NIST Technical Note
NIST TN 2338

Public Life Cycle Inventory Data Gap Analysis through Process Modeling

Gonzalo Rodriguez-Garcia
Sindhu Ranganath
Joshua D. Kneifel

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2338

NATIONAL INSTITUTE OF
STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

NIST Technical Note
NIST TN 2338

Public Life Cycle Inventory Data Gap Analysis through Process Modeling

Joshua Kneifel
Applied Economics Office
Engineering Laboratory

Gonzalo Rodriguez-Garcia
Sindhu Ranganath
Applied Economics Office
Engineering Laboratory
Department of Engineering Management
and Systems Engineering
George Washington University

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2338

April 2025

U.S. Department of Commerce
Howard Lutnick, Secretary

National Institute of Standards and Technology
Craig Burkhardt, Acting Under Secretary of Commerce for Standards and Technology and Acting NIST Director

NIST TN 2338
April 2025

Publication History
Approved by the NIST Editorial Review Board on 2025-04-09

How to Cite this NIST Technical Series Publication
Rodriguez-Garcia, G., Ranganath, S., and Kneifel, J. (2025) Public Life Cycle Inventory Data Gap Analysis through Process Modeling. (National Institute of Standards and Technology, Gaithersburg, MD), NIST Technical Note (TN) NIST TN 2338. https://doi.org/10.6028/NIST.TN.2338

Author ORCID iDs
Gonzalo Rodriguez-Garcia: 0000-0001-8084-8236
Sindhu Ranganath: 0009-0005-8689-4336
Joshua D. Kneifel: 0000-0002-3114-5531

Contact Information
joshua.kneifel@nist.gov

Abstract

Given the increasing prevalence of using Environmental Product Declarations (EPDs) for product comparisons and selection, both domestically and globally, there is a need to ensure the results reported in EPDs are useful for such comparisons (i.e., transparent and standardized to ensure quality decision making). One challenge that was identified more than a decade ago was the lack of common data sources, which could undermine the comparability of EPDs and similar claims. Federal agencies have targeted this issue through the development of public secondary datasets and gap assessments of currently available public life cycle inventory (LCI) datasets.

This study complements public data gap assessments completed by the Environmental Protection Agency (EPA) and Department of Energy (DOE) by providing a framework for a more in-depth approach to identify and quantify the impacts from public data gaps that can be implemented across any product category to assist in prioritizing data gaps to address. The scope of this study is to (1) develop a robust framework to identify public life cycle assessment (LCA) data gaps, (2) identify and quantify the impact of each data gap across each product category, and (3) provide qualitative rankings of data gaps within and across the product categories considered. Additionally, there is a brief comparison across data gap assessments from this study to those of EPA and DOE.

Keywords

Building materials; energy; greenhouse gases; life cycle assessment; representative inventory; resources; sustainability

Table of Contents

List of Tables

List of Figures

Preface

Given the increasing prevalence of using EPDs for product comparisons and selection, both domestically and globally, there is a need to ensure the results reported in EPDs are useful for such comparisons. One challenge for these comparisons is the lack of common public data sources for use in developing the LCA models used for estimating the results reported in EPDs. This study provides a framework to identify and quantify the impacts from public data gaps that can be implemented across any product category to assist in prioritizing data gaps to address, and applies this approach to several building material product categories to identify, quantify, and qualitatively rank public data gaps.

Acknowledgments

The authors wish to thank all those who contributed ideas and suggestions for this study, including Dr. David Webb and Dr. David Butry of EL’s Applied Economics Office, Steve Emmerich of EL’s Building Energy and Environment Division, Dr. Li Piin Sung of EL’s Materials and Structural Systems Division, and Dr. Xiaju (Julie) Chen from ERG. Thanks goes to our colleagues at ERG and EPA for providing guidance on formatting the LCA models for consistency with the requirements to publish those models on the Federal LCA Commons under the NIST repository, including Ben Young, Paige Weiler, and Jake Namovich. The authors also want to thank Dr. Rob Anex, from UW Madison, for his assistance with the Datasmart database.

Author Contributions

Gonzalo Rodriguez-Garcia: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Validation, Visualization, Writing- Original draft preparation.

Sindhu Ranganath: Conceptualization, Methodology, Investigation, Data curation, Validation.

Joshua Kneifel: Funding acquisition, Resources, Conceptualization, Supervision, Project administration, Writing- Reviewing and Editing.

1. Introduction and Scope

There has been steadily growing interest from consumers, industry, local and state jurisdictions in the US, and nation states globally for improved reporting of the environmental and human health impacts associated product purchases, particularly for construction-related materials [1–5]. A common approach to quantify these impacts is life cycle assessment (LCA), which provides a scientific methodology for calculating embodied emissions (carbon amongst others) of a product or service over its entire life cycle in accordance with the International Standards Organization (ISO) 14040 and ISO 14044 standards [6, 7]. While LCA is the quantification tool, environmental statements are the communication mechanism for providing decision-makers with information about a product's environmental impacts. ISO has established fundamental principles and requirements for various types of environmental statements in ISO 14020 [8], including Environmental Product Declarations (EPDs), whose requirement are further developed in ISO 14025 [9].

An EPD is a standardized third-party verified document that provides LCA-based information as well as additional information on the environmental aspects of products [9]. EPD programs are often built for specific product categories, groups of products capable of fulfilling equivalent functions that might require EPDs to be consistent with a distinct Product Category Rule (PCR) in addition to the aforementioned ISO standards. However, PCRs are not universal, and more than one PCR might exist for a given product category. For Portland cement, for example, there is at least a PCR for North America [10] and a global one, albeit aligned with European standards [11]. Efforts to harmonize the development and use of PCRs include ISO 14027 on development of PCRs and ISO 14029 on mutual recognition of EPDs and footprint communication programs [12, 13] as well as the PCR Open Standard from the American Center for Life Cycle Assessment (ACLCA) [14].

Using EPDs for documenting environmental and human health impacts of products has been common (and growing) since introduced into Green Building Rating Systems (GBRS), such as Leadership in Energy and Environmental Design (LEED) and Green Globes [2]. Additionally, EPDs are being used as the basis for product selection by building construction companies and building owners as well as a range of US jurisdictions and states [3, 4, 15–19]. Specifically, these programs require third-party verified EPDs compliant with ISO 14025 and ISO 21930 [20] standards for life-cycle stages A1-A3, known as “cradle-to-gate” because it includes impacts from raw material extraction through the product manufacturing, but excludes any impact after the product leaves the manufacturing site or “gate.” Along with domestic demand for products with EPDs, global demand is also growing as EPDs are increasingly being required in US export markets, particularly the European Union [21, 22].

Given the increasing prevalence of using EPDs for product comparisons and selection, both domestically and globally, there is a need to ensure the results reported in EPDs are useful for such comparisons. One challenge that was identified more than a decade ago was the lack of common data sources, which could undermine the comparability of EPDs and similar claims [23]. Some PCRs (e..g, concrete [24]), prescribe the use of secondary data sources to facilitate standardization and comparability of the EPDs . However, secondary data sources are still lacking, and those available are often commercial products and not necessarily representative of US industrial practices.

Federal agencies have formalized collaboration to improve LCA secondary data through an interagency initiative, the Federal LCA Commons (FLCAC) [25]. Activities of the FLCAC include providing support to enhance standardization, measurement, reporting, and verification of LCA modeling. These activities will assist industry in improving the transparency, trustworthiness, and comparability of results reported in EPDs, improving their competitiveness in domestic and global marketplace. Some agencies have already undertaken activities to identify secondary LCA data needs for EPD development with specific focus on embodied carbon of construction materials. The Environmental Protection Agency (EPA) has provided several resources for improving the state of PCRs and EPDs developed by industry [26–29]], including Life Cycle Inventory Data Gap Assessment that focused on identifying "life cycle inventory (LCI) data gaps in free-to-use and publicly accessible secondary LCI datasets, as relevant to the supply chains of the products and materials identified in the US Environmental Protection Agency's Interim Determination." The report was developed by reviewing existing PCRs and communicating with PCR Committee members for a variety of high priority construction materials to collect insights from industry and experts in the LCA field. The collected information was synthesized into a list of recommendations for prioritizing datasets to develop and fill public LCA data gaps. The study assessed the currently available public data sources, including the Federal LCA Commons mega-repository and the US Life Cycle Inventory (USLCI) database. Additionally, the Department of Energy (DOE) National Renewable Energy Laboratory (NREL) has completed a structural path analysis (SPA) to identify hotpots for seven product categories [30]:

- Cement manufacturing
- Ready-mix concrete manufacturing
- Glass and glass product manufacturing
- Asphalt paving mixture and block manufacturing
- Asphalt shingle and coating materials manufacturing
- Iron and steel mills and ferroalloy manufacturing
- Steel product manufacturing from purchased steel

The analysis used the US Environmentally Extended Input-Output (USEEIO) database [31] to identify data gaps in construction related industries as a whole. It also included a comparison to identify consistencies and variations between the EPA data gap assessment and underlying methodology.

This study is designed to complement these public data gap assessments completed by the EPA and NREL by providing a framework for a more in-depth approach to identify and quantify the impacts from public data gaps that can be implemented across any product category to assist in prioritizing data gaps to address.

Thus, the scope of this study is to:

(1) Develop a robust framework to identify and quantify public LCA data gaps
(2) Identify and quantify the impact of each data gap across each product category

(3) Provide qualitative rankings of data gaps within and across the product categories considered

The framework is applied to a variety of building materials that align with multiple NIST research programs:

- Net Zero Energy High Performance Buildings Program (all building materials)
- Carbon Capture and Accounting Program (concrete)
- Circular Economy Program (building materials using polymers)

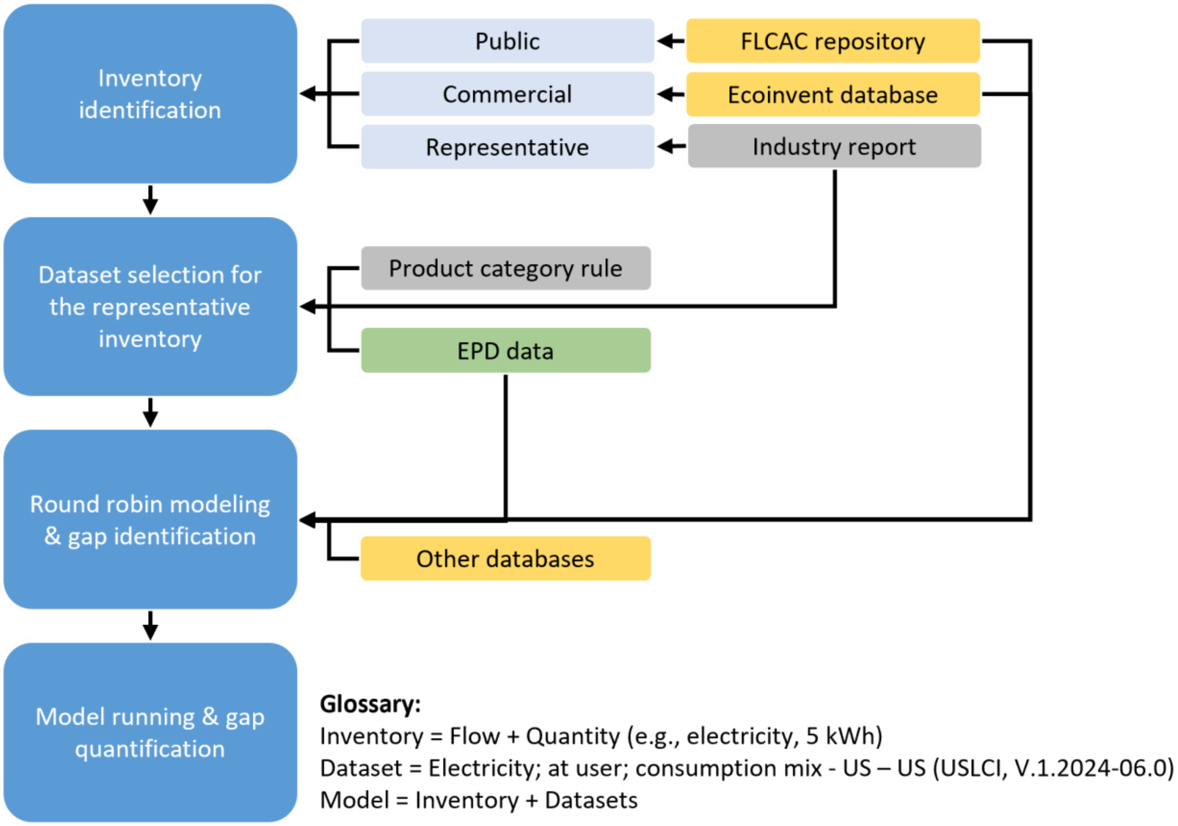
Additionally, products were selected to provide variability in the level of prescriptiveness for LCI data source selection and reporting within a PCR as well as format variability in published EPDs for a given product category. This variability allows for both validating the framework developed in this study for robustness while providing variability in published EPD information for a complementary study being completed in parallel – NIST TN XXXX. NIST TN XXXX evaluates LCA data source selections in existing EPDs and provides the life cycle inventory (LCI) for a product considered in this study without a publicly available inventory necessary for LCA modeling (i.e., gypsum board). For this study, the framework was applied to specific building materials, most of which have similar raw material inputs and manufacturing processes. However, the framework is applicable to other building materials as well as building systems, which will be discussed further in Section 5.

2. Methodology for a Product Category

This study develops a methodology to identify and quantify data gaps in public LCI databases and applies this methodology to the FLCAC, also referred to as the “public database” moving forward. Although the focus is the FLCAC, the methodology can be applied without substantial changes to any other database, public or commercial. This methodology is applied to individual products, which could be seen as an example for the applicable product categories. Product category rules (PCRs) have been developed for most the product categories considered in this study. The existence of a PCR suggests a maturity of the sector when it comes to life cycle assessments (LCAs) and/or EPDs. Therefore, it is expected that filling data gaps identified for a category with a PCR will be more immediately impactful to LCA practitioners than if the target of the data gap analysis is a single product without a defined product category or for a product category but no PCR.

For the purposes of this methodology, a data gap is defined as aa process (unit or system) that either produces or treats an environmentally relevant flow present in the inventory under assessment through a production/treatment that is considered equivalent to that described in the inventory (i.e., fit for purpose). For example, if the inventory indicates the use “Ammonia”, no data gaps are identified, because there is an “Ammonia, steam reforming, liquid, at plant” process in USLCI. However, if the same inventory were to indicate the use of “Ammonia, from partial oxidation”, then a data gap would be identified, as there are currently no processes for production of ammonia through partial oxidation of USLCI. No qualitative aspects, such as vintage or range of geographical or technological applicability, are evaluated.

As shown in Fig. 1, the methodology consists of four steps: 1) Inventory identification, 2) Dataset selection for the representative inventory, 3) Round robin modeling and gap identification, and 4) Model running and gap quantification. Each step is discussed in detail in the remainder of this section.



Glossary:
Inventory = Flow + Quantity (e.g., electricity, 5 kWh)
Dataset = Electricity; at user; consumption mix - US – US (USLCI, V.1.2024-06.0)
Model = Inventory + Datasets

Fig. 1. LCA Modeling Methodology Flow Diagram.

For this methodology, an LCA model consists of two components as illustrated in Figure 2: an inventory and a dataset(s). An **inventory** compiles and quantifies environmentally relevant **flows**: products, materials (including waste and emissions), or energy as defined in ISO 14040 [6]. For example, a simple inventory might consist of a single environmentally relevant input energy flow, electricity, of which 5 kWh are required, and a single output product flow, widgets, of which 1 unit is generated. For non-elementary flows (products and wastes), the other half of the model are the datasets. Datasets contain environmentally relevant information of the process producing or treating the related flow. Datasets are commonly referred to as "processes" or "process models" in LCA literature. For the purposes of this methodology, a dataset is a **process** taken from a specific **database** even though, strictly speaking, a dataset can exist on its own and not be part of a database. For the example above, the electricity use of the widget production process could be modeled using the **process** "Electricity; at user; consumption mix - US – US" included in the **database** USLCI, V.1.2024-06.0. The importance of this distinction will become apparent in Step 3, when inventories and datasets from different sources are combined to create round robin LCA models.

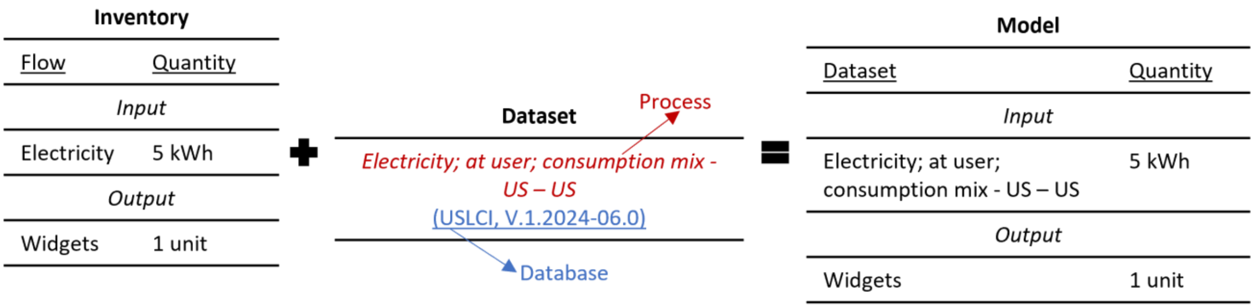


Figure 2 Distinction between life cycle inventory, dataset, and life cycle model in this methodology.

2.1. Inventory identification

The first step in the data gap assessment is the identification of available inventories. Three kinds of inventories may be identified: public, commercial, and representative. The public inventory is an inventory in the FLCAC. Because the main repository in FLCAC is USLCI, herein the terms public inventory, FLCAC inventory, and USLCI inventory are used interchangeably unless the distinction is explicitly mentioned. In addition, since USLCI V.1.2024-06.0 was used through all the different data gap analysis presented in this document, when USLCI is mentioned, it refers to version 1.2024-06.0 unless explicitly indicated. As mentioned above, if USLCI includes a dataset that generates or treats an environmentally relevant flow in the way described in the inventory, there is no data gap related to that flow. However, the existing dataset might still be used for data gap identification and quantification, as highlighted in the case study of Portland cement in Section 3.1. If a data gap analysis following this methodology is conducted for a database other that FLCAC, the “public” inventory becomes an inventory in the target database for assessment.

A commercial inventory is an inventory taken from a commercial database. For reasons of availability, the database ecoinvent [32] is used for this study. However, any other commercial database could be used (Managed LCA, Datasmart, etc.). Strictly speaking, the database does not have to be a commercial product, although because ecoinvent is a commercial database, that is the term used throughout the report. The key is that this alternative inventory must come from a database different than the target database to be used as an alternative reference. Thanks to their large number of datasets, however, commercial databases facilitate the identification of alternative inventories, becoming a “one-stop-shop” for both inventory identification and round robin modeling. For this study, ecoinvent 3.10 [33] was used and, when “ecoinvent” is mentioned it refers to version 3.10 unless otherwise specified.

The representative inventory is one coming from a source other than the public or the commercial database. Ideally, this inventory comes from an industry report, which may be linked to an industry average EPD. In the context of data gap assessment for FLCAC, these reports should be focused on US or North America (US / NA) markets. Regardless of location, these inventories are “representative” because they reflect an average of the existing industry, not a specific manufacturing plant or facility. For data gap identification, this is ideal because it might include flows that are present by a small fraction of the plants that might be missed if modeling a specific plant. For quantification of the impact of the data gap, however, these industry averages are less valuable because rarely reported flows may account for a large impact for one or more specific plants while the industry average value would appear small across the entire industry, leading to a low prioritization for the industry as a whole even though the flow is of significance for those plants that actually use or generate the flow. If no industry report reflects US/NA conditions, global reports, or reports from other geographies might be used. With the understanding that industrial processes vary across the globe, these inventories might still highlight some of the gaps present in FLCAC. However, these non-US/NA inventories may be less valuable for the development of models that could effectively close the FLCAC data gaps. Finally, if there are no reports of this kind, scientific literature might be used. However, it must be stressed that due to the limitation of geographical representativeness, it most likely provides a limited technological representativeness, as inventories in the scientific literature often evaluate specific technologies, and it is not uncommon for them to evaluate technologies that are not market available yet. For one such example, see the case study for limestone calcined clay cement (LC3) in Section 3.3.

2.2. Representative Inventory Dataset Selection

If no representative inventory can be identified, this step can be skipped in its entirety. When a representative inventory is available, then a source—ideally only one—should be identified as a guideline to build the representative model. For this study, a representative inventory should represent average production process operations in the US/NA, while the representative model shows how the LCA of such a process is typically modeled. Three possible sources of information are, in order or preference:

1) PCR of the product category of focus: This is the most normative guide, and since it is written by committees including industry leaders as well as LCA practitioners, it is likely to be representative of modeling choices at the time of writing. However, PCRs vary in their level of descriptiveness. Some PCRs have identified many environmentally relevant flows, and specified database, version, and specific dataset(s) to be used for LCA modeling while others offer little guidance. In the latter situation, the following two sources might be used.
2) Industry report, or the source from which the inventory was taken: If the LCI was followed by a Life Cycle Impact Assessment (LCIA), this source offers a level of completeness unlikely to be matched by the PCR, which might focus only on the most encountered flows.
3) Analysis of valid EPDs: If the PCR is not prescriptive enough for the inventory at hand, and the industry report does not include an LCIA, an EPD analysis might be conducted as described in a forthcoming NIST Technical Note on EPD database creation and data gap assessment that identifies the most used datasets for conducting an LCA for a given product category.

Although within the context of this methodology the intended use of PCRs, industry reports, and results of EPD analysis is to offer guidance on how to model a representative process, they can be used in themselves as a source for data gap identification. Effectively, any flow for which a dataset from a database other than FLCAC is used or recommended is a potential data gap. In fact, a data gap identification process can be conducted simply by comparing the datasets used/recommended in the three sources above with what is available in the FLCAC. Because the methodology here developed addresses both the identification and quantification of data gaps, and at least one of the three sources identified above will be used to build the representative model, no specific data gap identification is done at this stage. Instead, it is done in the next step while creating the round robin models. However, if two or more guidelines are available, and only one is used—e.g., if the PCR is sufficiently prescriptive, and the industry report includes information of which datasets have been used to conduct the LCIA—a data gap identification step should be conducted for the source not used for the representative model, to ensure those data gaps are not missed, even if they cannot be quantified.

2.3. Create Round Robin Models

For each product category, there will be between two and seven round robin models. The numbering for the models used in this section is shown in Table 1, which identifies each potential combination of public, commercial, and representative inventories and databases and the information each model may provide to the gap analysis.

Table 1 Round robin model numbering.

Model	Inventory	Database	Information provided
#1	Public	Public	Gap identification when cutoff flows are included
#2	Public	Commercial	Gap quantification when identified in model #1
#3	Commercial	Public	Gap identification when flow is absent from USLCI
#4	Commercial	Commercial	Gap quantification
#5	Representative	Public	Gap identification when flow is absent from USLCI
#6	Representative	Commercial	Gap quantification
#7	Representative	Representative	Limited modeling verification

The representative database refers to the datasets used to model an inventory following guidelines other than those provided by the public or commercial databases, as described in Section 2.2. No database per se is created, although it is referred as such throughout this document and could be a combination of public and commercial datasets.

As shown in Table 1, each model may provide valuable information for the data gap analysis. Some models present in the USLCI database—i.e., model #1–include cutoff flows. Cutoff flows in USLCI are flows that are considered environmentally relevant, but do not have a production or treatment process yet. Therefore, the processes that would treat or produce a cutoff flow are considered data gaps. Using USLCI to build models based on other inventories (models #3 and #5) may also identify data gaps, if no production/treatment process exist for the flows identified. In this case, it is the absence of a suitable dataset that indicates the existence of a data gap. Models built using the commercial database—#2, #4, and #6—may quantify the importance of a data gap for a certain impact category if there is a suitable dataset in the commercial database. It is not possible to quantify the importance of a data gap in the public database if the commercial database does not have an equivalent process. Model #7 is not used for data gap analysis because any gaps identified and quantified using model #7 will be through commercial databases and would already be identified and quantified through model #5 and model #6. However, building and running the representative model can be used for some limited model verification by comparing the impact results of model #7 with those included in the source of the representative inventory or related publication (e.g., industry average EPD). Large differences between these two sets of results may indicate modeling errors in model #7 and/or model #5 and model #6, including different quantities for a given flow, alternative dataset selection, etc. However, similar results may not imply consistency in modeling, and in a case where the representative model results have only been reported in total impacts, it is impossible to confirm this consistency due to the lack of transparency.

Prior to the construction of any model, ecoinvent 3.10 database was mapped using openLCA's flow mapping feature [34] and the mapping file developed by the EPA and the support of Green Delta and ERG [35]. This facilitates the use of LCIA methods compatible with USLCI with models that include ecoinvent datasets, either with a commercial or representative database.

Ideally, models #1 and #4 should remain unmodified. However, ecoinvent is a Swiss database and product models within the database are typically for geographies other than the US, such as Switzerland, Europe, or Rest of the World (RoW). Thus, when no US inventory is available, another geography must be selected. Preference is given to North American (NA), Canadian (CA), or Quebecoise (CA-QC) inventories, as they are closer geographically to the US. If there are no North American inventories available, the preference is to select one from a specific country—e.g., Switzerland—instead of RoW because country-specific inventories are easier to modify. By default, the only modification is to substitute electricity use from the country of origin—e.g., "market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - CH" for its US equivalent—"market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – US." Due to the lack of US specific datasets in ecoinvent, no further regionalization efforts were conducted unless specifically mentioned for a given product category. Note that, as mentioned in this section above, USLCI "cutoff flows" are those for which there is currently no production or treatment process in the database while in ecoinvent the cutoff term is used for models built using the recycled content approach [36]. The approach implemented in ecoinvent cuts off recyclable materials from the system in which they are produced, becoming available for any activity that consumes/treats those materials burden-free (e.g., recycling activitites).

When developing "mixed" models (#2 and #3) datasets from one database need to be substituted for similar datasets from another database. For example, when building a Model #2, the USLCI datasets used in Model #2 need to be substituted for equivalent ecoinvent datasets. The supplementary "ecoinvent to USLCI" workbook (Appendix B) offers guidance on for numerous flows encountered through the analyses described in the sections below. For other flows, expert knowledge is recommended because datasets are seldom equivalent.

Models can be built in any commercial LCA software. For the case studies below, openLCA 2.1 [37] was used.

2.4. Modeling and Gap Quantification

An LCA model produces an impact assessment and generates results for one or more impact categories [6]. The details on how to complete an impact assessment varies by the software used to build the models. In openLCA, a product system needs to be created for each dataset before potential environmental impacts can be calculated, and the LCIA method must be compatible with the selected database. For example, if the target database is USLCI, LCIA methods are limited to those available in FLCAC: TRACI 2.1 [38], ReCiPe2016v1.1 [39], ImpactWorld+v1.3 [40], International Panel on Climate Change's (IPCC) Global Warming Potential (GWP), inventory methods, and the Characterization Factors for Construction Material EPD Indicators, also referred as ISO 21930-LCIA-US [20]. This last LCIA method was used for the data gaps analyses in this study and reported results have been limited to the impact category "Greenhouse Gases" (referred to as GWP for the remainder of this document).

