the building sites, secondary data sources are used to develop assumptions and generate the results.

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

3.3.1. Installation (A5)

Installation refers to the installation of stone cladding at the building sites. Even though cladding fabrication (cutting and finishing to required size) is done at the processing plants and is typically delivered to the job site ready for installation, minor changes may be necessary to accommodate design revisions. For consistency with the industry-average LCA, a stone scrap rate of 5% during cladding installation was used.

The amount of ancillary materials depend largely on the building design, but most stone cladding installations incorporate anchors and mortar, used either as masonry bed or to fill veneer cavities. In the absence of primary data, the amount of ancillary materials (mortar and masonry connectors) required per m^2 of stone cladding installation were taken from a published Natural Stone Cladding EPD [4], which is consistent with the NSI industry-average LCA assumption. Installation of 1 m^2 of stone cladding using cement mortar will also require 1 liter of water [8]. Installation is considered to be manual. Waste generated in this stage includes stone scrap, and stone packaging waste. For stone scrap, US EPA's end of life scenarios for construction waste is used (31.5% landfilled) and for packaging waste, a landfilling rate of 37% is used based on US EPA's data for containers and packaging [9]. Regardless of disposal scenarios, waste transport distance for both stone scrap and packaging waste is taken to be 100 km, as suggested by the PCR.

Table 11 provides the ancillaries and energy use required for the installation of natural stone cladding.

Table 11. Information during the installation of natural stone cladding, per functional unit

Name	Granite	Limestone	Marble	Unit
Installation scrap rate assumed	5			%
Ancillary materials Mortar Masonry connectors	 4.88 0.62			 kg kg
Net freshwater consumption	0.001			m^3
Electricity consumption	Not necessary			
Product loss per functional unit (scrap)	4.94	4.07	6.50	kg
Waste materials at the construction site before waste processing, generated by product installation (stone scrap, packaging waste, and installation mortar waste)	7.36	7.47	9.61	kg
Output materials resulting from on-site waste processing	0	0	0	kg
Mass of packaging waste specified by type Cardboard Wood	 0.009 3.29	 0 2.53	 0 3.11	 kg kg
Biogenic carbon contained in packaging	6.05	4.64	5.70	kg CO_2
Direct emissions to ambient air, soil, and water	0	0	0	kg
VOC emissions[5]	0	0	0	μg/m^3

3.3.2. Use (B1-B7)

This stage is related to any activities to ensure the functionality of stone cladding in its lifetime. Estimated service life for building is 75 years and due to the nature of natural

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

stone, it is anticipated that the stone cladding products will last for the lifetime of the building. Reference service life (RSL) thus meets ESL of 75 years and cladding will need no replacements during its service life.

Consistent with the industry-average LCA assumption, it was assumed that under normal operating conditions, stone cladding will not require any cleaning. Stone cladding also does not require any repair, replacement, or refurbishment during its entire service life. It also does not consume energy during its operation. Table 12 provides an overview of cleaning scenarios and parameters for natural stone cladding.

Table 12. Information on maintenance of natural stone cladding

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

3.3.3. Deconstruction (C1)

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

3.3.4. End of Life Transport (C2)

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

3.3.5. Waste Processing (C3)

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

3.3.6. Final Disposal (C4)

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

Table 13 provides an overview of the end-of-life scenarios and parameters for natural stone cladding from Polycor.

Table 13. Information on end-of-life scenarios for natural stone cladding

Name		Granite	Limestone	Marble	Unit
Collection process	Collected separately	0	0	0	kg
	Collected with mixed construction waste	104.27	86.85	135.44	kg
Recovery	Reuse	0	0	0	kg
	Recycling (68.5%)	71.42	59.47	92.78	kg
	Landfill (31.5%)	32.85	27.38	42.66	kg
Waste transport		100	100	100	km
Final Disposal		32.85	59.47	92.78	kg
Removal of biogenic carbon (excluding packaging)		0	0	0	kg CO_2

3.4 Data selection and quality

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

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

Completeness is a measure of the flows (mass, energy, emissions) that are included in the study in relation to the total flows covered in the scope of the product life cycle. We developed separate data collection forms for quarries and producers and worked extensively with Polycor to obtain a comprehensive set of primary data associated with the processing and fabrication processes. We considered the dataset complete based on our understanding of the processor and fabricator sites and a review with key stakeholders on the Polycor team. Even though we observe cut-off criteria consistent with those prescribed in the PCR, no known flows are deliberately excluded from this analysis other than those defined to be outside the system boundary as stated in Table 5.

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

Time coverage. Time coverage describes the age of the inventory data, and the period of time over which data is collected. Polycor provided primary data for a time period of January 2020 to December 2021. This time period of 2 years will be able to represent typical operations of quarries and production facilities. 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 Polycor quarries and producers in covering a range of technologies as described earlier in this document. Incorporation of this range provides a representative depiction of the industry average.

Geographical coverage. Data were collected from quarries and producers mainly operating in North America (mainly the US and Canada). Quarries in France are responsible for 5% of the total quarried stone included in this study. As such, the geographical coverage for this study is based on North American conditions. Whenever geographically relevant background data were not readily available, other geographies were used as proxies. Following production, stone cladding is shipped for use within North America. Installation, use, and end-of-life impact were modeled using background data that represents average conditions.

3.5 Background data

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

3.5.1. Fuels and energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from databases in SimaPro. For fuels, specific US based datasets for specific fuels were used if available. In cases where fuel mixes were specified (e.g., fossil and biofuel mixes), manual datasets were created to reflect the fuel ratios. Manual electricity datasets were developed to represent average Polycor quarry and Polycor producer facilities based on the grouping of data provided. 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 / US average electricity dataset*, - 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, Canada, France
Electricity - Producer	Manual dataset based on production share: - e-grid datasets for US based quarries / US average electricity dataset*, - Canadian average electricity dataset for Canada based quarries*	US -EI 2.2, Ecoinvent v3 (for Canada)	2018	US, Canada
Gasoline	Gasoline, combusted in equipment NREL	US -EI 2.2	2018	US
Diesel (100% petroleum based)	Diesel, combusted in industrial equipment NREL	US -EI 2.2	2018	US
Propane	LPG combustion, at industrial furnace	US -EI 2.2	2018	US
Natural Gas	Natural gas, combusted in industrial equipment NREL	US -EI 2.2	2018	North America
Heating Oil	Heat, light fuel oil, at industrial furnace	US -EI 2.2	2018	US
Oil	Heat, heavy fuel oil, at industrial furnace	US -EI 2.2	2018	US
Gasoline E10	Manual dataset with 90% petroleum + 10% corn ethanol	US -EI 2.2	2018	US
Biodiesel 70%	Manual dataset with 30% diesel + 70% soybean biodiesel*	US -EI 2.2	2018	US

**represents proxy datasets used.*

3.5.2. Raw materials extraction and transport

Datasets for all upstream and downstream raw materials were obtained from the ecoinvent v3.8 database. Table 15 shows the LCI datasets used in modeling the main raw materials used in either of quarries, producers 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
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
Diamond	Boron 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	Fiber, cotton	Ecoinvent v3	2021	Global
Lacquer thinner	White Spirit	Ecoinvent v3	2021	Global
Detergent for cleaning	Soap	US-EI 2.2	2018	US
Masonry connectors	Steel hot-deep galvanized coil	Industry data 2.0	2019	Global
Denatured alcohol	Ethanol from ethylene*	Ecoinvent v3	2021	Rest of World (non-Europe)
Acrylics	Acrylic binder	US-EI 2.2	2018	US
Flocculant (water purifier)	Aluminum sulphate, powder	US-EI 2.2	2018	US
Well water	Well water	Input from nature	N/A	US
Municipal water	Tap water, at user	Ecoinvent v3	2018	US
Surface water	River water	Input from nature	N/A	US
Mortar	Manual dataset	TCNA's Industry wide EPD for Mortar [7]	2016	North America

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

3.5.4. Disposal

Disposal processes were also obtained from ecoinvent database to represent disposal scenarios in US. Table 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

Polycor 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 aggregated primary data of country- and stone-specific quarries and production facilities, so as to effectively represent the stone-specific results, but actual operations at each of the quarries and producers vary.
- Some of the facilities provided partial primary data on materials consumed. For gaps in materials data, an average from other facilities was assumed. Total material consumed was normalized with the total production mass to generate material consumption per production mass of each stone type.
- As it was very difficult to collect primary transportation data for purchased materials, 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 facility and for each material.
- For the quarries with partial or no primary data on stone transport to processors, we have taken a conservative stone transport distance of 100 km via truck & trailer. The actual distance varies.
- Energy consumed for cladding stone processing is assumed to be similar to the average energy consumed for stone processing for stone processing of all stone products. A sensitivity analysis is included in this study to see the robustness of this assumption.

- Generic data sets used for material inputs, transport, and waste processing are considered good quality, but actual impacts from material suppliers, transport carriers, and local waste processing may vary.
- The impact assessment methodology categories do not represent all possible environmental impact categories.
- Characterization factors used within the impact assessment methodology may contain varying levels of uncertainty.
- LCA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

3.7 Criteria for the exclusion of inputs and outputs

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

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

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

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

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

3.8 Allocation

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

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. Similarly, no co-product allocation was required for processor operations as well since processing data was collected from processing plants specific to each stone type. The processor inputs and outputs were divided evenly among the processed stone 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 three Polycor Stone Cladding Transparency Reports – one each for granite, marble, and limestone – which will be evaluated for conformance to the PCRs according to ISO 14025 [11] and the ISO 14040/14044 standards [12].