Quantifying a data gap is equivalent to assessing the contribution of that process to the impact of the full model. It can be expressed in absolute terms (e.g., kg CO_2 eq./ functional unit) or relative terms (e.g., percent of GWP impact). In the analyses below, data gaps are most often quantified as the relative contribution of the GWP. GWP was selected because it is currently the primary focus of most government policy targeting environmental impacts of building products. Note that selection of a different impact category could impact the relative importance of a given data gap, which will be discussed further in Appendix C.

3. Analysis by Product Category

This section describes the implementation of the methodology defined in Section 2 to complete LCA modeling and analysis as well as a summary of the findings for each product category evaluated in this study: cement, concrete, limestone calcined clay cement, slag cement, aggregates, and gypsum. Product categories were selected based on a combination of EPA prioritization, synergies with on-going NIST research, and variation in both availability of LCA inventories and prescriptiveness of data source requirements in the applicable PCR.

3.1. Portland Cement

Cement is the largest manufactured product by mass globally [41]. Its production was responsible for 7 % of global CO_2 emissions in 2014 [42], while in 2019, the production of this EPA priority material was the source for 10 % of the industrial sector's reported greenhouse gas (GHG) emissions [43]. The need to reduce the emissions of this key industrial sector, mentioned among others by Scrivener et al. [41], aligns well with the Carbon Capture and Accounting Program, Net Zero Energy High Performance Buildings Program, and Circular Economy Program at NIST.

The current PCR for cement [24], v.2.3., covers ordinary Portland cement (OPC) in addition to blended, masonry, mortar, and stucco cements. It does not prescribe what datasets to use as background data, merely indicating purchased electricity shall be regionalized data—NERC or similar for North America and per country or region-specific outside of the US and Canada—preferably to include transmission and distribution losses.

3.1.1. Identify Available Inventories

A public model is available in USLCI, labeled "Portland cement, at plant" and based on a 2006 report from the Portland Cement Association (PCA) [44]. This is a cradle-to-gate inventory, starting with limestone as a mineral resource, and ending with OPC as a finished product.

ecoinvent includes a model for OPC production, based on Boesch and Hellweg's [45], for ten geographies, including the US, as well as a number of models for European specifications. It is effectively a model for the grinding and mixing of gypsum, limestone, and clinker, the main component of cement. ecoinvent also has a US specific process for the production of clinker, although it is based on a 2007 report for ecoinvent 2.0 [46], itself based on a 2000 Swiss report [47].

Athena Sustainable Materials Institute (ASMI) created, on behalf of the Portland Cement Association (PCA), LCIs for OPC, blended, Portland limestone, and masonry cements, in addition to cement's precursors clinker, and quarried limestone [48]. This report is used here to build the representative inventories of these three materials for this study.

3.1.2. Round Robin Model Construction

The existence of a public, commercial, and representative inventory means the full set of seven models based on the combinations of available inventories and databases were developed—Table 2. In addition, an alternative version of OPC#1 (labeled OPC#1 ALT) was developed that removes identified duplicative emissions that are discussed in detail in Section 3.1.2.1. All models can be found in the supplemental "Cement models" workbook (Appendix B).

Table 2 Portland cement models.

Model	Inventory	Database	Comments
OPC #1	Public	Public	
OPC #1 ALT	Public	Public	Double counting of combustion emissions avoided
OPC #2	Public	Commercial	
OPC #3	Commercial	Public	
OPC #4	Commercial	Commercial	
OPC #5	Representative	Public	
OPC #6	Representative	Commercial	
OPC #7	Representative	Representative	

Models were also developed for intermediate steps of OPC production, limestone quarry, and clinker as described in [48]. Since there are three inventories for limestone quarry, all seven models were developed—Table 3. Contrarily, because USLCI does not have an inventory for clinker production, only five models were built for clinker—Table 4.

Table 3 Limestone quarry models.

Model	Inventory	Database
QUARRY #1	Public	Public
QUARRY #2	Public	Commercial
QUARRY #3	Commercial	Public
QUARRY #4	Commercial	Commercial
QUARRY #5	Representative	Public
QUARRY #6	Representative	Commercial
QUARRY #7	Representative	Representative

Table 4 Clinker models.

Model	Inventory	Database
CLINKER #3	Commercial	Public
CLINKER #4	Commercial	Commercial
CLINKER #5	Representative	Public
CLINKER #6	Representative	Commercial
CLINKER #7	Representative	Representative

Because the supplementary information to the ASMI report [48] only includes the inventories, the representative database is based on common practices followed by those EPD generators who chose to disclose the processes used in their models—additional details will be provided in the forthcoming NIST Technical Note on EPD database creation and data gap assessment. These common practices include using processes taken from USLCI, ecoinvent, and Datasmart. The models built exclusively with ecoinvent or USLCI processes follow, whenever possible, the examples given by those databases in their respective models for cement (see the Appendix B, and the workbook *Cement models*). The exact processes selected for each model are also detailed in that file.

3.1.2.1. Models based on the public inventory

The public model for the limestone quarry—based on a report by Franklin Associates from 2004 [49]—consists of only six inputs, none of which are identified as data gaps. As mentioned above, USLCI does not have an inventory for clinker, although the production of clinker is included as part of OPC production. This last inventory includes twelve input and six output cutoff flows. In addition, ten input flows are environmental inputs (resources), eight of which are considered data gaps. One exception is "Raw material, unspecified," which is not considered a data gap because it is not possible to model an unidentified raw material. "Limestone" is not a gap in this process because the quarrying needed for limestone extraction is included in this inventory as detailed in Marceau et al. [44], and there is a separate inventory for "Limestone, at mine" included in USLCI.

Two discrepancies were identified between the PCA inventory in [44], and how it was implemented in USLCI. First, in the report, fossil fuels are "raw" input materials, and their combustion results in a series of emissions quantified as outputs. In contrast, USLCI includes the combustion of fossil fuels as input processes, and the direct emissions as outputs. This effectively duplicates inclusion of the emissions generated during the combustion of fossil fuels. To remedy this issue, the model OPC#1 ALT was created with the combustion processes originally, included in the USLCI model substituted with processes supplying the fossil fuel. Second, five of the material outputs (i.e., wastes to be combusted) should be considered as inputs because the production of Portland cement does not generate these wastes, but instead it uses these as fuel. Since, as mentioned above, these are cutoff processes, the change will have no effect in the LCIA of the process. However, it would have consequences if these processes were ever modeled in detail because that would mean the production of Portland cement is the source of those impacts.

When modeling the process using datasets from ecoinvent, only the unspecified raw material remains as a data gap because the commercial database has either a model for the missing process, or a reasonable proxy. In this case, wastes used as inputs are deliberately left without a provider to ensure both that they are burden free and Portland cement production is not credited for the avoided production or combustion of those wastes.

3.1.2.2. Models based on the commercial inventory

At the quarry—limestone mine—level, three input data gaps were identified: "blasting"—i.e., the use of explosives—the "quarry infrastructure," and the "recultivation" of the limestone mine. The inventory for clinker production however, revealed thirteen data gaps: three kinds of refractory material for the kiln, two (output) waste treatment, two capital goods— "cement factory" and "heavy industrial machinery," and six material inputs—calcareous marl, clay, hydrated lime, meat and bone meal, sand, and water. Lime can also be considered a data gap, in as much as the production of lime in ecoinvent includes several processes, while USLCI only has one, "limestone mine"—see Figure 3. For OPC production, two data gaps were identified: "cement factory," and "clinker production". Note that the production of clinker is aggregated in the USLCI inventory for Portland cement production, as described in Section 3.1.1.

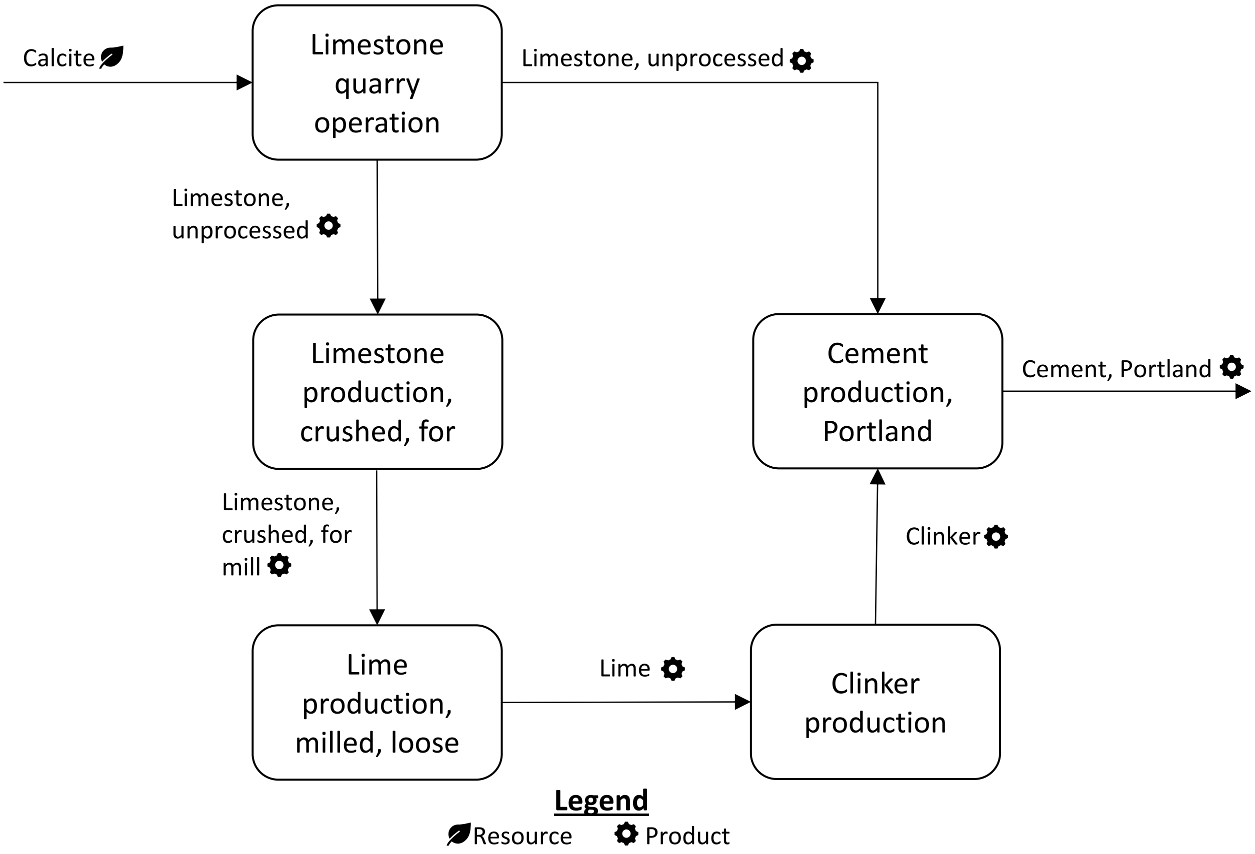


Figure 3 Process flow diagram for OPC production following ecoinvent, with a focus on the production of lime.

3.1.2.3. Models based on the representative inventory.

ASMI [48] was used to build representative models for 1) limestone quarry production, 2) clinker production, and 3) Portland cement using limestone and clinker as inputs—Figure 4.

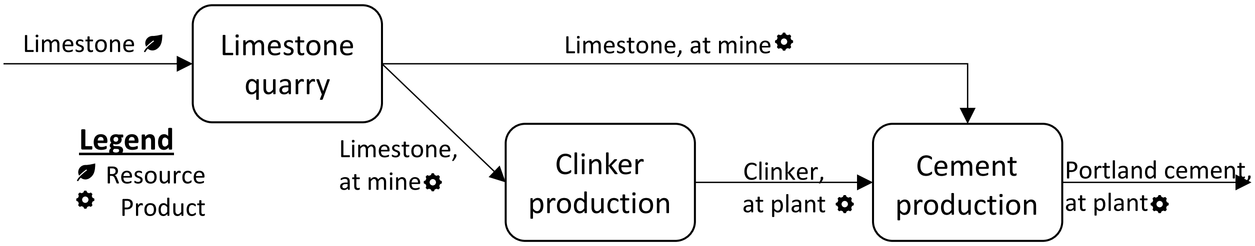


Figure 4 Flow diagram for the production of Portland cement with the representative inventories

As indicated in Section 3.1.2.1, there is already an inventory for Limestone quarry in USLCI, and it is not a data gap as defined in this study. Nevertheless, the inventory included in [48] was used as the representative inventory for limestone production because it offered the opportunity to update the LCI already included in USLCI and ensures consistency with the subsequent clinker and cement inventories. Clinker production was identified as a gap in Section 3.1.2.2. Clinker is a key component of the model for Portland cement as well as for other cements and, therefore, is used as the representative inventory.

With the limestone quarry inventory, three data gaps were identified: “explosives,” hydraulic fluid—for which ethylene glycol monoethyl ether (EGEE) was used in the commercial model—and the “landfilling of non-hazardous waste”. The representative model was built using mostly ecoinvent processes except for the transport—from USLCI—and electricity—from the Datasmart database.

Thanks to the clinker inventory, 66 unique data gaps were identified: 43 input flows, 11 output flows—waste treatment processes that did not appear as inputs—and 12 resource input flows—excluding “Raw material, unspecified” used to indicate other alternative material inputs—see the workbook *Cement models* (Appendix B) for the whole list. A large fraction of the input flows (20 out of 43) are wastes used as a resource in the kiln, as alternative fuel (e.g., tires) or as an alternative to limestone (e.g., slags). Although these materials enter the calcination process burden free. Their absence will have no impact in the LCIA as modeled below, they could become more environmentally relevant in the future if they stop being “burden free wastes” and become valuable raw materials, for which the plant operator is expected to pay.

For the representative model, USLCI is used in four out of five transport processes and two fuels: gasoline, and bituminous coal. ecoinvent is used for most of the remaining processes, although for nine processes, the Datasmart database was used. Although it falls outside the scope of this report, it is worth highlighting there are gaps in ecoinvent as well—21 identified for clinker production.

With the OPC inventory, 22 data gaps were identified: four elementary flows and eighteen cutoff flows. As for clinker production and limestone quarry, most of the processes used for the cement representative model are taken from ecoinvent, with limited input from USLCI and Datasmart—see the workbook *Cement models* and Appendix B for details.

3.1.3. Modeling Results

In the following subsections, the GWP results of the models developed in Section 3.1.2 are presented, organized by their source inventory. For the data gaps for which there was a commercial model available, their contribution as a percentage of the GWP of the commercial model were reported.

3.1.3.1. Models based on the public inventory

Differences between the models for limestone production are small, with the GWP of QUARRY#1 only 7.63 % higher than that of QUARRY#2—Figure 5. These differences are mostly driven by the higher GHG emissions of electricity in USLCI relative to ecoinvent—18.51 %. However, they are ameliorated by the higher impact of diesel combustion in model #2—4.52 % higher than in QUARRY#1. As mentioned in Section 3.1.2.1, there were no gaps in the public inventory of limestone production, and therefore they have no effect in its carbon footprint.

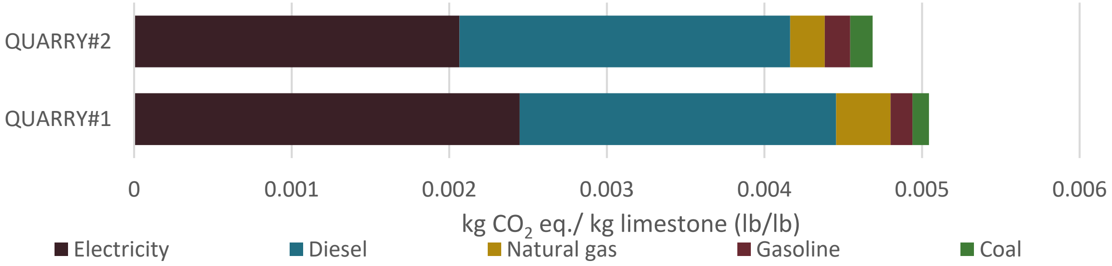


Figure 5 Global warming potential of 1 kg of limestone according to the public inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

The results in Figure 6 show the effects of “double counting” fuel combustion in the cement USLCI model (*OPC#1*). The most noticeable impact is due to hard coal, as the impact for the supply of this fuel is only 6 % of the impact of the combined supply and combustion impact. The effects from other fossil fuels are smaller, as is their contribution to the energy requirements of the production process.

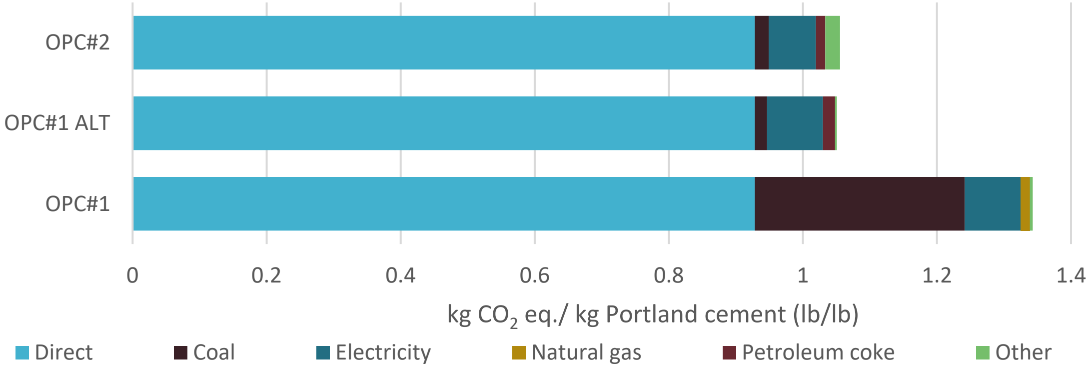


Figure 6. Global warming potential of 1 kg of Portland cement according to the public inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Once the fossil fuel in the baseline model is adjusted (OPC #1 ALT), there is less than 0.5 % difference between the GWP of OPC#1 ALT and OPC#2. Despite the overall alignment, there are small differences in the relative contributions of the background processes between both databases. Namely, the GWP of USLCI electricity is 18 % higher than that for ecoinvent. More importantly is the combined impact of the 15 quantifiable data gaps—i.e., the processes missing in USLCI but present in ecoinvent. These fifteen missing flows account for 1.33 % of the GWP when the model is built using ecoinvent, the two most significant gaps being cement paper bags/paper sacks (0.25 %) and ground granulated blast furnace slag (0.22 %), as shown in Table 5.

Table 5 Data gaps based on the public inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
0.25	market for paper sack | paper sack | Cutoff, U - RoW
0.22	market for ground granulated blast furnace slag | ground granulated blast furnace slag | Cutoff, U - US
0.13	market for explosive, tovex | explosive, tovex | Cutoff, U - GLO
0.13	market for iron ore concentrate | iron ore concentrate | Cutoff, U - GLO
0.12	market for diethylene glycol | diethylene glycol | Cutoff, U - RoW
0.1	market for tap water | tap water | Cutoff, U - RoW
0.0653	market for gypsum, mineral | gypsum, mineral | Cutoff, U - RoW
0.0645	market for clay | clay | Cutoff, U - RoW
0.0499	market for sand | sand | Cutoff, U - RoW
0.048	market for shale | shale | Cutoff, U - GLO
0.0437	market for refractory, high aluminium oxide, packed | refractory, high aluminium oxide, packed | Cutoff, U - GLO
0.0407	treatment of inert waste, sanitary landfill | inert waste | Cutoff, U - RoW
0.0327	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
1.75E-02	market for silica sand | silica sand | Cutoff, U - GLO
1.57E-02	market for textile, knit cotton | textile, knit cotton | Cutoff, U - GLO

3.1.3.2. Models based on the commercial inventory

According to the commercial inventory, at least 94.75 % of the GWP of a limestone quarry can be attributed to diesel combustion—Figure 7. Because this process is 4.76 % more carbon intense according to ecoinvent than according to USLCI, QUARRY#4 generates, logically, more GHG emissions than QUARRY #3—8.03 %. The data gap —modeled as “blasting”—is responsible for 2.37 % of QUARRY#4’s GWP—Table 6. The other two data gaps, “recultivation” and “infrastructure,” are far less significant in GWP terms.

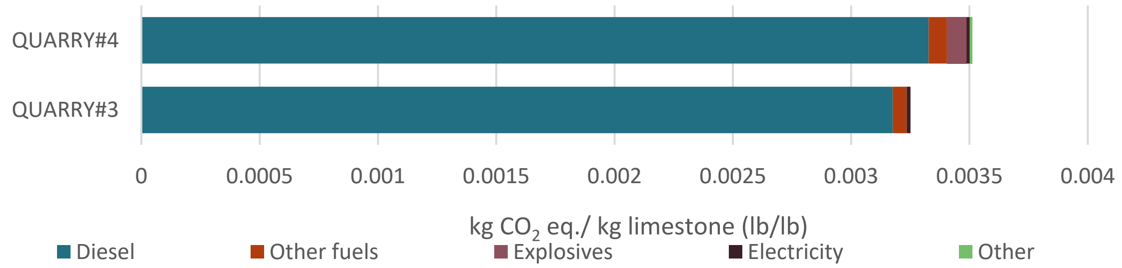


Figure 7 Global warming potential of 1 kg of limestone according to the commercial inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 6 Data gaps for limestone quarry operation based on the commercial inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
2.37	market for blasting | blasting | Cutoff, U - GLO
0.2	market for recultivation, limestone mine | recultivation, limestone mine | Cutoff, U - GLO
0.0907	market for limestone quarry infrastructure | limestone quarry infrastructure | Cutoff, U - GLO

By comparing Figure 5 and Figure 7 it is possible to appreciate the level of granularity of both inventories. The ecoinvent inventory used for the models presented in Figure 7 is solely for the operation of the quarry while the USLCI inventory likely includes crushing and/or milling and, therefore, it is reasonable that the GWP of QUARRY #1 is 55.18 % higher than that of QUARRY#3, and that QUARRY#2's GWP is 33.46 % higher than QUARRY#4's. The fact that, as shown Figure 3, the processing of limestone continues elsewhere in ecoinvent can also be seen in the near absence of electricity—required for crushing and milling—in QUARRY#3 and QUARRY#4, as it is responsible for less than 0.4 % of their GWP.

According to the commercial inventory for clinker production, at least 88.99 % of the GWP is due to direct emissions, both from calcination and fuel combustion. Because of that, it is worth stressing that the fuels appearing in Figure 8 are fuel supply processes, not combustion processes. Since most of GHG emissions are direct, differences between the models are small, with CLINKER#4 having a GWP 3.83 % higher than that of CLINKER#3. This are due to the higher impact of several processes in ecoinvent: coal, ammonia, steel, diesel combustion, natural gas, lubricant oil; and to the data gaps included under "others" in CLINKER#4. The thirteen gaps which are included in ecoinvent are responsible for 1.35 % of CLINKER#4's impact, as seen on Table 7.

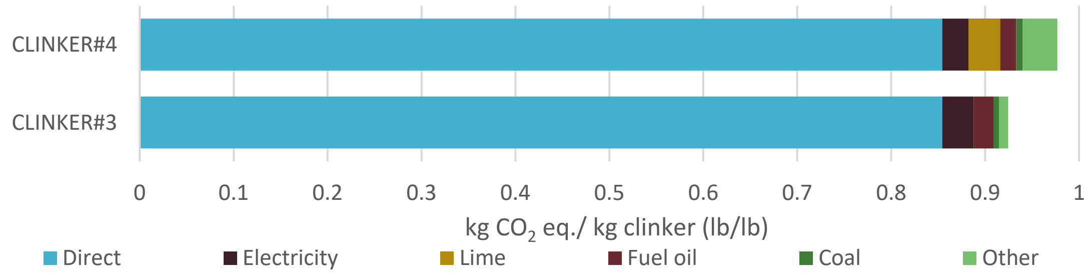


Figure 8 Global warming potential of 1 kg of clinker according to the commercial inventory when built using ecoinvent processes. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 7 Data gaps for clinker production based on the commercial inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
0.39	*market for clay | clay | Cutoff, U - RoW*
0.39	*market for lime, hydrated, loose weight | lime, hydrated, loose weight | Cutoff, U - RoW*
0.37	*market for calcareous marl | calcareous marl | Cutoff, U - RoW*

Contribution [%]	Process
0.0575	*market for refractory, basic, packed | refractory, basic, packed | Cutoff, U - GLO*
0.0363	*market for cement factory | cement factory | Cutoff, U - GLO*
0.0317	*market group for tap water | tap water | Cutoff, U - GLO*
0.0266	*market for meat and bone meal | meat and bone meal | Cutoff, U - RoW*
0.0125	*market for sand | sand | Cutoff, U - RoW*
0.0106	*market for industrial machine, heavy, unspecified | industrial machine, heavy, unspecified | Cutoff, U - RoW*
0.0102	*market for refractory, high aluminium oxide, packed | refractory, high aluminium oxide, packed | Cutoff, U - GLO*
0.00784	*market for refractory, fireclay, packed | refractory, fireclay, packed | Cutoff, U - GLO*
0.00541	*market for municipal solid waste | municipal solid waste | Cutoff, U - RoW*
0.00015	*market for inert waste, for final disposal | inert waste, for final disposal | Cutoff, U – RoW*

The results in Figure 9 show the commercial inventory from ecoinvent provides a more granular breakdown in modeling cement production than the public inventory from USLCI. As mentioned in Section 3.1.1, the latter is a cradle-to-gate inventory of OPC production, and thus does not have a process model for clinker production, which is responsible for 96.5 % of CLINKER#4's GWP. From a high-level perspective, this modeling difference might appear immaterial. After all, USLCI has a model for the final product, cement. However, more granular models are more flexible and, therefore, useful under more situations. In the case of cement, this means that with USLCI it is only possible to model OPC production. With ecoinvent however, it is possible to model other kinds of cement requiring different amounts of clinker—e.g., IS, IP, etc. Besides clinker, only one other process model was missing in USLCI. It is an infrastructure related flow, "cement factory," responsible for 0.33 % of CLINKER#4's GWP—Table 8.

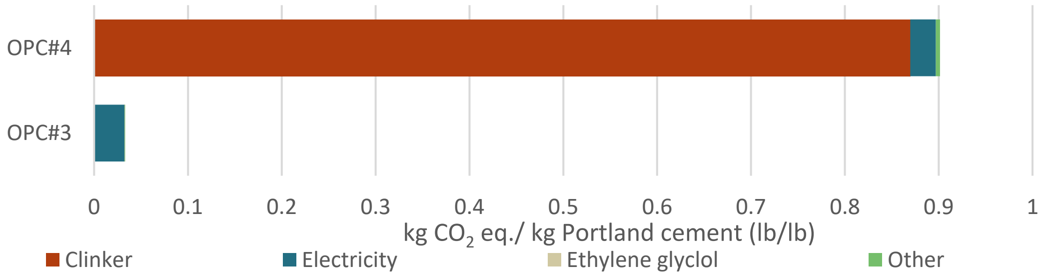


Figure 9 Global warming potential of 1 kg of cement according to the commercial inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 8 Data gaps based on the commercial inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
96.5	*clinker production | clinker | Cutoff, U - US*
0.33	*market for cement factory | cement factory | Cutoff, U - GLO*

3.1.3.3. Representative Model

The representative inventory for limestone production requires 58.63 % less electricity than the public inventory—$1.75 \cdot 10^{-3}$ kWh vs. $4.23 \cdot 10^{-3}$ kWh—and 14.21 % more diesel—see Figure 5 and Figure 10. The impact of these two flows is the main reason why the GWP of QUARRY#5 is 29.55 % lower than that of QUARRY#1, the equivalent model based on the public inventory—see Figure 5 and Figure 10. However, the GWP of QUARRY#6 is 20.40 % higher than that of QUARRY#2 because there is no lubricant, explosives, or hydraulic fluid in the public inventory (Figure 10). The last two flows are particularly important, not only because of their contribution to GWP (29.60 % and 4.20 % for QUARRY#6, respectively), but also because they are data gaps—see Table 9.

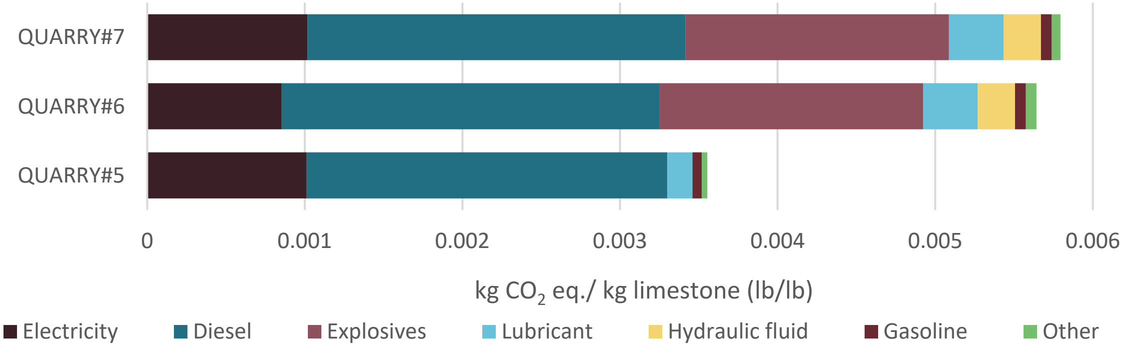


Figure 10 Global warming potential of 1 kg of limestone according to the representative inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 9 Data gaps for limestone quarry operation based on the representative inventory, and their contribution to GWP when the model is built using ecoinvent processes

Contribution [%]	Process
29.6	market for explosive, tovex | explosive, tovex | Cutoff, U - GLO
4.2	market for ethylene glycol monoethyl ether | ethylene glycol monoethyl ether | Cutoff, U - RoW
0.27	market for tap water | tap water | Cutoff, U - RoW
0.00504	process-specific burdens, inert material landfill | process-specific burdens, inert material landfill | Cutoff, U - RoW

Like for the commercial inventory, direct emissions constitute the vast majority of the GHG emissions of clinker production, at least 86.78 %—Figure 11. The GWPs of CLINKER#5 and CLINKER#7 are practically identical—less than 0.3 % difference—and even CLINKER#6's emissions are only 3.40 % to 3.65 % higher. Differences between CLINKER#5 and CLINKER #6 can be partially attributed to the data gaps presented in Table 10, all but "activated carbon" appearing in the figure as part of "others," and whose combined contribution to CLINKER#6's GWP is of 2.62 %. However, these data gaps are included in CLINKER#7. Therefore, the difference between CLINKER#6 and CLINKER#7 is entirely driven by the methodological choices behind both models. Specifically, CLINKER #7 selects petroleum coke, electricity, and diesel combustion from Datasmart and all transport activities but sea transport from USLCI, all having a lower impact than the equivalent flows in ecoinvent.

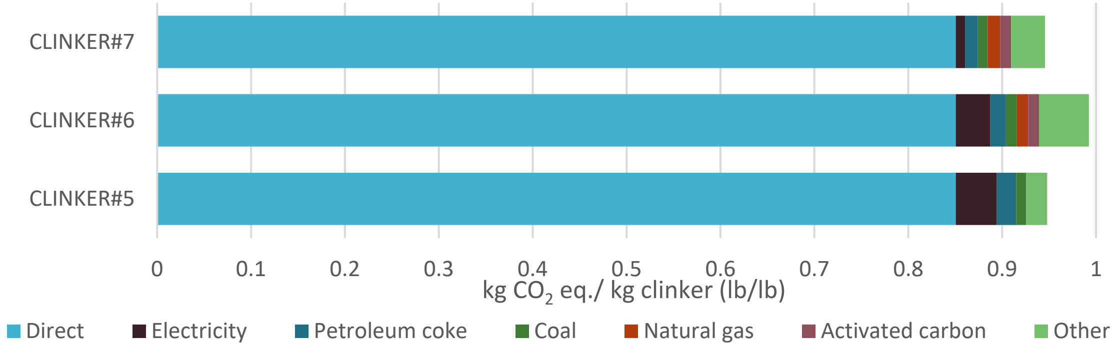


Figure 11 Global warming potential of 1 kg of clinker according to the representative inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 10 Data gaps for clinker production based on the representative inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
1.170	market for activated carbon, granular | activated carbon, granular | Cutoff, U - GLO
0.730	treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, U - RoW
0.098	market for lime, hydrated, loose weight | lime, hydrated, loose weight | Cutoff, U - RoW
0.096	market for iron ore concentrate | iron ore concentrate | Cutoff, U - GLO
0.0732	market for silica sand | silica sand | Cutoff, U - GLO
0.0729	aluminium oxide production | aluminium oxide, non-metallurgical | Cutoff, U - RNA
0.0641	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW
0.0586	market for clay | clay | Cutoff, U - RoW
0.0421	market for diethylene glycol | diethylene glycol | Cutoff, U - RoW
0.0415	market for shale | shale | Cutoff, U - GLO
0.0403	market for sand | sand | Cutoff, U - RoW
0.0383	market for tap water | tap water | Cutoff, U - RoW
0.0212	market for kaolin | kaolin | Cutoff, U - GLO
0.0164	market for calcium chloride | calcium chloride | Cutoff, U - RoW
0.00927	market for quicklime, milled, loose | quicklime, milled, loose | Cutoff, U - RoW
0.0089	market for granulated blast furnace slag | granulated blast furnace slag | Cutoff, U - BR
0.00875	market for calcareous marl | calcareous marl | Cutoff, U - RoW
0.00624	market for waste paperboard | waste paperboard | Cutoff, U - RoW
0.00599	market for refractory, basic, packed | refractory, basic, packed | Cutoff, U - GLO
0.00487	treatment of wastewater from concrete production, wastewater treatment | wastewater from concrete production | Cutoff, U - CH
0.00299	market for waste wood, untreated | waste wood, untreated | Cutoff, U - RoW
0.00235	market for gypsum, mineral | gypsum, mineral | Cutoff, U - RoW

Contribution [%]	Process
0.00193	market for refractory, high aluminium oxide, packed | refractory, high aluminium oxide, packed | Cutoff, U - GLO
0.00174	market for bentonite | bentonite | Cutoff, U - GLO
0.000428	treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, U - RoW
0.000111	treatment of hazardous waste, underground deposit | hazardous waste, for underground deposit | Cutoff, U - RoW
0.0000591	treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, U - RoW
0.0000139	treatment of sewage sludge, 97 % water, WWT, WW from concrete production, landfarming | sewage sludge, 97 % water, WWT, WW from concrete production | Cutoff, U - RoW
0.00000747	treatment of spent solvent mixture, hazardous waste incineration | spent solvent mixture | Cutoff, U - RoW
0.00000111	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - RoW
0	Treatment of waste oil, dummy

As in the case of the commercial inventory for OPC production, Figure 12 shows clinker production to be responsible for more than 95 % of the GHG emissions for all three models. The differences in impacts across models are less than 4 %. The models are also less than 2.1 % apart from the GWP for OPC from the industry average EPD, 0.922 kg CO_2 eq./kg [50]. These differences are mostly due to clinker production, whose GWP per kg of cement ranges between 0.87 in OPC#5 and OPC#7 to 0.90 in OPC#6. The processes available in ecoinvent but missing in USLCI—22 in total—are responsible for less than 0.3 % of the impact when modeling using ecoinvent processes—Table 11. Eight other processes are missing from both USLCI and ecoinvent. These are wastes used as inputs, and therefore currently assumed to be burden free.

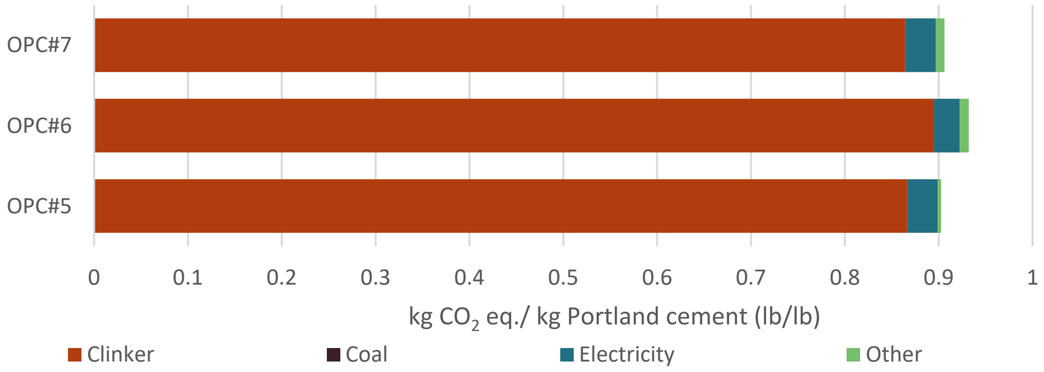


Figure 12 Global warming potential of 1 kg of Portland cement according to the representative inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 11 Data gaps based on the representative inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
0.16	market for diethylene glycol | diethylene glycol | Cutoff, U - RoW
0.0586	paper sack production | paper sack | Cutoff, U - RoW

Contribution [%]	Process
0.0376	market for gypsum, mineral | gypsum, mineral | Cutoff, U - RoW
0.0115	treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, U - RoW
0.00689	market for ground granulated blast furnace slag | ground granulated blast furnace slag | Cutoff, U - US
0.00635	market for extrusion, plastic film | extrusion, plastic film | Cutoff, U - GLO
0.00594	market for ethylene glycol monoethyl ether | ethylene glycol monoethyl ether | Cutoff, U - RoW
0.00392	market for EUR-flat pallet | EUR-flat pallet | Cutoff, U - RoW
0.00253	market for packaging, for fertilisers or pesticides | packaging, for fertilisers or pesticides | Cutoff, U - GLO
0.00187	market for tap water | tap water | Cutoff, U - RoW
0.00122	market for lime, hydrated, loose weight | lime, hydrated, loose weight | Cutoff, U - RoW
0.000729	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW
0.000654	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
0.000213	market for quicklime, milled, loose | quicklime, milled, loose | Cutoff, U - RoW
0.000157	market for anhydrite rock | anhydrite rock | Cutoff, U - RoW
0.0000903	market for waste paperboard | waste paperboard | Cutoff, U - RoW
0.0000213	treatment of hazardous waste, underground deposit | hazardous waste, for underground deposit | Cutoff, U - RoW
0.00000809	market for scrap steel | scrap steel | Cutoff, U - RoW
0.00000274	market for waste wood, untreated | waste wood, untreated | Cutoff, U - RoW
0.00000102	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U - RoW
0.000000668	treatment of wastewater from concrete production, wastewater treatment | wastewater from concrete production | Cutoff, U - RoW
4.12E-10	treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, U - RoW

3.1.4. Summary

This section summarizes the results of the data gap analysis, any other findings of interest identified through the analysis process, and limitations associated with the analysis.

3.1.4.1. Gap Analysis Results

Results were analyzed for cement production, clinker production, and limestone production, each of which is discussed here. Table 12 presents the five largest gaps in terms of their contribution to the GWP of OPC production, measured as the percentage of attributed impact in their respective models. The largest gap is by far “Clinker production”. However, this is a gap only in as much as it is not included as a separate process in USLCI. The production of clinker is part of the current inventory for Portland cement production in USLCI. As mentioned in Section 3.1.2.3, the ASMI’s report that was the basis of the representative model includes a model for clinker production, which can be used to fill this gap.

Outside clinker, other flows contribute less than 0.5 % to the GWP of their respective OPC models. These are small gaps that might not currently be a top priority based on their GWP impact. However, these gaps may be important for measuring other environmental impacts or for the GWP impacts for other product categories. For example, "cement factory" contributes more than 2 % to acidification (data not shown). Also, the contribution of ground granulated blast furnace slag (GGBFS) is small for cement, but GGBFS is a key component in Slag cement, which is also modeled and discussed more in Section 3.4.

Table 12 Priority gaps in GWP for Portland cement production

Rank	Flow	GWP (%)	Inventory
1	Clinker	96.5	Commercial
2	Cement factory	0.33	Commercial
3	Paper sack	0.25/0.06	Public/Representative
4	Ground granulated blast furnace slag	0.22	Public
5	Grinding aids (Diethylene glycol)	0.16	Representative

Regarding clinker production, the overall gap is largest for the representative inventory, but it is relatively small—2.62 %. The five largest gaps overall are presented in Table 13. The two largest—activated carbon and municipal solid waste incineration—were identified using the representative LCI, which also included the three largest impacts identified in the commercial inventory—clay, hydrated lime, and calcareous marl. Even though the contribution of these three flows is small, the differences between both inventories indicates the amount of these materials in the production of clinker can vary significantly and may be non-negligible sources of GWP for some plants.

Table 13 Priority gaps in GWP for clinker production

Rank	Flow	GWP (%)	Models
1	Activated carbon	1.17	Representative
2	Incineration of municipal solid waste	0.73	Representative
3	Clay	0.39/0.06	Commercial/Representative
4	Hydrated lime	0.39/0.10	Commercial/Representative
5	Calcareous marl	0.37/0.008	Commercial/Representative

The commercial inventories for limestone used as a feedstock for clinker production are more granular than the inventory built based on the ASMI report. The latter is a cradle-to-gate process consisting of a single stage as illustrated in Figure 4. ecoinvent's limestone production chain goes from quarry to crushing to milling before being used in the clinker kiln—Figure 3. That is reflected in Table 14, where each stage has different data gaps: "explosives" in the quarry, "conveyor belt" during crushing, and "industrial machinery" while milling. Explosives are the most significant data gap, although the large difference between the representative and commercial inventories indicate there might be large variability in the amounts of explosives used by different quarries. The use of hydraulic fluid and the "machinery required for milling and crushing" are also non-negligible data gaps from the perspective of limestone production.

Table 14 Priority gaps in GWP for limestone production

Rank	Flow	GWP (%)	Models
1	Explosives	29.6/2.37	Representative/ecoinvent (quarry)
2	Hydraulic fluid (EGEE)	4.2	Representative
3	Industrial machinery	3.86/0.41	Commercial (milled)/Commercial (crushed)
4	Conveyor belt	1.0	Commercial (crushed)
5	Water	0.27	Representative

3.1.4.2. Other Findings

Through this analysis one key additional finding was identified that needs to be highlighted. As discussed in Section 3.1.3.1, by comparing the GWP of the models based on the public inventory built using USLCI and ecoinvent, it was possible to infer this inventory overestimated the impact of OPC production by way of including fuel combustion processes in addition to direct emissions generated by the combustion of those fuels.

3.1.4.3. Limitations

The example of cement production stresses two limitations to the quantification aspect of this data gap analysis:

- It is only possible to quantify the importance of a gap if a process model is available in another database. In the case of OPC, the flows missing from both USLCI and ecoinvent are waste flows use as inputs, and therefore considered burden-free. However, that might not be case for other products.
- Prioritizing processes with high impacts might leave behind alternative processes that are key because they cause low impacts. —e.g., GGBFS. Not modeling these processes will overestimate their benefits, particularly if these alternatives are used in larger quantities in the future (e.g., clay).

3.2. Concrete

After water, concrete is the most used material in the world [41] and is the primary application for cement. Thus, it is also indirectly responsible for 7 % of global anthropogenic CO_2 emissions associated with cement [42]. Concrete is a material with a wide range of applications with a variety of constituents mixed in different proportions. The objective of this study is not to conduct an exhaustive data gap analysis of the concrete industry, but to illustrate how the procedure developed here can be applied in this sector and identify some of the most important processes and materials currently absent in public LCI databases. Thus, a mix design for one strength class of ready-mix concrete (RMC) was selected to conduct the analysis. This process can be replicated for other mix designs and strength classes to estimate the variability in the impact of the data gaps identified in this study as well as identify additional data gaps and their relative importance for alternative concrete mixes (e.g., limestone calcined clay cement or LC3).

The Concrete PCR was used as the basis for the representative modeling because it provides enough prescriptive requirements that it can be combined with an available inventory to construct an LCA model. Therefore, it was not necessary to identify an industry report (see section below) or conduct an EPD analysis to identify best/common practices when modeling RMC.

3.2.1. Identify Available Inventories

Along with identifying a representative inventory, it was also determined whether public and/or commercial inventories currently exist to model concrete. A review of these available inventories identified there is no publicly available inventory. USLCI does not have a model for RMC, and currently there are no models elsewhere in the FLCAC. Thus, no public model is included in our analysis. Nevertheless, a parametric model for concrete was once included as part of the Federal Highway Administration (FHWA)/Michigan Technological University (MTU) Asphalt Pavement Framework repository [51].

ecoinvent includes a model for North American concrete (concrete production, 20 MPa, with cement, Portland | concrete, 20MPa | Cutoff, U – CA-QC), which is roughly equivalent to the strength class of the RMC chosen for the representative model—20 MPa (approximately 2900 PSI). The model is based on Canadian reports [52–54], although the source of Portland cement is the US and the electricity is split between the US and Canada (excluding Quebec). For the subsequent analysis the model was modified to use “market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US” for all electricity processes.

The National Ready-Mix Concrete Association (NRMCA) commissioned ASMI with a Cradle-to-gate LCA of RMC manufactured by their members in 2019 [55]. It includes an appendix with national and regional LCA benchmarks based on industry averages, from which the “US National Benchmark Mix design for a 3000-psi concrete” as the representative concrete mix in combination with their “US National Transportation Mode and Distance” and “Gate to Gate manufacturing energy use” values to build the representative inventory. In their report, ASMI also indicates which datasets were used to conduct their LCA. However, here the concrete PCR [24] was followed to complete the representative model for this study.

3.2.2. Round Robin Model Construction and Gap Analysis

The absence of a public inventory means it was only possible to develop a set of five models based on the combination of commercial and representative inventories and public, commercial, and representative databases—Table 15. The tables containing the datasets used for all models can be found in the supplementary workbook “RMC models” (Appendix B).

Table 15 Models developed for ready mix concrete.

Model	Inventory	Database
RMC #3	Commercial	Public
RMC #4	Commercial	Commercial
RMC #5	Representative	Public
RMC #6	Representative	Commercial

Model	Inventory	Database
RMC #7	Representative	Representative

Public LCI data gaps were identified using both the commercial and representative inventories. As mentioned in Section 3.2.1, the commercial inventory for North America was modified to use the US average for all electricity. Nine gaps were identified while building the commercial inventory using USLCI datasets (RMC#3): three constituents of concrete (sand, gravel, and water), three auxiliary materials (alkylbenzene sulfonate linear, synthetic rubber, and unspecified organic chemical), one capital good (concrete mixing factory), and two waste outputs (waste concrete and wastewater from concrete production).

Twelve data gaps were identified while using USLCI to build a model based on the representative inventory (RMC#5). Nine of these gaps were concrete constituents: two additives, two supplementary cementitious materials (SCM), four aggregates, and mixing water. In addition, there was one auxiliary material (process water) and two waste incineration processes. It is worth mentioning "Hazardous waste, to incineration" is a process included in USLCI. However, it is a cut off flow despite not being labeled as such, and therefore is still a data gap.

When building a model based on the representative inventory using ecoinvent (RMC#6)—and when building the representative model proper (RMC#7)—one SCM remains a data gap: fly ash. This is because ecoinvent considers many SCMs as burden free and does not include them as part of the inventory. To account for the emissions generated during the incineration of hazardous waste and municipal solid waste, the waste treatment processes were included as outputs for both RMC #6 and RMC #7 even though they are technically fuel inputs.

The representative model proper (RMC #6) uses USLCI datasets for transport and fuel combustion and ecoinvent for most of the other flows. However, additives and slag cement—the other SCM—were modeled using their industry average EPDs as inputs by creating a process with a CO_2 output equal to the GWP value indicated in the EPD.

3.2.3. Modeling Results

In the subsections below, the GWP of the models developed in Section 3.2.2 are presented organized by their source inventory. The contribution of the identified data gaps as a percentage of the GWP of the model built with commercial datasets is also included.

3.2.3.1. Models based on the commercial inventory

As reflected in Figure 13, OPC production is by far the largest contributor to the carbon footprint of concrete because of the 15 % difference in GWP in OPC production found in Section 3.1.3.1 and Section 3.1.3.2**Error! Reference source not found.**, the GWP of RMC #3 is less than 2 % lower than that of RMC#4 despite the significant gaps for crushed gravel, sand, and others processes that make up more than 13 % of the carbon footprint of RMC #4 (Table 16). Thus, the models are less closely aligned than what their total GWP values may suggest.

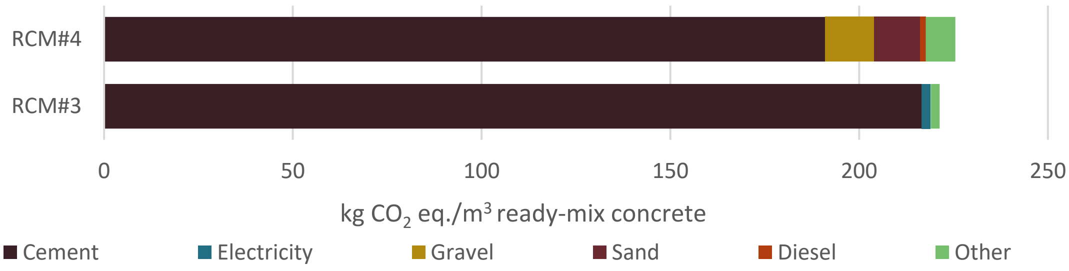


Figure 13 Global warming potential of 1 m^3 of 20 MPa concrete according to the commercial inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 16 Data gaps based on the commercial inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
5.72	*market for gravel, round | gravel, round | Cutoff, U - RoW*
5.39	*market for sand | sand | Cutoff, U - RoW*
0.96	*market for concrete mixing factory | concrete mixing factory | Cutoff, U - GLO*
0.88	*market for alkylbenzene sulfonate, linear, petrochemical | alkylbenzene sulfonate, linear, petrochemical | Cutoff, U - GLO*
0.2	*market for waste concrete | waste concrete | Cutoff, U - RoW*
0.11	*market for tap water | tap water | Cutoff, U - RoW*
0.0273	*market for chemical, organic | chemical, organic | Cutoff, U - GLO*
0.0107	*market for synthetic rubber | synthetic rubber | Cutoff, U - GLO*
0.00281	*market for wastewater from concrete production | wastewater from concrete production | Cutoff, U - RoW*

3.2.3.2. Models based on the representative inventory

The results in Figure 14 shows a good match between the carbon footprint of RMC#7—representative inventory modeled following the PCR—and the industry average for a 3000 psi concrete according to [55], 262.34 kg/m^3 (442.19 lb/yd^3). Since the carbon footprint of Portland cement using the models developed in Section 3.1.2 results are similar, the differences for other flows between RMC#5 and RMC#6 are highlighted. The impact of truck transport is higher in ecoinvent relative to USLCI (Figure 14). Data gaps explain a significant portion of remaining differences between both models, as the nine processes identified in Table 17 are responsible for 8.6 % of the impact generated by RMC#6.

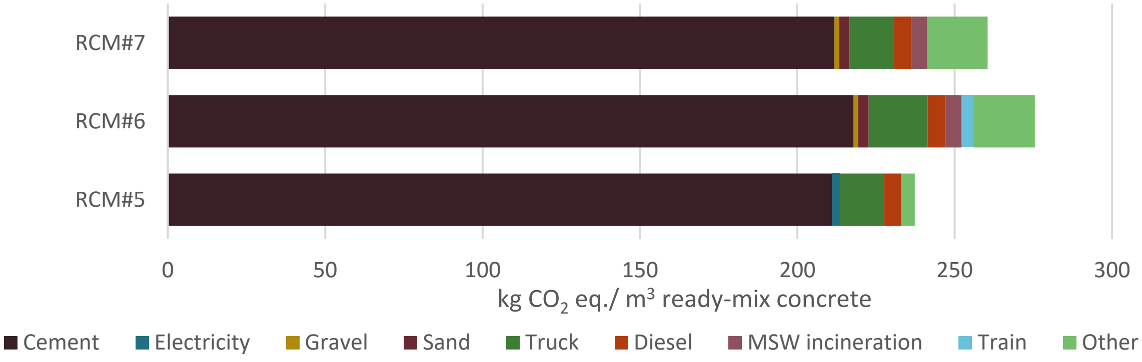


Figure 14 Global warming potential of 1 m^3 of 3000 Psi concrete according to the representative inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown. For results in lb/yd^3 multiply by 1.69

Table 17 Data gaps based on the representative inventory, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
2.89	*gravel production, crushed | gravel, crushed | Cutoff, U - RoW*
1.87	*treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, U - CA*
1.21	*gravel and sand quarry operation | sand | Cutoff, U - RoW*
0.82	*market for tap water | tap water | Cutoff, U - RoW*
0.78	*market for chemical, organic | chemical, organic | Cutoff, U - GLO*
0.52	*gravel and sand quarry operation | gravel, round | Cutoff, U - RoW*
0.43	*ground granulated blast furnace slag production | ground granulated blast furnace slag | Cutoff, U - RoW*
0.0244	*market for alkylbenzene sulfonate, linear, petrochemical | alkylbenzene sulfonate, linear, petrochemical | Cutoff, U - GLO*
0.0109	*treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, U - RoW*

3.2.4. Summary

This section summarizes the results of the data gap analysis, any other findings of interest identified through the analysis process, and limitations associated with the analysis of concrete.

3.2.4.1. Gap Analysis Results

Five of the nine data gaps identified in each inventory were the same, indicating a relative consistency between the commercial and representative inventories. Three of these data gaps—crushed gravel, sand, and air entraining admixture—constitute the first, second, and fifth priority gaps in terms of GWP, respectively, as seen in Table 18. The other two—tap water and set accelerator—are sixth and seventh in GWP impact. The relative contributions of aggregates and air-entraining admixture are more important in the commercial inventory than in the representative inventory, and the opposite is true for tap water and set accelerator. This was to be expected because they are for two similar, but ultimately different, concretes—20.00 MPa

(2901 PSI) and 20.68 MPa (3000 PSI), respectively. Thus, even when the importance of these concrete constituents is clear, their actual contribution—to GWP or any other environmental impact—will depend significantly on the actual composition of concrete. For example, as one moves towards higher compressive strength concretes, the fraction of aggregates decreases while the fraction of cement increases, making their relative contribution to GWP smaller [55]. Alternatively, lower carbon alternative concretes that substitute OPC with limestone (e.g., PLC) or calcinated clay (LC3) can reduce the importance of Portland cement in the mix design and make other constituents' relative impacts increase significantly.

Table 18 Priority gaps in GWP for concrete production

Rank	Flow	GWP (%)	Inventory
1	Crushed gravel	5.72/2.89	Commercial/Representative
2	Sand	5.39/1.21	Commercial/Representative
3	Incineration of municipal solid waste	1.87	Representative
4	Concrete mixing factory	0.96	Commercial
5	Air entraining admixture	0.88/ 0.0244	Commercial/Representative

3.2.4.2. Other findings

As a supplementary analysis to the traditional concrete data assessment, a representative model for one low carbon alternative concrete using limestone calcined clay cement was developed in Section 3.3.