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 [13] (see Table 18). The impact indicators are derived using the 100-year time horizon[6] factors, where relevant, as defined by TRACI 2.1 classification and characterization [14]. Long-term emissions (> 100 years) are not taken into consideration in the impact estimate. USEtox indicators[7] are used to evaluate toxicity. Emissions from waste disposal are considered part of the product system under study, according to the "polluter pays principle".

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.

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

[6] 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.

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

includes cement and calcium carbonate as ingredients. Calcination CO_2 emissions for cement are calculated and reported separately using a carbon intensity factor of 886 CO_2 per ton of cement [15]. Calcium carbonate is not calcined during the production of mortar.

Some emissions occur during blasting as explosives (ANFO, PETN) are used in quarrying. The emissions from the detonation of these explosives have been estimated using the emission factors from National Pollutant Inventory and added to the TRACI results [16].

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 [17] and weighting [18] 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 installed natural stone cladding). Results provided in this report may be scaled according to different thicknesses as desired.

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 [19].

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.

5.1.1. Resource use and waste flows – Granite cladding

Table 20 tabulates resource use, output and waste flows, and carbon emissions and removals per functional unit for granite cladding.

Table 20. Resource use; output and waste flows; carbon emissions and removals per functional unit of granite cladding

	Unit	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	Total
Resource use indicators																		
Renewable primary energy used as energy carrier (fuel) (RPRE)	MJ, LHV	5.95E+00	3.56E-02	1.02E+02	7.19E-02	1.96E+00	0	0	0	0	0	0	0	0	2.98E-02	0	2.33E-03	1.10E+02
Renewable primary resources with energy content used as material (RPRM)	MJ, LHV	6.83E-01	0	9.10E+01	0	0	0	0	0	0	0	0	0	0	0	0	0	9.17E+01
Total use of renewable primary resources with energy content (RPRT)	MJ, LHV	6.64E+00	3.56E-02	1.93E+02	7.19E-02	1.96E+00	0	0	0	0	0	0	0	0	2.98E-02	0	2.33E-03	2.02E+02
Non-renewable primary resources used as an energy carrier (fuel) (NRPRE)	MJ, LHV	1.30E+02	2.29E+01	3.61E+02	4.63E+01	4.18E+01	0	0	0	0	0	0	0	0	1.91E+01	0	1.13E+00	6.22E+02
Non-renewable primary resources with energy content used as material (NRPRM)	MJ, LHV	6.34E-01	0	5.81E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	6.44E+00
Total use of non-renewable primary resources with energy content (NRPRT)	MJ, LHV	1.30E+02	2.29E+01	3.67E+02	4.63E+01	4.18E+01	0	0	0	0	0	0	0	0	1.91E+01	0	1.13E+00	6.28E+02
Secondary materials (SM)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Renewable secondary fuels (RSF)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Non-renewable secondary fuels (NRSF)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recovered energy (RE)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Use of net freshwater resources (FW)	m^3	7.79E+01	1.20E-01	9.21E+00	2.43E-01	3.12E+00	0	0	0	0	0	0	0	0	1.00E-01	0	7.81E-03	9.07E+01
Output flows and waste category indicators																		
Hazardous waste disposed (HWD)	kg	8.00E-03	0	0.00E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	8.00E-03
Non-hazardous waste disposed (NHWD)	kg	1.49E-01	0	5.78E-01	0	2.50E+00	0	0	0	0	0	0	0	0	0	0	3.28E+01	3.61E+01
High-level radioactive waste, conditioned, to final repository (HLRW)	kg	7.98E-03	1.86E-06	2.57E-01	3.76E-06	3.17E-04	0	0	0	0	0	0	0	0	1.56E-06	0	1.21E-07	2.65E-01
Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW)	kg	2.84E-06	1.96E-08	2.63E-05	3.94E-08	6.48E-07	0	0	0	0	0	0	0	0	1.63E-08	0	1.28E-09	2.98E-05
Components for re-use (CRU)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Materials for recycling (MR)	kg	4.69E+02	0	3.49E+01	0	4.86E+00	0	0	0	0	0	0	0	0	0	0	7.14E+01	5.80E+02
Materials for energy recovery (MER)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exported energy (EE)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carbon emissions and removals																		
Biogenic Carbon Removal from Product (BCRP)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogenic Carbon Emission from Product (NCEP)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogenic Carbon Removal from Packaging (BCRK)	kg CO_2	0	0	6.05E+00	0	3.02E-01	0	0	0	0	0	0	0	0	0	0	0	6.35E+02
Biogenic Carbon Emission from Packaging (BCEK)	kg CO_2	0	0	0	0	4.59E+00	0	0	0	0	0	0	0	0	0	0	0	4.595E+00
Biogenic Carbon Emission from Combustion of Waste from Renewable Sources Used in Production Processes (BCEW)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Calcination Carbon Emissions (CCE)	kg CO_2	0	0	0	0	1.21E+00	0	0	0	0	0	0	0	0	0	0	0	1.21E+00
Carbonation Carbon Removals (CCR)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carbon Emissions from Combustion of Waste from Non-Renewable Sources used in Production Processes (CWNR)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5.1.2. Resource use and waste flows – Limestone cladding

Table 21 tabulates resource use, output and waste flows, and carbon emissions and removals per functional unit for limestone cladding.

Table 21. Resource use; output and waste flows; carbon emissions & removals per functional unit of limestone cladding

	Unit	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	Total
Resource use indicators																		
Renewable primary energy used as energy carrier (fuel) (RPRE)	MJ, LHV	1.94E+00	3.88E-01	1.11E+01	4.03E-02	1.96E+00	0	0	0	0	0	0	0	0	2.48E-02	0	1.94E-03	1.55E+01
Renewable primary resources with energy content used as material (RPRM)	MJ, LHV	7.54E-01	0	1.71E+01	0	0	0	0	0	0	0	0	0	0	0	0	0	1.78E+01
Total use of renewable primary resources with energy content (RPRT)	MJ, LHV	2.70E+00	3.88E-01	2.82E+01	4.03E-02	1.96E+00	0	0	0	0	0	0	0	0	2.48E-02	0	1.94E-03	3.33E+01
Non-renewable primary resources used as an energy carrier (fuel) (NRPRE)	MJ, LHV	7.69E+01	7.13E+01	1.43E+02	2.59E+01	4.18E+01	0	0	0	0	0	0	0	0	1.59E+01	0	9.43E-01	3.75E+02
Non-renewable primary resources with energy content used as material (NRPRM)	MJ, LHV	3.09E-01	0	4.60E-03	0	0	0	0	0	0	0	0	0	0	0	0	0	3.14E-01
Total use of non-renewable primary resources with energy content (NRPRT)	MJ, LHV	7.72E+01	7.13E+01	1.43E+02	2.59E+01	4.18E+01	0	0	0	0	0	0	0	0	1.59E+01	0	9.43E-01	3.76E+02
Secondary materials (SM)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Renewable secondary fuels (RSF)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Non-renewable secondary fuels (NRSF)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recovered energy (RE)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Use of net freshwater resources (FW)	m^3	9.08E+00	4.79E-02	3.47E+00	1.36E-01	3.12E+00	0	0	0	0	0	0	0	0	8.37E-02	0	6.50E-03	1.59E+01
Output flows and waste category indicators																		
Hazardous waste disposed (HWD)	kg	1.86E-02	0	0.00E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	1.86E-02
Non-hazardous waste disposed (NHWD)	kg	3.42E-02	0	7.42E-02	0	2.49E+00	0	0	0	0	0	0	0	0	0	0	2.74E+01	3.00E+01
High-level radioactive waste, conditioned, to final repository (HLRW)	kg	2.41E-03	7.42E-07	7.79E-03	2.11E-06	3.17E-04	0	0	0	0	0	0	0	0	1.30E-06	0	1.01E-07	1.05E-02
Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW)	kg	5.72E-09	7.79E-09	4.15E-05	2.21E-08	6.48E-07	0	0	0	0	0	0	0	0	1.36E-08	0	1.06E-09	4.22E-05
Components for re-use (CRU)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Materials for recycling (MR)	kg	2.07E+02	0	0.00E+00	0	4.98E+00	0	0	0	0	0	0	0	0	0	0	5.95E+01	2.71E+02
Materials for energy recovery (MER)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exported energy (EE)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carbon emissions and removals																		
Biogenic Carbon Removal from Product (BCRP)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogenic Carbon Emission from Product (NCEP)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogenic Carbon Removal from Packaging (BCRK)	kg CO_2	0	0	4.65E+00	0	2.32E-01	0	0	0	0	0	0	0	0	0	0	0	4.88E+00
Biogenic Carbon Emission from Packaging (BCEK)	kg CO_2	0	0	0	0	3.53E+00	0	0	0	0	0	0	0	0	0	0	0	3.53E+00
Biogenic Carbon Emission from Combustion of Waste from Renewable Sources Used in Production Processes (BCEW)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Calcination Carbon Emissions (CCE)	kg CO_2	0	0	0	0	1.21E+00	0	0	0	0	0	0	0	0	0	0	0	1.21E+00
Carbonation Carbon Removals (CCR)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carbon Emissions from Combustion of Waste from Non-Renewable Sources used in Production Processes (CWNR)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5.1.3. Resource use and waste flows – Marble cladding

Table 22 tabulates resource use, output and waste flows, and carbon emissions and removals per functional unit for marble cladding.