3.2.4.3. Limitations

No limitations specific to the data gap assessment of concrete products were identified, and those of Section 3.1.4.3 for cement do not apply for concrete.

3.3. Limestone calcined clay cement

Limestone calcined clay cement (LC3) is an alternative to Portland cement made with clinker, limestone, and calcined clay, and whose GWP could be up to 40 % lower than that of OPC [56]. Although the structure and the outcome of this section is similar to the sections for other product categories, the objective is different. The focus is not on identifying data gaps but to illustrate how the impact of the data gaps identified in Section 3.2 may increase for alternative, lower carbon cement. LC3 is not currently commercially available in the US or included under an existing PCR. Therefore, there are no EPDs or any industry reports for LC3.

3.3.1. Identify Available Inventories

At present, USLCI does not have an inventory for LC3, calcined clay, or clay proper. The latter was already identified as a data gap for OPC. For LC3, not having data for the main raw material of the product could significantly underestimate the impact, and consequently overestimate the relevance of the data gaps identified in Section 3.2 when LC3 is used to produce RMC. As an alternative, "Kaolin coarse filler; production; at plant" from the European Platform on Life Cycle

Assessment (EPLCA) was used. This inventory was the best available proxy despite its temporal and geographical scope [57]. This dataset is a system process, with thousands of inputs and outputs. Because no mapping between EPLCA and Federal Elementary Flow List (FEDEFL) was found and this study focuses on GWP, the inventory was stripped down to the resource inputs and the GHG emissions and manually converted to FEDEFL to include in the model.

ecoinvent also does not have an inventory for LC3. However, it has a model for “calcined clay production” in Brazil, which this study adapted to represent the US by switching from Brazilian to American electricity averages. The material input for this process, clay, comes from “clay pit operation | clay | Cutoff, U - CH,” which is available for Switzerland—see Figure 15. Since this process did not include electricity consumption, the model was not modified for the purposes of this study. No data gaps were identified for the calcination process besides clay itself. For the clay pit, two data gaps were identified related to the infrastructure of the pit: “clay pit construction” and “mine recultivation”.

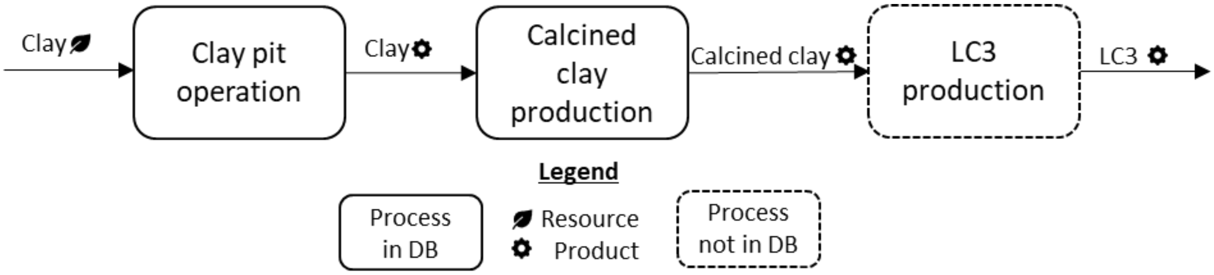


Figure 15 Process flow diagram for LC3 production. Note that ecoinvent does not have an inventory for the production of LC3 proper, although it includes Brazilian cements where a small fraction of calcinated clay is used.

The are no industry reports or published EPDs to use as a reference for a representative inventory. Instead the representative inventory is based on a model for calcined clay and LC3 production in Cuba [58], with modifications to energy inputs to align with those of OPC production in the US, and using the mixing proportions offered in https://lc3.ch/. Besides calcinated clay, “gypsum” was the other data gap identified for the representative inventory.

3.3.2. Round Robin Model Construction and Gap Analysis

The absence of a public or commercial inventory combined with the lack of best/common practices means that only two models (LC3 #5 and LC3 #6) could be developed based on the combination of the representative inventory and the public and commercial databases—Table 19.

Table 19 Models developed for limestone calcined clay cement.

Model	Inventory	Database
LC3 #5	Representative	Public
LC3 #6	Representative	Commercial

Note that for both LC3 models, the limestone and clinker models built as part of the data gap analysis for OPC in Section 3.1 were used. In addition, the following models were developed for the intermediate steps of clay production/clay pit operation—Table 20—and clay calcination—Table 21.

Table 20 Models developed for clay pit.

Model	Inventory	Database
CLAY #1	Public	Public
CLAY #3	Commercial	Public
CLAY #4	Commercial	Commercial

Table 21 Models developed for clay calcination.

Model	Inventory	Database
CC #3	Commercial	Public
CC #4	Commercial	Commercial
CC #5	Representative	Public
CC #6	Representative	Commercial

The tables containing the datasets used for all models can be found in the supplementary workbook "LC3 models" (Appendix B).

3.3.3. Modeling Results

In the subsections below, the GWP of the models developed in Section 3.3.2 is presented, organized by their source inventory. The contribution of the identified data gaps as a percentage of the GWP of the model built with commercial datasets was also included.

3.3.3.1. Models based on the public inventory

Due to the absence of a US public inventory for LC3 or clay calcination, the alternative EPLCA model was used for clay production, which had a GWP of 0.09 kg CO_2 eq./kg clay. Because it is a system process, there were no data gaps, as the contributions from unit processes are unknown.

3.3.3.2. Models based on the commercial inventory

Because there is no model for LC3 in the commercial database, an assessment could only be completed for its two intermediates—calcined clay and clay proper. Figure 16 shows the impact of calcined clay production (CC). The largest source of impact is "direct emissions" for both models of CC production. These represent emissions from the combustion of petroleum coke. The production of petroleum coke is the second most important source of GHG emissions for CC#4. In CC#3 however, "production of clay," is the second most contributing process. This data gap, whose contribution to CC#4 is not as large, as shown in Table 22, is assessed below.

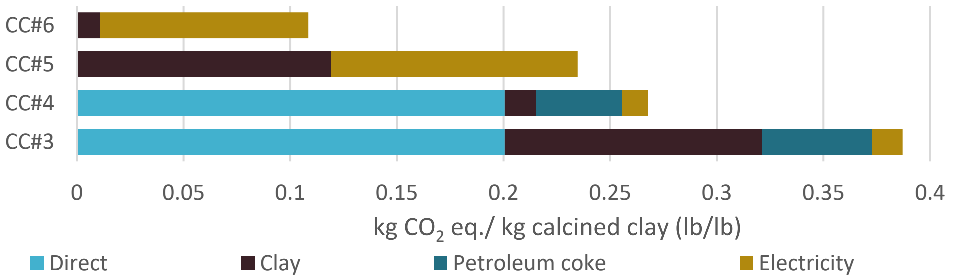


Figure 16 Global warming potential for 1 kg of calcined clay according to the commercial inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 22 Data gaps based on the commercial inventory for clay calcination, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
5.53	market for clay | clay | Cutoff, U - RoW

Figure 17 shows the GWP for clay production following the commercial inventory. In this case, the main data gap, “clay pit construction”—Table 23—is also the main source of impact for CLAY #4. The other data gap, “recultivation,” has a smaller, but not insignificant GWP impact. A noteworthy finding is that the impact of CLAY #1 (modeled in Section 3.3.3.1) is more than 30 times greater than that of CLAY#4, which explains the differences in sizes of the impacts for clay in Figure 16 even though the two processes should, in theory, be producing the same product. Unfortunately, the EPLCA model is a system process, which makes it is impossible to evaluate the source of the differences in the two inventories and resulting emissions.

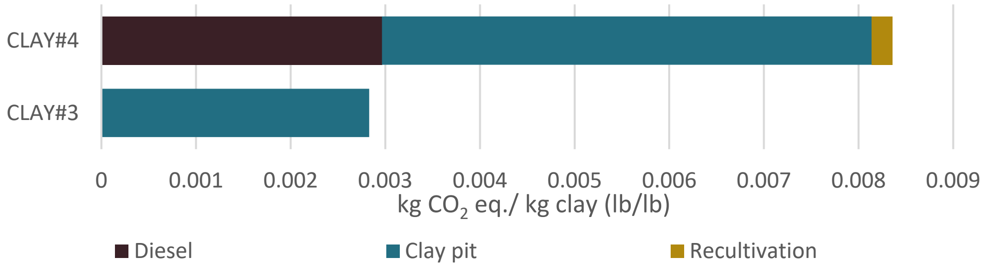


Figure 17 Global warming potential for the extraction of 1 kg of clay according to the commercial inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 23 Data gaps based on the commercial inventory for clay pit operation, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
61.9	clay pit construction | clay pit infrastructure | Cutoff, U - CH
2.61	market for recultivation, bauxite mine | recultivation, bauxite mine | Cutoff, U - GLO

3.3.3.3. Models based on the representative inventory

For both LC3 #5 and LC3 #6, "Clinker" remains as the main source of impact for LC3 production, despite its lower concentration when compared to OPC—Figure 18. The second largest impact is from the production of "calcined clay," which is the largest identified data gap for LC3 as seen on Table 24. The other data gap, "gypsum," has a minimal contribution to GWP.

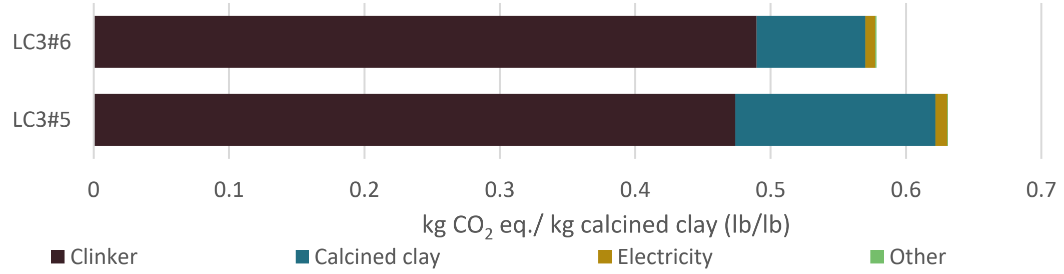


Figure 18 Global warming potential of 1 kg of LC3 according to the representative inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 24 Data gaps based on the representative inventory for LC3 production, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
13.90	calcined clay production | calcined clay | Cutoff, U - US
0.02	gypsum quarry operation | gypsum, mineral | Cutoff, U - RoW

For the commercial inventory-based models, the large differences between "clay production" using public and commercial processes is reflected in Figure 19. The impact of CC#5 is 20 % larger than that of CC#6 due to the differences in clay production as well as the emissions of natural gas combustion and electricity production, which are 57 %, and 18 % larger, respectively, in CC#5 than in CC#6. The 20 % total difference would have been even larger, except that "combustion coal" offset a significant portion—the combined GWP of ecoinvent's hard coal and lignite combustion used in CC#6 is 5 % higher than for the equivalent processes in USLCI used in CC#5.

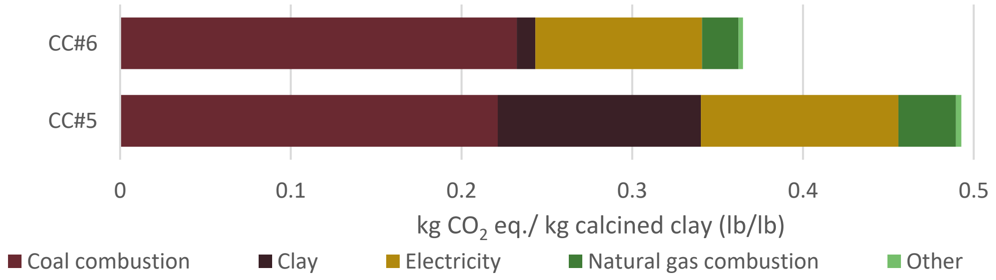


Figure 19 Global warming potential of 1 kg of calcined clay according to the representative inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 25 Data gaps based on the representative inventory for clay calcination, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
2.98	clay pit operation | clay | Cutoff, U - RoW

3.3.4. Summary

This section summarizes the results of the data gap analysis, any other findings of interest identified through the analysis process, and limitations associated with the analysis of LC3.

3.3.4.1. Gap Analysis Results

The limited amount of data gaps identified in this section are provided in a prioritized list in Table 26. The first and fourth are infrastructure-related data gaps and not relevant for EPD purposes, although they may be beneficial to address other applications of LCA. The other two data gaps show the importance of the clay production chain: calcination is an important gap for LC3 production and clay production is a significant gap for calcination. However, clay production is responsible for less than 1 % of the GWP generated from producing LC3. Gypsum's impact on the GWP for LC3 is lower than its impact on OPC—Table 5 and Table 11.

Table 26 Priority gaps in GWP for LC3 production

Rank	Flow	GWP (%)	Inventory
1	Clay pit construction	61.9	Commercial (Pit operation)
2	Clay calcination	13.9	Representative (LC3 production)
3	Clay production/Clay pit operation	5.53/2.98	Commercial/Representative (Calcination)
4	Mine recultivation	2.61	Commercial (Pit operation)
5	Gypsum production	0.02	Commercial (LC3 production)

3.3.4.2. Other findings

Although not in the target scope of this study, it was determined useful to compare the results for LC3 to those of OPC from Section 3.2. Substituting OPC with LC3 in the RCM#6 3000 PSI concrete reduces its impact by 30 %— from 275 kg CO_2 eq./m^3 to 193 kg CO_2 eq./m^3 of concrete (464 lb/yd^3 and 325 lb/yd^3, respectively). Although this is a significant reduction, it is not as large as the 40 % reduction mentioned in Section 3.3 above [56]. Table 27 shows the reduction in the overall GWP causes the percentage of GWP impact associated with the data gaps identified in Section 3.2 to increase by approximately 43 % from 8.6 % to 12.2 %. Additionally, two data gaps ("tap water" and "air entraining mixture") increase above the common cut-off threshold of 1 %.

Table 27 Size of data gaps for 3000 PSI concrete with OPC or LC3

	[%] With OPC	[%] With LC3	Increase in the relative contribution
Crushed gravel	2.89	4.13	43 %
MSW incineration	1.87	2.67	43 %
Sand	1.21	1.73	43%
Tap water	0.82	1.17	43 %
Air entraining admixture	0.78	1.11	42 %
Round gravel	0.52	0.74	42 %
GGBFS	0.43	0.61	42 %
Alkylbenzene sulfonate, linear	0.0244	0.0349	43 %
Hazardous waste incineration	0.0109	0.0156	43 %

3.3.4.3. Limitations

The lack of a flow mapping file between EPLCA and FEDEFL limits the use of the “Kaolin coarse filler” process created for this study to model the GWP impact and it should not be used for other impact categories. However, it also highlights an opportunity to 1) create such a file and 2) use EPLCA as a backup public repository for those processes for which there is currently no model in USLCI. This creates an alternative, even if it is not an ideal match geographically or temporally, to leaving the process blank.

The fact that EPLCA is a system unit process limits its value for the purpose of this study. First, it could not be used as a public inventory for data gap identification purposes. Second, the large differences between its GWP and that of the commercial model—where impacts can be associated with individual unit processes—creates concerns about applicability of the EPLCA outside this study.

Finally, the need to rely on several scientific publications from outside the US stresses the need for a US or North American focused industry report. Combining different sources that may not be applicable for the US further increases uncertainty and hinders their use as reliable public models.

3.4. Slag Cement

Slag cement is another low-carbon alternative to the conventional OPC and, similar to LC3, its key component, GGBFS, may be a component of OPC—as seen in Section 3.1—and concrete—as shown in Section 3.2. Unlike LC3, however, there exists a PCR for slag cement [59] and at least three product EPDs and an industry wide EPD [60] have been published under those guidelines in North America. This study considers GGBFS analogous to slag cement because the industry-wide EPD slag cement is >99 % slag, which is consistent with the commercial inventory for slag cement—see below. Note that according to the PCR, iron blast furnace slag (the raw material for production of GGBFS) is a recovered material and, therefore, the environmental impacts allocated to slag are those related to treatment and transport.

3.4.1. Identify Available Inventories

USLCI does not currently have an inventory for slag cement. ecoinvent has an inventory (named "ground granulated blast furnace slag") for the US based on one developed for the Slag Cement Association (SCA) in 2002 [61]. The SCA inventory is also used for this study as the representative inventory because there is not a more recent inventory available. Because underlying data is the same for both inventories, all four data gaps identified in the reference inventory— "air filter," "treatment of inter waste, to sanitary landfill," "organic solvents," and "blast furnace slag"—were also found in the commercial inventory. In the latter, two other data gaps were identified: "cement factory" (representing the infrastructure needed to produce GGBFS), and "wastewater treatment."

3.4.2. Round Robin Model Construction and Gap Analysis

The two inventories available combined with the two databases creates the four models included in Table 28, and detailed in the supplemental "Slag Cement models" workbook (Appendix B).

Table 28 Models developed for slag cement.

Model	Inventory	Database
GGBFS #3	Commercial	Public
GGBFS #4	Commercial	Commercial
GGBFS #5	Representative	Public
GGBFS #6	Representative	Commercial

3.4.3. Modeling Results

In the subsections below, the GWP results of the models developed in Section 3.4.2 are presented organized by source inventory. The contribution of the identified data gaps as a percentage of the GWP of the model built with commercial datasets are also included.

3.4.3.1. Models based on the commercial inventory

When using the commercial inventory, the GWP of GGBFS#4 (built using the commercial database) is 12 % higher than that of GGBFS#3—Figure 20. The main driver behind this difference are the data gaps identified in Table 29, namely "blast furnace slag" and to a lesser extent "cement factory," which contributed 14.0 % and 3.47 % to the GWP of GGBFS#4, respectively. In addition, the higher impact of natural gas delivery in GGBFS#4 also contributed to this difference, as it is 69 % more GHG intensive for the commercial database than for the public database. The emissions from natural gas and fuel oil combustion are identical for both models and included as "direct" emissions. The difference from these flows is partially offset by higher emissions from electricity production in GGBFS#3, which are 18 % higher than GGBFS#4.

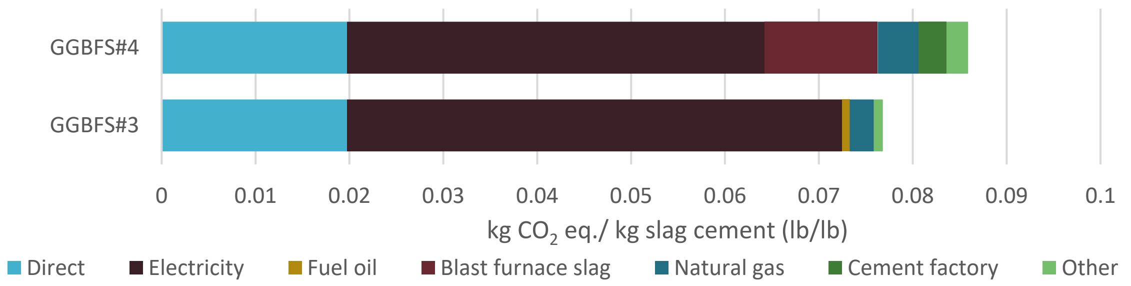


Figure 20 Global warming potential of 1 kg of slag cement according to the commercial inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 29 Data gaps based on the commercial inventory for slag cement, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
14.00	market for blast furnace slag | blast furnace slag | Cutoff, U - US
3.47	market for cement factory | cement factory | Cutoff, U - GLO
0.20	market for air filter, central unit, 600 m3/h | air filter, central unit, 600 m3/h | Cutoff, U - GLO
0.08	market for wastewater from ground granulated blast furnace slag production | wastewater from ground granulated blast furnace slag production | Cutoff, U - US
0.02	market for inert waste | inert waste | Cutoff, U - RoW
>0.01	market for solvent, organic | solvent, organic | Cutoff, U - GLO

As mentioned in Section 3.4, (iron) blast furnace slag should only include impacts related to transport and treatment. The treatment itself is the process represented by both GGBFS models, and ecoinvent's "market for blast furnace slag | blast furnace slag | Cutoff, U - US" only includes a 77 km (47.85 mi) truck transport activity. Because this distance in ecoinvent is a generic default assumptions, it remains (nominally) a data gap since it may not be representative of blast furnace slag transportation in the US.

3.4.3.2. Models based on the representative inventory

For the representative inventory, using the commercial database leads the GWP for slag cement to be 22.5 % higher than when using the public database, as seen in Figure 21. One of the main drivers of this difference is the largest public data gap, "blast furnace slag," whose production is responsible for 9.66 % of the potential GHG emissions of GGBFS#6—Table 30. Another reason for the disparity is land transport, for which between 2.3 and 3.2 times higher emissions are generated from these three processes in GGBFS#6 than in GGBFS#5. The gap between both models would have been larger had the emissions from electricity and ship transport not been higher in USLCI than in ecoinvent—18 % and 79 % higher, respectively. As seen on Table 30, the contribution of the data gaps to GGBFS#6 other than "blast furnace slag" are approximately 0.15 %.

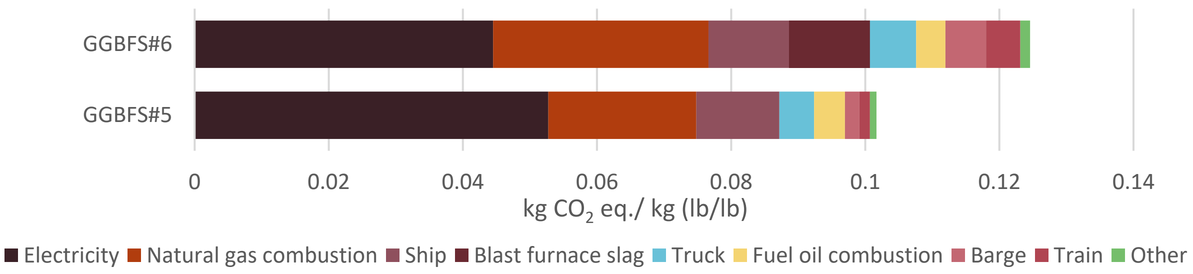


Figure 21 Global warming potential of 1 kg of slag cement according to the representative inventory. Only processes contributing >1 % to the GWP of at least one scenario are shown.

Table 30 Data gaps based on the representative inventory for slag cement, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
9.66	market for blast furnace slag | blast furnace slag | Cutoff, U - US
0.14	market for air filter, central unit, 600 m3/h | air filter, central unit, 600 m3/h | Cutoff, U - GLO
0.01	treatment of inert waste, sanitary landfill | inert waste | Cutoff, U - RoW
0.00	market for solvent, organic | solvent, organic | Cutoff, U - GLO

3.4.4. Summary

This section summarizes the results of the data gap analysis, any other findings of interest identified through the analysis process, and limitations associated with the analysis for slag cement.

3.4.4.1. Gap Analysis Results

Both inventories are based on the same source, which makes it reasonable to expect a significant overlap between their results. Blast furnace slag, the main raw material for production of GGBFS, is an important public data gap that needs to be addressed. Otherwise, there is a risk of underestimating the carbon footprint of GGBFS. There are also discrepancies between both inventories. ecoinvent includes both the infrastructure (3.47 %) and wastewater treatment (0.08 %) that are not available in the public data.

Table 31 Priority gaps in GWP for slag cement production

Rank	Flow	GWP (%)	Inventory
1	Blast furnace slag	14.00/9.66	Commercial/representative
2	Factory	3.4	Commercial
3	Air filter	0.20/0.14	Commercial/representative
4	Wastewater treatment	0.08	Commercial
5	Inter waste landfill	0.02/0.01	Commercial/representative

3.4.4.2. Other findings

Although both the commercial and reference inventories share a common source, the differences in the GWP of their models are not insignificant. Models based on the representative inventory—GGBFS#5 and GGBFS#6—have 32 % and 45 % higher GWP than those based on the commercial inventory—GGBFS#3 and GGBFS#4, respectively. One reason is transport activities, which are responsible for 21 % and 24 % of GGBFS#5 and GGBFS#6, respectively. This is due to three factors. First, transport of the finished slag cement is not included in the commercial model (it is part of the market process for GGBFS). Second, the providers of the different material in the commercial inventory are market processes and, therefore, transport activities are not provided at the level at which this assessment is performed. Finally, there is a limitation on how the representative inventory was implemented in GGBFS#5 and GGBFS #6—see Figure 22 and Section 3.4.4.3 below.

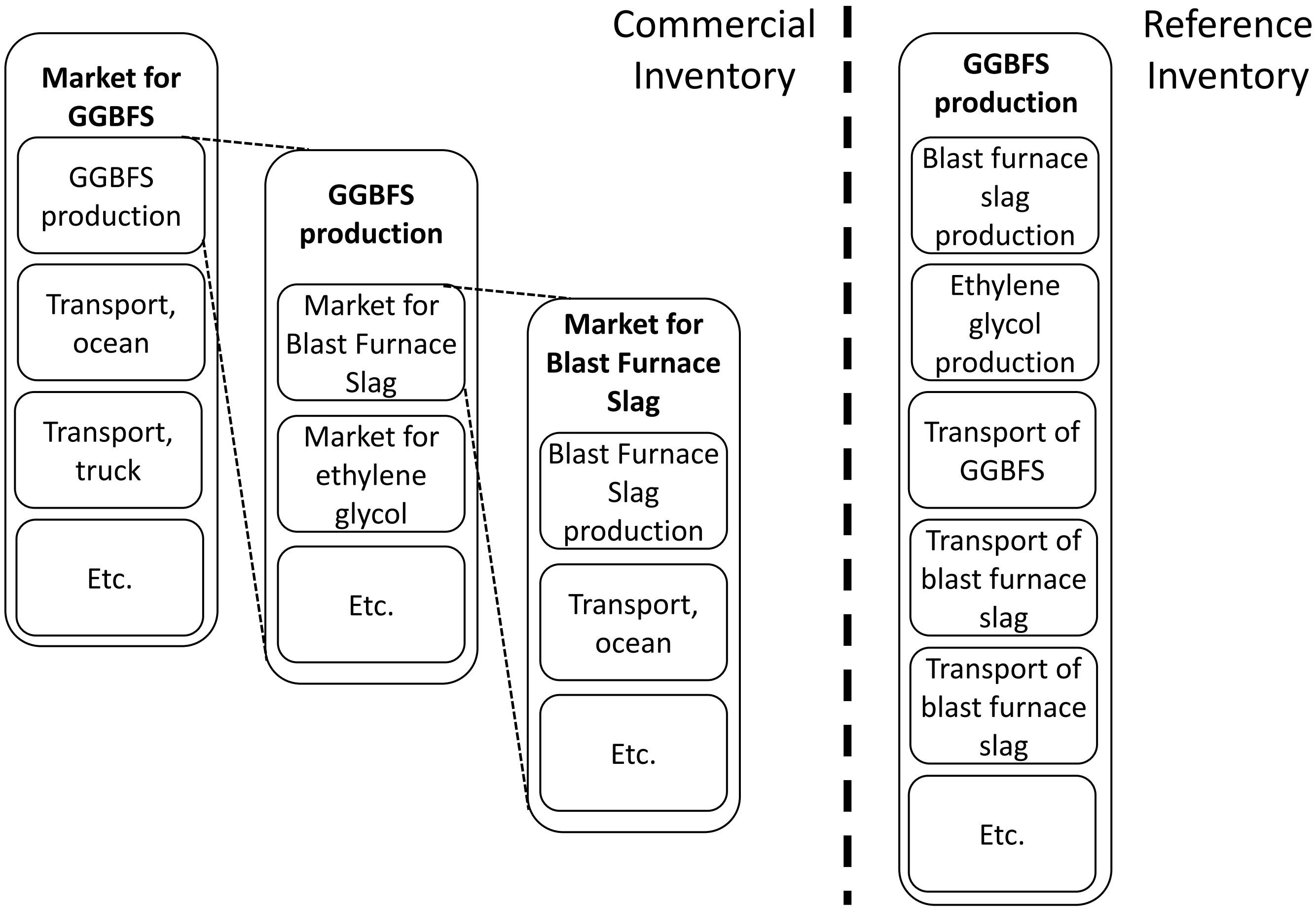


Figure 22 Structure of the commercial and reference inventories, focusing on how transport is implemented.

Another contributing factor is the different approach taken to model combustion processes. The SCA report did not include direct emissions for combustion of fuel oil or natural gas and, thus, GGBFS#5 and GGBFS#6 were modeled using processes that include the combustion of these fuels. Contrarily, the commercial database opted for using an additional source to quantify direct GHG emissions from combustion and use processes that deliver fossil fuels, but do not burn the fuels. Due to these modeling differences, the impact of fuel production and combustion in GGBFS#5 and GGBFS#6 are 15 % and 46 % higher than that of GGBFS#3 and GGBFS#4, respectively. While none of these approaches is technically incorrect, it is argued in Section 3.3.4.3 that combining different data sources to collect an inventory can increase the uncertainty of the resulting models. In the case of slag cement, the commercial model adds elements not present in the initial inventory— “factory” and “wastewater” treatment—which can be seen as complementary because the original source did not include them. However, the benefits of combining two sources to model a related outcome—combustion of fossil fuels—are perhaps less evident.

Finally, the GWP of the industry-average EPD (0.172 kg CO_2 eq./kg slag cement) [60]—is significantly higher than any of the modeling results presented in this study (between 1.38 and 2.24 times higher). This variability highlights the need for an updated representative inventory. While it is reasonable to assume “blast furnace slag” is likely a public data gap worth filling, other data gaps identified here may be less relevant. More importantly, this large difference indicates there may be data gaps in the production of slag cement that were not identified in this analysis.

3.4.4.3. Limitations

Two limitations have already been discussed: mixing data sources identified in the commercial inventory and the difference in GWP results between the models presented in this study and the industry-wide EPD. One additional limitation is that while the SCA report identified material and energy flows needed for the production of slag cement, the same cannot be said regarding transport processes. These are described as the fraction of materials transported through certain modes (e.g., 21 % truck) and an average distance for that material and mode (e.g., ancillary materials, truck, 30 miles) as shown in Table 32. There are, nevertheless, modes and distances not reported. Rather than leaving these modes and distances blank, truck was chosen as the default mode of transport and the same distance as the other modes in the same material was used as the default distance. For example, the “not reported” transport for slag cement to distribution terminal was assumed to be a truck traveling the weighted average of the distances covered by truck, rail, and barge. This approach is meant to prevent underestimating the contribution of transport but estimates higher impacts relative to models based on the commercial inventory. However, considering the high GWP of the industry average EPD, it is possible that the commercial model is already underestimating these impacts.

Table 32 Transportation for slag cement production, according to [61]

Material and mode of transported (sic)	Material transported	Average distance, mile
Iron blast furnace slag to granulators		
Rail	36.4 %	3
Mode not specified	63.6 %	Not reported
Granulated slag to grinding facility		
Truck	54.2 %	5.3
Ship	21.0 %	5000
Mode not specified	24.8 %	Not reported
Slag cement to distribution terminal		
Truck	6.9 %	70
Rail	29.4 %	170
Barge	40.2 %	180
Mode not specified	23.5 %	Not reported
Ancillary materials		
Truck (solids)	9.2 %	30
Mode not specified (solids)	90.8 %	10
Truck (liquids), gallon	25.4 %	Not reported
Mode not specified (liquid), gallon	74.6 %	Not reported
Purchased fuels		
Truck (liquid fuels), gallon	21.7 %	Not reported
Mode not specified (liquid fuels), gallon	78.3 %	Not reported
Pipeline (natural gas), standard ft**3**	22.8 %	Not reported
Mode not specified (natural gas), standard ft**3**	77.2 %	Not reported

3.5. Aggregates

Although not very carbon dense, aggregates are the largest constituent of most concretes, and as shown in Section 3.2, a non-negligible source of GWP. In North America, there is a PCR for construction aggregates [62], which prescribes several datasets from USLCI, mostly related to transport and fuel combustion, and includes several impact factors for processes not currently included in USLCI (manganese steel and explosives, among others).

3.5.1. Identify Available Inventories

As mentioned in Section 3.2, there is no inventory for any kind of aggregate in USLCI. The commercial database includes inventories for three kinds of aggregate: sand, round gravel, and crushed gravel. The first two inventories, “gravel and sand quarry operation | sand | Cutoff, U - CH” and “gravel and sand quarry operation | gravel, round | Cutoff, U - CH” are effectively the same LCI with different outputs. Thus, only one was used to model both kinds of natural aggregates. In addition, both the quarry operation and the “gravel production, crushed | gravel, crushed | Cutoff, U - CH” inventories were slightly adapted for US production, substituting the Swiss electricity mix with the US electricity mix. The Natural Stone, Sand, and Gravel Association (NSSGA) has published an industry wide EPD whose associated LCA contains sufficient information to be used as representative inventories for natural aggregates, mined with and without explosives [63]. The inventory for crushed aggregates is taken from a Swiss report, which was also the basis of the ecoinvent inventory, due to lack of more representative data [47].

Nine data gaps were identified in the commercial inventories. Five were related to capital goods, two are waste treatment processes, and the other two are auxiliary materials (rubber and water). These last two were also identified in the representative inventory, together with other waste treatment processes, polyacrylamide, and explosives.

3.5.2. Round Robin Model Construction and Gap Analysis

The five inventories available combined with the two datasets creates the ten inventories included in Table 33, and detailed in the supplemental "Aggregate models" workbook (Appendix B).

Table 33 Models developed for aggregates.

Model	Inventory	Database	Notes
NATURAL#3	Commercial	Public	For both Sand and coarse gravel
NATURAL#4	Commercial	Commercial	For both Sand and coarse gravel
CRUSHED#3	Commercial	Public	Crushed gravel
CRUSHED#4	Commercial	Commercial	Crushed gravel
w/o EXPLOSIVES#5	Representative	Public	
w/o EXPLOSIVES #6	Representative	Commercial	
w/EXPLOSIVES#5	Representative	Public	
w/EXPLOSIVES #6	Representative	Commercial	
CRUSHED#5	Representative	Public	
CRUSHED#6	Representative	Commercial	

3.5.3. Modeling Results

In the subsections below, we present the GWP of the models developed in Section 3.5.2 organized by their source inventory. We also included the contribution of the identified data gaps as a percentage of the GWP of the model built with commercial datasets.

3.5.3.1. Models bases on the commercial inventory

Figure 23 shows the impact of both natural and crushed aggregates based on the commercial inventory. Crushed aggregates have a higher impact than natural aggregates, between 16 % and 42 % greater. Models built using commercial datasets—NATURAL#4 and CRUSHED#4—have a larger GWP than their counterparts built with public datasets—NATURAL#3 and CRUSHED#3—16 % and 42 % higher, respectively. Although electricity use and diesel combustion are the largest contributors to all models, differences between models are driven by the data gaps shown in Table 34. The nine processes identified are responsible for 15.49 % of the impact of NATURAL#4 and 34.34 % for CRUSHED#4. The reason, as shown in Figure 23, is that the contribution of the "building" process to the CRUSHED#4 model is 5.66 times greater than the contribution of this process to NATURAL#4. There is no additional information in the dataset that might explain the difference. However, a possible explanation is that unlike quarrying, most activities related to crushing occur within facilities.

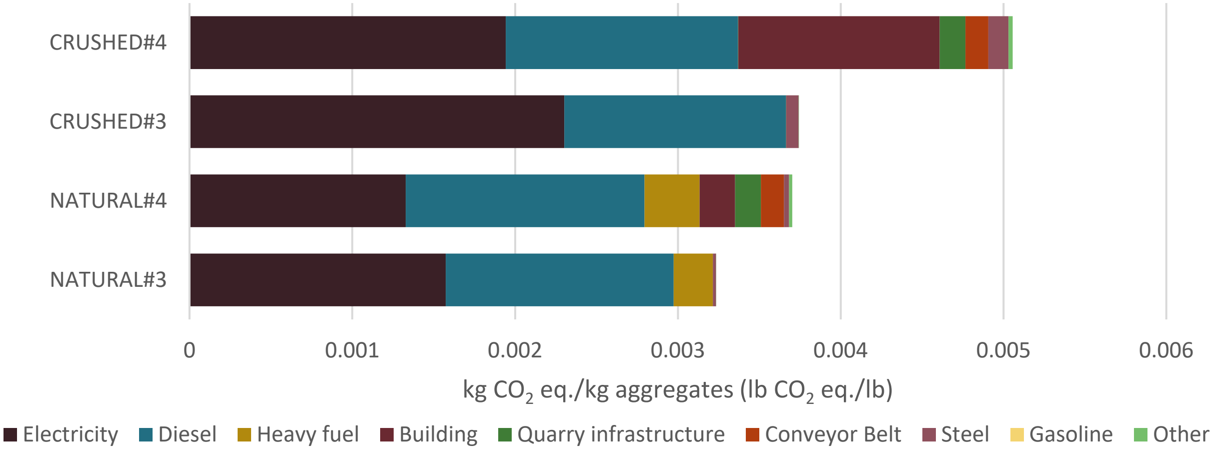


Figure 23 Global warming potential of 1 kg of aggregates according to the commercial inventory. Only processes contributing >1 % to the GWP of that model are shown individually.

Table 34 Data gaps based on the representative inventory for aggregates, and their contribution to GWP when the model is built using ecoinvent processes. The first contribution corresponds to the value for natural aggregates (sand and gravel), and the second for crushed gravel.

Contribution [%]	Process
5.82/23.3	building construction, hall, steel construction | building, hall, steel construction | Cutoff, U - RoW
4.23/2.97	gravel/sand quarry construction | gravel/sand quarry infrastructure | Cutoff, U - RoW
3.76/2.64	market for conveyor belt | conveyor belt | Cutoff, U - GLO
0.81/4.84	market for industrial machine, heavy, unspecified | industrial machine, heavy, unspecified | Cutoff, U - RoW
0.35/0.29	market for tap water | tap water | Cutoff, U - RoW
0.18/0.25	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
0.17/0.0177	recultivation, limestone mine | recultivation, limestone mine | Cutoff, U - RoW
0.0879/0.0459	market for municipal solid waste | municipal solid waste | Cutoff, U - RoW
0.0853/0.0177	clinker production | waste mineral oil | Cutoff, U - RoW

3.5.3.2. Models based on the representative inventory

Figure 24 shows the impact for natural aggregates, mined with and without explosives, and crushed aggregates. As in Section3.5.3.1crushed aggregates have a higher GWP than natural aggregates, but the differences are larger in this case, as CRUSHED#5 has 2.44 times higher GWP than wo EXPLOSIVES#5. These differences are mainly driven by the additional need of electricity to run the crushers, with electricity in the USLCI having an 18 % higher GWP value than the electricity in ecoinvent.

Natural aggregates quarried with explosives have significantly higher impacts that those quarried without explosives (65 % higher when comparing wo EXPLOSIVES #6 and w

EXPLOSIVES#6). Explosives are responsible for 25.10 % of the GWP of EXPLOSIVES#6 (Table 35), but the larger electricity requirement—48 % higher—also increases the impact of the wo EXPLOSIVES models. Other data gaps, specifically "tap water" and the flocculant "polyacrylamide," have small yet non-negligible contributions to the GWP of aggregates.

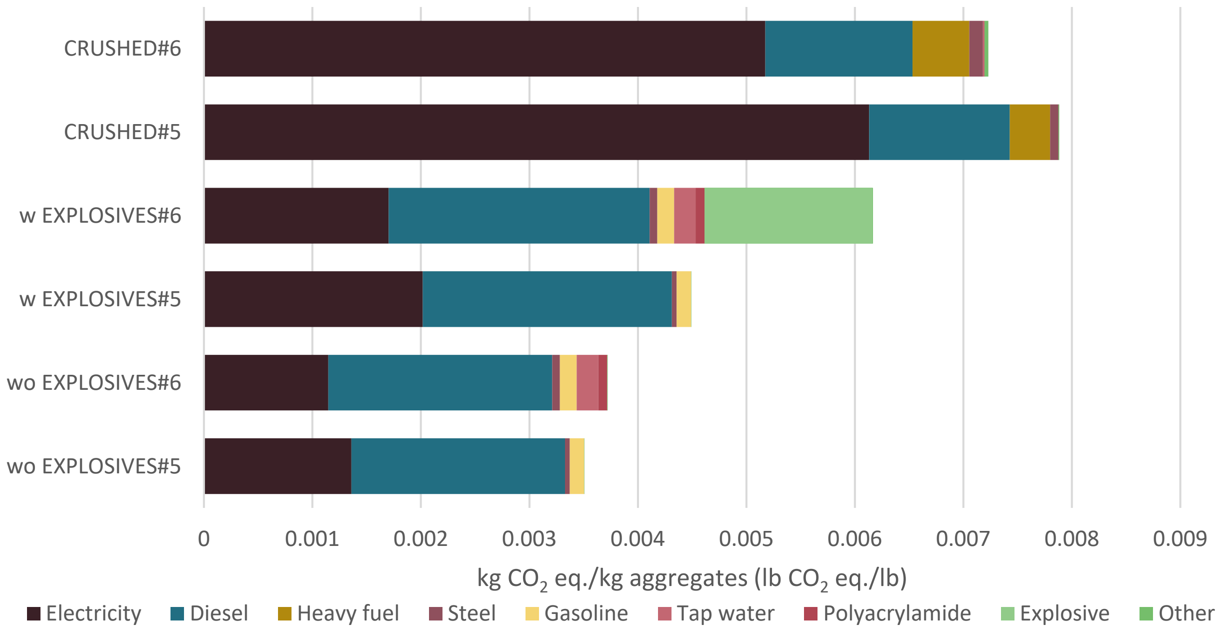


Figure 24 Global warming potential of 1 kg of aggregates according to the representative inventory. Only processes contributing >1 % to the GWP of that model are shown individually.

Table 35 Data gaps based on the representative inventory for aggregates, and their contribution to GWP when the model is built using ecoinvent processes. The first contribution corresponds to natural aggregates, mined without explosives, the second one to natural aggregates, mined with explosive, and the third one to crushed aggregates.

Contribution [%]	Process
0.00/25.10/0.00	explosive production, tovex | explosive, tovex | Cutoff, U - RoW
5.34/3.22/0.21	market for tap water | tap water | Cutoff, U - RoW
2.22/1.34/0.00	market for polyacrylamide | polyacrylamide | Cutoff, U - GLO
0.00/0.00/0.21	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - RoW
0.00/0.00/0.11	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO

3.5.4. Summary

In this section, we summarize the results of the data gap analysis, any other findings of interest identified through the analysis process, and limitations associated with the analysis for aggregates.

3.5.4.1. Gap Analysis Results

Table 36 introduces the main data gaps identified through this analysis. The commercial inventory highlighted the contribution of capital goods, which has already been observed in other inventories, but is particularly significant for aggregates, especially the “building” for crushed aggregates. This might be because the overall impact of aggregates is small, less than 0.008 kg CO_2 eq./kg of aggregate, when compared with other materials in this study, such as cement (0.8 kg CO_2 eq./kg to 1.1 kg CO_2 eq./kg). The same might be said about tap water, a gap appearing in all aggregate inventories as well as in the analysis of other materials in this study, but not in the priority list. Finally, the largest gap identified for aggregates, “explosives,” was identified with a similar relative contribution in the assessment of limestone quarry in Section 3.1, corroborating explosives is an important source of impact for those mining operations where they are used.

Table 36 Priority gaps in GWP for aggregate production

Rank	Flow	GWP (%)	Inventory
1	Explosives	25.1	Representative, natural aggregates with explosives
2	Building	23.3/5.82	Commercial (both)
3	Tap water	5.34/3.22/0.21 0.35/0.29	All
4	Industrial machinery	0.81/4.84	Commercial (both)
5	Quarry infrastructure	4.23/2.97	Commercial (both)

3.5.4.2. Other findings

There were no additional findings as a result of this data gap analysis.

3.5.4.3. Limitations

No particular limitations were detected while conducting this data gap analysis.

3.6. Gypsum

Gypsum was identified as a data gap both for OPC and LC3—Section 3.1 and Section 3.3, respectively—although with little relevance in terms of GWP. Although not identified as a priority material by the EPA, gypsum board is a common construction material for which there exists a PCR [64] and industry wide EPD [65].

3.6.1. Identify Available Inventories

USLCI includes two inventories for gypsum wallboard: 1/2 in (12.7 mm) Regular, and 5/8 in (15.9 mm) Type X. These inventories are based on an LCA ASMI developed for the Gypsum Association [66], and was representative of US production in 2010. These are system models, and therefore unsuitable for proper data gap analysis. Nevertheless, the 1/2 in (12.7 mm) board was modeled to offer a reference point in the sections below.

The updated version of ASMI's LCA, [67], is the basis for the industry wide EPD [65] mentioned above. Because differences between both boards are more quantitative than qualitative, only the LCI for ½ in (12.7 mm) board was used here as representative inventory. This inventory is broken into three smaller inventories: natural gypsum ore extraction, gypsum paper production, and gypsum plaster production, as show in Figure 25. The data gap assessment is performed at all three levels.

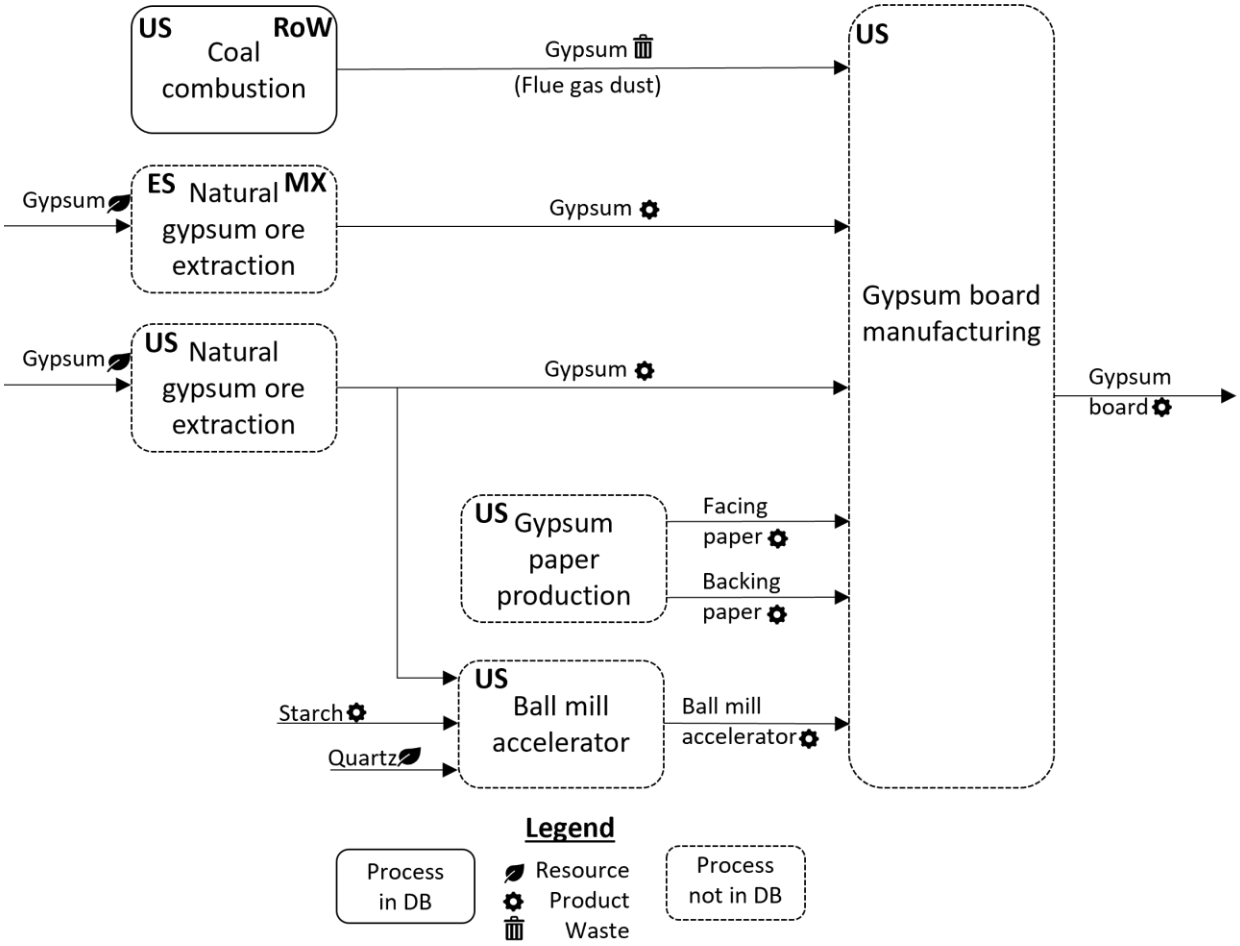


Figure 25 Production process of gypsum board, according to [67]. Note that only processes and flows relevant to the data gap analysis are presented in the figures.

ecoinvent 3.10 also includes two inventories for gypsum board, fiberboard and plasterboard production, for two geographies, Switzerland and the Rest of the World (RoW). Plasterboard was selected as a better representative of the indoor applications of gypsum and subsequently used as the commercial inventory. The Swiss inventory was modified to better reflect US production by substituting Swiss electricity with US electricity, and Swiss heat with Quebecoise heat. The same changes were implemented for the production of stucco, the main material component of gypsum board according to ecoinvent—Figure 26. The electricity was also switched for the gypsum quarry operation, which is the source of the raw material for stucco production, and equivalent to the "gypsum ore extraction" in the representative model. The market for stucco was modified for all the stucco used in plasterboard production to be produced in the US while the market for gypsum was modified to better reflect US market shares. According to [67], 34.41 % of the natural gypsum ore used in the US for the production of plasterboard is of domestic origin, while the remaining 65.59 % comes from Spain and Mexico, for which the RoW quarry was kept.

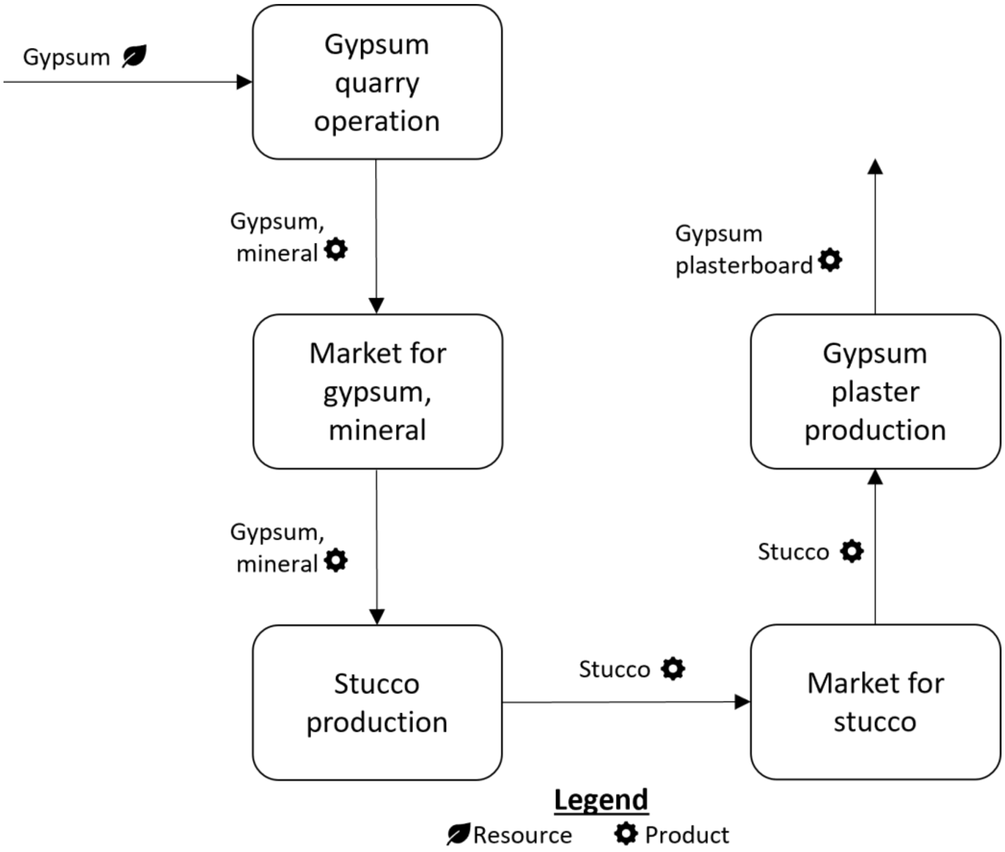


Figure 26 Gypsum plasterboard production, according to ecoinvent.

3.6.2. Round Robin Model Construction and Gap Analysis

As mentioned in the section above, because public inventories are based on system models rather than process models, only the initial model can be run and cannot be modified to create other models. This results in having the six models detailed in Table 37. Detailed information on each model can be found in the "Gypsum models" workbook (Appendix B).

Table 37 Models developed for gypsum board.

Model	Inventory	Database
GYPSUMBOARD#1	Public	Public
GYPSUMBOARD#3	Commercial	Public
GYPSUMBOARD#4	Commercial	Commercial

Model	Inventory	Database
GYPSUMBOARD#5	Representative	Public
GYPSUMBOARD#6	Representative	Commercial
GYPSUMBOARD#7	Representative	Representative

At this level, seven data gaps were identified using the commercial inventory: the surfactant “linear alkylbenzene sulfonate,” “silicone,” “starch,” “tap water,” “corrugated board box,” the infrastructure flow “wooden board factory,” and “stucco”. Despite the stucco being a gap, it was modeled using public datasets to be able to link GYPSUMBOARD#3 with GYSUMORE#3—see below. The representative inventory included 21 data gaps. To the tap water and starch already identified, it added “acrylic filler,” “boric acid,” generic “inorganic chemicals,” the hydraulic fluid “ethylene glycol monoethyl ether (EGEE),” “ethylene oxide,” “glucose,” “glycine,” “isopropanol,” “polyurethane adhesive”—used as proxy for edge paste, and as adhesive— two kinds of “ink,” reclaimed water—modeled as “rainwater harvest”—"wire drawing,” and five waste treatment processes, including wastewater.

In addition to gypsum board, the models for gypsum ore and gypsum paper were developed as presented in Table 38.

Table 38 Models developed for gypsum ore and gypsum paper.

Model	Inventory	Database
GYSUMORE#3	Commercial	Public
GYSUMORE#4	Commercial	Commercial
GYSUMORE#5	Representative	Public
GYSUMORE#6	Representative	Commercial
GYPSUMORE#7	Representative	Representative
FACINGPAPER#5	Representative	Public
FACINGPAPER#6	Representative	Commercial
FACINGPAPER#7	Representative	Representative
BACKINGPAPER#5	Representative	Public
BACKINGPAPER#6	Representative	Commercial
BACKINGPAPER#7	Representative	Representative

Regarding gypsum ore, the commercial inventory included five gaps already found in other mining activities: “blasting,” and the capital goods “conveyor belt,” “heavy industrial machine,” “limestone quarry infrastructure,” and “recultivation”. The representative inventory also contained “blasting” in addition to other already identified gaps (tap water, reclaimed water, and hydraulic fluid).