Table 22. Resource use; output and waste flows; carbon emissions and removals per functional unit of marble cladding

	Unit	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	Total
Resource use indicators																		
Renewable primary energy used as energy carrier (fuel) (RPRE)	MJ, LHV	1.95E+01	8.94E-02	7.04E+00	4.08E-02	1.96E+00	0	0	0	0	0	0	0	0	3.87E-02	0	3.02E-03	2.87E+01
Renewable primary resources with energy content used as material (RPRM)	MJ, LHV	0.00E+00	0	4.19E+01	0	0	0	0	0	0	0	0	0	0	0	0	0	4.19E+01
Total use of renewable primary resources with energy content (RPRT)	MJ, LHV	1.95E+01	8.94E-02	4.89E+01	4.08E-02	1.96E+00	0	0	0	0	0	0	0	0	3.87E-02	0	3.02E-03	7.06E+01
Non-renewable primary resources used as an energy carrier (fuel) (NRPRE)	MJ, LHV	3.06E+02	5.75E+01	5.03E+02	2.63E+01	4.23E+01	0	0	0	0	0	0	0	0	2.49E+01	0	1.47E+00	9.61E+02
Non-renewable primary resources with energy content used as material (NRPRM)	MJ, LHV	4.20E-01	0	1.85E+01	0	0	0	0	0	0	0	0	0	0	0	0	0	1.89E+01
Total use of non-renewable primary resources with energy content (NRPRT)	MJ, LHV	3.06E+02	5.75E+01	5.21E+02	2.63E+01	4.23E+01	0	0	0	0	0	0	0	0	2.49E+01	0	1.47E+00	9.80E+02
Secondary materials (SM)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Renewable secondary fuels (RSF)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Non-renewable secondary fuels (NRSF)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recovered energy (RE)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Use of net freshwater resources (FW)	m^3	5.65E+01	3.02E-01	4.69E+00	1.38E-01	3.12E+00	0	0	0	0	0	0	0	0	1.30E-01	0	1.01E-02	6.49E+01
Output flows and waste category indicators																		
Hazardous waste disposed (HWD)	kg	3.22E-02	0	3.16E-04	0	0	0	0	0	0	0	0	0	0	0	0	0	3.25E-02
Non-hazardous waste disposed (NHWD)	kg	1.86E+00	0	4.19E-01	0	2.04E+00	0	0	0	0	0	0	0	0	0	0	4.27E+01	4.70E+01
High-level radioactive waste, conditioned, to final repository (HLRW)	kg	1.46E-02	4.68E-06	3.90E-02	2.14E-06	3.17E-04	0	0	0	0	0	0	0	0	2.02E-06	0	1.58E-07	5.40E-02
Intermediate- and low-level radioactive waste, conditioned, to final repository (ILLRW)	kg	2.10E-08	4.91E-08	2.33E-04	2.24E-08	6.49E-07	0	0	0	0	0	0	0	0	2.12E-08	0	1.66E-09	2.34E-04
Components for re-use (CRU)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Materials for recycling (MR)	kg	1.78E+03	0	6.91E+01	0	6.41E+00	0	0	0	0	0	0	0	0	0	0	9.28E+01	1.95E+03
Materials for energy recovery (MER)	kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Exported energy (EE)	MJ, LHV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carbon emissions and removals																		
Biogenic Carbon Removal from Product (BCRP)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogenic Carbon Emission from Product (NCEP)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biogenic Carbon Removal from Packaging (BCRK)	kg CO_2	0	0	5.70E+00	0	2.85E-01	0	0	0	0	0	0	0	0	0	0	0	5.99E+00
Biogenic Carbon Emission from Packaging (BCEK)	kg CO_2	0	0	0	0	4.33E+00	0	0	0	0	0	0	0	0	0	0	0	4.33E+00
Biogenic Carbon Emission from Combustion of Waste from Renewable Sources Used in Production Processes (BCEW)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Calcination Carbon Emissions (CCE)	kg CO_2	0	0	0	0	1.21E+00	0	0	0	0	0	0	0	0	0	0	0	1.21E+00
Carbonation Carbon Removals (CCR)	kg CO_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carbon Emissions from Combustion of Waste from Non-Renewable Sources used in Production Processes (CWNR)	kg CO_2	0	0	0	0	0	0	0	0	0	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 cladding processed and fabricated by Polycor. Unlike life cycle inventories, which only report sums for individual inventory flows, the LCIA includes a classification of individual emissions with regard to the impacts they are associated with and subsequently a characterization of the emissions by a factor expressing their respective contribution to the impact category indicator. The end result is a single metric for quantifying each potential impact, such as 'global warming potential.'

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

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

5.2.1. Life cycle impact assessment – Granite cladding

Impact Assessment Results

The impact results have been calculated per functional unit of granite cladding and have been tabulated per life cycle stage in Table 23.

For granite cladding, the cradle to gate stages (A1-A3) dominates the results for all the impact categories. Impacts generated at quarries (A1) and processors (A3) are mainly because of the use of grid electricity and fuels consumed in those stages. Material inputs in those stages generate little impacts on comparison to electricity and fuel consumed. Cement mortar used during the installation (A5) of granite cladding also generates significant environmental impacts. Cladding delivery to construction sites (A4) and stone transport from quarry to processor (A2) impacts are dependent of transport distance between the quarries to processor plants and processor plants to the sites respectively, and these stages also make considerable impacts in numerous impact categories.

Table 23. Potential impact results per functional unit of granite cladding

Impact category	Unit	Quarry Operation	Quarry to Processor Transport	Processor Operation	Transport to Building site	Installation	Product use	Maintenance	Repair	Replacement	Refurbishment	Op. energy use	Op. water use	Deconstruction	End of Life Transport	Waste Processing	Final Disposal
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Ozone depletion (ODP)	kg CFC-11 eq	1.64E-07	3.41E-07	9.47E-07	6.88E-07	1.19E-07	0	0	0	0	0	0	0	0	2.85E-07	0	1.38E-08
Global warming	kg CO_2 eq	8.55E+00	1.71E+00	2.09E+01	3.45E+00	4.49E+00	0	0	0	0	0	0	0	0	1.43E+00	0	8.07E-02
Smog (SFP)	kg O_3 eq	2.83E+00	1.41E-01	2.24E+00	2.84E-01	2.46E-01	0	0	0	0	0	0	0	0	1.17E-01	0	2.35E-02
Acidification (AP)	kg SO_2 eq	9.16E-02	5.36E-03	1.00E-01	1.08E-02	1.69E-02	0	0	0	0	0	0	0	0	4.47E-03	0	7.79E-04
Eutrophication (EP)	kg N eq	6.68E-03	7.20E-04	1.44E-02	1.45E-03	9.23E-04	0	0	0	0	0	0	0	0	6.02E-04	0	7.62E-05
Carcinogenics	CTUh	3.83E-07	7.11E-10	9.35E-07	1.43E-09	2.67E-08	0	0	0	0	0	0	0	0	5.93E-10	0	2.36E-11
Non-carcinogenics	CTUh	1.13E-06	6.42E-08	1.75E-06	1.30E-07	3.23E-07	0	0	0	0	0	0	0	0	5.36E-08	0	9.36E-10
Respiratory effects	kg $PM_{2.5}$ eq	5.19E-03	3.36E-04	1.10E-02	6.78E-04	1.47E-03	0	0	0	0	0	0	0	0	2.81E-04	0	1.01E-04
Ecotoxicity	CTUe	2.10E+01	9.31E-01	2.21E+01	1.88E+00	9.27E-01	0	0	0	0	0	0	0	0	7.78E-01	0	7.67E-03
Fossil fuel depletion (ADP_{fossil})	MJ, LHV	1.66E+01	3.48E+00	2.36E+01	7.02E+00	2.97E+00	0	0	0	0	0	0	0	0	2.91E+00	0	1.71E-01

Single score results

The SM 2013 Methodology single figure millipoint (mPts) score by life cycle phase for granite cladding is presented below in Table 24. The scores are consistent with the trends in the results using the impact assessment results before normalization and weighting. For granite cladding, the processor operation stage (A3) dominates the results (~60%) followed by the quarry operation (A1) stage (~30%). Transport of cladding to installation sites (A4) and the installation (A5) also make considerable contributions to the single score results.

Table 24. SM 2013 scores for granite cladding by life cycle stage per functional unit

Impact category	Unit	Quarry Operation	Quarry to Processor Transport	Processor Operation	Transport to Building site	Installation	Product use	Maintenance	Repair	Replacement	Refurbishment	Op. energy use	Op. water use	Deconstruction	End of Life Transport	Waste Processing	Final Disposal
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
SM single score	mPts	1.37E+00	7.21E-02	2.72E+00	1.45E-01	1.86E-01	0	0	0	0	0	0	0	0	6.028E-02	0	4.34E-03

Contribution Analysis

Table 25 and Figure 3 show the contributions of each stage of the life cycle for granite cladding to the environmental impact categories.

Table 25. Percent contributions of each stage to each impact category for granite cladding

Impact category	A1	A2	A3	A4	A5	C2	C4
Ozone depletion	6.4%	13.3%	37.0%	26.9%	4.7%	11.1%	<1%
Global warming	21.0%	4.2%	51.5%	8.5%	11.1%	3.5%	<1%
Smog	48.1%	2.4%	38.1%	4.8%	4.2%	2.0%	<1%
Acidification	39.8%	2.3%	43.6%	4.7%	7.3%	1.9%	<1%
Eutrophication	26.9%	2.9%	58.0%	5.8%	3.7%	2.4%	<1%
Carcinogenics	28.4%	<1%	69.4%	<1%	2.0%	<<1%	<<1%
Non-carcinogenics	32.7%	1.9%	50.8%	3.8%	9.4%	1.6%	<<1%
Respiratory effects	27.3%	1.8%	57.6%	3.6%	7.7%	1.5%	<1%
Ecotoxicity	44.1%	2.0%	46.4%	3.9%	1.9%	1.6%	<<1%
Fossil fuel depletion	29.2%	6.1%	41.6%	12.4%	5.2%	5.1%	<1%

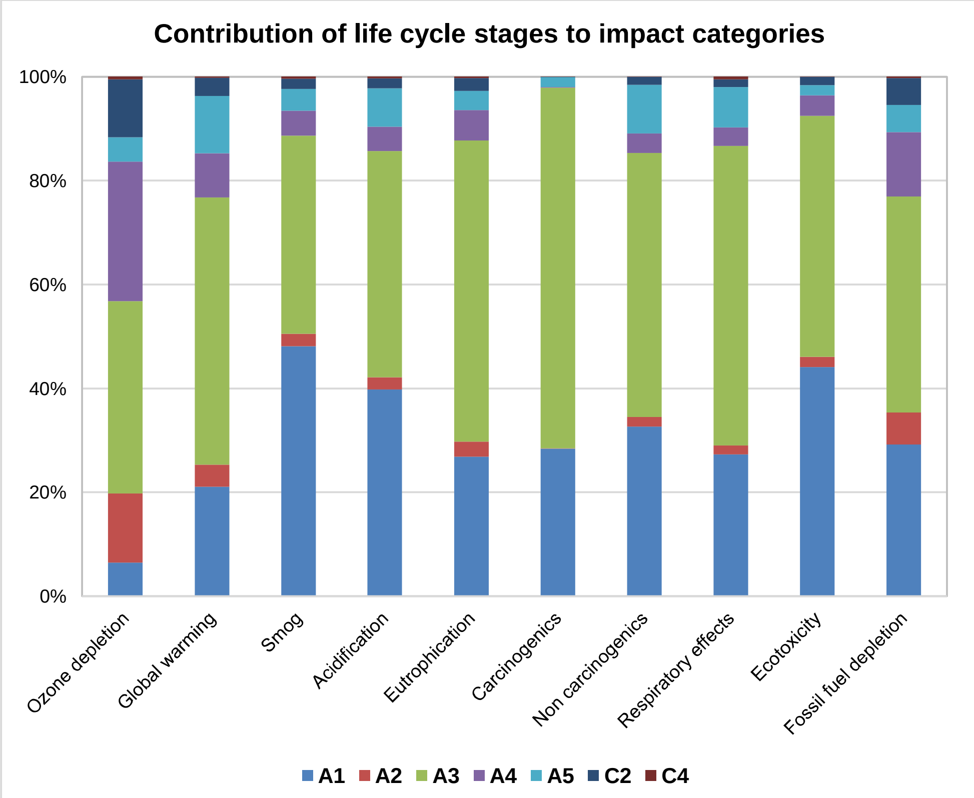


Figure 3. Contribution of each life cycle stages of granite cladding to each impact category

Processor operations (A3) stage is the highest contributor to most of the impact categories, followed by the quarry operations (A1). Cradle to gate stages (A1-A3) contribute to ~75% of the total impacts in all the impact categories but ozone depletion.

A detailed study has been performed for global warming potential and fossil fuel depletion as this is deemed most relevant and of interest to Polycor. Breakdown for potential CO_2 equivalent emissions is represented by Figure 4. Processor operations (A3) stage is responsible for ~52% of total CO_2 emissions while quarry operations make up ~21% of total CO_2 emissions. Within A3, fuels (mainly diesel, propane, and natural gas) used for various purposes contributes to ~50%, and grid electricity contributes to ~42% of the total emissions generated from processors. Electricity and fuels used also share most of the A1 emissions; electricity makes up ~15% of total A1 emissions while combustion/use of fuels contributes to ~76%.

Transport of granite stone from quarries to processors contributes to 4% of potential CO_2 emissions while the transport of granite cladding from processing sites to the installation sites make up ~9% of that. Installation makes ~11% of total CO_2 emissions and use of cement mortar is responsible for ~59% of the CO_2 emissions in this stage. At the end of life, transportation of discarded waste to either landfilling centers or recycling centers also generates considerable CO_2 emissions, ~4% of total.

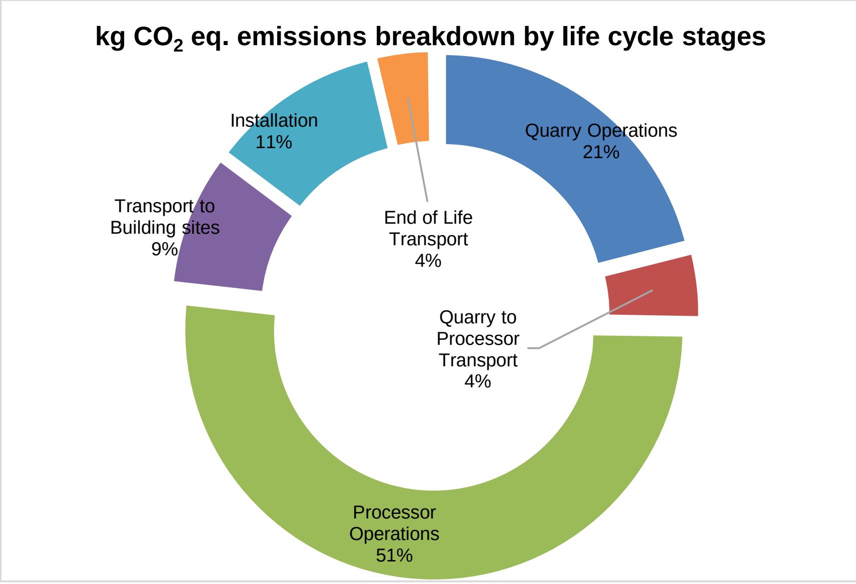


Figure 4. Breakdown of kg CO_2 eq emissions by life cycle stage for granite cladding

Similar breakdown study for potential fossil fuel depletion is represented in Figure 5. Processor operations (A3) stage contributes to ~42% in this category while quarry operations make up ~29%. Fuels (mainly natural gas, gasoline, and LPG) used for various purposes contributes to ~38%, and grid electricity contributes to ~48% of the total fossil fuel depletion impacts generated in A3 stage. Electricity and fuels used also share most of the A1 fossil fuel depletion impacts; electricity makes up ~8% of total A1 emissions while combustion/use of fuels contributes to ~80%. Installation of cladding makes ~5% of total impacts, with ~73% of that coming from the use of cement mortar. Stone transport from quarries to processors (A2) and cladding transport to building sites (A4) make significant share in the total fossil fuel depletion impacts with a combined share of ~19%, with two-third of that coming from A4 stage.

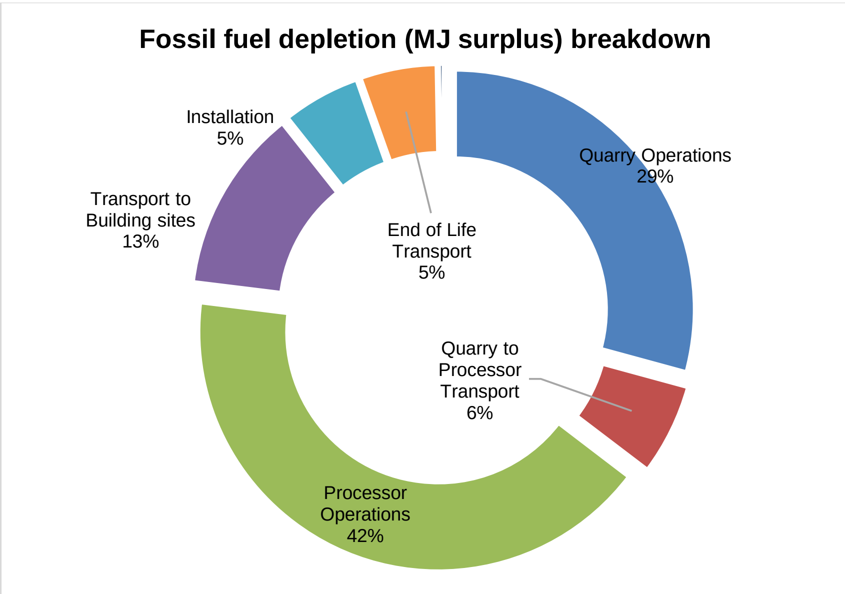


Figure 5. Breakdown of fossil fuel depletion impacts by life cycle stage for granite cladding

For other required impact categories per PCR, unit processes that contribute to more than 10% of the overall life cycle impacts of granite cladding have been identified and tabulated in Table 26.

Table 26. Drivers of life cycle impacts for granite cladding

Impact categories	Major flows (impacts > 10%)	Actual contribution
Ozone depletion	Transport of cladding to building sites	26.9%
	Electricity for stone processing	26.3%
	Transport of stone from quarries to processing sites	13.3%
	End of life transport	11.1%
Smog	Electricity for stone processing	27.4%
	Electricity for stone quarrying	24.8%
Acidification	Diesel combusted during stone quarrying	34.9%
	Diesel combusted during stone processing	18.7%
	Electricity for stone processing	15.5%
Eutrophication	Electricity for stone processing	37.9%
	Diesel combusted during stone quarrying	20.6%
	Diesel combusted during stone processing	11.0%

Sensitivity Analysis – Processor energy variation

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

A sensitivity analysis was performed to check the robustness of the results when the energy consumed is +-20% of the estimate used in this study. As shown in Table 27, a ~20% variation in the A3 stage is observed in both potential CO_2 equivalent emissions and fossil fuel depletion. But the variation in total life cycle impacts of granite cladding is ~10% for potential CO_2 equivalent emissions and ~8% for fossil fuel depletion impact category. Other impact categories also follow the similar trend.