Facing paper included 16 data gaps. With the exception of “treatment of waste paper” used to model mixed recovered paper, these same gaps can also be found in backing paper. These include “acrylic binder”—used as proxy for polymer emulsifier—the sizing agent “alkylketene dimer,” generic “inorganic chemical,” hydraulic fluid, “starch,” “polyacrylamide”—used as proxy for both retention aid and for chemicals used for on-site wastewater treatment—"synthetic rubber,” “tap water,” “waste paperboard”—as an input, proxy for old corrugated container, and double-lined kraft corrugated cuttings—"wire drawing," and five waste treatment processes, including wastewater treatment.

Finally, as shown in Figure 25, ball mill accelerator is another input for gypsum board production. According to [68], it is a process with only three inputs. Due to its simplicity, only the two models shown in Table 39 were developed and a gap analysis was not conducted at this level.

Table 39 Models developed for ball mill accelerator.

Model	Inventory	Database
ACCELERATOR#5	Representative	Public
ACCELERATOR#6	Representative	Commercial

The database used in [67], and therefore considered the representative database in all gypsum-related #7 models (GYPSUMBOARD#7, GYSUMORE#7, FACINGPAPER#7, and BACKINGPAPER#7), combines USLCI with ecoinvent 3.5. ecoinvent 3.10 has been used in place of ecoinvent 3.5 for the sake of consistency for the remainder of this study with one exception. The provider for natural gas combustion "Heat, district or industrial, natural gas {US}| market for heat, district or industrial, natural gas | Cut-off, U" was available in ecoinvent 3.5 but not in ecoinvent 3.10., likely because not all processes included that constitute the market in ecoinvent 3.5 are available in ecoinvent 3.10. To include this process, its ecoinvent 3.5 version was run and its GWP included in a dummy process with the same name, which was subsequently used as a provider in this assessment.

One other aspect in which GYPSUMBOARD#6 and GYPSUMBOARD#7 differ is that while GYPSUMBOARD#7 uses the process mentioned in [67], some alternative choices were made to the former for the purpose of more precise modeling. For example: "waste paperboard" was used instead of "waste paper" for corrugated carboard waste, and specific chemicals have been used whenever possible instead of the generic organic and inorganic chemical. Additional information can be found in the "Gypsum" spreadsheet.

3.6.3. Modeling Results

In the subsections below, we present the GWP of the models developed in Section 3.6.2 by their source inventory. We also included the contribution of the identified data gaps as a percentage of the GWP of the model built with commercial datasets.

3.6.3.1. Models based on the public inventory

As mentioned in Section 3.6.1, the system model included in USLCI cannot be used for data gap identification or quantification. Nevertheless, GYPSUMBOARD#1 was run and, for reference, had a GWP of 2.59 kg CO_2 eq./m^2 (0.53 lb/ft^2).

3.6.3.2. Models based on the commercial inventory

The differences caused by using different databases for the modeling of natural gypsum production are relatively small, with the GWP of GYSUMORE#4 being 18 % higher than that of GYSUMORE#3—Figure 27. For both models, the two main sources of impact are diesel combustion and electricity generation. Because the GWP of natural gas combustion is 5 % higher in ecoinvent—and therefore in model GYSUMORE#4—while electricity production generates 18 % higher GHGs in USLCI—and thus in GYSUMORE#3—the combined impact of these two sources is roughly equivalent for both models (within 1 %). Thus, the main difference between models resides in the data gaps presented in Table 42, particularly blasting (explosives), which is responsible for 13.3 % of model GYSUMORE#4's GWP. The remaining four data gaps contribute 2.36 % to the GWP of model #4.

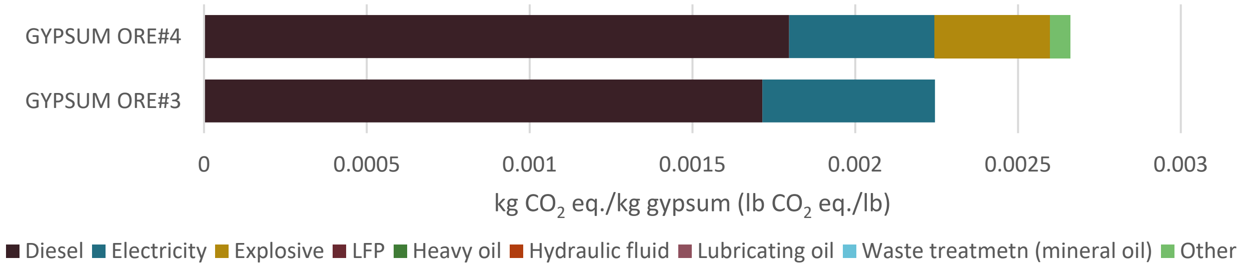


Figure 27 Global warming potential of 1 kg of gypsum ore according to the commercial inventory. Only processes contributing >1 % to the GWP of that model are shown individually.

Table 40 Data gaps based on the commercial inventory for gypsum ore, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
13.3	blasting | blasting | Cutoff, U - RER
0.79	limestone quarry construction | limestone quarry infrastructure | Cutoff, U - CH
0.58	market for conveyor belt | conveyor belt | Cutoff, U - GLO
0.52	recultivation, limestone mine | recultivation, limestone mine | Cutoff, U - CH
0.47	market for industrial machine, heavy, unspecified | industrial machine, heavy, unspecified | Cutoff, U - RER

The effect of selecting a database is more significant for production of gypsum board. The GWP of model GYPSUMBOARD#4 is 26 % higher than that of GYPSUMBOARD#3. Figure 28 shows this difference is driven mostly by missing flows, namely cardboard and starch, which are responsible for 22.40 % and 1.59 % of the GHG emissions from GYPSUMBOARD#4, respectively—Table 42. The largest gap in GWP terms is stucco production (22.50 %), which does not appear as a gap in Figure 28 because an adapted version of stucco production using the public database was developed for GYPSUMORE#3 and used here. Had a model not been built, the GWP of GYPSUMBOARD#3 would have been only 0.19 kg CO_2 eq./kg, 44.22 % lower than that of GYPSUMBOARD#3. Finally, it should be mentioned gypsum quarry operation, which is part of stucco, only causes 2.91 % of the GWP of gypsum board.

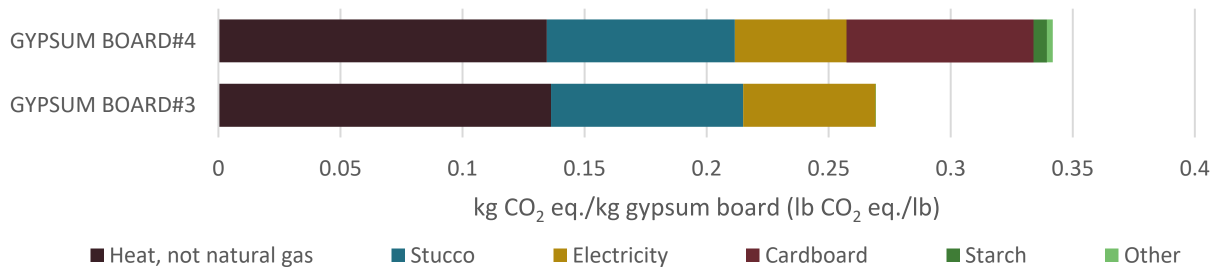


Figure 28 Global warming potential of 1 kg of gypsum board according to the commercial inventory. Only processes contributing >1 % to the GWP of that model are shown individually.

Table 41 Data gaps based on the commercial inventory for gypsum board, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
22.50	market for stucco | stucco | Cutoff, U (US alternative) - GLO
22.40	market for corrugated board box | corrugated board box | Cutoff, U - RER
1.59	market for potato starch | potato starch | Cutoff, U - GLO
0.44	wooden board factory construction, organic bonded boards | wooden board factory, organic bonded boards | Cutoff, U - RER
0.13	market for silicone product | silicone product | Cutoff, U - RER

3.6.3.3. Models based on the representative inventory

The gypsum ore extraction is 2.8 to 3.3 times higher for models based on the representative inventory—shown in Figure 29—than the equivalent model based on the commercial inventory from Figure 27. This is mainly driven by the larger diesel consumption—0.052 MJ/kg gypsum versus 0.018 MJ/kg (22.34 BTU/lb versus 7.73 BTU/lb). In the case of the models built using the commercial database, larger use of explosives— 2.80E-04 kg/kg versus 7.73E-05 kg/kg—was an additional driver.

Despite the differences in absolute terms between models based on different inventories, diesel and electricity are the main sources of GWP for the gypsum ore models shown in Figure 29. Variation between models based on the representative inventory are partially driven by data gaps (Table 42) that are responsible for 22.92 % of GYSUMORE#6's GWP. As for the models based on the commercial inventory, blasting is the main data gap, but the hydraulic fluid EGEE is also an important source of GHG emissions. Modeling choices also play a role if explaining the results of Figure 29. EGGE, whose GWP is 3.45 kg CO_2 eq./l (2.00 lb/gal), was selected as hydraulic fluid for GYSUMORE#6 based on previous models of this assessment. However, ASMI's LCA [67] uses lubricating oil as a proxy for these and other fuels, whose GWP is only of 1.53 kg CO_2 eq./l (12.76 lb/gal), is included in GYSUMORE#7. These differences can be seen in Figure 29, where the contribution of hydraulic fluid plus lubricant oil in model #6 is 1.65 times larger than that of lubricant alone in GYSUMORE#7.

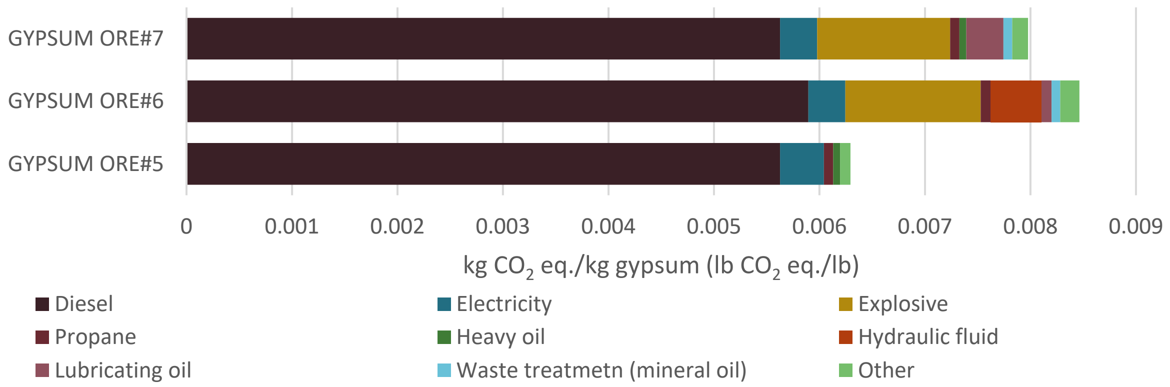


Figure 29 Global warming potential of 1 kg of gypsum ore according to the representative inventory. Only processes contributing >1 % to the GWP of that model are shown individually.

Table 42 Data gaps based on the representative inventory for aggregates, and their contribution to GWP when the model is built using ecoinvent processes. The first contribution corresponds to the value for natural aggregates (sand and gravel), and the second for crushed gravel.

Contribution [%]	Process
15.1	blasting | blasting | Cutoff, U - RoW
5.7	ethylene glycol monoethyl ether production | ethylene glycol monoethyl ether | Cutoff, U - RoW
0.98	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - RoW
0.92	treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, U - RoW
0.22	tap water production, underground water without treatment | tap water | Cutoff, U - RoW
0.0015	rainwater harvesting | water, harvested from rainwater | Cutoff, U - GLO

Figure 30 shows the GWP of facing paper is between 13.68 % and 14.62 % higher than the equivalent backing paper. Most of these differences are quantitative. For example, facing paper requires more natural gas and electricity, the two main sources of GWP in both cases and for all models. Nevertheless, there are also qualitative differences, because facing paper requires mixed paper—modeled as “treatment of waste paper”—one of the data gaps presented in Table 43. This difference also explains the higher contribution of waste paperboard in backing paper. In Figure 30, both treatments are included under “waste paper and paperboard.”

As shown in Table 43, the contribution of data gaps is significant, 31.10 % and 32.67 % to FACING #6 and BACKING #6, respectively. In Figure 30, the relevance of these data gaps might seem smaller than in reality because the differences between those two models and FACING #5 and BACKING #5 is smaller than that—17.86 % and 18.14 %, respectively—due to the higher GWP of natural gas and electricity in the public database—39.03 % and 18.50% respectively.

The different modeling choices made for FACING/BACKINGPAPER#6 and FACING/BACKINGPAPER#7 can easily be observed in Figure 30, with the former slightly higher than the latter—13.71 % to 14.62 %. This is due to the lower GWP of USLCI’s truck transport (25.54 % and 34.26 % lower for short and long haul, respectively), lower impact of waste paper treatment when compared to paperboard treatment (39.46 % lower), higher impact of "alkylketene dimer sizing agent" over the generic chemicals (2.01 to 2.97 times greater), and, most important of all, the inclusion of municipal solid waste treatment, which is quantified in the inventory of [67] without any indication of which process to use.

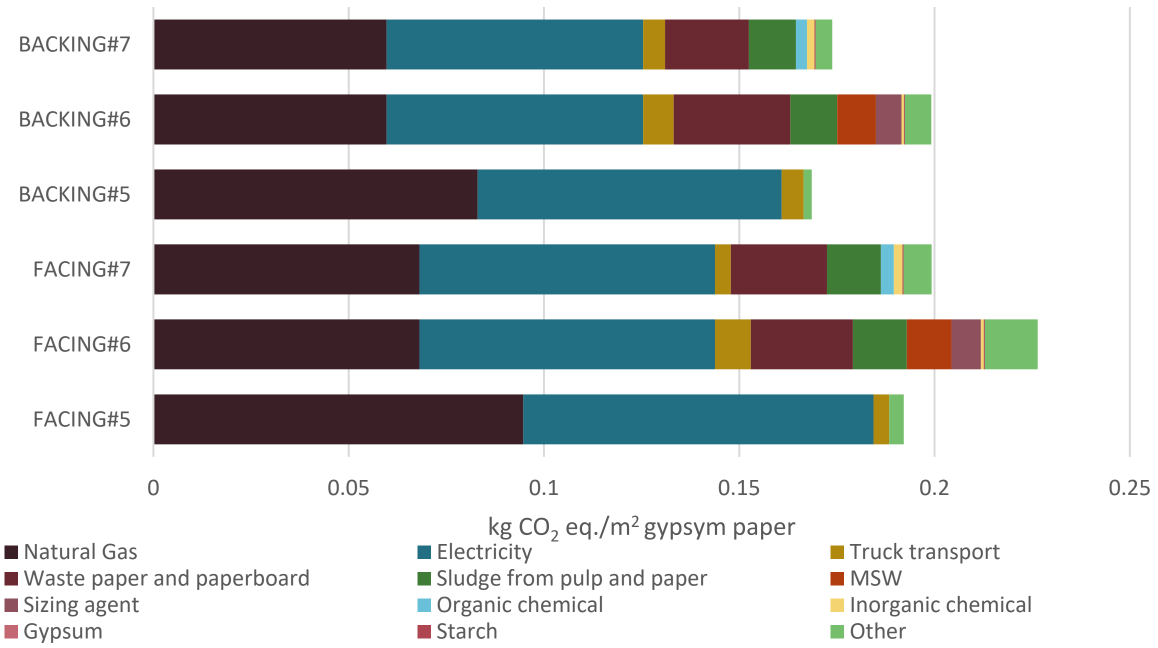


Figure 30 Global warming potential of 1 m^2 of gypsum paper according to the representative inventory. Only processes contributing >1 % to the GWP of that model are shown individually. For the results in lb/ft^2, multiply by 2.048*10^{-1}.

Table 43 Data gaps based on the representative inventory for gypsum paper, and their contribution to GWP when the model is built using ecoinvent processes. The first contribution corresponds to facing paper the second one to backing paper.

Contribution [%]	Process
11.6/15.00	treatment of waste paperboard, unsorted, sorting | waste paperboard, sorted | Cutoff, U - RoW
6.13/6.06	treatment of sludge from pulp and paper production, sanitary landfill | sludge from pulp and paper production | Cutoff, U - RoW
5.07/4.99	treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, U - RoW
3.34/3.30	alkylketene dimer sizing agent production, for paper production | alkylketene dimer sizing agent, for paper production | Cutoff, U - RoW
2.59/0.00	treatment of waste paper, unsorted, sorting | waste paper, sorted | Cutoff, U - RoW
0.63/0.63	polyacrylamide production | polyacrylamide | Cutoff, U - GLO
0.48/0.47	tap water production, conventional treatment | tap water | Cutoff, U - RoW
0.41/0.40	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U - RoW
0.33/0.32	acrylic binder production, with water, in 54 % solution state | acrylic binder, with water, in 54 % solution state | Cutoff, U - RoW
0.32/0.31	chemical production, inorganic | chemical, inorganic | Cutoff, U - GLO
0.13/0.13	maize starch production | maize starch | Cutoff, U - RoW
0.0511/0.0487	synthetic rubber production | synthetic rubber | Cutoff, U - RoW
0.00843/0.00835	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - RoW
0.00295/0.00294	wire drawing, steel | wire drawing, steel | Cutoff, U - RoW
0.00119/0.00122	treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, U - RoW
0.00104/0.00103	ethylene glycol monoethyl ether production | ethylene glycol monoethyl ether | Cutoff, U - RoW

Contrary to the gypsum paper above, Figure 31 shows GYPSUMBOARD#7 to be 15.74 % higher than GYPSUMBOARD#6. The main reason is that, as mentioned in 3.6.2 for the representative database, the GWP for natural gas was taken from the US market in ecoinvent 3.5. Its value is only 4.06 % higher than that for USLCI, but 63.52 % higher than the RoW market from ecoinvent 3.10 used in GYPSUMBOARD#6. This difference has consequences in the data gaps included Table 44, whose contributions might have been smaller than 8.31 % had an updated market for natural gas in the US been available in ecoinvent 3.10. Only two of the data gaps—starch and ethylene oxide—are over the 1 % threshold, and therefore the only two visible in Figure 31.**Error! Reference source not found.** The combined contribution of the remaining 19 data gaps is only of 2.43 %, shown in the figure as part of “Others,” which also includes 19 other processes that are not data gaps, but whose individual contribution is less than 1 %. Besides heat—as natural gas— and electricity, paper— including facing, backing, and kraft paper—is a large source of impact, with a combined impact of up to 29.93 % for GYPSUMBOARD#6.

As a side note, it is worth mentioning the combined impact gypsum ore production—domestic and imported—is less than 1 % of the GWP of gypsum board. Nevertheless, natural gypsum is less than 33 % of all the gypsum used in the manufacturing of the board, as the remaining 67 % is flue gas dust (FGD) synthetic gypsum. Currently, it is considered a waste, but the environmental profile of gypsum board will likely be affected if it becomes a coproduct in the future. Because the production of FGD gypsum is a different process than natural gypsum extraction, the roughly 3 % contribution to GWP obtained above with the commercial inventory cannot not be seen as a proper upper bound. Nevertheless, it might be considered as a reference value for how much the GWP of gypsum board might increase in the future.

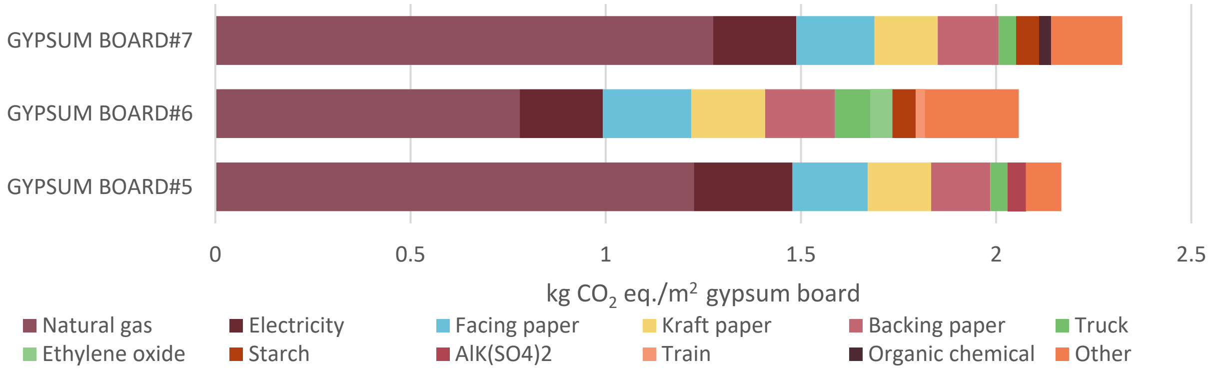


Figure 31 Global warming potential of 1 m^2 of gypsum board according to the representative inventory. Only processes contributing >1 % to the GWP of that model are shown individually. For the results in lb/ft^2, multiply by $2.048*10^{-1}$.

Table 44 Data gaps based on the representative inventory for gypsum board, and their contribution to GWP when the model is built using ecoinvent processes.

Contribution [%]	Process
2.98	maize starch production | maize starch | Cutoff, U - RoW
2.87	ethylene oxide production, ethylene oxidation | ethylene oxide | Cutoff, U - RoW
0.88	glycine production | glycine | Cutoff, U - RoW
0.74	polyurethane adhesive production | polyurethane adhesive | Cutoff, U - GLO
0.32	glucose production | glucose | Cutoff, U - RoW
0.28	boric acid production, anhydrous, powder | boric acid, anhydrous, powder | Cutoff, U - RoW
0.12	tap water production, conventional treatment | tap water | Cutoff, U - RoW
0.056	chemical production, inorganic | chemical, inorganic | Cutoff, U - GLO
0.0244	acrylic filler production | acrylic filler | Cutoff, U - RoW
0.00984	market for printing ink, rotogravure, without solvent, in 55 % toluene solution state | printing ink, rotogravure, without solvent, in 55 % toluene solution state | Cutoff, U - RoW
0.00911	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - RoW
0.00664	ethylene glycol monoethyl ether production | ethylene glycol monoethyl ether | Cutoff, U - RoW
0.006	market for wastewater, average | wastewater, average | Cutoff, U - RoW
0.00233	isopropanol production | isopropanol | Cutoff, U - RoW
0.00164	treatment of hazardous waste, hazardous waste incineration | hazardous waste, for incineration | Cutoff, U - RoW

Contribution [%]	Process
0.00143	printing ink production, offset, product in 47.5 % solution state | printing ink, offset, without solvent, in 47.5 % solution state | Cutoff, U - RoW
0.00107	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U - RoW
0.000895	rainwater harvesting | water, harvested from rainwater | Cutoff, U - GLO
0.000162	treatment of spent solvent mixture, hazardous waste incineration | spent solvent mixture | Cutoff, U - RoW
0.0000766	treatment of sludge from pulp and paper production, sanitary landfill | sludge from pulp and paper production | Cutoff, U - RoW
0.00000147	wire drawing, steel | wire drawing, steel | Cutoff, U - RoW

3.6.4. Summary

In this section, we summarize the results of the data gap analysis, any other findings of interest identified through the analysis process, and limitations associated with the analysis for gypsum board and its inputs.

3.6.4.1. Gap Analysis Results

The commercial model for gypsum board brought to the forefront the two largest data gaps, stucco and cardboard—Table 45. Stucco does not appear in the representative inventory, but the importance of other kinds of paper products can also be seen in Table 45. Similarly, the treatment of waste paperboard—as an input—and of the sludges related to paper production identified in the facing and backing papers representative inventories stress the importance that paper production and waste treatment have for gypsum board production. As for other mineral products, blasting—the use of explosives—is a significant source of GHG emissions.

Table 45 Priority gaps in GWP for gypsum board production

Rank	Flow	GWP (%)	Inventory
1	Stucco	22.50	Commercial, board
2	Cardboard	22.40	Commercial, board
3	Treatment of waste paperboard	11.6/15.00	Representative, facing/backing paper
4	Blasting	15.10/13.30	Representative/commercial, ore
5	Treatment of sludge from pulp and paper	6.13/6.06	Representative, facing/backing paper

3.6.4.2. Other findings

Figure 32 corroborates that although there are important differences depending on the inventory and database used to model gypsum board, their GWP roughly falls around the 2 kg CO_2 eq./m^2 (0.41 lb/ft^2). It is worth highlighting that the differences between the GWP of GYPSUMBOARD#7, built using the representative inventory and database, and the industry average, which is built using the same information, is only 2.1 %. Since the GWP of the industry average is not broken into sources, it is not possible to identify what is driving these differences. However, considering there is a significant amount of proprietary information regarding chemicals use, and therefore its GWP is not publicly known, these differences are deemed to be small.

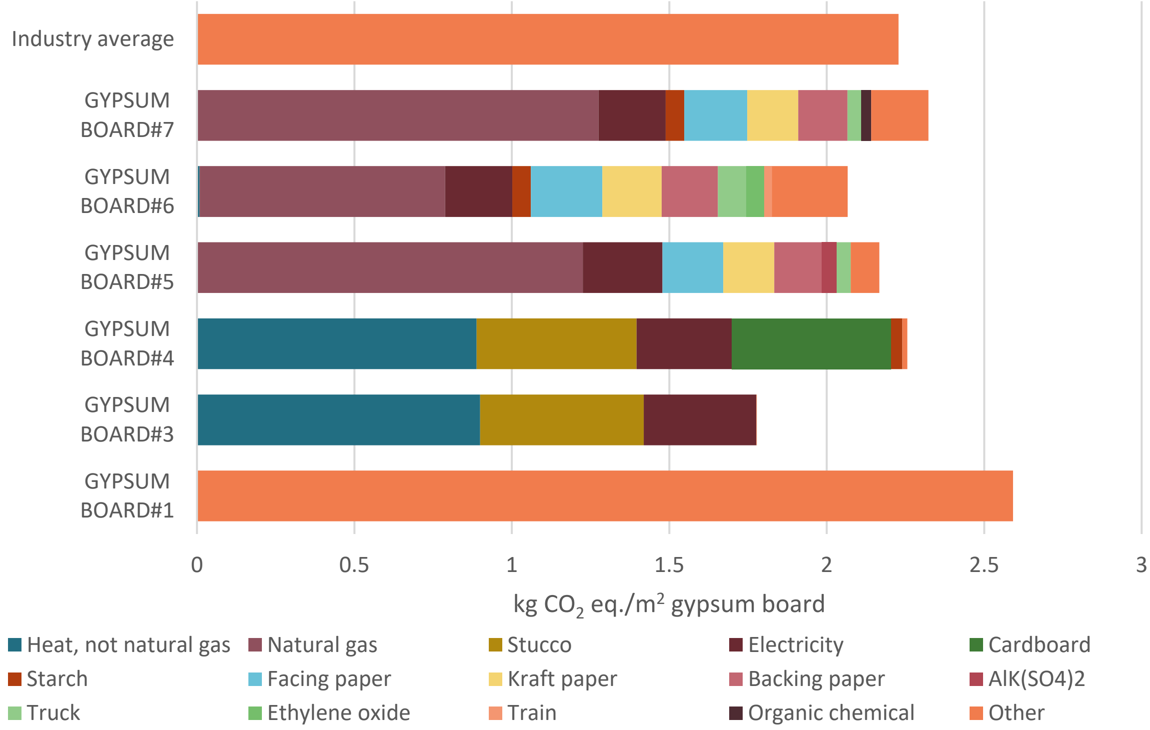


Figure 32 Global warming potential of 1 m^2 of gypsum board according to public, commercial, and representative, and to the industry average inventory. Only processes contributing >1 % to the GWP of that model are shown individually. For the results in lb/ft^2, multiply by 2.048*10^{-1}.