Table 27. Sensitivity analysis per functional unit of granite cladding (varying processor energy)

Stone processing scenarios for stone cladding	A3 stage impacts				Total life cycle impacts			
	kg CO_2 eq emissions	% change from base	Fossil fuel depletion (MJ surplus)	% change from base	kg CO_2 eq emissions	% change from base	Fossil fuel depletion (MJ surplus)	% change from base
Base stone processing	20.901		23.569		40.599		56.679	
Stone processing with 20% more energy	25.081	120%	28.282	120%	44.779	110%	61.393	108%
Stone processing with 20% less energy	16.721	80%	18.855	80%	36.418	90%	51.965	92%

5.2.2. Life cycle impact assessment – Limestone cladding

Impact Assessment Results

The impact results have been calculated per functional unit of limestone cladding and have been tabulated per life cycle stage in Table 28.

Similar to granite cladding, for limestone cladding also the cradle to gate stages (A1-A3) dominate the results for all the impact categories. Impacts generated at quarries (A1) and processors (A3) are mainly because of the use of grid electricity and fuels consumed in those stages. Material inputs in those stages generate little impacts on comparison to electricity and fuel consumed. Cement mortar used during the installation (A5) of granite cladding also generates significant environmental impacts. Cladding delivery to construction sites (A4) and stone transport from quarry to processor (A2) impacts are dependent of transport distance between the quarries to processor plants and processor plants to the sites respectively, and these stages also make considerable impacts in numerous impact categories.

Table 28. Potential impact results per functional unit of limestone cladding

Impact category	Unit	Quarry Operation	Quarry to Processor Transport	Processor Operation	Transport to Building site	Installation	Product use	Maintenance	Repair	Replacement	Refurbishment	Op. energy use	Op. water use	Deconstruction	End of Life Transport	Waste Processing	Final Disposal
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Ozone depletion (ODP)	kg CFC-11 eq	1.42E-07	1.36E-07	3.60E-07	3.86E-07	1.19E-07	0	0	0	0	0	0	0	0	2.37E-07	0	1.15E-08
Global warming	kg CO_2 eq	5.24E+00	6.81E-01	7.86E+00	1.93E+00	4.49E+00	0	0	0	0	0	0	0	0	1.19E+00	0	6.72E-02
Smog (SFP)	kg O_3 eq	1.65E+00	5.60E-02	1.23E+00	1.59E-01	2.46E-01	0	0	0	0	0	0	0	0	9.79E-02	0	1.95E-02
Acidification (AP)	kg SO_2 eq	5.68E-02	2.13E-03	4.81E-02	6.06E-03	1.69E-02	0	0	0	0	0	0	0	0	3.72E-03	0	6.49E-04
Eutrophication (EP)	kg N eq	6.98E-03	2.87E-04	5.78E-03	8.15E-04	9.24E-04	0	0	0	0	0	0	0	0	5.01E-04	0	6.35E-05
Carcinogenics	CTUh	8.93E-08	2.83E-10	8.74E-08	8.04E-10	2.67E-08	0	0	0	0	0	0	0	0	4.94E-10	0	1.97E-11
Non-carcinogenics	CTUh	5.84E-07	2.56E-08	6.34E-07	7.26E-08	3.23E-07	0	0	0	0	0	0	0	0	4.47E-08	0	7.79E-10
Respiratory effects	kg $PM_{2.5}$ eq	3.58E-03	1.34E-04	1.16E-02	3.80E-04	1.47E-03	0	0	0	0	0	0	0	0	2.34E-04	0	8.42E-05
Ecotoxicity	CTUe	1.05E+01	3.71E-01	8.49E+00	1.05E+00	9.28E-01	0	0	0	0	0	0	0	0	6.48E-01	0	6.39E-03
Fossil fuel depletion (ADP_{fossil})	MJ, LHV	9.37E+00	1.39E+00	1.38E+01	3.94E+00	2.97E+00	0	0	0	0	0	0	0	0	2.42E+00	0	1.42E-01

Single score results

The SM 2013 Methodology single figure millipoint (mPts) score by life cycle phase for limestone cladding is presented below in Table 29. The scores are consistent with the trends in the results using the impact assessment results before normalization and weighting. For limestone cladding, the processor operation stage (A3) dominates the results (~41%) followed by the quarry operation (A1) stage (~36%). Transport of cladding to installation sites (A4) and the installation (A5) also make considerable contributions to the single score results.

Table 29. SM 2013 scores for limestone cladding by life cycle stage per functional unit

Impact category	Unit	Quarry Operation	Quarry to Processor Transport	Processor Operation	Transport to Building site	Installation	Product use	Maintenance	Repair	Replacement	Refurbishment	Op. energy use	Op. water use	Deconstruction	End of Life Transport	Waste Processing	Final Disposal
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
SM single score	mPts	5.43E-01	2.87E-02	6.09E-01	8.15E-02	1.87E-01	0	0	0	0	0	0	0	0	5.01E-02	0	3.62E-03

Contribution Analysis

Table 30 and Figure 6 show the contributions of each stage of the life cycle for limestone cladding to the environmental impact categories.

Table 30. Percent contributions of each stage to each impact category for limestone cladding

Impact category	A1	A2	A3	A4	A5	C2	C4
Ozone depletion	10.2%	9.8%	25.9%	27.7%	8.6%	17.0%	<1%
Global warming	24.4%	3.2%	36.6%	9.0%	20.9%	5.5%	<1%
Smog	47.7%	1.6%	35.6%	4.6%	7.1%	2.8%	<1%
Acidification	42.3%	1.6%	35.8%	4.5%	12.6%	2.8%	<1%
Eutrophication	45.5%	1.9%	37.6%	5.3%	6.0%	3.3%	<1%
Carcinogenics	43.6%	<1%	42.6%	<1%	13.0%	<1%	<<1%
Non-carcinogenics	34.7%	1.5%	37.6%	4.3%	19.2%	2.7%	<<1%
Respiratory effects	20.5%	<1%	66.3%	2.2%	8.4%	1.3%	<1%
Ecotoxicity	47.8%	1.7%	38.6%	4.8%	4.2%	2.9%	<<1%
Fossil fuel depletion	27.6%	4.1%	40.5%	11.6%	8.7%	7.1%	<1%

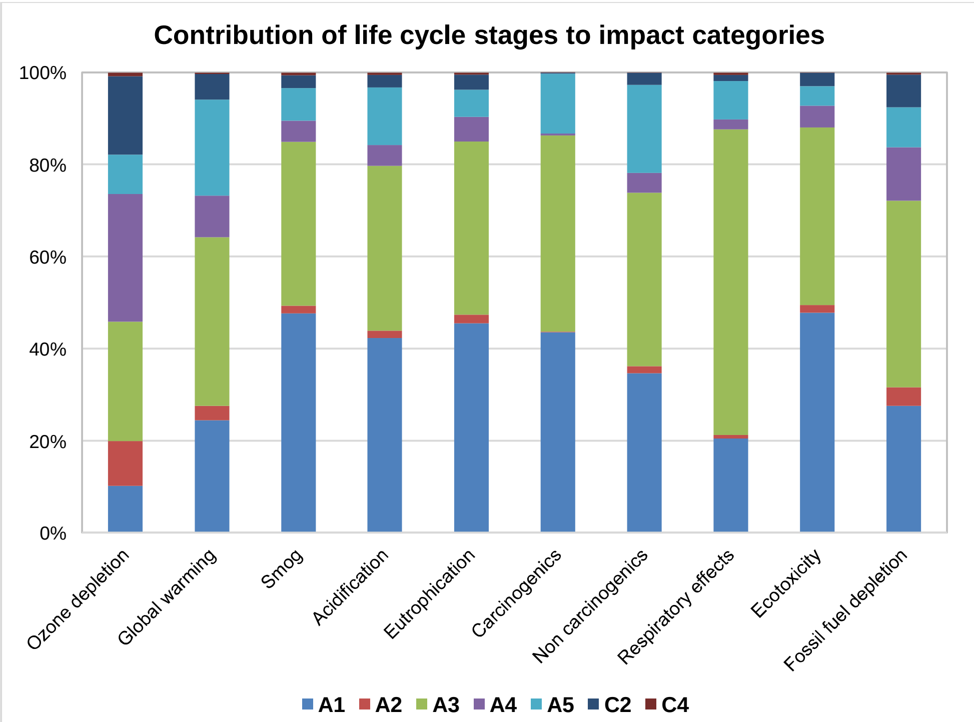


Figure 6. Contribution of each life cycle stages of limestone cladding to each impact category

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

A detailed study has been performed for global warming potential and fossil fuel depletion as this is deemed most relevant and of interest to Polycor. Breakdown for potential CO_2 equivalent emissions is represented by Figure 7. Processor operations (A3) stage is responsible for ~37% of total CO_2 emissions while quarry operations make up ~24% of total CO_2 emissions. Within A3, fuels (mainly diesel, propane, and natural gas) used for various purposes contributes to ~36%, and grid electricity contributes to ~46% of the total emissions generated from processors. Electricity and fuels used also share most of the A1 emissions; electricity makes up ~21% of total A1 emissions while combustion/use of fuels contributes to ~72%.

Transport of limestone from quarries to processors contributes to 3% of potential CO_2 emissions while the transport of granite cladding from processing sites to the installation sites make up ~9% of that. Installation makes ~21% of total CO_2 emissions and use of cement mortar is responsible for ~59% of the CO_2 emissions in this stage. At the end of life, transportation of discarded waste to either landfilling centers or recycling centers also generates considerable CO_2 emissions, ~6% of total.