3.6.4.3. Limitations

As mentioned in Section 3.6.3.3, the lack of a US market for natural gas in ecoinvent 3.10 might have increased the relative relevance of the data gaps for the representative inventory of gypsum board. However, the priority list in Table 45 would only be affected if the impact of natural gas in this updated model were to be substantially lower than the RoW market in ecoinvent 3.10.

4. Summary, prioritization, and comparison to other gap assessments

4.1. Summary and potential prioritization criteria to fill out identified data gaps

In total, 123 data gaps from 25 models were used for quantification purposes in Section 3, all of which can be found in the supplementary workbook "Gap summary" (Appendix B). This analysis is limited in scope. The selected products and associated models cover a small fraction of processes in LCA databases and represent exclusively construction materials with similar inputs. Given this limited scope, any data gap prioritization is ultimately subjective. Two ways of ranking the importance of these gaps are presented: (1) relative contribution to the GWP of the model and (2) number of models in which a process is included. Table 46 reports all data gaps contributing more than 10 % to the GWP for at least one model. Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis **[27]**

Table 47 includes the gaps appearing in more than two models. The only gap included in both tables is explosives, appearing three times as the material (explosive, tovex) and three times as the blasting activity. Explosive, tovex is responsible for more than a quarter of the GWP of the limestone quarry model #6. Other gaps with a larger share of the GWP of their respective model are less pervasive (i.e., clinker production and clay pit construction) while gaps more commonly identified (strictly speaking, only tap water appears more than explosives) have lower GWP contribution.

Table 46 Data gaps contributing more than 10 % to the GWP of a model %,

Gap	**Max GWP (%)**	Model with Max GWP	**# models**
Clinker	96.5	OPC#4	1
Clay pit construction	61.9	CLAY#4	1
Explosive, tovex	29.6	QUARRY#6	3
Building construction, hall, steel construction	23.2	CRUSHED#4	2
Stucco	22.5	GYPSUMBOARD#4	1
Corrugated board box	22.4	GYPSUMBOARD#4	1
Blasting	15.1	GYPSUMORE#6	3
Sorting of waste paperboard	15	BACKING#6	2
Blast furnace slag	14	GGBFS#4	2
Calcined clay production	13.9	LC3#6	1

Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis **[27]**

Table 47 Data gaps appearing in more than two models

Gap	Max GWP (%)	Model with Max GWP	# models
Tap water	5.34	wo EXPLOSIVES#6	13
Municipal solid waste, to sanitary landfill	5.07	FACING#6	5
Municipal solid waste	0.085	NATURAL#4	5
Ethylene glycol monoethyl ether	5.7	GYPSUMORE#6	4
Clay	5.53	CC#4	4
Sand	5.39	RMC#4	4
Waste mineral oil incineration	0.98	GYPSUMORE#6	4
Synthetic rubber	0.25	CRUSHED#4	4
Hazardous waste incineration	0.011	RMC#6	4
Explosive, tovex	29.6	QUARRY#6	3
Blasting	15.1	GYPSUMORE#6	3
Sludge from pulp and paper production, to sanitary landfill	6.13	FACING#6	3
Industrial machine, heavy, unspecified	4.84	CRUSHED#4	3
Conveyor belt	3.76	NATURAL#4	3
Cement factory	3.47	GGBFS#4	3
Maize starch	2.98	GYPSUMBOARD#6	3
Alkylbenzene sulfonate, linear, petrochemical	0.88	RMC#4	3
Municipal solid waste incineration	0.73	CLINKER#6	3
Tap water production, conventional treatment	0.48	FACING#6	3
Wastewater treatment, average	0.41	FACING#6	3
Lime, hydrated, loose weight	0.39	CLINKER#4	3
Chemical, inorganic	0.32	FACING#6	3
Diethylene glycol	0.16	OPC#6	3
Gypsum, mineral	0.065	OPC#2	3
Refractory, high aluminum oxide, packed	0.044	OPC#2	3
Wire drawing, steel	0.003	FACING#6	3

Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis [27]

The differences in ranked data gaps between Table 46 and Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis **[27]**

Table 47 highlights a key difficulty in establishing the importance of data gaps. Even with using a single impact category of interest (see Appendix C for an example of a data gap analysis with multiple impact categories), some gaps are critical to only one model (e.g., clinker, clay pit, stucco, corrugated board, calcined clay) while some gaps found in several models have relatively low impacts (e.g., hazardous waste incineration). One option is to prioritize data gaps by combining the ranking approaches, such as prioritizing data gaps appearing in more than one model and contributing at least 1 % to the GWP in one of those models. A priority list with those constraints is presented in Table 48 although this approach does not explicitly mean the higher ranked data gaps are more important.

Table 48. Data gaps identified in more than one model, and contributing more that 1% to the GWP of at least one model

Process	Max GWP (%)	Model with Max GWP	# models
Explosive, tovex	29.6	QUARRY#6	3
Building construction, hall, steel construction	23.2	CRUSHED#4	2
Blasting	15.1	GYPSUMORE#6	3
Sorting of waste paperboard	15	BACKING#6	2
Blast furnace slag	14	GGBFS#4	2
Tap water	5.34	wo EXPLOSIVES#6	13
Municipal solid waste, to sanitary landfill	5.07	FACING#6	5
Ethylene glycol monoethyl ether	5.7	GYPSUMORE#6	4
Clay	5.53	CC#4	4
Sand	5.39	RMC#4	4
Sludge from pulp and paper production, to sanitary landfill	6.13	FACING#6	3
Industrial machine, heavy, unspecified	4.84	CRUSHED#4	3
Conveyor belt	3.76	NATURAL#4	3
Cement factory	3.47	GGBFS#4	3
Maize starch	2.98	GYPSUMBOARD#6	3

Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis [27]

Excluding explosives, the missing processes in Table 48 can be roughly classified into four groups: capital goods, waste treatment, mineral commodities and related raw materials, and chemicals and ancillary materials, as shown in Table 49. These groups can be seen as categories of need of more public modeling. However, it is also necessary to acknowledge these groupings are partially the result of two factors. First, the limited products selected for analysis and commercial database selection because the construction materials evaluated use many of the same mineral commodities as a key component of the products. Second, the commercial database used (ecoinvent) includes the production capital goods, which are often excluded from LCAs and explicitly excluded from EPDs of the product categories evaluated in this study [24, 24, 62, 64, 69]. Thus, the priority to fill some of those gaps might be lower for other sectors and some gaps could be ignored if the main reason to expand the database is to support the development of EPDs.

Table 49 Classification of the most relevant data gaps

Capital goods	Steel construction	Heavy industrial machine	Conveyor belt	Cement factory
Waste treatment	Sorting of waste paperboard	MSW to sanitary landfill	Sludge from pulp and paper production, to sanitary landfill	
Mineral commodities	Blast furnace slag	Clay	Sand	
Ancillary materials	Water	Maize starch	Ethylene glycol monoethyl ether	

4.2. Comparison to EPA’s data gap analysis

As was discussed in Section 1, EPA’s data gap analysis focused on collecting expert opinion on the most important data gaps for EPD development and covered a range of building material product categories that were determined to be high priority for EPA’s low carbon labeling program. Along with three of the categories this study evaluated (cement, concrete, and aggregates), EPA also included asphalt binder, lightweight aggregates, fenestration materials, steel, and wood. However, this study covers three product categories not included in the EPA analysis (gypsum, slag cement, and limestone calcined clay cement).

Despite the difference in scope and approach, there are commonalities between both evaluations. Table 50 provides the identified gaps in the EPA report and which of those gaps are identified in this study. Explosives, aggregates (sand), and tires (synthetic rubber) are identified as data gaps to prioritize in both studies (see Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis [27]

Table 47 and Table 50). Concrete admixtures appeared in Table 18 and Table 50, but are not a priority gap identified in Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis [27]

Table 47 because the contribution to GWP was less than 1 %. The same is true for the flocculant polyacrylamide, which is identified in Table 35 for aggregates and Table 43 for gypsum, but did not make the priority gap list.

Table 50 Data gaps identified through PCR Committee Engagement, adapted from [27] Gaps in italics were also identified in the analyses presented in this report

	Gaps	Cement	Concrete	Construction Aggregates
Raw Materials and Extraction	*Aggregates*		XX	
	Manganese wear parts			X
	Tires			XX
	Concrete admixtures		XX	
Chemicals and Additives	*Explosives*			XX
	Flocculants			XX
Fuels (Consumption Mixes)	Biofuels		X	X
	CNG			X
	Electric vehicles			X
	Hydrogen			X
	LNG			X
	Propane			X
	Renewable diesel			X

X = Identified by EPA study only
XX = Identified by both the EPA study and this study

The commonalities between both analyses exceed the gaps summarized in Table 50 because these gaps are not the only ones reported by the EPA. Fuel and electricity, which have consistently shown as key sources of GWP across the different assessment, were identified as gaps, not because of the absence of datasets, but to their quality, namely their age. Two other important data gaps identified in the EPA assessment [27] as well as here are tap water supply, and end-of-life activities, i.e., waste management and treatment.

There are also differences between the results of both analyses, highlighting two limitations of the analysis presented here. One is a direct result of the different methodological approaches followed by the two analyses, while the other is a result of LCA modeling choices in this study. As shown in Table 50, there is a group of data gaps, consumption mixes of fuels, identified by the EPA through the Construction Aggregates Committee but missed by the data gap analysis in this study. This is because those flows do not appear in any inventory evaluated. This points at a weakness of the methodology already articulated in Section 3.1.4.3: if a flow is not reported in an inventory, then its related process cannot be identified as a data gap. It also illustrates the compartmentalized knowledge surrounding the application of LCA: members of a PCR Committee are aware of current industrial practices (e.g., use of alternative fuels) [27], which have not yet been reflected in the LCIs used for the data gap analysis in this study.

Another data gap identified in Table 50 but not in this report are manganese wear parts. Unlike consumption mixes of fuels, metal wear parts were part of the commercial and representative inventories for aggregates and, thus, were not identified as a data gap. However, the commercial inventory had included wearing parts as made of "steel, low-alloyed, hot rolled" which was equated to “Steel, hot rolled coil” in USLCI. Nevertheless, none of these flows are likely to be manganese steel used in mining and quarrying. Manganese mass fraction is at least 6 % for mining and quarrying [70] while ecoinvent’s manganese mass fraction is estimated at around 0.40 % and USLCI’s is a maximum of 1.1 %. Thus, these available processes might be regarded as rough proxies. These modeling choices highlight the need of subject matter expertise on the part of the LCA practitioner building LCA models used in data gap analysis. A given practitioner may not have sufficient expertise in all processes across different industries, which might lead to modeling choices that are deemed at best as imprecise by subject matter experts. In this case “hot rolled steel” might be seen as a suitable proxy for “manganese steel” by both ecoinvent modelers and the authors of this report but might not be accurate enough for the members of the Construction Aggregates PCR Committee. To partially fill this data gap, the PCR includes the impact of manganese steel [62], based on a paper on manganese production [71] and industry wide EPD for steel plate [72]. The report upon which the EPD is based, “LCI of North American Products” [73] is also the basis for USLCI steel models, including “hot rolled coil” and “plate”. This suggests the key data gap in USLCI is “manganese production,” which would be necessary before the data gap “manganese steel wear parts” can be filled.

4.3. Comparison to NREL’s data gap analysis

The goal and scope of NREL’s data gap analysis [30, 74] is similar to that of this study, evaluating gaps at the process level with a focus on construction materials (specifically cement, RMC, glass, asphalt, iron and steel). Its definition of data gap, however, is broader than the one used in this study. In addition to missing process and cutoff flows in FLCAC, processes with insufficient data quality (e.g., more than 10 years old) are also considered data gaps.

The main difference between the studies is their methodological approach. While this study uses process modeling and process-based databases, NREL’s analysis is based on Input-Output (IO) modeling using the USEEIO database [31] and uses the Structural Path Analysis (SPL) method [75, 76] to separate impacts by tiers (stages) and nodes (sectors). That means that when assessing one sector, a one-tier SPA will reveal sectors that directly interact with the target sector (Stage 1). For example, if the target sector is cement manufacturing as shown in Figure 33, directly impacting sectors would include “coal mining,” “electric power generation, transmission, and distribution,” and “cement manufacturing”. If a two-tier SPA is conducted, the sectors interacting with those of Stage 1 will also be identified. A two-tier SPA for cement manufacturing indicates, for example, that all Stage 1 sectors mentioned above are linked to Stage 2 “coal mining.” Thus, SPA indicates the link between the “cement manufacturing” and “coal mining” sectors is stronger that what might have been inferred from the initial IO tables. The sectors identified are those contributing more than 0.1 % to the impact categories of GWP, Smog Formation Potential, and Energy Use.

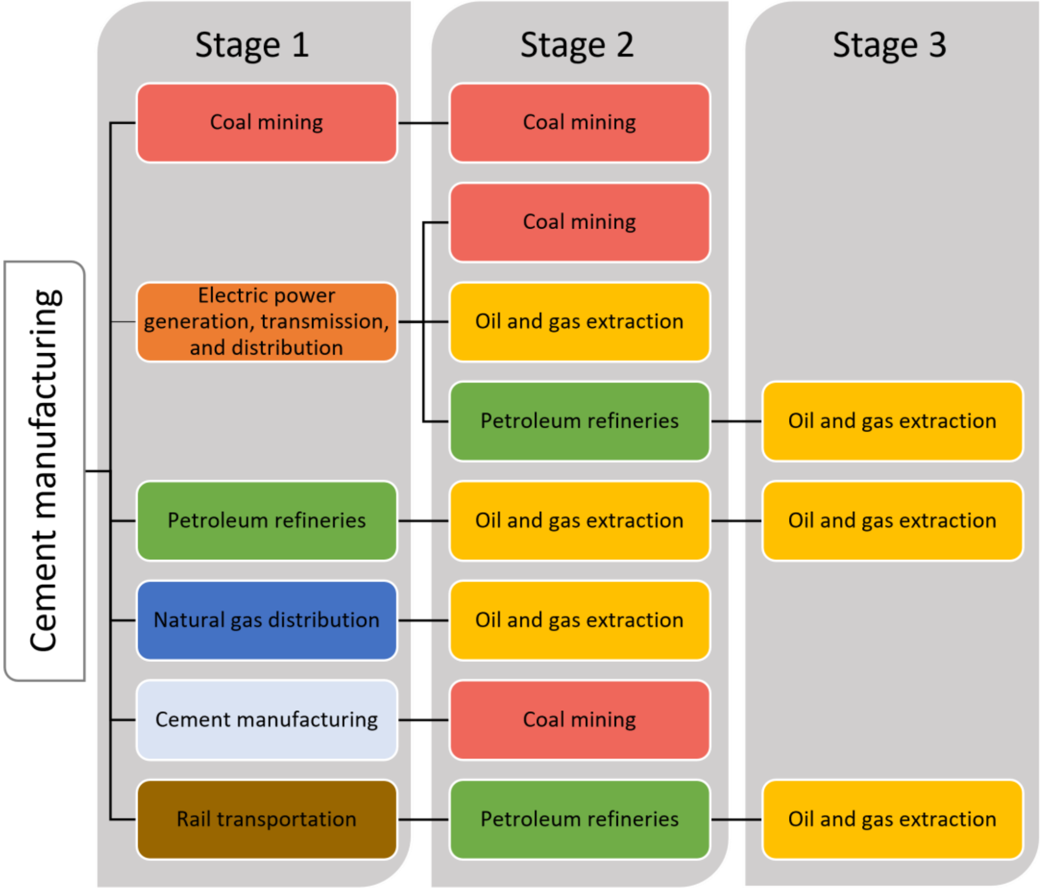


Figure 33 Representation of the structural path analysis for the cement manufacturing sector, according to USEEIO, adapted from [30, 74]

The IO sectors identified through SPA are linked to specific processes in the FLCAC using the North America Industry Classification System (NAICS) [77]. For example, the “natural gas distribution” sector is linked to the process “natural gas, through transmission,” which appears in the FLCAC under the NAICS code “2212: Natural gas distribution”. Using these linkages, NREL used models from ecoinvent 3.8 for eight such processes (“Portland Cement,” “Concrete,” “Bitumen (asphalt),” “Flat Glass Coated,” “Flat Glass Uncoated,” “Steel Converter Low Allow,” “Steel Electric Chromium,” “Steel Electric Low Alloy”). The list of NREL’s data gaps is presented in Table 51.

Table 51 NREL's data gap analysis, and comparison with gaps identified in this study

Process	Identified in this study?
Clinker production	Yes, Section 3.1.2.2
Cobalt	No
Cobalt mining	No
Ferrochromium production	No
Ferromanganese production	No

Process	Identified in this study?
Ferronickel production	No
Flat glass	No
Iron ore mining	Yes, Section 3.1.3.1
Iron pellet production	No
Magnesium oxide production	No
Pig iron production	No
Pitch	No
Smelting and refining of nickel concentrate	No
Synthetic fuel production	No
Zinc	No
Zinc mining	No
Semiconductor	No
Mineral wool	No

Note: NREL's preliminary results did not indicate in which sector/process these gaps were identified. Therefore, it is possible the reason some of the gaps were not identified in this study has to do with the scope of the study and not with the methodology.

It is difficult to assess how well the results of the two studies align for two reasons: (1) limited overlap between the sectors/processes evaluated in both studies (cement and concrete) and (2) NREL's list of gaps does not indicate in which sector/process those gaps were identified because the purpose of the study was to identify data gaps in construction related industries as a whole. Clinker is a straightforward match across the two studies. It is reasonable to assume NREL identified clinker as part of their cement sector assessment, as it is the case in this study. Iron ore mining was also identified in both studies, but it is not possible to determine whether NREL identified this gap as part of their assessment on cement (as in this study), any of the steel-related process, or both. Although it is merely a speculation, it is not unreasonable to assume that "flat glass" was identified during the evaluation of "Flat Glass Coated" and/or "Flat Glass Uncoated." Similarly, it is reasonable to assume that "cobalt" and "cobalt mining," "ferrochromium production," "ferromanganese production," "ferronickel production," "iron pellet production," "magnesium oxide production," "pig iron," "smelting and refining of nickel concentrate," "zinc," and "zinc mining" were identified while evaluating the steel production processes. Thus, it is not unexpected that this study did not identify these data gaps because it did not include glass nor steel products in the analysis. It is, however, more difficult to elucidate the source of two other data gaps identified by NREL ("Semiconductors" and "mineral wool").

5. Conclusions

Given the increasing prevalence of using EPDs for product comparisons and selection, both domestically and globally, there is a need to ensure transparent, trusted, consistent LCA results are being reported in EPDs. One key issue that must be addressed to improve the quality of LCA results in EPDs is to improve the availability and quality of secondary public LCI datasets. This report provides a methodology to identify and quantify LCI data gaps and successfully implements the methodology for a series of construction materials. Due to the limited number and type of products analyzed, the conclusions in this study will not be broadly applicable to products with significantly different manufacturing inputs and processes. Future research could apply the methodology to different construction materials (e.g., flooring, steel, wood) as well as building systems (e.g., solar panel and battery production) to broaden the assessment to provide a more robust list and prioritization of data gaps.

For the five mineral-based construction materials evaluated, more than a hundred data gaps were identified. However, most data gaps are not common and/or have relatively small contributions to the single impact category evaluated in this study, GWP. Only fourteen of them contributed to more than 1 % to the GWP impact of at least one model and present in at least 3 of the 25 models developed in this study. Some important data gaps in terms of GWP impact, namely clinker for OPC production and stucco for gypsum board manufacturing, are more indicative of different modeling approaches between databases than of an absence of information regarding production processes.

The use of explosives emerged as a key data gap, both due to its large contribution to the GWP impact of mining operations and because mining operations were an important fraction of the processes evaluated. Other important data gaps can generally be classified as production of mineral commodities and related raw materials, manufacturing of ancillary material and chemicals, waste treatment and management activities, and the construction of capital goods. This last group (capital goods) is often excluded by LCA but has shown to be relevant for activities closely linked with raw material extraction.

Although not a data gap as defined this study, it is important to emphasize that most of the processes evaluated had energy as their main GWP contributor, either as electricity or as combustible fossil fuels. Although this might seem self-evident, it is also positive feedback for the recommendation found in EPA’s data gap analysis to update the datasets for these two kinds of energy sources [27]. Similarly, the EPA identified end-of-life activities as a key data gap, which would include waste management, waste treatment and wastewater treatment processes, some of which were also identified as key data gaps in this study.

Compared to NREL’s data gap analysis [30, 74], this study is one tier deep. Gaps are accounted for only in the processes for which they were identified, not further down the supply chain. For example, explosives were identified as a gap for the quarrying of limestone, but not for processes that used that limestone, such as clinker production. This is not as much a limitation, as it is a difference in the implemented approach, IO analysis versus process modeling. These approaches are complementary because IO analysis may quantify the relative importance of an industry sector level gap across the entire US economy (top-down approach) while process modeling may identify gaps for individual products (bottom-up approach). Both approaches attempt to address the need to identify data gaps to quantify the GWP impact for production of a product or sector (e.g., concrete production), which leads to the evaluation of data gaps in its main constituents (cements, aggregates, etc.) up the supply chain. The production supply chain showed products with lower absolute GWPs on a mass basis (e.g., raw limestone naturally has a lower GWP than clinker) and which production processes had larger data gaps on a percentage basis. Thus, one recommendation is to start at the beginning of the production supply chain (mining, oil extraction, wood products, etc.) when identifying data gaps because those inputs are the building blocks of all economic sectors. A second recommendation is to focus on data gaps for energy use because energy is a major input into every step of the manufacturing process.

However, these two recommendations are focused solely on GWP impacts, but might not apply to other impact categories. In fact, there is a potential for completely different recommendations depending on which alternative impact categories are considered. Thus, the importance of identified data gaps should be framed around both the purpose and target stakeholders for which the gap assessment is being completed. For example, this study found the contribution of tap water production to GWP to be relatively small. However, tap water would be a key data gap if the purpose of the study were to identify data gaps for a water footprint. An example of how including additional impact categories alters the relative importance of data gaps can be seen in Appendix C. A broader data gap prioritization was also performed using mass and energy inputs as cut-off criteria in Appendix D. Future research should consider broadening the scope of LCI data gap assessment to include other impact categories and alternative threshold criteria as specified in ISO standards to provide a more robust assessment and prioritization.

References

[1] Frey S, Bar Am J, Doshi V, Malik A, Nobel S (2023) Consumers care about sustainability—and back it up with their wallets. Available at https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/consumers-care-about-sustainability-and-back-it-up-with-their-wallets#/

[2] AzariJafari H, Rangelov M, Gregory J, Kirchain R (2023) Suitability of EPDs for Supporting Life Cycle and Comparative Analysis of Concrete Mixtures. *Environmental Science & Technology* 57(19):7321–7327. https://doi.org/10.1021/acs.est.2c05697

[3] City of Portland, OR (2003) *Sustainable Procurement Policy*, Portland Policy Documents Adm. §1.09. Available at https://www.portland.gov/policies/administrative/purchasing/adm-109-sustainable-procurement-policy

[4] State of Colorado (2021) *Buy Clean Colorado Act*, Colorado Revised Statue §24-92-117. Available at https://osa.colorado.gov/energy-environment/buy-clean-colorado-act

[5] European Parliament and the Council of the European Union (2024) *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC*. Available at https://eur-lex.europa.eu/eli/reg/2024/1781/oj

[6] ISO (2006) ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. Available at https://www.iso.org/standard/37456.html

[7] ISO (2006) ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. Available at https://www.iso.org/standard/38498.html

[8] ISO (2022) ISO 14020:2022 Environmental statements and programmes for products — Principles and general requirements. Available at https://www.iso.org/standard/79479.html

[9] ISO (2010) ISO 14025:2006 Environmental labels and declarations — Type III environmental declarations — Principles and procedures. Available at https://www.iso.org/standard/38131.html

[10] National Center for Sustainability Standards (2020) PCR for Portland, Blended, Masonry, Mortar, and Plastic (Stucco) Cements. Available at https://www.cement.org/docs/default-source/pcr-2020/pcr-portland-cement-2020.pdf

[11] EPD International (2024) Cement and building lime (EN 16908:2017+A1:2022). Available at https://api.environdec.com/api/v1/EPDLibrary/Files/9434600c-4629-4fbc-07cf-08dc685f3598/Data

[12] ISO (2017) ISO/TS 14027:2017 Environmental labels and declarations — Development of product category rules. Available at https://www.iso.org/standard/66123.html

[13] ISO (2022) ISO/TS 14029:2022 Environmental statements and programmes for products — Mutual recognition of environmental product declarations (EPDs) and footprint communication programmes. Available at https://www.iso.org/standard/78513.html

[14] Bhat CG, Adhikari T, Mellentin J, Feraldi R, Swack T, Mukherjee A, Dylla H, Rangelov M (2022) ACLCA PCR Guidance – Process and Methods Toolkit. Available at https://www.aclca.org/initiatives#PCR-Open-Standard

[15] Port Authority of New York and New Jersey (2021) Clean Construction. Available at https://www.panynj.gov/content/port-authority/en/about/Environmental-Initiatives/clean-construction.html

[16] Marin County, CA (2019) *Carbon Concrete Requirements*, Marin County, California-Municipal Code §19.07. Available at https://www.marincounty.gov/departments/cda/sustainability/green-build-req/lcc

[17] City and County of Denver, CO (2018) *Green Buildings*, Building Code of the City and County of Denver, Article XIII. Available at https://www.denvergov.org/Government/Agencies-Departments-Offices/Agencies-Departments-Offices-Directory/Community-Planning-and-Development/Plan-Review-Permits-and-Inspections/Commercial-and-Multifamily-Projects/Green-Buildings-Ordinance

[18] State of California (2017) *Buy Clean California Act*, Public Contract Code §3500-3505. Available at https://www.dgs.ca.gov/pd/resources/page-content/procurement-division-resources-list-folder/buy-clean-california-act

[19] State of New York (2022) *NYS Buy Clean Concrete guidelines*, State Financial Law §136-d. Available at https://ogs.ny.gov/nys-buy-clean-concrete-guidelines-0

[20] ISO (2017) ISO 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services. Available at https://www.iso.org/standard/61694.html

[21] European Parliament and the Council of the European Union (2023) *Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism*. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.130.01.0052.01.ENG&toc=OJ%3AL%3A2023%3A130%3ATOC

[22] European Commission (2023) *Commission Implementing Regulation (EU) 2023/1773 of 17 August 2023 laying down the rules for the application of Regulation (EU) 2023/956 of the European Parliament and of the Council as regards reporting obligations for the purposes*

of the carbon border adjustment mechanism during the transitional period. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.130.01.0052.01.ENG&toc=OJ%3AL%3A2023%3A130%3ATOC

[23] Ingwersen WW, Stevenson MJ (2012) Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment. *Journal of Cleaner Production* 24:102–108. https://doi.org/10.1016/j.jclepro.2011.10.040

[24] National Center for Sustainability Standards (2024) PCR for Concrete v2.3 – 2024 Extension.

[25] Federal LCA Commons (2024) Memorandum of Understanding among the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), U.S. Department of Agriculture (USDA), U.S. Department of Transportation (DOT), and the National Institute of Standards and Technology (NIST) on the Federal Life Cycle Assessment (LCA) Commons. Available at https://www.lcacommons.gov/memorandum-understanding-0

[26] EPA (2022) Interim Determination on “Substantially Lower Embodied Carbon” Construction Materials. Available at https://www.epa.gov/system/files/documents/2023-01/2022.12.22%20Interim%20Determination%20on%20Low%20Carbon%20Materials%20under%20IRA%2060503%20and%2060506_508.pdf

[27] EPA (2024) Life Cycle Inventory Data Gap Assessment. (Environmental Protection Agency, Washington D.C.), p 40. Available at https://www.epa.gov/greenerproducts/label-program-low-embodied-carbon-construction-materials

[28] EPA (2024) A Vision and Plan to Improve Secondary Life Cycle Assessment Data Used in Environmental Product Declarations. (Environmental Protection Agency, Washington D.C.), p 35. Available at https://www.epa.gov/greenerproducts/label-program-low-embodied-carbon-construction-materials

[29] EPA (2024) U.S. EPA Criteria for Product Category Rules (PCRs) to Support the Label Program for Low Embodied Carbon Construction Materials (EPA’s PCR Criteria) (Version 1—2024). (Environmental Protection Agency, Washington D.C.), EPA-740-R-24-009, p 65. Available at https://www.epa.gov/greenerproducts/label-program-low-embodied-carbon-construction-materials

[30] Bacas P, Carpenter A, Cashman S, Chen J, Hottle T, Ingwersen W, Kneifel J, Oiwa L, Ranganath S, Rodriguez-Garcia G, Young B (2024) Federal Life Cycle Inventory Data Gap and Data Quality Assessments. Available at https://virtual.oxfordabstracts.com/event/public/24956/session/121528

[31] Ingwersen WW, Li M, Young B, Vendries J, Birney C (2022) USEEIO v2.0, The US Environmentally-Extended Input-Output Model v2.0. *Scientific Data* 9(1):194. https://doi.org/10.1038/s41597-022-01293-7

[32] Steubing B, Wernet G, Reinhard J, Bauer C, Moreno-Ruiz E (2016) The ecoinvent database version 3 (part II): analyzing LCA results and comparison to version 2. *International Journal of Life Cycle Assessment* 21(9):1269–1281. https://doi.org/10.1007/s11367-016-1109-6

[33] FitzGerald D, Bourgault G, Vadenbo C, Sonderegger T, Symeonidis A, Fazio S, Mutel CL, Mueller JF, Dellenbach D, Skoikou N, Baumann D, Clementi M, Ioannidou D, Cirone F, Superti V, Beckert P, Treichel A, Kaarlea O, Kunde S, Valsasina L, Moreno-Ruiz E (2023) Documentation of changes implemented in the ecoinvent database v3.10 (2023.12.14). (Ecoinvent, Zurich, Switzerland), pp 1–138. Available at https://19913970.fs1.hubspotusercontent-na1.net/hubfs/19913970/Knowledge%20Base/Database/Releases/Change%20Report%20v3.10%20-%2020231214.pdf

[34] Srocka M, Cashman S, Edelen A, Young B, Ciroth A, Ingwersen W (2020) Flow Mapping in openLCA. (Environmental Protection Agency, Washington D.C.), p 16. Available at https://www.openlca.org/wp-content/uploads/2020/06/General-openLCA-Mapping-Instructions_05182020.pdf

[35] Edelen A, Hottle T, Cashman S, Young B, Ingwersen W, Srocka M, Ciroth A (2020) Mapping file for conversion from openLCA reference elementary flow list to the U.S. Federal LCA Commons Elementary Flow List (FEDEFL). (Environmental Protection Agency, Washington D.C.), p 3. Available at https://www.openlca.org/wp-content/uploads/2020/07/Flow-mapping-file_openLCA_to_FEDEFL.pdf

[36] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment* 21(9):1218–1230. https://doi.org/10.1007/s11367-016-1087-8

[37] GreenDelta (2024) openLCA. Available at https://share.greendelta.com/index.php/s/D1xa3haTiHJdhqt?path=%2F2.1.0

[38] Bare J (2012) Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) User's Guide. (U.S. Environmental Protection Agency, Cincinnati, OH), EPA/600/R-12/554, Vol. 600/R–12/5, p 24. Available at https://nepis.epa.gov/Adobe/PDF/P100HN53.pdf

[39] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Zelm RV (2016) ReCiPe2016 : a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-016-1246-y

[40] Bulle C, Margni M, Patouillard L, Boulay A-M, Bourgault G, Bruille VD, Cao V, Hauschild M, Henderson A, Humbert S, Kashef-Haghighi S, Kounina A, Laurent A, Levasseur A, Liard G, Rosenbaum RK, Roy P-O, Shaked S, Fantke P, Jolliet O (2019) IMPACT World+: a globally regionalized life cycle impact assessment method. *The International Journal of Life Cycle Assessment 2019 24:9* 24(9):1653–1674. https://doi.org/10.1007/S11367-019-01583-0

[41] Scrivener KL, John VM, Gartner EM (2018) Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cement and Concrete Research* 114:2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

[42] IEA and WBCSC (2018) Technology Roadmap - Low-Carbon Transition in the Cement Industry. Available at https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

[43] EPA (2021) U.S. Cement Industry Carbon Intensities (2019). Available at https://www.epa.gov/system/files/documents/2021-10/cement-carbon-intensities-fact-sheet.pdf

[44] Marceau ML, Nisbet MA, VanGeem MG (2006) Life Cycle Inventory of Portland Cement. PCA R&D. (Portland Cement Association, Skokie, IL), 2095, p 69. Available at http://large.stanford.edu/courses/2016/ph240/pourshafeie2/docs/marceau-2007.pdf

[45] Boesch ME, Hellweg S (2010) Identifying Improvement Potentials in Cement Production with Life Cycle Assessment. *Environmental Science & Technology* 44(23):9143–9149. https://doi.org/10.1021/es100771k

[46] Kellenberger D, Althaus H-J, Künniger T, Lehmann M, Jungbluth N, Thalmann P (2007) Life Cycle Inventories of Building Products. Ecoinvent report. (Ecoinvent Centre, Dübendorf, Switzerland), 7, p 914. Available at https://belglas.com/wp-content/uploads/2019/01/07_buildingproducts.pdf

[47] Künniger T, Werner F, Richter K (2000) Oekologische Bewertung von Kies, Zement und Beton in der Schweiz. Analyse und Bewertung von Sachbilanzdaten der Schweizerischen Kies-, Zement- und Betonindustrie. (EMPA, Dübendorf, Switzerland), p 173. Available at https://www.dora.lib4ri.ch/empa/islandora/object/empa:34086

[48] Athena Sustainable Materials Institute (2021) Portland Cement Association Life Cycle Inventory Summary Report. (Athena Sustainable Materials Institute, Ottawa, ON), p 22.

[49] NREL (2024) USLCI. Available at https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI_Database_Public/datasets

[50] Portland Cement Association (2023) Environmental Product Declaration: Portland Cement. (Portland Cement Association, Skokie, IL), p 13. Available at https://www.cement.org/a-sustainable-future/reaching-our-goal/quantifying-environmental-impact/#chapter=chapter4

[51] Mukherjee A (2024) Personal communication.

[52] Athena Sustainable Materials Institute (2005) Cement and Structural Concrete Products: Life Cycle Inventory Update #2. (Ottawa, ON), p 31. Available at https://www.athenasmi.org/resources/publications/

[53] Venta, Glaser & Associates (1999) Cement and Structural Concrete Products: Life Cycle Inventory Update. (Ottawa, ON), p 34. Available at https://www.athenasmi.org/resources/publications/

[54] Canada Centre for Mineral & Energy Technology and Radian Canada Inc (1993) Raw Material Balances, Energy Profiles and Enviromental Unit Factor Estimates. (Ottawa, ON), p 117. Available at https://www.athenasmi.org/resources/publications/

[55] Athena Sustainable Materials Institute (2022) A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members – Version 3.2. (Athena Sustainable Materials Institute, Ottawa, ON), p 101. Available at https://www.nrmca.org/wp-content/uploads/2022/02/NRMCA_LCAReportV3-2_20220224.pdf

[56] Hasanbeigi A, Srinivasan P, Chen H, Esram N (2024) Adoption of Limestone Calcined Clay Cement and Concrete in the U.S. Market. (ACEEE and GEI., Washington DC), p 68. Available at www.aceee.org/research-report/i2401.

[57] Fazio S, Pennington D (2006) Kaolin coarse filler; Production; at plant (Location: EU-27). Available at http://data.europa.eu/89h/jrc-eplca-4a1ebe7c-6835-4a22-8b2e-3201f1cd32e8

[58] Sánchez Berriel S, Favier A, Rosa Domínguez E, Sánchez Machado IR, Heierli U, Scrivener K, Martirena Hernández F, Habert G (2016) Assessing the environmental and economic potential of Limestone Calcined Clay Cement in Cuba. *Journal of Cleaner Production* 124:361–369. https://doi.org/loss

[59] NST/ASTM (2020) PCR for Slag Cement v2.0. Available at https://www.slagcement.org/_files/ugd/7a9259_a725895f5104489c9f89bc1bcab01411.pdf

[60] Athena Sustainable MAterials (2021) An Industry Average Environmental Product Declaration for Slag Cement. Available at https://www.slagcement.org/_files/ugd/7a9259_077074050db442d2a001cd2d2fdc2afc.pdf

[61] Dunlap R (2003) Life Cycle Inventory of Slag Cement Concrete CTL Project No. 312012. Available at https://web.archive.org/web/20131001104528/http://www.slagcement.org/Sustainabilit

y/pdf/Slag%20Cement%20Concrete%20LCI%20Letter%20Report%20August%2011%202003.pdf

[62] NST/ASTM (2023) PCR for Construction Aggregates. Available at https://d2evkimvhatqav.cloudfront.net/documents/PCR-Product-Category-Rules/NSF-1126-23.pdf?v=1701797591

[63] Miller L, Ciavola B (2024) Life Cycle Assessment of Construction Aggregates. (National Stone, Sand & Gravel Association, Alexandria, VA), p 48. Available at https://www.nssga.org/sites/default/files/2024-08/Construction_Aggregates_LCA_Report_v3.pdf

[64] National Center for Sustainability Standards (2020) PCR for Gypsum Panel Products. Available at https://d2evkimvhatqav.cloudfront.net/documents/pcr_gypsum_panel_products_2019_1.1.pdf?v=1594929936

[65] NSF Certification, LLC (2020) An industry average cradle-to-gate EPD for 5/8” Type X Conventional Gypsum Board produced by Gypsum Association member companies for the USA and Canadian Markets. (NSF International, Ann Arbor, MI), 10270, p 23. Available at https://www.usg.com/content/dam/USG_Marketing_Communications/united_states/product_promotional_materials/finished_assets/2020-type-x-wallboard-epd-en.pdf

[66] Bushi L, Meil J (2010) A Cradle-to-Gate Life Cycle Assessment of ½” Regular and 5 /8” Type X Gypsum Wallboard. (Athena Sustainable Materials Institute, Ottawa, ON), p 152. Available at https://gypsum.org/wp-content/uploads/2019/05/15_Gypsum_Wallboard-1_2-in-Regular-5_8-in-Type-X.pdf

[67] Athena Sustainable Materials Institute (2020) An Industry Average Cradle-to-Gate Life Cycle Assessment of 1/2” Lightweight and 5/8” Type X Conventional Gypsum Board for the USA and Canadian Markets. (NSF International, Ann Arbor, MI), p 52. Available at https://www.athenasmi.org/wp-content/uploads/2020/05/GypsumAssociation-IndustryAverage-CradleToGate-LCA-GypsumBoard-USA-CAN.pdf

[68] National Gypsum Company (2006) Material Safety Data Sheet - Gold Bond® BRAND Ball Mill Accelerator. Available at https://sweets.construction.com/swts_content_files/146/E807973.pdf

[69] Smart EPD (2024) PCR for Supplementary cementitious materials. Available at https://smartepd.com/pcr-library

[70] Tasker J, Amuda MOH (2017) Austenitic Steels: Non-Stainless. *Reference Module in Materials Science and Materials Engineering* (Elsevier). https://doi.org/10.1016/B978-0-12-803581-8.09206-7

[71] Farjana SH, Huda N, Mahmud MAP, Lang C (2019) A global life cycle assessment of manganese mining processes based on EcoInvent database. *Science of The Total Environment* 688:1102–1111. https://doi.org/10.1016/j.scitotenv.2019.06.184

[72] UL Environment (2021) Environmental Product Declaration - Fabricated Steel Plate. Available at https://www.aisc.org/globalassets/why-steel/epd-aisc-plate-2021.pdf

[73] Rybl V, Montalbo T, Liddie J, Kanekar H (2020) Life Cycle Inventory of North American Steel Products. (Sphera/AISI), p 47. Available at https://shop.steel.org/products/life-cycle-inventory-lci-report

[74] ERG, NREL (2024) Data Gap and Data Quality Analysis Final Report., p 22. Available at https://github.com/FLCAC-admin/FLCAC-docs/blob/b45875cf70d0b464b2333d72d00d64173c058d23/docs/resources/FLCAC%20Data%20gap%20and%20quality%20workflow_final.pdf

[75] Defourny J, Thorbecke E (1984) Structural Path Analysis and Multiplier Decomposition within a Social Accounting Matrix Framework. *The Economic Journal* 94(373):111–136. https://doi.org/10.2307/2232220

[76] Xie R, Zhao Y, Chen L, Xie R, Zhao Y, Chen L (2020) Structural path analysis and its applications: literature review. *National Accounting Review* 2(1):83–94. https://doi.org/10.3934/NAR.2020005

[77] Office of Management and Budget (2022) North American Industry Classification System. Available at https://www.census.gov/naics/

Appendix A. List of Abbreviations

ACLCA
American Center for Life Cycle Assessment

AP
Acidification potential

ASMI
Athena Sustainable Materials Institute

CC
Calcined clay

EGEE
ethylene glycol monoethyl ether

EP
Eutrophication potential

EPA
Environmental Protection Agency

EPD
Environmental Product Declaration

EPLCA
European Platform on Life Cycle Assessment

FEDEFL
Federal Elementary Flow List

FHWA
Federal Highway Administration

FLCAC
Federal LCA Commons

DOE
Department of Energy

GGBFS
ground granulated blast furnace slag

GHG
Greenhouse gases

GSA
General Services Administration

GWP
Global Warming Potential

IPCC
International Panel on Climate Change

ISO

International Standards Organization

LC3
limestone calcined clay cement

LCA
Life Cycle Assessment

LCI
Life Cycle Inventory

LCIA
Life Cycle Impact Assessment

LEED
Leadership in Energy and Environmental Design

MTU
Michigan Technological University

NREL
National Renewable Energy Laboratory

NRMCA
National Ready-Mix Concrete Association

NSSGA
Natural Stone, Sand, and Gravel Association

ODP
Ozone depletion potential

OPC
ordinary Portland cement

PCA
Portland Cement Association

PCR
Product Category Rule

PLC
Portland-limestone cement

POCP
photochemical oxidant creation potential

RMC
ready-mix concrete

RoW
Rest of World

SCM
supplementary cementitious materials

SPA
structural path analysis

USEEIO
US Environmentally Extended Input-Output

USLCI
US Life Cycle Inventory

Appendix B. Supplemental Material

The following workbooks were built for and used during the data gap analyses presented here and are available at XXXXX.

1) **ecoinvent to USLCI**: Includes the approximate equivalents between ecoinvent and USLCI used throughout the data analyses in these reports. These are split between the worksheets:
   - Technosphere: Product to product equivalent. Indicates the flow and the process that produces it (provider in openLCA). When the flow is available in USLCI, but there is no production, the cutoff flow is used. If the cutoff flow was not available in USLCI, one was created and labeled as cutoff flow (New).
   - Waste: As in Technosphere, but instead of provider, the categories where the flows/processes can be found are detailed. Note that waste treatment processes are not yet properly modeled in USLCI and those present are effectively dummy or empty processes.
   - Technosphere to resource: ecoinvent product to FLCAC elementary flows (resources). Used when the processed product is not available in USLCI.
   - Emissions: Offers guidance on specific ecoinvent elementary flows that were not appropriately mapped.

The “models” worksheets below include the following information regarding the models built through the data gap analyses of this report: Flow, provider (process) or category in case there is no actual process providing the flow or when they are elementary flows, and additional modeling information. Flows in *italics* were identified as data gaps. Quantities are explicitly excluded, but they can be found in the original USLCI and ecoinvent models. The quantities for the models based on the representative inventories can be found in their respective source reports and, for the model using USLCI processes referenced at the end of this appendix.

2) **Cement models**: Includes OPC#1-7, OPC#1 ALT, QUARRY#1-7, and CLINKER#3-7.
3) **RCM models**: Includes RCM#3-#7.
4) **LC3 models**: Includes CLAY#1, CLAY#3-4, CC#3-6, LC3#5-6, plus a worksheet on how the “Calcination Energy” was calculated.
5) **Slag cement models**: Includes SLAG#3-6
6) **Aggregate models**: Includes NATURAL#3-4, CRUSHED#3-6, wo EXPLOSIVES#5-6, and w EXPLOSIVES#5-6.
7) **Gypsum models**: Includes GYPSUMBOARD#1, GYPSUMBOARD#3-7, GYSUMORE#3-7, FACING PAPER#5-7, BACKING PAPER#5-7, ACCELERATOR#5-6.
8) Gap summary forms the numerical basis for Section 4 and contains the following four worksheets:
   - **TOTAL**: Includes the GWP of all the data gaps quantified in 25 models.

- **UNIQUE**: Includes in column B a list of all unique data gaps identified in the "TOTAL" worksheet. Columns C:D use the data in column B as well as in the "TOTAL" spreadsheet to quantify in how many models the gap is present (# models, column E), what is the largest relative gap in GWP terms for this process (Column D, Max GWP), and which model the largest gap can be found (Model with Max GW, column F). This information is the basis for Table 46Max GWP indicates the largest contribution to the GWP of a model. Model with Max GWP is the model in question, while # of model stands for the number of models where this data gap was identified. Gaps in *italics* were also identified in the EPA data gap analysis [27]
- Table 47Table 48Table 49.
- **EPA**: Is a worksheet copy of the data gap analysis presented in [27], used to develop the worksheet "EPA condensed" below.

EPA Condensed: Summarizes the content of the "EPA" worksheet, including only those product categories evaluated in this report, and it is the bases for Table 50. In addition, the following models based on the representative inventories and built using USLCI processes are available in the NIST repository on the FLCAC at XXXXX. Note there are no models for LC3 or Slag Cement, as these rely partially on ecoinvent inventories.

- QUARRY#5
- CLINKER#5
- OPC#5
- RMC#5
- wo EXPLOSIVES#5
- w EXPLOSIVES#5
- GYSUMORE#5
- FACING#5
- BACKING#5
- GYPSUMBOARD#5

Appendix C. Data gap analysis with additional impact categories

Considering multiple impact categories in evaluating LCI data gaps will provide a more holistic analysis that could lead to changes in prioritization rankings. To illustrate the importance of multi-impact assessment evaluation, the representative RMC 3000 psi inventory built with the commercial database (model RMC #6) is rerun, but this time modeling LCIA results for each of the five impact categories included in the ISO 21930 LCIA methodology: acidification (AP), eutrophication (EP), ozone depletion (ODP), climate change (GWP), and photochemical oxidant creation (POCP) potentials. Figure 34 illustrates that while general trends might be observed across categories—e.g., cement is the main source of impact in all five of them—contributions on a percentage basis vary.

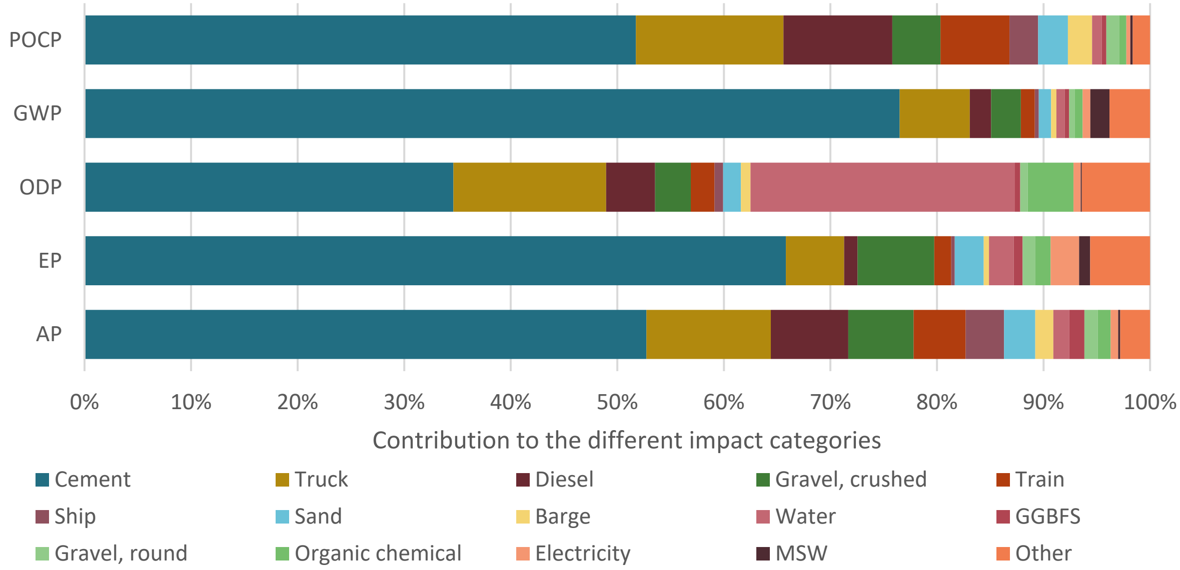


Figure 34 Contribution to the ISO 21930 LCIA impact categories for model RMC#6. Only flows contributing more than 1% to one of the impact categories are shown individually, the rest are combined in "Others"

The contribution of the data gaps to the different impact categories for RMC #6 is presented in Table 52. The identified data gaps are the smallest on a percentage basis for GWP, which has been the focus of this study. The percentage contribution of the data gaps for two of the other four impact categories, eutrophication and ozone layer depletion, is more than double that of GWP. All data gaps excluding linear alkylbenzene sulfonate and hazardous waste incineration contribute more than 1 % to at least one impact category. Additionally, tap water contributes 26.1 % to ozone depletion. This example shows that "environmental hotspot" and "key data gap" is not necessarily synonymous with "large source of GHG." Thus, it should be emphasized that this study only used GWP in the qualitative prioritization ranking and further research should consider how to incorporate additional impact categories into the methodology to provide a more robust, holistic ranking approach.

Table 52 Percentage contribution to the ISO 21930 LCIA impact categories for RMC#6

	AP	**EP**	**ODP**	**GWP**	**POCP**
Crushed gravel	6.27	7.59	3.53	2.89	4.57
MSW incineration	0.19	1.11	0.10	1.87	0.23
Sand	3.00	2.88	1.75	1.21	2.83
Tap water	1.55	2.45	26.10	0.82	0.93
Organic chemical	1.22	1.54	4.52	0.78	0.68
Gravel, round	1.29	1.24	0.76	0.52	1.22
GGBFS	1.44	0.87	0.52	0.43	0.43
Linear alkylbenzene sulfonate	0.06	0.05	0.09	0.02	0.03
Hazardous waste incineration	0.01	0.02	0.03	0.01	0.00
TOTAL	**15.03**	**17.75**	**37.40**	**8.56**	**10.92**

AP: acidification potential, EP: eutrophication potential, ODP: Ozone depletion potential, GWP, global warming potential, POCP: photochemical oxidant creation potential

Appendix D. Data gap analysis using mass and energy inputs

ISO 21930 establishes the foundation for PCRs of construction materials. Section §7.1.9 indicates that "Particular care should be taken to include materials and energy flows […] that contribute significantly to any of the pre-set indicators," those indicators being the five impact categories included in Appendix C: acidification, eutrophication, ozone depletion, greenhouse gases, and photochemical oxidant creation. Subsequently, it defines the cut-off criteria for data gaps as "1 % of renewable primary […] energy, 1 % non-renewable primary […] energy, 1 % of the total mass input […] and 1 % of environmental impacts".

Appendix C shows that that including more impact categories could expand the list of data gaps over the cut-off criteria of "1 % of the impact". In this appendix, the mass and energy cut-off criteria are applied to the 25 models used to quantify data gaps using GWP (see Section 4). The purpose of this analysis is to identify additional data gaps that might meet the other thresholds despite being under the 1 % threshold in terms of GWP. As shown in Table 53, all identified flows are materials as no energy flow contributes more than 1 % to any process identified as a data gap.

Table 53 Gaps identified using 1% of mass and energy input as cutoff criteria. Models not included in the table did not present additional data gaps.

Model	"New" gaps	Gaps over 1 % mass but not GWP
CLINKER#4	Water*	Tap water
CLINKER#6	Fly ash and scrubber sludge Chalk Limestone residue	Clay Sand Shale Tap water
OPC#2		Gypsum Clay Sand Shale Tap water
OPC#6		Gypsum Tap water
RMC#4		Tap water
RMC#6	Fly ash and scrubber sludge	Organic chemical Round gravel Tap water
GGBFS#4	Water*	
GGBFS#6	Water*	
NATURAL#4	Water*	
CRUSHED#4	Water*	
CRUSHED#6	Water*	Tap water
GYPSUMORE#6		Tap water Process water
FACING#6		Tap water
BACKING#6		Tap water
GYPSUMBOARD#4	Water*	Tap water
GYPSUMBOARD#6	Waste gypsum	Tap water

* Water is not a new data gap as it was previously identified as tap water. However, these are instances in which water appears as a natural resource and not as product from the technosphere.

Using these alternative thresholds, five “new” data gaps were identified: two elementary flows (water and chalk) and three waste inputs (fly ash and scrubber sludge, limestone residue, and waste gypsum). These elementary and cut-off flows (flows without a process model producing or treating them) had already been identified as data gaps in previous analysis. However, by their nature as elementary and cut-off flows, the GWP impact for these flows could not be quantified. Therefore, these flows do not appear in the discussion in Section 4. Thus, using mass and energy thresholds could be a useful alternative to evaluate the potential importance of data gaps not appearing in any available database. Of these five data gaps, “Water” is different because it has already been identified as a key data gap in multiple models as “tap water”. Here however, “Water” refers to water reported as a natural resource input, and although the distinction is appropriate, it could indicate “tap water” (or any other process providing process water) could be a better modeling alternative because the supply of water to an industrial process is not without impact.

Table 53 also identifies, for each process modeled, data gaps whose GWP impact is less than 1 %, but whose mass (as they are all material flows) represent more than 1 % of the material inputs to each process. “Tap water” is the most common, indicating water procurement could be considered a key environmental flow even for those processes in which its contribution to GWP is considered small. Similarly, clay and sand had been identified already as key data gaps in Section 4, but are above the mass-based threshold for additional models. Three gaps that are not included in Section 4 but included with a mass-based threshold are “organic chemical,” “gypsum,” and “shale” because of their low GWP.

In summary, the mass and energy cut-off criteria offer additional metrics to identify priority data gaps. Unlike contributions to an impact category, it does not rely on an alternative database and can, therefore, be conducted using only USLCI. However, using an approach that considers a combination of criteria for mass, energy, and impact will provide the most robust, holistic data gap assessment because each provides unique insights. For example, impact category results can highlight data gaps used in small quantities, but generating significant impacts. Additionally, mass and energy cut-off criteria exclude outputs, and therefore generated wastes, and inputs not measured in terms of mass (e.g., capital goods). These two groups, waste and capital goods, were identified as significant data gaps in Section 4.