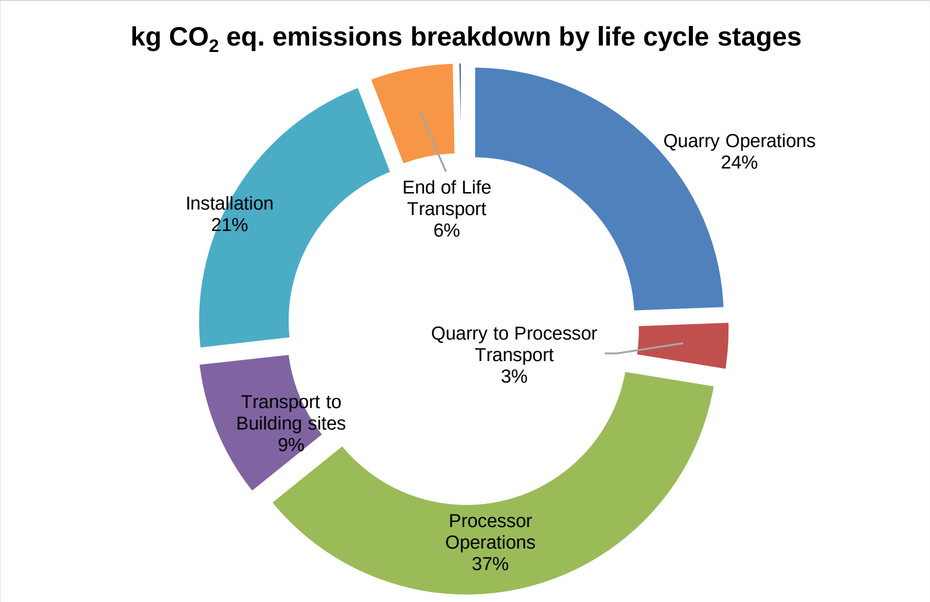


Figure 7. Breakdown of kg CO_2 eq emissions by life cycle stage for limestone cladding

Similar breakdown study for potential fossil fuel depletion is represented in Figure 8. Processor operations (A3) stage contributes to ~41% in this category while quarry operations make up ~28%. Fuels (mainly natural gas, gasoline, and LPG) used for various purposes contributes to ~59%, and grid electricity contributes to ~38% of the total fossil fuel depletion impacts generated in A3 stage. Electricity and fuels used also share most of the A1 fossil fuel depletion impacts; electricity makes up ~12% of total A1 emissions while combustion/use of fuels contributes to ~77%. Installation of cladding makes ~9% of total impacts, with ~73% of that coming from the use of cement mortar. Stone transport from quarries to processors (A2) and cladding transport to building sites (A4) make significant share in the total fossil fuel depletion impacts with a combined share of ~16%, with three quarters of that coming from A4 stage.

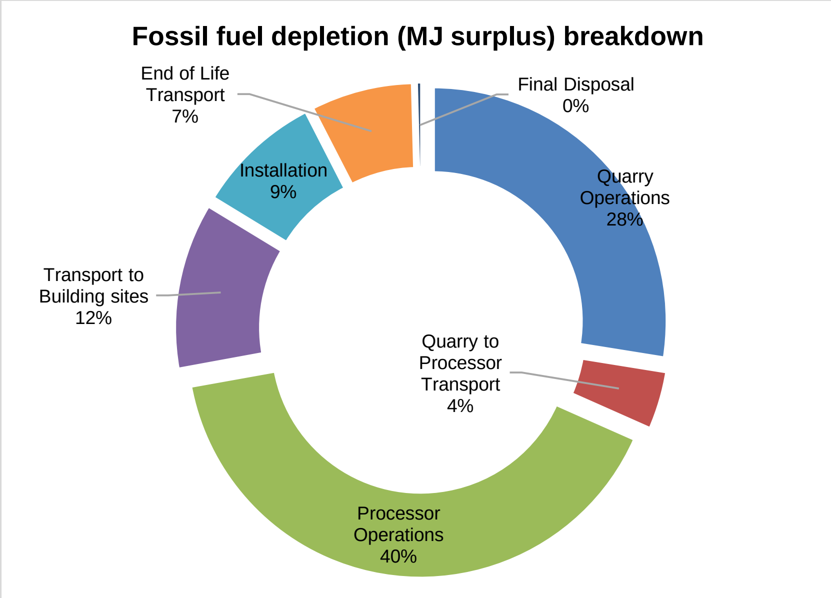


Figure 8. Breakdown of fossil fuel depletion impacts by life cycle stage for limestone cladding

For other required impact categories per PCR, unit processes that contribute to more than 10% of the overall life cycle impacts of limestone cladding have been identified and tabulated in Table 31.

Table 31. Drivers of life cycle impacts for limestone cladding

Impact categories	Major flows (impacts > 10%)	Actual contribution
Ozone depletion	Transport of cladding to building sites	27.7%
	Electricity for stone processing	23.2%
	End of life transport	17.0%
Smog	Diesel combusted during stone processing	30.0%
	Diesel combusted during stone quarrying	29.1%
	Electricity for stone quarrying	10.0%
Acidification	Diesel combusted during stone quarrying	31.3%
	Diesel combusted during stone processing	23.8%
Eutrophication	Electricity for stone processing	21.4%
	Bio-diesel combusted during stone quarrying	21.1%
	Diesel combusted during stone quarrying	17.5%
	Diesel combusted during stone processing	13.3%

Sensitivity Analysis – Processor energy variation

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

A sensitivity analysis was performed to check the robustness of the results when the energy consumed is +-20% of the estimate used in this study. As shown in Table 32, a ~20% variation in the A3 stage is observed in both potential CO_2 equivalent emissions and fossil fuel depletion. But the variation in total life cycle impacts of limestone flooring is ~7% for potential CO_2 equivalent emissions and ~8% for fossil fuel depletion impact category. Other impact categories also follow the similar trend.

Table 32. Sensitivity analysis per functional unit of limestone cladding (varying processor energy)

Stone processing scenarios for stone cladding	A3 stage impacts				Total life cycle impacts			
	kg CO_2 eq emissions	% change from base	Fossil fuel depletion (MJ surplus)	% change from base	kg CO_2 eq emissions	% change from base	Fossil fuel depletion (MJ surplus)	% change from base
Base stone processing	7.858		13.772		21.454		34.004	
Stone processing with 20% more energy	9.429	120%	16.527	120%	23.025	107%	36.759	108%
Stone processing with 20% less energy	6.286	80%	11.018	80%	19.882	93%	31.250	92%

5.2.3. Life cycle impact assessment – Marble cladding

Impact Assessment Results

The impact results have been calculated per functional unit of marble cladding and have been tabulated per life cycle stage in Table 33.

Similar to granite and limestone cladding, for marble cladding also the cradle to gate stages (A1-A3) dominate the results for all the impact categories. Impacts generated at quarries (A1) and processors (A3) are mainly because of the use of grid electricity and fuels consumed in those stages. Material inputs in those stages generate little impacts on comparison to electricity and fuel consumed. Cement mortar used during the installation (A5) of marble cladding also generates significant environmental impacts. Cladding delivery to construction sites (A4) and stone transport from quarry to processor (A2) impacts are dependent of transport distance between the quarries to processor plants and processor plants to the sites respectively, and these stages also make considerable impacts in numerous impact categories.

Table 33. Potential impact results per functional unit of marble cladding

Impact category	Unit	Quarry Operation	Quarry to Processor Transport	Processor Operation	Transport to Building site	Installation	Product use	Maintenance	Repair	Replacement	Refurbishment	Op. energy use	Op. water use	Deconstruction	End of Life Transport	Waste Processing	Final Disposal
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Ozone depletion (ODP)	kg CFC-11 eq	7.22E-07	8.55E-07	2.04E-06	3.91E-07	1.25E-07	0	0	0	0	0	0	0	0	3.70E-07	0	1.79E-08
Global warming	kg CO_2 eq	1.99E+01	4.29E+00	2.64E+01	1.96E+00	4.52E+00	0	0	0	0	0	0	0	0	1.85E+00	0	1.05E-01
Smog (SFP)	kg O_3 eq	4.26E+00	3.53E-01	7.35E-01	1.61E-01	2.49E-01	0	0	0	0	0	0	0	0	1.53E-01	0	3.05E-02
Acidification (AP)	kg SO_2 eq	1.50E-01	1.34E-02	6.74E-02	6.14E-03	1.70E-02	0	0	0	0	0	0	0	0	5.81E-03	0	1.01E-03
Eutrophication (EP)	kg N eq	1.61E-02	1.81E-03	1.44E-02	8.26E-04	9.38E-04	0	0	0	0	0	0	0	0	7.81E-04	0	9.90E-05
Carcinogenics	CTUh	2.30E-07	1.78E-09	1.36E-07	8.15E-10	2.67E-08	0	0	0	0	0	0	0	0	7.71E-10	0	3.07E-11
Non-carcinogenics	CTUh	1.86E-06	1.61E-07	1.36E-06	7.36E-08	3.24E-07	0	0	0	0	0	0	0	0	6.97E-08	0	1.22E-09
Respiratory effects	kg $PM_{2.5}$ eq	2.23E-02	8.43E-04	3.48E-02	3.85E-04	1.48E-03	0	0	0	0	0	0	0	0	3.65E-04	0	1.31E-04
Ecotoxicity	CTUe	3.01E+01	2.34E+00	8.81E+00	1.07E+00	9.44E-01	0	0	0	0	0	0	0	0	1.01E+00	0	9.97E-03
Fossil fuel depletion (ADP_{fossil})	MJ, LHV	3.12E+01	8.74E+00	3.75E+01	3.99E+00	3.04E+00	0	0	0	0	0	0	0	0	3.78E+00	0	2.22E-01

Single score results

The SM 2013 Methodology single figure millipoint (mPts) score by life cycle phase for marble cladding is presented below in Table 34. The scores are consistent with the trends in the results using the impact assessment results before normalization and weighting. For marble cladding, the quarry operation stage (A1) dominates the results (~47%) followed by the processor operation (A3) stage (~37%). Transport of marble from quarries to processing plants (A2) and the installation (A5) also make considerable contributions to the single score results.

Table 34. SM 2013 scores for marble cladding by life cycle stage per functional unit

Impact category	Unit	Quarry Operation	Quarry to Processor Transport	Processor Operation	Transport to Building site	Installation	Product use	Maintenance	Repair	Replacement	Refurbishment	Op. energy use	Op. water use	Deconstruction	End of Life Transport	Waste Processing	Final Disposal
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
SM single score	mPts	1.64E+00	1.81E-01	1.30E+00	8.26E-02	1.88E-01	0	0	0	0	0	0	0	0	7.82E-02	0	5.64E-03

Contribution Analysis

Table 35 and Figure 9 show the contributions of each stage of the life cycle for marble cladding to the environmental impact categories.

Table 35. Percent contributions of each stage to each impact category for marble cladding

Impact category	A1	A2	A3	A4	A5	C2	C4
Ozone depletion	16.0%	18.9%	45.1%	8.6%	2.8%	8.2%	<1%
Global warming	33.7%	7.3%	44.7%	3.3%	7.7%	3.1%	<1%
Smog	71.7%	5.9%	12.4%	2.7%	4.2%	2.6%	<1%
Acidification	57.6%	5.1%	25.8%	2.3%	6.5%	2.2%	<1%
Eutrophication	46.1%	5.2%	41.2%	2.4%	2.7%	2.2%	<1%
Carcinogenics	58.0%	<1%	34.4%	<1%	6.7%	<1%	<<1%
Non-carcinogenics	48.3%	4.2%	35.3%	1.9%	8.4%	1.8%	<<1%
Respiratory effects	37.0%	1.4%	57.7%	<1%	2.5%	<1%	<1%
Ecotoxicity	68.0%	5.3%	19.9%	2.4%	2.1%	2.3%	<<1%
Fossil fuel depletion	35.3%	9.9%	42.4%	4.5%	3.4%	4.3%	<1%

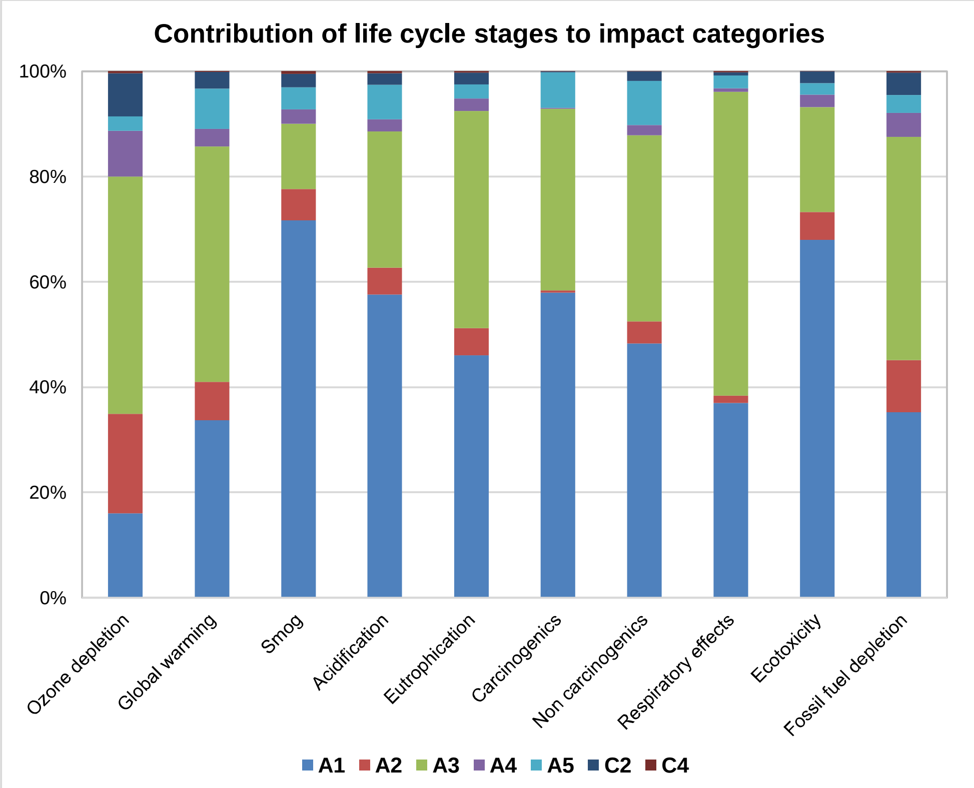


Figure 9. Contribution of each life cycle stages of marble cladding to each impact category

Quarry operations (A1) stage is the highest contributor to most of the impact categories, followed by the processor operations (A3). A3 leads A1 in some impact categories, namely ozone depletion, global warming, respiratory effects, and fossil fuel depletion. Cradle to gate stages (A1-A3) contribute to ~80% of the total impacts in all the impact categories.

A detailed study has been performed for global warming potential and fossil fuel depletion as this is deemed most relevant and of interest to Polycor. Breakdown for potential CO_2 equivalent emissions is represented by Figure 10. Processor operations (A3) stage is responsible for ~45% of total CO_2 emissions while quarry operations make up ~34% of total CO_2 emissions. Within A3, fuels (mainly diesel, propane, and natural gas) used for various purposes contributes to ~4%, and grid electricity contributes to ~92% of the total emissions generated from processors. Electricity and fuels used also share most of the A1 emissions; electricity makes up ~47% of total A1 emissions while combustion/use of fuels contributes to ~50%.

Transport of marble from quarries to processors contributes to 7% of potential CO_2 emissions while the transport of marble cladding from processing sites to the installation sites make up ~3% of that. Installation makes ~8% of total CO_2 emissions and use of cement mortar is responsible for ~59% of the CO_2 emissions in this stage. At the end of life, transportation of discarded waste to either landfilling centers or recycling centers also generates considerable CO_2 emissions, ~3% of total.

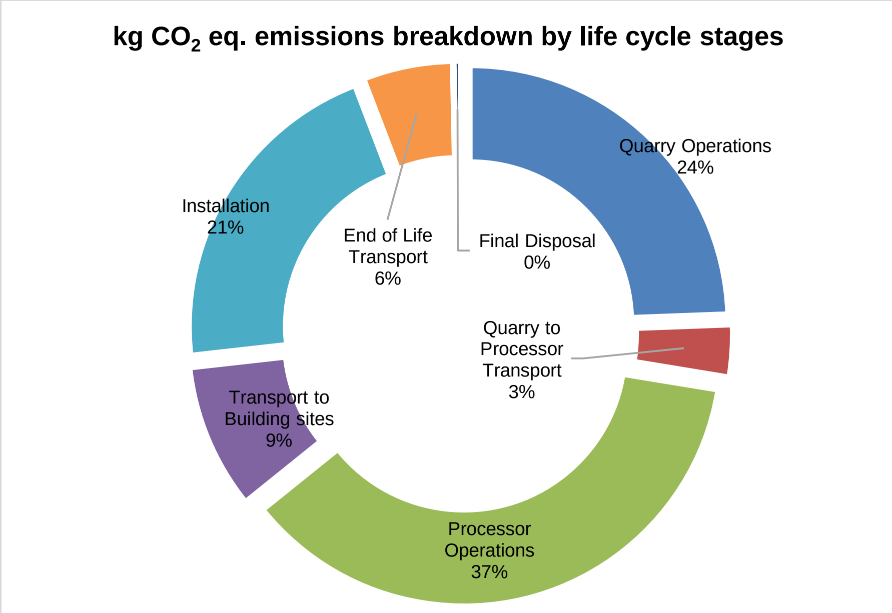


Figure 10. Breakdown of kg CO_2 eq emissions by life cycle stage for marble cladding

Similar breakdown study for potential fossil fuel depletion is represented in Figure 11. Processor operations (A3) stage contributes to ~42% in this category while quarry operations make up ~35%. Grid electricity contributes to ~82% of the total fossil fuel depletion impacts generated in A3 stage. Electricity and fuels used also share most of the A1 fossil fuel depletion impacts; electricity makes up ~32% of total A1 emissions while combustion/use of fuels contributes to ~64%. Stone transport from quarries to processors (A2) and cladding transport to building sites (A4) make significant share in the total fossil fuel depletion impacts with a combined share of ~14%, with two-third of that coming from A2 stage. Installation of cladding makes ~3% of total impacts, with ~72% of that coming from the use of cement mortar.

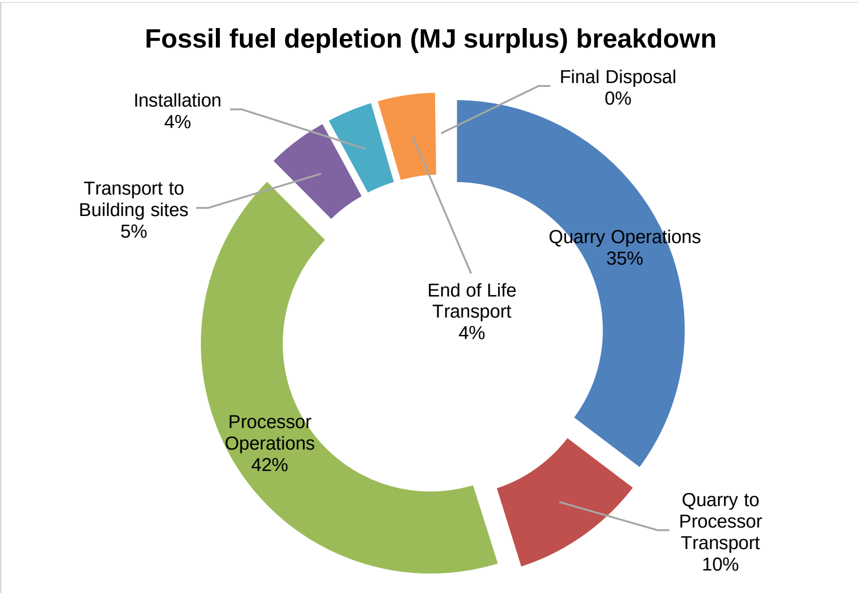


Figure 11. Breakdown of fossil fuel depletion impacts by life cycle stage for marble cladding

For other required impact categories per PCR, unit processes that contribute to more than 10% of the overall life cycle impacts of marble flooring have been identified and tabulated in Table 36.

Table 36. Drivers of life cycle impacts for marble cladding

Impact categories	Major flows (impacts > 10%)	Actual contribution
Ozone depletion	Electricity for stone processing	42.9%
	Transport of stone from quarries to processing sites	18.9%
	Electricity for stone quarrying	13.7%
Smog	Diesel combusted during stone quarrying	51.5%
	Electricity for stone processing	10.1%
Acidification	Diesel combusted during stone quarrying	50.5%
	Diesel combusted during stone processing	23.0%
Eutrophication	Electricity for stone processing	38.9%
	Diesel combusted during stone quarrying	35.3%

Sensitivity Analysis – Processor energy variation

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

A sensitivity analysis was performed to check the robustness of the results when the energy consumed is +-20% of the estimate used in this study. As shown in Table 37, a ~20% variation in the A3 stage is observed in both potential CO_2 equivalent emissions and fossil fuel depletion. But the variation in total life cycle impacts of marble flooring is ~9% for potential CO_2 equivalent emissions and ~8% for fossil fuel depletion impact category. Other impact categories also follow the similar trend.

Table 37. Sensitivity analysis per functional unit of marble cladding (varying processor energy)

Stone processing scenarios for stone cladding	A3 stage impacts				Total life cycle impacts			
	kg CO_2 eq emissions	% change from base	Fossil fuel depletion (MJ surplus)	% change from base	kg CO_2 eq emissions	% change from base	Fossil fuel depletion (MJ surplus)	% change from base
Base stone processing	26.370		37.488		58.990		88.448	
Stone processing with 20% more energy	31.644	120%	44.985	120%	64.264	109%	95.945	108%
Stone processing with 20% less energy	21.096	80%	29.990	80%	53.716	91%	80.950	92%

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 largely to most impact categories, which is mostly driven by use of grid electricity and fuels in quarries and processor plants. Within A1-A3, processor operations (A3) contribute the most to the total impacts, followed by the impacts from quarry operations (A1). Transport of quarried stone from quarries to processor plants (A2) also has significant contribution to the total impacts. Cradle to gate impacts are higher for marble cladding than for limestone and granite cladding because both quarry operations and processor operations for marble cladding is much energy intensive than other two. Impacts for limestone cladding is the least among all three because it requires lesser energy during both quarrying and processing than marble and granite cladding.

Cradle to gate impacts are followed by the impacts from A5 and A4 stages. For all granite, limestone, and marble cladding, installation impacts are driven by the use of cement mortar. Maintenance stage is not a contributor as it is assumed that stone cladding does not require any maintenance and repair to achieve its reference service life, which is modeled as being equal to that of the building. No replacements are necessary; therefore, results represent the impacts associated with one square meter of natural stone cladding.

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

5.4 Discussion on data quality

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source), and representativeness (geographical, temporal, and technological). Primary data has been used, when available, for all unit processes that contribute over 15% to any indicator result. In the absence of primary data for cleaning, secondary sources have been used.

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 Polycor quarries and processors. Most of them are from North America (US and Canada), a few quarries were from France. When possible, secondary data were selected to represent US conditions. Global datasets have been used for most of the materials. Electricity datasets are country averages based on the geographical distribution of the facilities, 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 Polycor's natural stone cladding to develop three SM Transparency Reports / EPDs. 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 for all granite, marble, and limestone cladding.

Operations at quarries to quarry the natural stone and operations at processors to process quarried stone into final stone cladding drive environmental performance. As marble cladding is more energy intensive in both quarrying and processing, overall impacts are higher for marble cladding than other two. Use of cement mortar for the installation of all stone claddings also result into significant impacts. The end-of-life stages account for minimal contribution to life cycle performance.

The major potential source of impact reduction is in cradle to gate stages. Within this stage, there are several opportunities, including both quarries and processor plants. This is an important area for Polycor to focus their efforts, since they can directly influence their own operations. Most of the impacts in both quarries and processors are coming from the use of grid electricity and fuels. Polycor can reduce their operations impacts by decreasing the use of electricity and fuels. They can achieve this by either using latest and more effective technologies/equipment or incorporate green energy sources to reduce the dependence on grid electricity. Waste stone is generated in both quarries and processors, this issue should be periodically revisited to incorporate new technology considerations for further improvement mainly to reduce the stone scrap. Polycor 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 also outside of Polycor's control. Cement mortar used during installation also makes a significant contribution to impact categories so Polycor should consider engaging partners to investigate more environment friendly adhesives. There is also an opportunity to reduce the installation waste. This will also significantly reduce the overall impacts.

REFERENCES

[1] Polycor, [Online]. Available: https://www.polycor.com.

[2] UL, Product Category Rules for Building-Related Products and Services in Brazil, China, Europe, India, Japan, Korea, North America, South East Asia, Part A: Life Cycle Assessment Calculation Rules and Report Requirements, Standard 10010, Version 3.2, UL, 2018.

[3] UL, Product Category Rules for Building-Related Products and Services Part B: Cladding Product Systems EPD Requirements, UL 10010–25, UL, 2021.

[4] Arriscraft, "Natural Stone Cladding," 2016. [Online]. Available: https://pcr-epd.s3.us-east-2.amazonaws.com/323.EPD_for_Arriscraft_Natural_20161208.pdf.

[5] Mineral Skiffer, "Natural Stone quartzite schist EPD," 2018. [Online]. Available: https://www.epd-norge.no/getfile.php/139111-1530872785/EPDer/Byggevarer/Naturstein/609_Natural-stone-quartzite-schist--natural-cleft-surface--sawn-edge--Offerdal_en.pdf.

[6] United States Environmental Protection Agency, Construction and Demolition Debris: Material-Specific Data, USEPA, 2018.

[7] Sustainable Minds, "SM Transparency Report / EPD Framework, PCR Part B: Product group definition for Interior and exterior stone flooring," 2022. [Online].

[8] SilkarStone, "Natural Stone EPD," 2020. [Online]. Available: https://api.environdec.com/api/v1/EPDLibrary/Files/a87c6d3c-227f-4f93-acc8-08d9952442c5/Data.

[9] United States Environmental Protection Agency, "Containers and Packaging: Product-Specific Data," 2018. [Online].

[10] TCNA, "Industry wide EPD for cement mortar," 2016. [Online]. Available: https://www.tcnatile.com/images/pdfs/EPDs/EPD-for-Cement-Mortar-Made-in-North-America.pdf.

[11] ISO 14025, Environmental labels and declarations -- Type III environmental declarations -- Principles and procedures, International Organization for Standardization, 2006.

[12] ISO 14044, Environmental management - Life cycle assessment - Requirements and guidelines, International Organization for Standardization, 2006.

[13] J. Meijer, "Sustainable Minds SM2013 Methodology and Database," 2013. [Online]. Available: http://www.sustainableminds.com/showroom/shared/learn-single-score.html .

[14] J. Meijer and J. Bare, "Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) TRACI version 2.1 User's Guide," US EPA Office of Research and Development, EPA/600/R-12/554,, Washington, DC, 2014, https://nepis.epa.gov/Adobe/PDF/P100HN53.pdf .

[15] United States Environmental Protection Agency, "U.S. Cement Industry Carbon Intensities (2019), EPA 430-F-21-004," 2021. [Online]. Available: https://www.epa.gov/system/files/documents/2021-10/cement-carbon-intensities-fact-sheet.pdf.

[16] National Pollutant Inventory, "Emission Estimation Technique Manual for Explosives Detonation and Firing Ranges," 1999. [Online]. Available: https://cwm.unitar.org/publications/publications/cbl/prtr/pdf/cat5/fexplos.pdf.

[17] M. Ryberg, M. Vieira and M. e. a. Zgoal, "Updated US and Canadian normalization factors for TRACI 2.1," *Clean Technologies and Environmental Policy 16: 329,* 2014.

[18] T. Gloria, B. Lippiatt and J. Cooper, "Life cycle impact assessment weights to support environmentally preferable purchasing in the United States," *Environmental Science & Technology, 41(21),* pp. 7551-7557, 2007.

[19] The American Center for Life Cycle Assessment, ACLCA guidance to Calculating Non-LCA Inventory Metrics in Accordance with ISO 21930:2017, ACLCA, May, 2019.

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 Polycor and LCI development workbook
- Polycor Stone Cladding LCA results workbook